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Water flows on Cooper Creek in arid Australia determine 'boom' and 'bust' periods for waterbirds

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Abstract

Cooper Creek is probably the longest and most important dryland river in Australia and one of the largest endorheic catchments in the world. Long dry periods ('busts') are punctuated by floods of high productivity ('boom' periods). Data on waterbird distribution and abundance were collected during a boom period (1989/1990 flood) when Cooper Creek ran into Lake Eyre and overflowed into Strzelecki Creek to fill Lake Blanche. There were about 500 000 waterbirds in December 1990: Lower Cooper (138 000), Lake Eyre (325 000), Lake Blanche (40 000). Given underestimates of aerial surveys, conceivably there were one million waterbirds, making the area one of the most important for waterbirds in Australia. Colonies of Australian pelicans, cormorants, black swans, terns and silver gulls established during this flood. We used flow data and rainfall to estimate how often such habitat (boom periods) is created over a 100-year period, 1885–1995. Rainfall (cumulative index of four rainfall stations—Muttaburra, Tangorin, Isisford and Innamincka), was significantly related to total annual flow (ML), measured at Cullamurra ($R^2 = 0.86$). We estimated that the Lower Cooper (south of Lake Hope) receives water about every 4.5 years but these floods seldom reach Lake Eyre (8 years in 100 years). There is water in Lake Hope and the Lower Cooper Creek: respectively, 62% and 39% of the time. Cooper Creek overflowed into Strzelecki Creek when there were large floods (1906, 1950, 1974) or two or more consecutive years of high flows (1916–1918, 1955–1956, 1989–1990). Lake Blanche filled six times and Lake Callabonna filled four times in 100 years. Occasionally, local rainfall also fills lakes (e.g. Lake Callabonna in 1931). Like all terminal river systems, these wetlands depend predominantly on upstream flows of water. Potential irrigation developments in the catchment will divert water from the river and decrease the frequency and flooding of wetlands of the Lower Cooper. There will be fewer feeding areas and less breeding opportunities for waterbirds. Boom periods will be shorter and bust periods longer.

Keywords: Waterbirds; Wetlands; Arid; Irrigation; Cooper Creek; Flow

1. Introduction

About 70% of Australia is arid, receiving less than 200–500 mm mean annual rainfall (Comin and Williams, 1994). This area has many wetlands supplied by dryland rivers which fill during episodic rainfall events that are highly unpredictable in space and time (Stafford Smith and Morton, 1990). Running from north to south down the centre of the continent is Cooper Creek (Fig. 1) which is the longest and probably most important dryland river in Australia. Floods on the river fill many thousands of hectares of wetlands.

There is increasing pressure on rivers such as Cooper Creek to divert water for irrigation (Walker et al., 1997; Kingsford et al., 1998). In Australia, about 70% of water diverted is for irrigated agriculture and the majority of this is in the southeast of the continent, in the Murray–Darling Basin (Wasson et al., 1996; Crabb, 1997). Flow in Cooper Creek has not yet been affected by diversion of water for irrigated agriculture or major dams or weirs (Morton et al., 1995) but elsewhere in the Murray–Darling Basin, regulation of rivers and diversion for irrigation has caused considerable impacts on river hydrology and wetland ecosystems (Walker, 1985; Kingsford, 1995a). In 1995, a threat to Cooper Creek came in the form of a proposal to pump 42 000 megalitres of water annually to irrigate cotton at Currareva (Walker et al., 1997). The proposal overcame the problem of accessing highly variable flows on a dryland river. Large pumps (> 600 mm diam.) would be switched on during floods and the water transferred into constructed storages on the floodplain (Kingsford et al., 1998). In April 1998, the Queensland Government released a flow management plan that if fully implemented would

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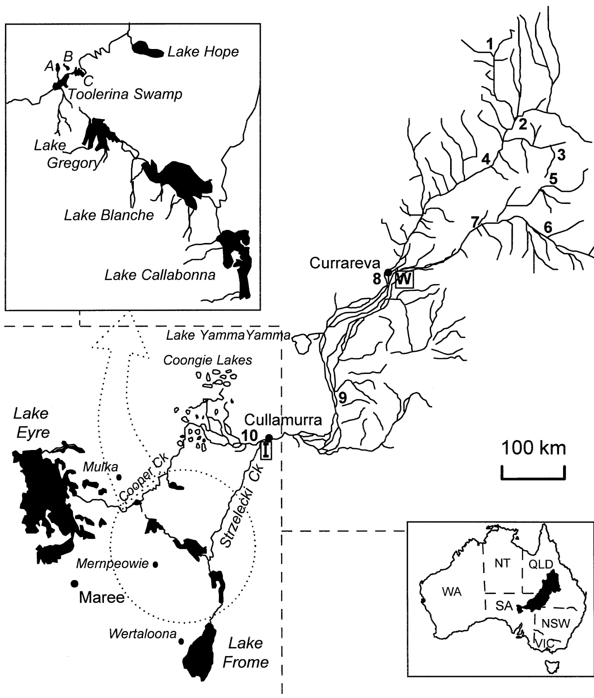

Fig. 1. Significant wetlands filled by Cooper Creek in Central Australia. Top left insert shows area of focus for this study. Hydrological data were from flow gauges at Cullamurra and Currareva. A, B and C are Lakes Killalpaninna, Kooperamanna and Killamperpunna, respectively. Numbers 1 to 10 are rainfall stations: 1, Tangorin; 2, Muttaburra; 3, Aramac; 4, Longreach; 5, Barcaldine; 6, Blackall; 7, Isisford; 8, Windorah; 9, Durham Downs; 10, Innamincka. I is the town Innamincka and W is Windorah.

result in a maximum diversion of 390 000 megalitres per annum at the junction of the Barcoo and Thomson Rivers for irrigation (DNR, 1998).

Relatively little is known about biological processes on dryland rivers such as Cooper Creek (Comìn and Williams, 1994) because our knowledge is geographically and culturally biased (Williams, 1988; Kingsford, 1995b). Even less is known about the impacts that proposals to divert water may have on floodplains and their biota. Anthropogenic impacts on aquatic ecosystems only become apparent many years after upstream impacts have taken effect (Micklin, 1988; Wiens et al., 1993; Kingsford and Thomas, 1995; Green et al., 1996), when there is relatively little hope of radically changing management or reversing impacts if we could (Kingsford, 1999).

Flows in dryland rivers, such as Cooper Creek, are primarily dependent on highly variable and unpredictable rainfall patterns in their catchments. Episodic flooding events drive biological processes (Ruello, 1976; Briggs and Maher, 1985; Briggs et al., 1985; Maher and Carpenter, 1984; Puckridge et al., 1998) which begin a sequence of events that often culminates in waterbird breeding at the height of a dryland river's biological productivity (Crome, 1986). The productive pulse may be brief as high evaporation rates take effect and wetlands dry out. Invertebrates die or encyst (Williams, 1987), some frogs burrow and encase themselves (Lee and Mercer, 1967), fish die (Ruello, 1976) and waterbirds probably move on (Briggs, 1992).

Floods on Cooper Creek create habitats that support large numbers of waterbirds (Kingsford and Porter, 1993; Kingsford and Halse, 1998) and sometimes spectacular breeding events (e.g. Lake Eyre—Badman, 1991; Burbidge and Fuller, 1982; Bellchambers and Carpenter, 1990; Waterman and Read, 1992; Kingsford and Halse, 1998). The aim of this study was to investigate the periodicity of these wet and dry periods, the 'boom' and 'bust' cycles and report on the responses of waterbirds on the lower part of Cooper Creek (Lower Cooper), which included Strzelecki Creek and its wetlands. To do justice to such a variable system, we extended the existing flow record by deriving estimates for Cooper Creek for the 100-year period, 1895–1995, to determine how often wetland habitats are created. Impacts of proposals to divert water upstream were then examined to determine potential effects on these wetland ecosystems and their waterbirds, drawing on examples from other river systems where ecological impacts are apparent.

2. Methods

2.1. Study area

Cooper Creek begins in south-western Queensland and ends in Lake Eyre (Fig. 1), the fifth largest salt lake in the world (Dulhunty, 1990). The region is semi-arid to arid with median annual rainfall less than 200 mm (Kotwicki, 1986). The driest areas are close to Lake Eyre. Average maximum temperatures are 18–24°C in July and 36–39°C in January (Kotwicki, 1986). Summer temperatures often exceed 45°C (Badman, 1989). Annual evaporation rates are high: 2000–3600 mm (Bonython, 1955; Specht, 1972; Kotwicki, 1986; Williams and Kokkinn, 1988).

Cooper Creek begins in the semi-arid region of the continent. It is a region characterised by highly variable rainfall, a flat landscape with highly weathered soils which are usually poor in nutrients (Stafford Smith and Morton, 1990). The landscape tends to be dominated by long-lived perennial plants (shrublands). Floodplain eucalypts, mainly river red gum *Eucalyptus camaldulensis*, grow on the margins of the river. Lignum *Muehlenbeckia florulenta*, a perennial aquatic plant that can form a dense bush, dominates the floodplain and swamps and remains a permanent feature during the dry periods.

The Cooper Creek catchment covers 306 000 km^2 (Graetz, 1980). This study was confined to the terminal part of the Cooper Creek catchment: the lower half of Cooper Creek from Lake Hope to Lake Eyre (Lower Cooper) (Fig. 1). It also included three temporary lakes in north-eastern South Australia: Lake Blanche (29°15′S, 139°40′E), Lake Callabonna (29°39′S, 140°03′E), supplied by Strzelecki Creek and Lake Hope (28°23′S, 139°17′E) on Cooper Creek (Fig. 1). Strzelecki Creek has a relatively simple floodplain compared to Cooper Creek (Graetz, 1980). Depending on flow magnitude, about 30% of the flow volume in Cooper Creek at Currareva reaches the Coongie Lakes (see Fig. 1) (Knighton and Nanson, 1994) which usually have water (Reid and Puckridge, 1990). How much water then flows on to fill Lake Hope and the wetlands of the Lower Cooper is not known, but floods only reach Lake Eyre from Cooper Creek about once every 6 years (Kotwicki, 1986).

2.2. Waterbird surveys

Most of the waterbird data reported in this study are from the period 1990/1991, following the 1989/1990 flood on Cooper Creek which was the last major flood to reach Lake Eyre (Kingsford and Porter, 1993). It took about a month to reach Lake Eyre from Lake Hope (Kingsford and Porter, 1993). During such large floods, the river fills a string of lakes south of Lake Hope (e.g. Killamperpunna, Kopperamanna, Pandruannie, Warrawarrina, Killalpannina) and a large lignum swamp (Toolerinna Swamp). Aerial surveys of waterbirds on wetlands in the study area were flown at 2-month intervals, between August 1990 and February 1991: 8–12 August, 12–13 October, 17–19 December and 12–13 February. Aerial surveys of Lakes Hope, Killamperpunna, Kopperamanna and Killalpannina (Fig. 1) were also flown in October of each year between 1983 and 1997 when they had water.

Aerial surveys of waterbirds are briefly described here (for further descriptions see Kingsford and Porter, 1993, 1994). The method used to count birds was dependent on the size and shape of the wetland. In general, the aircraft was flown within 150–200 m of the shore; observers recorded birds within a 400-m band around the edge of the lake or along the creek where most birds are found (Kingsford and Porter, 1994).

