The Macquarie Marshes in Arid Australia and Their Waterbirds: A 50-Year History of Decline

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ABSTRACT / We investigated the relationship between total annual flow of water in the Macquarie River and the extent of flooding in the northern part of the Macquarie Marshes and trends in waterbird populations from 1983 to 1993. The amount of water in the Macquarie River measured each year within the Macquarie Marshes explained about 86% of the variation in area flooded in the northern part of this wetland. This allowed use of long-term data on flow at Oxley, a gauge within the Macquarie Marshes, as an index to flooding. Annual flows at Oxley have decreased significantly for high and medium rainfall events in the catchment, despite no trend in rainfall between 1944 and 