Surveys of Lake Blanche in August, October and December were flown within 150–200 m of the shore because the lake was mostly open water. In August 1990, the lake had a pH of 8.5, salinity of 300–400 ppm and appeared full (0.5 m depth) although Strzelecki Creek was flowing strongly (Drewien and Best, 1992). The proportions of the lake counted during aerial surveys were estimated, to account for small inlets around which the aircraft could not be flown. This was used to calculate final numbers of waterbirds. During these surveys in August, October and December, 20 random blocks of 3390 m^2 (200-m-wide transect flown for 30 s) were counted along a longitudinal (north-east to south-west, see Fig. 1) transect over the open water that ran down the middle of the lake. The beginning of the transect was randomly determined on the short axis along the north-western shoreline and the transect then flown parallel to the long axis of the lake. Transects determined numbers of waterbirds in the centre of the lake. In addition for December surveys, after flying the perimeter, islands were surveyed by flying around each within 150–200 m of their shorelines.

In February 1991, Lake Blanche was a collection of hundreds of islands. Twenty random transects were counted across the lake, perpendicular to the long axis. Each transect was 200 m wide. To form each 200-m transect, the two observers estimated waterbirds in a 100-m band on each side of the aircraft, determined by markers on the struts of the aircraft. Transects were flown at a constant height of 46 m above ground and a constant speed of 100 knots. Totals and variances for each waterbird species were calculated using variable transect lengths separately for each day (Caughley, 1977).

Another survey team collected data from Lake Blanche on the ground on 18 August, 14–17 October, 18–19 December, 27–28 January 1991. Counts were made using telescopes from five accessible sites: 29°16′S, 139°32′E (Aug.); 29°18′S, 139°33′E (Oct., Dec., Jan.); 29°23′S, 139°39′E (Oct.); 29°27′S, 139°45′E (Aug., Oct., Dec., Jan.); 29°23′S, 139°48′E (Dec., Jan.), 29°22′S, 139°51′E (Dec., Jan.). The numbers and species of small and large wader species were collected over a 2-h period at each site.

The Lower Cooper was surveyed in December 1990 and February 1991 from Lake Eyre to Lake Hope (Fig. 1). Lake Hope was also counted in October 1990. A transect was flown across Toolerinna Swamp (28°40′S, 138°37′E) and counts extrapolated to form a total count for the swamp in December 1990 and February 1991. All wetlands along Cooper Creek from Lake Hope to Lake Eyre were partly counted. The counted parts of each wetland, which was 50% or more, was estimated at the time of survey and numbers of waterbirds derived.

All waterbird species at each wetland were totalled and a final estimate derived by adding the percentage of the wetland not counted during surveys. Where two total counts were done on consecutive days, a mean was calculated for each waterbird type and the difference between this and the two counts presented. Waterbirds were also split into four groups (see Appendix A), piscivores, ducks, herbivores and wading birds (Charadriiformes) to examine separately any changes in the abundance of different foraging communities (Lane, 1987; Barker and Vestjens, 1989; Kingsford and Porter, 1994).

Numbers of waterbirds' nests and broods breeding were also estimated during surveys. These included colonies, single nests and broods of waterfowl. Aerial photographs were taken of colonies of Australian pelicans, silver gulls, Caspian terns and gull-billed terns on Lake Blanche (in February). It was not possible to differentiate silver gulls and Caspian tern nests, so aerial counts of the respective adults of these species were used to determine what proportion of nests were silver gulls and Caspian terns.

2.3. Flooding history 1895–1995

There are three river flow gauges on Cooper Creek, Currareva, Nappa Merrie and Cullamurra with differing periods of flow data: respectively, 1940–1987; 1967–1989; and 1973–1990. Because Cullamurra is closest to Strzelecki Creek and Currareva has most data (Fig. 1), we focused on flow data at these points. As Cullamurra is the furthest point south downstream on the river, we began by deriving an annual flow data set for Cullamurra which covered the period 1940–1990, using Currareva flow data.

There are 14 years of common data (1974–1987). Initial analyses showed a linear model relating annual flows at Cullamurra and Currareva dominated by 2 years of data, 1974 and 1976, which were considerably higher (>1.8 km^3) than any other data points. We omitted these data points from initial analyses. For flows <1.8 km^3 ($n=12$), the relationship between the two gauges was best expressed by the equation:

$$\text{Cullamurra (km}^3) = 0.41 \times \text{Currareva (km}^3) - 180\ 141 \quad (R^2 = 0.81).$$

To determine larger flows (>1.8 km^3) a graph with distance weighted least squares smoothing was used on the full data set (Wilkinson, 1990).

We then focused on deriving flows in the river over a 100-year period, 1895–1995. Flows in Cooper Creek are primarily determined by rainfall in the catchment (Knighton and Nanson, 1994) and rainfall records exist for at least 100 years. We modelled the relationship between rainfall in the catchment and derived flows at Cullamurra for the period 1940–1990. A rainfall index (R_a in mm) was derived from cumulative combinations of annual rainfall for 10 stations, distributed predominantly in the upper catchment of Cooper Creek (see Fig. 1). The cumulative combination of rainfall stations included in the index were trialled to determine which combination best explained flow at Cullamurra. Cumulative rainfall for four stations, Tangorin and Muttaburra on the Upper Thomson River, Isisford on the Barcoo River and Innamincka (see Fig. 1) explained most variability in flow data at Cullamurra. We trialled polynomials of the various orders (1–4) to determine which curve best represented the data. The quadratic model fitted best.

$$\text{Cullamurra (km}^3) = 0.011 \times (R_a\ \text{(mm)} - 5875.03)^2 \quad (R^2 = 0.86).$$

This relationship was used to determine flows on Cooper Creek over the 100-year period, 1895–1995. Because we were primarily interested in major flows (i.e. ones that reached the Lower Cooper and Lake Blanche), we restricted analysis to points above the median rainfall index over the 100-year period (1895–1995). Published information (see Table 1) on when there was water in the Lower Cooper, Lake Eyre (from Cooper Creek), Lake Hope and Lakes Blanche, Gregory and Callabonna was used to estimate how often the Cooper Creek flowed into these major lakes over a 100-year period.

Also, as local rainfall can be an important contributor to flooding (Kotwicki, 1986), we derived a local rainfall index for the Lower Cooper and Lakes Callabonna and Blanche for the period 1895–1995. This was a cumulative rainfall index derived from rainfall records for Murnpeowie (29°37′S, 139°03′E), Mulka (28°21′S, 138°39′E) and Wertaloona (30°38′S, 139°20′E) Stations in north-eastern South Australia (Fig. 1). Missing data points for Mulka ($n=32$) and Murnpeowie Stations ($n=11$) were predicted from the relationship of rainfall at these localities to rainfall records for Maree ($R^2=0.75$ and 0.90, respectively). Missing data ($n=11$) for Wertaloona Station were predicted from nearby Arrowie Station ($R^2=0.91$). Rainfall at individual stations and the cumulative rainfall index were investigated to determine when local rainfall events may have contributed to flooding in wetlands of the study area.

Relatively little is known about duration of flooding of wetlands. Once completely filled Lake Hope holds water for 4 years (Badman, 1989) while some of the major lakes on the Lower Cooper are believed to retain water for up to 2 years (Bonython, 1971; Morton et al., 1995). Based on duration of flooding and analysis of flows, we predicted how long the major wetlands held water and so provided feeding and breeding habitat for waterbirds over the 100-year period, 1895–1995.

3. Results

3.1. 1989/1990 flood

In 1989, the flood on Cooper Creek reached Lake Hope but did not reach Lake Eyre until October 1990, augmented by the 1990 flood. The flood of 1990 caused widespread flooding of the wetlands on the Lower Cooper (94 000 ha) in August 1990. Strzelecki Creek filled Lake Blanche (73 300 ha) in March–April 1990 but did not fill Lake Gregory (18%—August 1990) to the north or Lake Callabonna to the south (13%—August 1990) (Fig. 1). These partly filled lakes were dry by October. Cooper Creek stopped flowing soon after it reached Lake Eyre. By February 1991, water was confined to the major freshwater lakes of the Lower Cooper and remained in some lakes until after October 1993. Between August and October 1990, the distribution

Table 1
Historical floods recorded on Lower Cooper Creek (1895–1995), Strzelecki Creek, Lake Blanche, Lake Gregory, Lake Callabonna and Lake Hope

Year	Extent of Cooper Creek flood	Breeding events
1898	Lower Cooper flood	
1906	To Strzelecki Creek and Lake Eyre[d]	
1917	Filled Lake Hope	
1918	To Lake Eyre[d]	BSW 10 000s and AVO 1000s probably Lake Blanche or Callabonna[b]
	Strzelecki Creek to Lake Blanche[a]	
1920	Lake Hope flood	
1923	Water in Lake Callabonna[b]	
1930	Lake Callabonna flooded from local rainfall[c]	
1931	Lake Callabonna flooded from local rainfall[c]	27 000 BST (n), 42 GBT (n), and AVO (n)[c]
	Cooper Creek half filled Lake Hope	
1936	Cooper Creek flooded	
1949	To Lake Eyre[d,e]	
1950	To Lake Eyre[d] Lake Hope flooded[e] Strzelecki Creek flooded Lakes Blanche, Gregory and Callabonna	
1951	To Lake Eyre[d,e]	
1954	To Birdsville Track[d]	
1955	Cooper Creek flooded from Queensland and heavy local rain[d]	GTL (u)[f]
1956	Cooper Creek flooded from Queensland and heavy local rain[d]	
1963	Cooper Creek flooded from Queensland and heavy local rain[d,g]	
1966	Lower Cooper Creek flooded from local rain[d]	
1971	Lake Callabonna flooded from local rainfall[h]	AVO 100s, RCP[h]
1974	To Lake Eyre[d]	PEL 200[j,k,l], SGU 10 000[m], WFH[l], WST[n], GBT[l], CST[o] Lake Eyre; FDU[d] andand BSW[p] Lower Cooper
	Strzelecki Creek flooded Lakes Blanche, Gregory and Callabonna[d]	AVO 100s[h] and RCP[h] Lake Callabonna
1975	Lake Callabonna flooded[h]	AVO 100s[h] and RCP[h] Lake Callabonna
1976	To Lake Eyre[d]	
1977	Lake Hope flooded[d] Lake Eyre flooded (Georgina flood)	PEL 4000[i] pair breeding Lake Eyre
1984	Local rain lower Cooper Creek[d]	PEL > 7000 (n)[q], PCO 50 (n)[q], AVO[s], SGU[s], GBT[s] CST[s] Lake Eyre, BSW Lake Gregory[d]

Breeding events are described for species as the number of nests (n) and number of broods (b). Unless otherwise stated the flooding events referred to are from Kotwicki (1986) (for references a–s and species codes see footnotes). Species codes: grebes, GRE; Australian pelican, PEL; greater cormorant, GRC; pied cormorant, PCO; little black cormorant, LBC; white-faced heron, WFH; yellow-billed spoonbill, YSB; freckled duck, FDU; black swan, BSW; grey teal, GTL; banded stilt, BST; red-necked avocet, AVO; red-capped plover, RCP; silver gull, SGU; whiskered tern, WST; gull-billed tern, GBT; Caspian tern, CST.

[a] Bonython (1971); [b]McGilp (1923); [c]McGilp and Morgan (1931); [d]Badman (1989); [e]Williams (1990); [f]Glover (1957); [g]Allan (1990); [h]Badman and May (1983); [i]Marchant and Higgins (1990); [j]Parker et al. (1979); [k]Dulhunty (1984); [l]Barker et al. (1989); [m]Cox and Pedler (1977); [n]Bonython and Fraser (1989); [o]Serventy (1985); [p]Ellis (1982); [q]Lane (1984); [r]Mossel, pers. comm.

of flooded area on Lake Blanche was similar. By December, the lake had dried back and created about 20 islands near the shore and down the middle of the lake. In February, the lake contained hundreds of small islands. Lake Blanche was dry in about a year. Lake Hope retained water for longest and did not dry up until after October 1994, more than 5 years after it had filled in 1989. No flood reached Lake Hope or the Lower Cooper after the 1990 flood until the time of writing.

3.2. Waterbird abundance and diversity

Forty-one species of waterbird were seen during aerial surveys. This number did not include those species that could not separately be identified to species (Appendix A). In December 1990, there were an estimated 178 000 waterbirds on the wetlands of the Lower Cooper (134 000) and Lakes Hope (4400) and Blanche (40 000). Most of these waterbirds (65%) were on Lower Cooper Creek. By February 1991, this number had risen to about 260 000 waterbirds. Nearly 60% of these were on Lake Blanche and the rest on Cooper Creek. Lake Gregory had water in August 1990 with 22 small waders. On Lake Callabonna, there were about 7700 banded stilts but few other birds.

More than 100 000 waterbirds were estimated on the wetlands of Lower Cooper Creek during aerial surveys in 1990 and 1991 (Table 2). Grey teal (34, 30%), pink-eared

Table 2
Aerial counts of waterbirds on Cooper Creek and Lake Hope

Waterbird	Lower Cooper		Lake Hope		
	December	February	October	December	February
Great crested grebe	0	0	0	0	1
Small grebes	245	167	0	0	212
Australian pelican	302	8328	218	25	80
Darter	5	160-1n	6	16	7
Great cormorant	596, 20n	1596, 308n	27	42	129
Pied cormorant	42	2006, 400n	31	172, 30n	161
Little black cormorant	78, 20n	23	3	83	42
Little pied cormorant	1	90	0	1	2
White-necked heron	0	10	0	0	1
White-faced heron	120	255	6	24	62
Great egret	12	462, 100n	0	1	5
Egrets	3	0	3	0	0
Glossy ibis	22	40	0	0	0
White ibis	3	1	0	0	0
Royal spoonbill	0	3	0	0	0
Yellow-billed spoonbill	478	179	3	12	59
Black swan	3774	3502	330	385, 4b	913
Freckled duck	86	6	0	0	0
Australian shelduck	55	209	94	16	5
Pacific black duck	3600	2863	260	16	65
Grey teal	45 728, 2b	29 569, 1b	1653	254	519
Australasian shoveler	498	46	6	4	0
Pink-eared duck	29 575, 3b	11 883	872	230, 3b	120
Hardhead	10 526	3422	138	178	316
Maned duck	1102	2869	14	1489	641
Blue-billed duck	2	0	0	0	0
Musk duck	6	26	0	0	7
Black-tailed native-hen	3635	13	6	505	0
Eurasian coot	24 048	22 078	212	467	3909
Brolga	3	10	0	0	0
Masked lapwing	66	115	48	14	27
Banded lapwing	341	91	0	0	10
Black-winged stilt	1946	232	114	0	10
Banded stilt	6	0	0	0	0
Red-necked avocet	2118	29	986	8	0
Small waders	2732	396	937	0	0
Large waders	0	35	0	0	0
Silver gull	1463	6750	656	408	113
Whiskered tern	625	539	138	2	212
Gull-billed tern	50	353	180	45	2
Caspian tern	332	696	24	65	91
Total	134 224	99 052	6965	4461	9052

On Cooper Creek, counts were done in December 1990 and February 1991. On Lake Hope, counts were done between October 1990 and February 1991. Estimates of nests (n) and broods (b) are given.

duck (22, 12%) and Eurasian coot (18, 22%) were the most numerous species in the two counts (Table 2). Many species showed dramatic changes in abundance (Table 2).

Thirty-seven species of waterbirds were recorded on Lake Blanche (Table 3). Estimated total numbers of waterbirds on Lake Blanche increased throughout the study from about 6000 in August 1990 to about 150 000 in February 1991 (Fig. 2). All broad foraging categories of waterbirds followed a similar pattern (Fig. 2). Most birds were distributed around the edge of the lake or islands. Only 2.0 and 8.8% of waterbirds in October and December, respectively, were to be found outside a 400-m band around the edge of the lake with only a few individuals in the middle of the lake.

Grey teal (32%), black swans (24%) and silver gulls (11%) were the most numerous among 25 waterbird species on Lake Blanche in August 1990, making up about 6000 waterbirds (Table 3). For small wading birds, five red-kneed dotterels and two red-capped plovers were seen during ground counts on 18 August 1990. By October, small waders (31%) were second only to grey teal (35%) in abundance (Table 3). Of 118 waders identified on the ground, red-necked stints comprised 59%; curlew sandpipers 17%; red-capped plover 13%; sharp-tailed sandpiper 9% and red-kneed dotterel 2%. Small waders (32%), grey teal (29%) and pink-eared duck (8%) were the more numerous of the waterbird species in December 1990. Of 55 small waders identified on the ground counts on 18–19 December, 76% were sharp-tailed sandpipers and 24% were red-capped plovers and there were two greenshanks. Most waterbirds in February 1991 were wading birds (Charadriiformes) (49%) and of this number most were small waders (68%) (Table 3, Appendix B). Of 52 small waders identified on the

Table 3
Mean aerial counts ($n=2$) of waterbirds on Lake Blanche

Waterbird	August	October	December	February[a]
Great crested grebe	0 (0)	0 (0)	0 (0)	26 (26)
Small grebes	34 (6)	1 (1)	0 (0)	638 (139)
Australian pelican	0 (0)	1 (1)	3 (1)	649 (117), 327n
Darter	0 (0)	0 (0)	3 (1)	0 (0)
Great cormorant	1 (1)	3 (3)	5 (5)	14 (7)
Little black cormorant	0 (0)	0 (0)	1 (1)	0 (0)
White-faced heron	2 (1)	3 (2)	6 (3)	154 (110)
Great egret	0 (0)	1 (1)	0 (0)	0 (0)
Egrets	0 (0)	1 (1)	0 (0)	0 (0)
Glossy ibis	0 (0)	1 (1)	15 (15)	0 (0)
Australian white ibis	0 (0)	0 (0)	1 (1)	0 (0)
Yellow-billed spoonbill	0 (0)	8 (2)	3 (1)	0 (0)
Black swan	1488 (244), 162n, 14b	572 (72), 36b	1327 (19), 19b	3410 (1687), 1n
Freckled duck	29 (26)	0 (0)	123 (123)	389 (366)
Australian shelduck	22 (4)	45 (9)	43 (38)	41 (19)
Pacific black duck	75 (6)	167 (42)	144 (9)	2057 (1375)
Grey teal	1995 (1336), 2b	4217 (528)	11 583 (2635)	46 207 (4649)
Australasian shoveler	32 (18)	6 (3)	76 (75)	180 (41)
Pink-eared duck	61 (28)	220 (41)	3145 (136)	9200 (2923)
Hardhead	373 (103)	91 (33)	310 (69)	2721 (2112)
Maned duck	1 (1)	0 (0)	2099 (1628)	2805 (759)
Blue-billed duck	2 (1)	0 (0)	0 (0)	0 (0)
Musk duck	0 (0)	0 (0)	0 (0)	11 (11)
Black-tailed native-hen	0 (0)	0 (0)	468 (222)	0 (0)
Eurasian coot	201 (193)	38 (38)	259 (224)	708 (85)
Brolga	0 (0)	0 (0)	3 (0)	0 (0)
Masked lapwing	5 (1)	9 (3)	36 (10)	151 (26)
Banded lapwing	5 (5)	44 (25)	272 (142)	202 (48)
Black-winged stilt	118 (75)	213 (14)	293 (125)	1016 (77)
Banded stilt	422 (242)	766 (115)	1640 (890)	14 861 (12 543)
Red-necked avocet	317 (52), 10n	715 (85)	866 (218)	8012 (649)
Small waders	344 (253)	3633 (1690)	12 703 (92)	50 669 (2123)
Large waders	6 (6)	4 (3)	0 (0)	92 (92)
Silver gull	708 (315)	744 (144)	996 (43), 6	4514 (554), 117n
Whiskered tern	8 (8)	24 (20)	313 (159)	389 (37)
Gull-billed tern	5 (4)	262 (74)	1392 (27), 50n	1537 (114)
Caspian tern	6 (0)	123 (35)	1509 (1085), 515n	2736 (103), 149n

Counts were done on consecutive days in August, October and December 1990 and February 1991. Figures in parentheses are the differences between counts and the mean. Estimates of nests (n) and broods (b) are given.

[a] Estimates were derived from transect counts (see Appendix B).

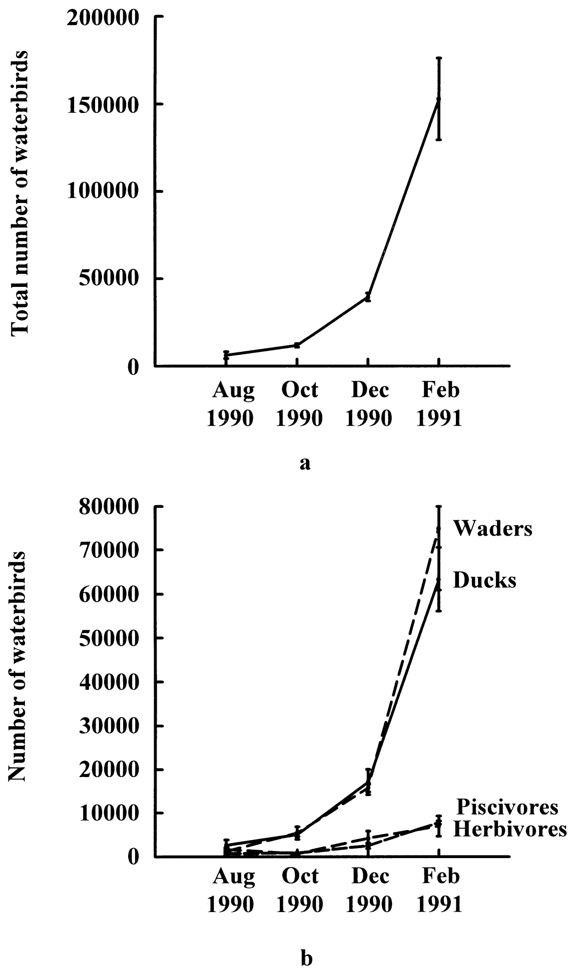

Fig. 2. (a) Total number of waterbirds counted on Lake Blanche from August 1990 to February 1991. (b) Four broad community groups of waterbirds recorded at Lake Blanche: wading birds, ducks (includes terns and grebes), piscivores and herbivores.

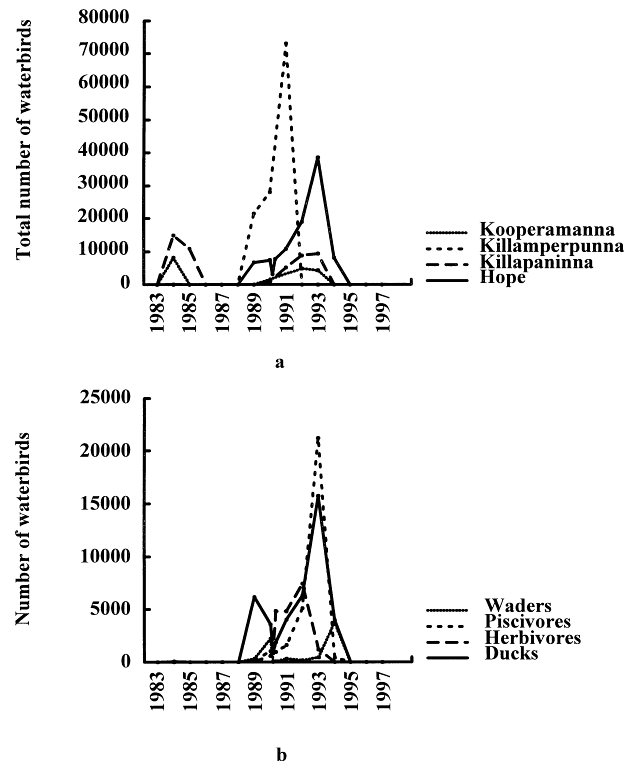

Fig. 3. (a) Total number of waterbirds counted on Lake Hope and Lakes Killapaninna, Killamperpunna and Kooperamanna on the Lower Cooper between 1983 and 1997. (b) Four broad community groups of waterbirds recorded at Lake Hope: wading birds, ducks (includes terns and grebes), piscivores and herbivores.

ground, 96% were sharp-tailed sandpipers and the rest were red-capped plovers and four greenshanks were also seen.

In the 14-year period between 1983 and 1997, Lake Hope had water for 5 years (1989–1994). The inflows were in 1989 and 1990 after which the lake received no more water; after filling, it took 4 years to dry out (Fig. 3). During this time it supported large numbers of waterbirds, particularly in 1993 (38 585). The main waterbird response was between 1991 and 1993 (Fig. 3a). Initially (1989), duck species were almost exclusively dominant with 4820 grey teal making up most of the birds (72%) on the lake (Fig. 3b). Numbers of all groups fell during the three counts of the 1990 flood (Fig. 3b). From February 1991 to October 1992 herbivores (7435), specifically coot, were the most common group but the abundance of herbivores fell in 1993, at least a year before the lake was dry (Fig. 3b). In contrast, piscivore populations were low between 1989 and 1991 and then rose rapidly so that, in 1993, piscivores (21 212) were the most abundant foraging group. Sixty-four per cent were great cormorants and 10% pied cormorants. Duck populations also peaked in 1993 (15 723) when the population was dominated by hardhead (79%). The number of piscivores and ducks declined dramatically in 1994, which was the year in which abundance of waders reached a maximum (3776) (Fig. 3b). The lake was extremely shallow and appeared to be hypersaline based on the smell and water clarity.

Lakes Killalpannina and Koppermanna filled from local rainfall in 1984 but the latter was dry in 1985 (Fig. 3a). Both supported about 10 000 waterbirds when they had water (Fig. 3a). The 1989 flood reached Lakes Koppermanna and Killamperpunna but not Lake Killalpannina which filled in the following year (Fig. 3a). Lakes Killalpannina and Koppermanna then held water until after October 1993, 4 and 5 years after filling and supported 5000–10 000 waterbirds (Fig. 3a). On Lake Killamperpunna waterbird numbers reached more than 70 000 in 1991 but the lake retained water for only 3 years after 1989 (Fig. 3a).

3.3. Waterbird breeding

The timing of breeding followed a different pattern on all lakes and varied among species. Twelve species bred

Table 4
Flow frequency from Cooper Creek, duration of flooding, period between annual flows (dry periods) and total time flooded in years for wetlands over the period 1895–1995 (all measures in years)

Wetland	Frequency	Duration	Dry periods[a]	Total time flooded[b]
Lake Hope	4.3	4	3 (0–7)	62
Lower Cooper	4.5	1–4	3 (0–11)	37 (2)
Lake Eyre[c]	12.5	1	10 (0–31)	8
Lake Blanche	14.0	1	13 (0–31)	7
Lake Callabonna	20.0	1	16 (0–43)	5 (4)

[a] Mean with range in parentheses.
[b] Flows from Cooper Creek with local rainfall in parentheses.
[c] From Cooper Creek.

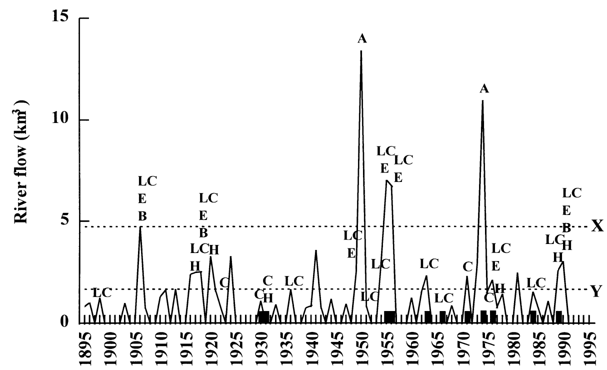

Fig. 4. Riverflow (km³) predicted for Cooper Creek 1895–1995. X is the minimum predicted height of known floods of Lake Blanche (based on the 1906 flood level) and Y is the minimum predicted height of known floods of the Lower Cooper (based on the 1936 flood level). The location of historical flooding events is identified by letters, A is all wetlands in the study area, B is Lake Blanche, C is Lake Callabonna, E is Lake Eyre, H is Lake Hope and LC is the Lower Cooper. The solid bars mark years of major local rainfall events.

on the wetlands of the study area. Ten species bred on Lower Cooper Creek (Table 2). The most obvious were colonially breeding waterbirds. Silver gulls, gull-billed and Caspian terns bred on islands in Cooper Creek in October (Table 2) at 28°33′S, 138°14′E. Small numbers of great cormorant and little black cormorant were breeding during December (Table 2) on Lake Killamperpunna (29°11′S, 138°46′E). By February, some of these colonies were estimated in the hundreds. A great egret colony had also become established (Table 2). Grey teal and pink-eared duck broods were also sighted in December and February. Black swans bred on Lake Blanche in August and October (Table 3) on nests built up out of the shallow water. In December, there was a breeding colony of terns and silver gulls on an island in the middle of Lake Blanchethe (Table 3). In February, there was a colony of 327 Australian pelicans (on nests) along with the same colony of terns and silver gulls (Table 3).

3.4. Flooding history 1895–1995

Modelled data for flows on the Cooper at Cullamurra for 1895–1995, agreed reasonably well with anecdotal observations of floods on the Lower Cooper, Lake Blanche and Lake Callabonna (Fig. 4; Table 1). We used the 1936 flood peak on Cooper Creek as the cut-off for flooding to the Lower Cooper because this was the second lowest flood peak; there was some question about the veracity of the 1898 flood (Table 1; Fig. 4). The Lower Cooper flowed 22 years in 100, about every 4.5 years (Table 4). Eighteen years of flows (1906, 1917, 1918, 1920, 1931, 1936, 1949, 1950, 1954–1956, 1963, 1974, 1976, 1989, 1990) were reported (Table 1) with a further seven not reported (1913, 1916, 1924, 1941, 1971, 1973, 1981). Five of the latter preceded (1916, 1973) or proceeded (1924) large flows or coincided with local rainfall (1920, 1971) (Fig. 4).

Water flowed into Lake Eyre from Cooper Creek in 8 years (1906, 1918, 1950, 1955, 1956, 1974, 1976, and 1990) (Table 1; Fig. 4), about once every 13 years (Table 4). Each was associated with a single large flow or two or more consecutive years of flow (Fig. 3). Large flows (1906, 1950, 1974) or two or more consecutive years of high flows at Cullamurra (1916–1918, 1955–1956, 1989–1990), caused Cooper Creek to overflow into Strzelecki Creek and into Lake Blanche. Our model agreed with the recorded floods of Lake Blanche (1906, 1918, 1950, 1974 and 1990) and also predicted that water would have flowed into Lake Blanche in 1955/1956 (Fig. 4). So, flows in seven out of 100 years reached Lake Blanche, a frequency of nearly once every 14 years (Table 4). Flows would need to be of a greater magnitude than the 1989/1990 flood to overflow from Lake Blanche into Lakes Gregory and Callabonna. This probably occurred in the four largest floods: 1906, 1950, 1955/1956 and 1974 between 1895 and 1995. The mean number of years between flows to Lakes Gregory and Callabonna was 16 (Table 4). Floods were reported for both lakes only in 1950 and 1974 (Table 1). Local rainfall was sufficient to flood Lakes Blanche and Callabonna in 1920 and Callabonna only in 1930/1931 and 1971.

3.5. Wetland habitat (1895–1995)

Each time a flood reaches the Lower Cooper, Lake Blanche or Lake Callabonna, it creates wetland habitat for waterbirds which lasts for varying amounts of time. Most floods are dependent on flows in Cooper Creek with a few fillings from local rainfall (Fig. 4). Habitat for waterbirds lasts until the wetland dries (Fig. 5). Lake Hope more often than not (62% of time) has water while Lake Callabonna only has water 5% of the time, based on Cooper Creek floods (Table 4; Fig. 4).

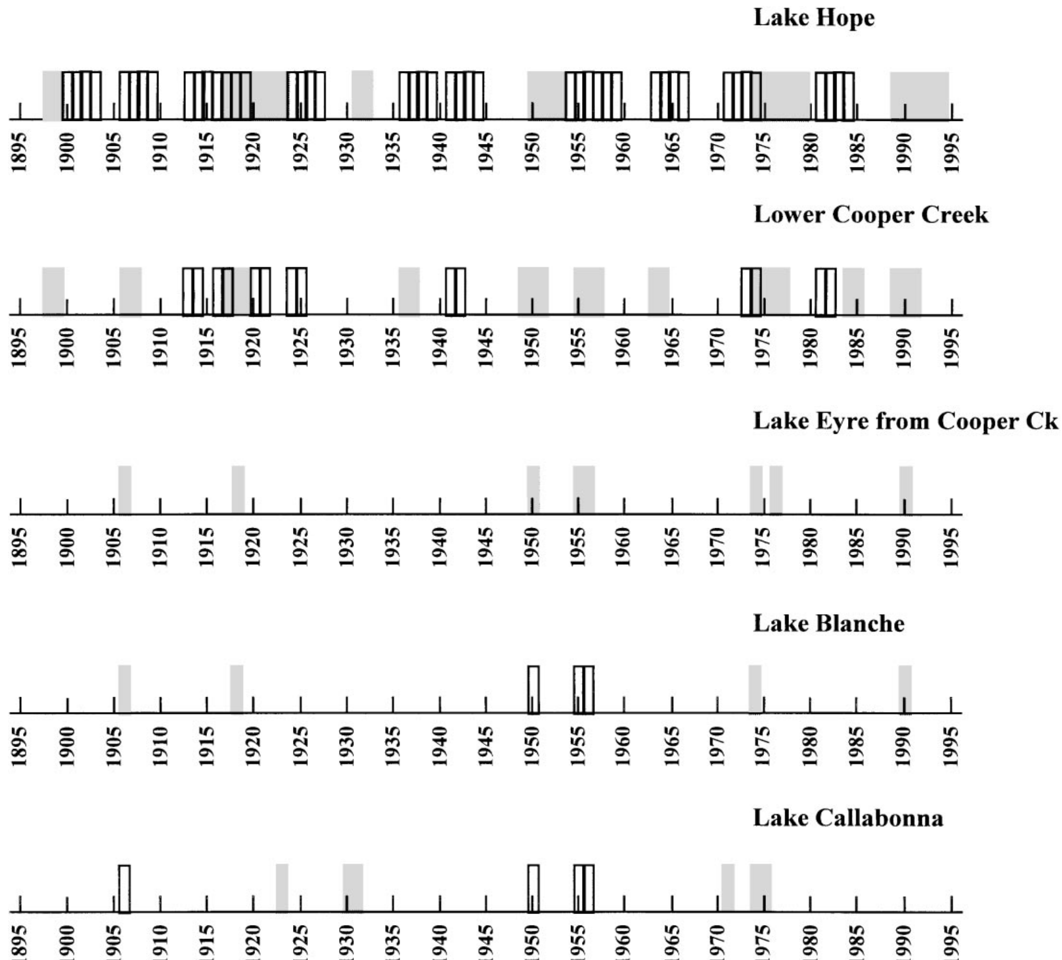

Fig. 5. Periodicity and duration of flooded areas based on known floods (solid bars) and predicted floods (open bars), with durations of flooding (see Table 4) for Lake Hope, the Lower Cooper, Lake Eyre, Lake Blanche and Lake Callabonna.

Flooding frequency on Lake Callabonna nearly doubles when local rainfall is taken into account (Table 4; Fig. 4). Because Lakes Eyre, Blanche and Callabonna only remain inundated for a year after they fill, except when another flood follows, they provide relatively little habitat for waterbirds over a 100-year period (Fig. 5; Table 4). The lakes of the Lower Cooper, including Lake Hope, are the most frequently flooded parts of the system (Fig. 5; Table 4).

4. Discussion

4.1. 'Boom' periods

Cooper Creek is one of the most variable rivers in the world (Walker et al., 1995, 1997). Periods of extreme aridity are punctuated by floods that supply an extensive floodplain of about 102 000 km^2 (Graetz, 1980). These are the boom periods for biota, when there are spectacular concentrations of waterbirds. We estimated about half a million birds during aerial surveys in December 1990 along the Lower Cooper, including Lake Hope (138 000), Lake Blanche (407 000) and Lake Eyre (325 000) (Kingsford and Porter, 1993; Figs. 2 and 3; Tables 2 and 3). Such aerial survey estimates can be biased by up to 50% or more (Bayliss and Yeomans, 1990; Morton et al., 1990a, b; Kingsford, 1998a). Conceivably, the 1990 flood on Cooper Creek provided habitat for more than one million waterbirds. And, this Lower Cooper is only a part of the wetlands filled by Cooper Creek. Large numbers of waterbirds also concentrate on Coongie Lakes (e.g. 35 000 ducks—ANCA, 1996) and Lake Yamma Yamma (Kingsford, unpubl. data) upstream (see Fig. 1). Few other river systems in Australia support such large concentrations of waterbirds (Kingsford and Halse, 1998). At an international scale, only six out of 94 wetlands surveyed during 1991 in Africa (Perennou, 1991) and 26 of 1686 wetlands surveyed in Asia (Perennou and Mundkur, 1991) supported more than 50 000 waterbirds.

The number of species of waterbirds on the Lower Cooper and Lake Blanche was also high (Appendix A) with at least 41 species of waterbirds seen during aerial surveys (Tables 2 and 3). Such surveys estimate about 70% of the waterbird species present on a wetland because species that occur in low numbers or dive in response to the aircraft are not detected (Kingsford, 1998a). As well, a suite of migratory waders could not be differentiated (Appendix A). Probably, a similar number of species uses the wetlands of the Lower Cooper as use the Coongie Lakes on which 75 species of waterbirds, including 17 migratory species have been recorded (ANCA, 1996). Such high abundance and diversity contrasts with a previous view of central Australia as "... virtually useless for waterfowl" because it was "arid, with no permanent surface water" (Frith, 1982, p. 20). Our understanding of the importance of arid zone wetlands for waterbirds (Braithwaite et al., 1986; Bolen et al., 1989; Maher and Braithwaite, 1992; Kingsford and Halse, 1998) reflects our changing perspective and focus on such variable systems (see Williams, 1988; Comìn and Williams, 1994; Kingsford, 1995b).

Boom periods for waterbirds, such as the 1990 flood, are driven by availability of food. Composition and abundance of waterbird communities on arid wetlands often reflects abundance of prey (Kingsford and Porter, 1994). On Cooper Creek, such other biota have peaks of abundance as spectacular as for waterbirds although the data are poor. Fish die in phenomenal numbers as wetlands dry back. Thousands of dead fish lay in Lake Killalpannina on the Lower Cooper after the 1924 flood (Bonython, 1971). On Lake Eyre in 1975, about 40 million dead fish, bony bream *Nematalosa erebi* and hardyhead *Craterocephalus eyresii* lay in contours around the lake (Ruello, 1976), and more were still washing ashore 5 months later (Glover, 1989). Rows of fish covered the shoreline of Lake Eyre after the 1990 flood (Kingsford and Porter, 1993) which was reflected in abundance of piscivores in the system (Figs. 2 and 3). Lake Hope also supports large fish populations (bony bream, Lake Eyre callop and Welch's grunter) (Morton et al., 1995).

Herbivorous waterbirds (e.g. black swan, Eurasian coot and maned duck), present in large numbers (Tables 1–4), probably fed on aquatic macrophytes. Several species occur in Coongie Lakes (*Ludwigia peploides*, *Azolla filiculoides*, *Myriophyllum verrucosum*, *Spirogyra* sp. and *Hydrodictyon reticulatum*) (Gillen and Reid, 1988; ANCA, 1996). *Myriophyllum* sp. grew in Lake Blanche in 1990 (Drewien and Best, 1992). Our estimate of high abundance of Eurasian coot accompanies accumulating data (Kingsford et al., 1994) that this species occurs in much larger numbers on arid zone wetlands than anywhere else on the continent. Terrestrial plants that colonised areas as they dried were also an important food source for maned duck and black swans on Lake Blanche (Table 3).

A wide range of invertebrate species (Williams and Kokkinn, 1988; Williams, 1990; Drewien and Best, 1992) are potential prey for waterbirds on wetlands in the arid zone (Maher, 1984; Maher and Carpenter, 1984; Crome and Carpenter, 1988; Kingsford and Porter, 1994; Seaman et al., 1995). In the 1972 and 1975 flood of Lake Eyre, adults and larvae of the chironomid midge *Tanytarsus barbitarsis* covered the shore (Ruello, 1976). High abundance of pink-eared duck (Table 2), exclusively an invertebrate feeder (Barker and Vestjens, 1989), probably reflected an abundance of such food. There was also a range of other invertebrate feeders including stilts, red-necked avocets, grey teal, Australasian shoveler, hardhead and migratory shorebirds on other wetlands.

The importance of arid zone wetlands in Australia for migratory shorebirds was underlined by the presence of 50 000 small wading birds on Lake Blanche in February 1991 (Table 3) and about 3800 on Lake Hope in October 1994 (Fig. 3). These birds are believed to pass through the centre of the continent, "inhospitable desert" (Lane, 1987), on their southern migration to the coast. But clearly migratory shorebirds remain in large numbers on the wetlands of the arid zone when suitable habitat is available (Tables 2 and 3). Largest numbers of shorebirds were on wetlands during their drying phases when foraging areas were exposed in Lake Eyre (Kingsford and Porter, 1993), Lake Blanche (Fig. 2) and Lake Hope (Fig. 3). But this period probably lasted only a few months. Many of the individuals on Lake Blanche in February 1991 probably flew from Lake Eyre where there were 125 000 migratory shorebirds in December 1990 (Kingsford and Porter, 1993).

Boom periods varied among species and wetlands. Each species or foraging guild presumably tracks food resources. Waterbird abundance was generally at its highest during the drying phases of wetlands (see also Maher and Braithwaite, 1992). Numbers were greatest on Lake Eyre in December 1990 after the flood had reached the lake in August (Kingsford and Porter, 1993); Lake Blanche in February 1991 (Fig. 2) and Lake Hope and lakes of the Lower Cooper in 1993 (Fig. 3a). Waterbirds were distributed around the edge of wetlands where water is relatively shallow (Kingsford and Porter, 1994). High evaporation rates mean that such large shallow wetlands dry reasonably quickly, usually within a year or two. During the drying period, areas are exposed, providing feeding opportunities for most species. When Lake Blanche was a series of islands, waterbirds were spread all over the lake in contrast to when it was full. Piscivores, ducks, herbivores and waders all increased in numbers, though not to the same degree (Fig. 2b).

When food resources reach sufficient abundance and waterbirds gain enough weight they will breed (Braithwaite and Frith, 1969; Crome, 1986; Kingsford, 1989; Lawler and Briggs, 1991; Maher and Braithwaite, 1992). Many species of waterbirds bred during the 1990 flood on Cooper Creek (Tables 1 and 2) and others probably bred but were not detected during aerial surveys. On Lake Blanche, black swans had broods and were nesting in August but had stopped nesting by October (Table 3). Aquatic macrophytes, probably *Myriophyllum* sp. (Drewien and Best, 1992), become established relatively quickly, providing the necessary food resources for black swans to breed. In contrast, the piscivores, Australian pelicans, Caspian and gull-billed terns and silver gulls were the last to breed (Table 3), establishing nests in December 1990 and February 1991 on Lake Blanche, the Lower Cooper and Lake Hope (Tables 2 and 3). It may take some time for fish populations to reach a high enough level for these species to breed (van Tets, 1978). A drawback of such a delay is that there may not be sufficient time to complete breeding. Australian pelicans abandoned their colony on Lake Eyre in 1990 after eggs were laid because the flood was no longer sufficient (Kingsford and Porter, 1993).

Breeding events of the magnitude of 1990 probably occur about once every 10 years (Fig. 4). Of these, there are some particularly significant events when large numbers of many species breed. In the 100-year period modelled, there were probably four of these: 1916–1920; 1949–1951; 1955–1957 and 1973–1977 (Fig. 5). Observations of breeding colonies in the region, although mainly qualitative, began during the 1974 flood of Lake Eyre when large colonies of Australian pelicans and cormorants bred until 1975 (Bonython and Fraser, 1989; Barker et al., 1989; Marchant and Higgins, 1990) and bred in 1984 and 1989 (Marchant and Higgins, 1990; Waterman and Read, 1992). Banded stilts also nest on arid zone lakes during major floods (Burbidge and Fuller, 1982; Bellchambers and Carpenter, 1990). On Lake Callabonna, banded stilts constructed about 27 000 nests following local rainfall in 1931 (McGilp and Morgan, 1931). They may have nested there in 1950, 1955–1956 or 1974–1976 but there are no records. Even with only some water reaching Lake Callabonna in 1990, about 7000 banded stilts were present in August. For many waterbird species the extreme floods may be critical because breeding during boom periods depends on the filling of terminal lakes (Maher and Braithwaite, 1992). Cooper Creek floods result in major breeding events (Table 1) but other river systems also support breeding (Burbidge and Fuller, 1982; Bellchambers and Carpenter, 1990; Kingsford and Porter, 1994; Kingsford and Halse, 1998). Such major breeding events have continental relevance because so few such breeding sites are known. One major breeding event every 10 years on an arid zone wetland may be critical to the conservation of these species. While some waterbirds may survive up to 20–30 years, adult mortality may be much less (Brooke and Birkhead, 1991). Reducing the potential for wetlands, such as Lakes Callabonna, Blanche or Eyre, to provide breeding habitat would have severe repercussions for the waterbird species that depend on availability of this habitat to breed. The impact wcould be at a continental scale, given movements of these species (Kingsford, 1996).

The 1989/1990 flood was part of the spectrum of floods on the Lower Cooper (Fig. 4). Our frequency estimates of Lower Cooper Creek floods occurring every 4.5 years were similar to observations of others. Aboriginal memory and legends and local knowledge contended that a Cooper flood occurred about every 5 years (Bonython, 1971, p. 22) while Kotwicki (1986) estimated that the Lower Cooper receives water about every 6 years. Only two floods (1913 and 1941), not recorded in the literature (Table 1), were calculated by us to reach the Lower Cooper. Kotwicki (1986) records Cooper Creek reached the South Australian border in 1911, Coongie Lakes in 1910 and 1913 and Lake Hope in 1920 and 1924. Also, other annual flows that coincided, preceded or proceeded major floods may not have been recorded. Such discrepancies are not surprising, given the isolation of the area and sporadic records of flooding. Floods of Lake Blanche and Callabonna are probably even less likely to be recorded because no major roads pass by them.

On top of the floods of the Cooper, local rainfall fills wetlands in the study area. Until a flow in Frome Creek filled Lake Eyre, the role of local rainfall for arid zone wetlands was not well appreciated (Kotwicki, 1986). Five years later, a similar event filled Lake Eyre (South) (Waterman and Read, 1992). The 1984 and 1985 filling of lakes of the Lower Cooper showed that local rainfall can create wetland habitat for waterbirds that can last up to 2 years (Fig. 3a). The most important recorded breeding event for banded stilts on Lake Callabonna in 1931 resulted from local rainfall (McGilp and Morgan, 1931). It is difficult to estimate the importance of such rainfall events but they occur reasonably infrequently (Fig. 4). Undoubtedly local rainfall events also create habitat on Lakes Blanche and Gregory if of sufficient magnitude but records are few for their importance on these lakes. It is unlikely that local rainfall will be of sufficient magnitude to fill the lakes very often. The role of localised rainfall in filling lakes is still less than floods.

Some lakes of the Lower Cooper (Lakes Koppermanna and Killalpannina) retained water for 4 or 5 years following the 1989 and 1990 flood (Fig. 3a). This extends previous estimates of 2 years (Bonython, 1971). Lake Hope retains water the longest (Table 4). It was full for 5 years after the 1989 and 1990 flood and supported high numbers of waterbirds while it held water (Fig. 3a). Such wetlands become particularly important for species as wetlands in the vicinity dry back (Maher and Braithwaite, 1992; Kingsford, 1996). 'Boom periods' for other wetlands in the area were generally brief. Lake Callabonna seldom floods, only receiving water about every 20 years (Table 4) and then unless receiving significant inflows probably dries within a year. Similarly, Lakes Gregory, Blanche and Eyre seldom flood from Cooper Creek and these floods seldom last more than a year (Fig. 5; Table 4). There is little predictability about flows in dryland rivers and Cooper Creek is no exception (Walker et al., 1995). Floods may come in rapid succession and dry periods may be long (Fig. 4; Table 4). The 1949 flood reached Lake Blanche and within 5 years, the lake was full again (Fig. 5). By contrast, Lake Blanche did not flood for 31 years between 1918 and 1949. These are the 'bust' periods.

4.2. 'Bust' periods

By 1995, no water remained in any of the wetlands of the Lower Cooper, Lakes Blanche or Callabonna. The last wetland with water was Lake Hope which had lasted 5 years since it filled in 1989 and again in 1990 (Fig. 3a). Fortunately where one dryland river system is on a bust cycle others can be in a boom cycle. Thus the Eyre Creek system, to the north, on the edge of the Simpson Desert experienced the most extensive floods for 15 years based on aerial surveys (Kingsford, unpubl. data).

The common understanding is that waterbirds, unlike other biota, escape as the wetland drys completely, to find suitable habitat. Banding data have shown that most species of Australian waterbirds are capable of flights exceeding 1000 km (Blakers et al., 1984). But it is simplistic to assume that all waterbirds find wetland habitat. Waterbird populations may crash after a boom period. For example, nearly 1000 dead cormorants were recovered from a concrete tank with 30–50 cm of water after Lake Eyre dried up in 1974 (Barker et al., 1989). A similar mass die-off of cormorants occurred on Lake Salisbury some 370 km to the east of Lake Eyre (Kingsford, unpubl. data). Dead or dying Australian pelicans are sometimes also observed during bust periods (Barnard, 1927; Blakers et al., 1984). For highly mobile species such as waterbirds, the availability of wetland habitat during 'bottleneck' dry periods across the continent may be critical.

4.3. Potential impact of diversion of water

The proposal to divert 42 000 ml of water annually from Cooper Creek for irrigation in 1996 (Walker et al., 1997) was critical for two reasons. It marked a considerable geographic expansion of irrigated agriculture in Australia; the nearest established irrigation is at Bourke (Kingsford, 1995a), some 600 km to the east. The extension was against a background of severe impact by irrigated agriculture on rivers and wetlands of the Murray–Darling Basin (Walker, 1985; Kingsford, 1995a; MDBMC, 1995) which prompted five Australian Governments to agree to cap diversions of water (MDBMC, 1996). It was also potentially the greatest anthropogenic disturbance of our most important dryland river (Kingsford et al., 1998). Further sanctioning of irrigation expansion in the catchment in April 1998 by the Queensland Government shows that such a development imperative is difficult to control (Walker et al., 1997; Kingsford et al., 1998). The latest proposals to divert water (DNR, 1998) potentially exceed the diversion first considered for this river.

The legacy of water resource developments on rivers that supply terminal wetlands provide a sharp warning about potential ecological impacts of diverting water from Cooper Creek. Water diverted to supply the citizens of Los Angeles from the river that supplies Mono Lake has had serious ecological impacts (Wiens et al., 1993). Many wetlands in the western United States are affected by diversions of water for agriculture (Lemly, 1994). Aquatic ecosystems on the Aral Sea have all but collapsed as a result of upstream diversion of water to irrigate cotton (Micklin, 1988; Kotlyakov, 1991). Water levels have fallen in the Dead Sea (Israel), and Qinghai (China) (Comìn and Williams, 1994). Water resource developments in Nigeria have reduced wetland areas and decreased fish populations (Thomas, 1995; Thompson and Hollis, 1995). Burdur Lake in Turkey has contracted from 246 to about 140 km^2 with the building of dams and diversions of water (Green et al., 1996). Water resource development on the Senegal River, mainly for rice, threatens social, economic, and ecological health of this river (Venema et al., 1997). In Australia, the Macquarie Marshes have contracted by at least 40–50% (Kingsford and Thomas, 1995) and flows to the Gwydir wetlands are 70% less than they were naturally (Keyte, 1994). This has resulted in reductions in plant and animal populations on these wetlands (Keyte, 1994; Kingsford and Thomas, 1995) and affected breeding of colonial waterbirds (Kingsford and Johnson, 1998). The ecological impacts of diverting water from rivers are ubiquitous (Lemly et al., 1998).

Until recently, dryland rivers such as Cooper Creek with highly variable flows were not the focus for water resource developments because of the absence of suitable sites for dams (Kingsford, 1998a). But large pumps (> 600 mm diameter) located on these rivers can now deliver water from highly variable flows to large storages on the floodplain (Kingsford et al., 1998). Such diversions would reduce frequency and duration of flooding for wetlands of an endorheic basin, like Cooper Creek (Fig. 1). Only 30% of flow in Cooper Creek reaches Coongie Lakes (Knighton and Nanson, 1994) which must fill before water flows on to the Lower Cooper and Lake Eyre. The synergies of different floods are undoubtedly important. The 1989/1990 flood on Cooper Creek only just reached Lake Eyre (Kingsford and Porter, 1993) and yet it was of sufficient magnitude to be considered a one in 10-year flood event (Fig. 4). Water extraction at levels below this flood (Fig. 4) will reduce flooding frequency and duration of upstream wetlands. The many waterholes on Cooper Creek (Knighton and Nanson, 1994) would still need to be filled before water flowed south. The 1990 flood was so extensive because it followed a flood in 1989 that had already reached Lake Hope. With a reduction in flooded areas, there will be less feeding habitat for waterbirds and fewer breeding opportunities (Fig. 4). Diversion of water during the few major floods that occur each century (Fig. 4) may also diminish the extreme breeding events that occur for waterbirds during extensive flood periods, affecting continental populations.

The extent of impact will depend on the amount of water diverted, relative to flood levels. History of water resource development in Australia has exhibited a 'ratchet effect' with diversions to irrigation, increasing and never relaxing (see Walker et al., 1997). In 10–15 years, irrigation licences were issued on the Macintyre River on the border of Queensland and New South Wales that resulted in removal of a substantial proportion of the flows in a river (Kingsford, 1998c). It is extremely difficult to halt development and reverse changes by restoring water to the environment in such systems (Kingsford, 1998b).

4.4. Conservation options

Some of the wetlands of Cooper Creek are formally recognised for their conservation at an international scale. The Lower Cooper Creek and Coongie Lakes, covering 1 980 000 ha, is one of the larger Ramsar sites (ANCA, 1996). Coongie Lakes and part of the Lower Cooper (11 000 km^2) are also listed on the register of the National Estate (Michaelis and O'Brien, 1988; Morton et al., 1995) and Lake Eyre is in the National Reserve Network. Coongie Lakes and parts of Strzelecki Creek are proclaimed as Regional Reserves and Lake Callabonna is a Fossil Reserve (Morton et al., 1995). Nomination of some of the area as a World Heritage Area was considered (Reid, 1994) because wetlands of the Lower Cooper floodplain and Lake Eyre met three World Heritage criteria: outstanding examples of physiographic features, outstanding examples of significant ongoing ecological and biological processes, and superlative natural phenomena and areas of exceptional natural beauty and aesthetic importance (Morton et al., 1995).

None of these conservation measures guarantees sustainability of the river or its wetlands. All measures use land as their currency for conservation, not water. Most of the functioning and sustainability of wetlands is dependent on a guaranteed supply of water from upstream. The Macquarie Marshes, recognised as a wetland of international importance under the Ramsar Convention, registered on the National Estate of Australia, and formally protected under legislation was not quarantined from degradation by extraction of water for irrigation upstream (Kingsford and Thomas, 1995). The ecology of a wetland is determined primarily by what happens outside the wetland boundary, beyond the jurisdiction of conservation measures (Barendregt et al., 1995). Diversion of water from the Okavango River to Namibia (see Ramberg, 1997) is likely to register more severe impacts on the Okavango Delta than those that occur within this extensive wetland (Ellery and McCarthy, 1994).

This local focus to wetland conservation is manifested in the Directory of Important Wetlands in Australia (ANCA, 1996), published a year after the proposal to divert water for irrigation from Cooper Creek (Walker et al., 1997). The Directory lists four current threats (grazing, tourism, seismic lines and hydrocarbon exploration and production) but only one potential threat (uncontrolled visitor access) to the wetlands of Cooper Creek and Strzelecki Creek. There was no mention of upstream diversion of water. This exhibits a fundamental problem affecting wetland conservation around the world: a preoccupation with on site issues in the ignorance of the fundamental changes that may be wrought by upstream impacts.

Conservation of the wetlands of Cooper Creek will only occur if the source of their water upstream is protected. Most of the wetlands on Cooper Creek are in South Australia which is downstream of where the irrigation proposal was put forward in Queensland. Different Governments with polarised views of water resource development present difficult challenges for the conservation of a unique river system such as Cooper Creek (Kingsford et al., 1998). A catchment focus that recognises the conservation values of downstream ecosystems and the impacts of diversion of water on them must be adopted with an independent arbitrator to determine priorities for water resource developments (Kingsford et al., 1998). Extending bust periods at the expense of boom periods for the wetlands and waterbirds will be the consequence of diverting water upstream.

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Appendix A

Species of waterbirds recorded from Lower Cooper Creek, Lake Eyre, Lake Hope, Lake Blanche and Lake Callabonna

Common name	Specific name
Great crested grebe (P)	*Podiceps cristatus*
Small grebes (D)	
Hoary-headed grebe (D)	*Poliocephalus poliocephalus*
Australasian little grebe (D)	*Tachybaptus novaehollandiae*
Australian pelican (P)	*Pelicanus conspicillatus*
Darter (P)	*Anhinga melanogaster*
Great cormorant (P)	*Phalacrocorax carbo*
Pied cormorant (P)	*Phalacrocorax varius*
Little black cormorant (P)	*Phalacrocorax sulcirostrus*
Little pied cormorant (P)	*Phalacrocorax melanoluecos*
Great egret (P)	*Ardea alba*
Intermediate egret (P)	*Ardea intermedia*
White-faced heron (P)	*Ardea novaehollandiae*
Little egret (P)	*Ardea garzetta*
Glossy ibis (P)	*Plegadis falcinellus*
Australian white ibis (P)	*Theskiornis molucca*
Royal spoonbill (P)	*Platalea regia*
Yellow-billed spoonbill (P)	*Platalea flavipes*
Blue-billed duck (D)	*Oxyura australis*
Musk duck (D)	*Biziura lobata*
Freckled duck (D)	*Stictonetta naevosa*
Black swan (H)	*Cygnus atratus*
Australian shelduck (H)	*Tadorna tadornoides*
Maned duck (H)	*Chenonetta jubata*
Pink-eared duck (D)	*Malacorhynchus membranaceus*
Grey teal (D)	*Anas gracilis*
Pacific black duck (D)	*Anas superciliosa*
Australasian shoveler (D)	*Anas rhynchotis*
Hardhead (D)	*Aythya australis*
Brolga (H)	*Grus rubicundus*
Black-tailed native-hen (H)	*Gallinula ventralis*
Eurasian coot (H)	*Fulica atra*
Black-winged stilt (W)	*Himantopus himantopus*
Red-necked avocet (W)	*Recurvirostra novaehollandiae*
Banded lapwing (W)	*Vanellus tricolor*
Masked lapwing (W)	*Vanellus miles*
Large waders	
Bar-tailed godwit (W)	*Limosa lapponica*
Black-tailed godwit (W)	*Limosa limosa*
Greenshank (W)	*Tringa nebularia*
Small waders	
Marsh sandpiper (W)	*Tringa stagnatilis*
Sharp-tailed sandpiper (W)	*Calidris acuminata*
Curlew sandpiper (W)	*Calidris ferruginea*
Wood sandpiper (W)	*Tringa glareola*
Common sandpiper (W)	*Tringa hypoleucos*
Red-necked stint (W)	*Calidris ruficollis*
Long-toed stint (W)	*Calidris subminuta*
Red-capped plover (W)	*Charadrius ruficapillus*
Black-fronted plover (W)	*Elseyornis melanops*
Inland dotterel (W)	*Peltohyas australis*
Red-kneed dotterel (W)	*Erythrogonys cinctus*
Silver gull (P)	*Larus novaehollandiae*
Whiskered tern (D)	*Chlidonias hybrida*
Gull-billed tern (D)	*Gelochelidon nilotica*
Caspian tern (P)	*Hydroprogne caspia*

Waterbirds were classified into four broad community groups: piscivores (P), ducks, terns and grebes (D), herbivores (H) and wading birds (W).

Appendix B

Aerial estimates (+95% C.L.) for waterbirds on Lake Blanche in February 1991

Waterbird	Day 1		Day 2	
	Total	95% C.L.[a]	Total	95% C.L.[a]
Great crested grebe	51	103	0	0
Small grebes	777	51	792	83
Australian pelican	439	79	205	107
Great cormorant	21	176	7	273
White-faced heron	264	148	44	133
Black swan	5096	54	1723	47
Freckled duck	755	128	22	168
Australian shelduck	22	171	59	118
Pacific black duck	3432	60	682	67
Grey teal	50 856	30	41 558	32
Australasian shoveler	220	73	139	67
Pink-eared duck	12 122	38	6277	42
Hardhead	609	71	4833	97
Maned duck	3564	66	2046	57
Musk duck	0	0	22	170
Eurasian coot	623	101	792	83
Masked lapwing	176	129	125	111
Banded lapwing	249	88	154	100
Black-winged stilt	1093	62	939	55
Banded stilt	27 404	171	2317	45
Red-necked avocet	7363	37	8661	35
Small waders	52 792	91	48 546	80
Large waders	0	0	183	81
Silver gull	3960	47	5067	40
Whiskered tern	352	78	425	83
Gull-billed tern	1423	94	1650	86
Caspian tern	2633	73	2838	85
Total	171 035	60	123 933	37

Estimates for 2 days are based on 20 transects, counted perpendicular to the long axis of the lake. Calculation of variance and estimates based on ratio method, sampling without replacement.

[a] Given as a percentage of the estimate.

References

Allan, R.J., 1990. Climate. In: Tyler, M.J., Twidale, C.R., Davies, M., Wells, C.B. (Eds.), Natural History of the North East Deserts. Royal Society of South Australia, Northfield, Australia, pp. 81–84.

ANCA (Australian Nature Conservation Agency), 1996. A Directory of Important Wetlands in Australia, 3rd Edition. Australian Nature Conservation Agency, Canberra.

Badman, F.J., 1991. Birds. In: Badman, F.J., Arnold, B.K., Bell, S.L., (Eds.), A Natural History of the Lake Eyre Region: a Visitors Guide. The National Parks and Wildlife Services Northern Consultative Committee, Port Augusta, South Australia, pp. 27–38.

Badman, F.J., May, I.A., 1983. Waders in northern South Australia. South Aust. Ornithol. 29, 29–39.

Barendregt, A., Wassen, M.J., Schot, P.P., 1995. Hydrological systems beyond a nature reserve, the major problem in wetland conservation of Naardermeer (the Netherlands). Biological Conservation 72, 393–405.

Barker, R.D., Vestjens, W.J.M., 1989. The Food of Australian Birds. I, Non-Passerines. CSIRO Division of Wildlife and Ecology. Parchment Press, Melbourne.

Barker, S., Cornwall, G.C., Lay, B.G., 1989. Terrestrial biology of the Lake Eyre region. In: Bonython, C.W., Fraser, A.S. (Eds.), The Great Filling of Lake Eyre in 1974. Royal Geographical Society of Australasia, Adelaide, South Australia, pp. 67–93.

Barnard, H.G., 1927. Effects of droughts on bird-life in central Queensland. Emu 27, 35–37.

Bayliss, P., Yeomans, K.M., 1990. Use of low-level aerial photography to correct bias in aerial survey estimates of magpie goose and whistling duck density in the Northern Territory. Aust. Wildl. Res. 17, 1–10.

Bellchambers, K., Carpenter, G., 1990. Birds recorded at Lake Torrens during its 1989 flooding. S.A. Ornithol. 31, 1–7.

Blakers, M., Davies S.J.J.F., Reilly, P.N., 1984. The Atlas of Australian Birds. Royal Ornithologists Union. Melbourne University Press, Melbourne.

Bolen, E.G., Smith, L.M., Schramm, H.L., 1989. Playa lakes: prairie wetlands of the southern high plains. BioSscience 39, 615–623.

Bonython, C.W., 1955. Lake Eyre South Australia: the Great flooding of 1949–50. Report of the Lake Eyre Committee. Royal Geographical Society of Australasia, South Australian Branch. Griffin Press, Adelaide.

Bonython, C.W., 1971. Where the Seasons Come and Go. Hawthorn Press, Melbourne.

Bonython, C.W., Fraser, A.S., 1989. The Great Filling of Lake Eyre in 1974. Royal Geographical Society of Australasia, Adelaide, South Australia.

Braithwaite, L.W., Frith, H.J., 1969. Waterfowl in an inland swamp in New South Wales. III Breeding. CSIRO Wildl. Res. 14, 65–109.

Braithwaite, L.W., Maher, M., Briggs, S.V., Parker, B.S., 1986. An aerial survey of three game species of waterfowl (Family Anatidae) in eastern Australia. Aust. Wildl. Res. 13, 213–223.

Briggs, S.V., 1992. Movement patterns and breeding characteristics of arid zone ducks. Corella 16, 15–22.

Briggs, S.V., Maher, M.T., 1985. Limnological studies of waterfowl habitat in south-western New South Wales. II. Aquatic macrophyte productivity. Aust. J. Mar. Freshw. Res. 36, 59–67.

Briggs, S.V., Maher, M.T., Davey, C.C., 1985. Hunter activity and waterfowl harvests in New South Wales, 1977–1982. Aust. Wild. Res. 12, 515–522.

Brooke, M., Birkhead, T., 1991. The Cambridge Encyclopedia of Ornithology. Cambridge University Press, Cambridge.

Burbidge, A.A., Fuller, P.J., 1982. Banded stilt breeding at Lake Barlee, Western Australia. Emu 82, 212–216.

Caughley, G., 1977. Sampling in aerial survey. J. Wildl. Manage. 41, 605–615.

Comìn, F.A., Williams, W.D., 1994. Parched continents: our common future? In: Margalef, R. (Ed.), Limnology Now: a Paradigm of Planetary Problems. Elsevier Science, Amsterdam, pp. 473–527.

Cox, J.B., Pedler, L.P., 1977. Birds recorded during three visits to the far north-east of South Australia. S.A. Ornithol. 27, 231–250.

Crabb, P., 1997. Murray–Darling Basin Resources. Murray–Darling Basin Commission, Canberra.

Crome, F.H.J., 1986. Australian waterfowl do not necessarily breed on a rising water level. Aust. Wildl. Res. 13, 461–480.

Crome, F.H.J., Carpenter, S.M., 1988. Plankton community cycling and recovery after drought—dynamics in a basin on a floodplain. Hydrobiologia 164, 193–211.

DNR (Department of Natural Resources), 1998. Draft Water Management Plan for Cooper Creek. Department of Natural Resources, Longreach, Queensland.

Drewien, G., Best, L., 1992. A Survey of the Waterbirds in Northeast South Australia 1990–1991. South Australian National Parks and Wildlife Service, Adelaide.

Dulhunty, R., 1984. When the Dead Heart Beats Lake Eyre Lives. Seaforth, NSW.

Dulhunty, R., 1990. Lake Eyre. In: Tyler, M.J., Twidale, C.R., Davies, M., Wells, C.B. (Eds.), Natural History of the North East Deserts. Royal Society of South Australia, Adelaide, pp. 101–106.

Ellery, W.N., McCarthy, T.S., 1994. Principles for the sustainable utilization of the Okavango Delta ecosystem, Botswana. Biological Conservation 70, 159–168.

Ellis, R., 1982. Bush Safari. Rigby, Adelaide, Australia.

Frith, H.J., 1982. Waterfowl in Australia, 2nd Edition. Angus and Robertson, Sydney.

Gillen, J.S., Reid, J., 1988. Vegetation. In: Reid, J., Gillen, J. (Eds.), The Coongie Lakes Study. Department of Environment and Planning, Adelaide, pp. 109–139.

Glover, B., 1957. A journey to Cooper Creek. S.A. Ornithol. 30–36

Glover, C.J.M., 1989. Aquatic fauna. In: Bonython, C.W., Fraser, A.S. (Eds.), The Great Filling of Lake Eyre in 1974, Royal Geographical Society of Australasia, Adelaide, South Australia, pp. 94–96.

Graetz, R.D., 1980. The potential application of landsat imagery to land resource management in the channel country. Commonwealth Scientific and Industrial Research Organisation, Division of Land Resource Management, Technical Memorandum, Vol. 80.

Green, A.J., Fox, A.D., Hilton, G., Hughes, B., Yarar, M., Salathe, Green, T., 1996. Threats to Burdur Lake ecosystem, Turkey and its waterbirds, particularly the white-headed duck Oxyura leucocephala. Biological Conservation 76, 241–252.

Keyte, P., 1994. Lower Gwydir Wetland—Plan of Management 1994 to 1997. Report by NSW Department of Water Resources for the Lower Gwydir Wetland Steering Committee, Sydney.

Kingsford, R.T., 1989. Food of the maned duck *Chenonetta jubata* during the breeding season. Emu 89, 119–124.

Kingsford, R.T., 1995a. Ecological effects of river management in New South Wales. In: Bradstock, R., Auld, T.D., Keith, D.A., Kingsford, R.T., Lunney, D., Sivertsen, D. (Eds.), Conserving Biodiversity: Threats and Solutions. Surrey Beatty and Sons, Sydney, pp. 144–161.

Kingsford, R.T., 1995b. Occurrence of high concentrations of waterbirds in arid Australia. J. Arid Environ. 29, 421–425.

Kingsford, R.T., 1996. Wildfowl (Anatidae) movements in arid Australia. In: Proceedings of the Anatidae 2000 Conference, Strasbourg, France, 5–9 December 1994.

Kingsford, R.T., 1998a. Aerial surveys of waterbirds on wetlands as a landscape measure of river health. Freshwater Biol., in press.

Kingsford, R.T., 1998b. The Border Rivers Region of Arid Australia: government, irrigation and the environment. Wetlands Ecology and Management, in press.

Kingsford, R.T., 1999. Counting the costs on wetlands of taking water from dryland rivers. In: Robertson, A.I, Watts, R.J., (Eds.), Preserving Rural Landscapes: Issues and solutions. CSIRO Publishing, Melbourne, in press.

Kingsford, R.T., Halse, S.A., 1998. Waterbirds as the 'flagship' for the conservation of arid zone wetlands in Australia? In: McComb, A.J., Davis, J.A. (Eds.), Wetlands for the Future. Proceedings of INTECOL's V International Wetlands Conference. Gleneagles Press, Adelaide.

Kingsford, R.T., Johnson, W.J., 1998. The impact of water diversions on colonially nesting waterbirds in the Macquarie Marshes in arid Australia. Colonial Waterbirds, submitted for publication.

Kingsford, R.T., Porter, J.L., 1993. Waterbirds of Lake Eyre, Australia. Biological Conservation 65, 141–151.
Kingsford, R.T., Porter, J.L., 1994. Waterbirds on an adjacent freshwater lake and salt lake in arid Australia. Biological Conservation 69, 219–228.
Kingsford, R.T., Thomas, R.F., 1995. The Macquarie Marshes in arid Australia and their waterbirds: a 50 year history of decline. Environmental Management 19, 867–878.
Kingsford, R.T., Bedward, M., Porter, J.J., 1994. Wetlands and waterbirds in north-western New South Wales. National Parks and Wildlife Service Occasional Paper 19.
Kingsford, R.T., Boulton, A.J., Puckridge, J.T., 1998. Challenges in managing dryland rivers crossing political boundaries: lessons from Cooper Creek and the Paroo River, central Australia. Aquatic Conservation: Marine and Freshwater Ecosystems, Vol. 8, 361–378.
Knighton, A.D., Nanson, G.C., 1994. Waterholes and their significance in the anastomosing channel system of Cooper Creek, Australia. Geomorphology 93, 11–24.
Kotlyakov, V.M., 1991. The Aral Sea Basin: a critical environmental zone. Environment 33, 4–38.
Kotwicki, V., 1986. The Floods of Lake Eyre. Government Printer, Adelaide, South Australia.
Lane, B.A., 1984. Report on a trip to Lake Eyre North, 20–24 September 1984. Unpublished RAOU, Wader studies programme.
Lane, B.A., 1987. Shorebirds in Australia. Nelson, Melbourne.
Lawler, W., Briggs, S.V., 1991. Breeding of maned duck and other waterbirds on ephemeral wetlands in north-western New South Wales. Corella 15, 65–76.
Lee, A.K., Mercer, A.H., 1967. Cocoon surrounding desert-dwelling frogs. Science 157, 87–88.
Lemly, A.D., 1994. Irrigated agriculture and freshwater wetland: a struggle for coexistence in the western United States. Wetlands Ecology and Management 3, 3–15.
Lemly, D., Kingsford, R.T., Thompson, J.R., 1998. Irrigated agriculture and wildlife conservation: conflict on a global scale. Environmental Management, in press.
Maher, M.T., 1984. Benthic studies of waterfowl breeding habitat in south-western New South Wales. I. The fauna. Aust. J. Mar. Freshwater Res. 35, 85–96.
Maher, M.T., Braithwaite, L.W., 1992. Patterns of waterbird use in wetlands of the Paroo: a river system of inland Australia. Rangel. J. 14, 128–142.
Maher, M., Carpenter, S.M., 1984. Benthic studies of waterfowl breeding habitat in south-western New South Wales. II. Chironomid populations. Austr. J. Mar. Freshw. Res. 35, 97–110.
Marchant, S., Higgins, P.J., 1990. Handbook of Australian, New Zealand and Antarctic Birds, Vol. 1, Ratites to Ducks. Oxford University Press, Melbourne.
McGilp, J.N., 1923. Birds of the Lake Frome district, South Australia. Emu 23, 237–243.
McGilp, J.N., Morgan, A.M., 1931. The nesting of the banded stilt. S.A. Ornith. 11, 37–61.
MDBMC (Murray–Darling Basin Ministerial Council), 1995. An Audit of Water Use in the Murray–Darling Basin. Murray–Darling Ministerial Council, Canberra
MDBMC (Murray–Darling Basin Ministerial Council), 1996. Setting the Cap. Report of the Independent Audit Group. Murray–Darling Basin Ministerial Council, Canberra.
Michaelis, F.B., O'Brien, M., 1988. Preservation of Australia's wetlands: a commonwealth approach. In: McComb, A.J., Lake, P.S. (Eds.), Conservation of Australian Wetlands. Surrey Beatty and Sons, New South Wales, Australia, Sydney, pp. 167–177.
Micklin, P.P., 1988. Dessication of the Aral Sea: a water management disaster in the Soviet Union. Science 241, 1170–1176.
Morton, S.R., Brennan, K.G., Armstrong, M.D., 1990a. Distribution and abundance of magpie geese, *Anseranas semipalmata*, in the Alligator Rivers region, Northern Territory. Aust. J. Ecol. 15, 307–320.
Morton, S.R., Brennan, K.G., Armstrong, M.D., 1990b. Distribution and abundance of ducks in the Alligator Rivers region, Northern Territory. Aust. Wildl. Res. 17, 573–590.
Morton, S.R., Smith, D.M.S., Friedel, M.H., Griffin, G.F., Pickup, G., 1995. The stewardship of arid Australia: ecology and landscape management. J. Environ. Manage. 43, 195–217.
Parker, S.A., Eckert, H.J., Ragless, G.B., Cox, J.B., Reid, N.C.H., 1979. An Annotated Checklist of the Birds of South Australia. Part 2A: Waterfowl. South Australian Ornithological Association, Adelaide.
Perennou, C., 1991. African waterfowl census. In: Population Dynamics. Slimbridge, UK.
Perennou, C., Mundkur, T., 1991. Asian waterfowl census—midwinter waterfowl counts, January 1991. International Wetlands and Wildfowl Research Bureau. Slimbridge, UK.
Puckridge, J.T., Sheldon, F., Walker, K.F., Boulton, A.J., 1998. Flow variability and the ecology of arid zone rivers. J. Mar. Freshw. Res., 49, 59–72.
Ramberg, L., 1997. A pipeline from the Okavango River? Ambio 26, 129.
Reid, J., 1994. The Prime Minister's pre election promise of world heritage listing for the Lake Eyre Basin: flight or flight of fancy? Rangelands J. 16, 273–297.
Reid, J., Puckridge, J.T., 1990. Coongie Lakes. In: Tyler, M.J., Twidale, C.R., Davies, M., Wells, C.B. (Eds.), Natural History of the North-East Deserts. Royal Society of South Australia, Adelaide, pp. 119–131.
Ruello, N.V., 1976. Observations on some massive fish kills in Lake Eyre. Aust. J. Mar. Freshwater Res. 27, 667–672.
Seaman et al., 1995.
Serventy, V., 1985. The Desert Sea. MacMillan, Melbourne.
Smith, R.G.B., Brock, M.A., 1996. Coexistence of *Juncus articulatus* L and *Glyceria australis* CE Hubb in a temporary shallow wetland in Australia. Hydrobiologia 340, 147–151.
Specht, R.L., 1972. The vegetation of South Australia, 2nd Edition. Government Printer, Adelaide.
Stafford Smith, D.M., Morton, S.R., 1990. A framework for the ecology of arid Australia. J. Arid Environ. 18, 255–278.
Thomas, D.H.L., 1995. Artisanal fishing and environmental change in a Nigerian floodplain wetland. Environmental Conservation 22, 117–142.
Thompson, J.R., Hollis, G.E., 1995. Hydrological modelling and the sustainable development of the Hadejia–Nguru Wetlands, Nigeria. Hydrological Sciences Journal—Journal Des Sciences Hydrologiques 40, 97–116.
van Tets, G., 1978. Transmarine dispersal of Australian pelican. Australian Seabird Group Newsletter 11, 5–6.
Venema, H.D., Schiller, E.J., Adamowski, K., Thizy, J.M., 1997. A water resources planning response to climate change in the Senegal River Basin. J. Environ. Manage. 49, 125–155.
Walker, K.F., 1985. A review of the ecological effects of river regulation in Australia. Hydrobiologia 125, 111–129.
Walker, K.F., Sheldon, F., Puckridge, J.T., 1995. A perspective on dryland river ecosystems. Regulated Rivers—Research and Management 11, 85–104.
Walker, K.F., Puckridge, J.T., Blanch, S.J., 1997. Irrigation development on Cooper Creek, central Australia-prospects for a regulated economy in a boom-and-bust ecology. Aquatic Conservervation: Marine and Freshwater Ecosystems 7, 63–73.
Wasson, B., Banens, B., Davies, P., Maher, W., Robinson, S., Tait, D., Watson-Browne, S., 1996. Inland waters. In: Australia: State of Environment 1996. CSIRO Publishing, Collingwood, Australia, pp. 1–55.
Waterman, M.H., Read, R.J.L., 1992. Breeding success of the Australian pelican *Pelecanus conspicillatus* on Lake Eyre South in 1990. Corella 16, 123–126.
Wiens, J.A., Patten, D.T., Botkin, D.B., 1993. Assessing ecological impact assessment: lessons from Mono Lake, California. Ecologicalogical Applications 3, 595–609.

Wilkinson, L., 1990. Systat: The System for Statistics. Systat Inc., Evanston, IL.
Williams, D.D., 1987. The Ecology of Temporary Waters. Croom Helm, London.
Williams, W.D., 1988. Limnological imbalances: an antipodean viewpoint. Freshwater Biol. 20, 407–420.
Williams, W.D., 1990. Salt lakes: the limnology of Lake Eyre. In: Tyler, M.J., Twidale, C.R., Davies, M., Wells, C.B. (Eds.), Natural History of the North East Deserts. Royal Society of South Australia, Adelaide, pp. 85–89.
Williams, W.D., Kokkinn, M.J., 1988. The biogeographical affinities of the fauna in episodically filled salt lakes: a study of Lake Eyre South, Australia. Hydrobiologia 158, 227–236.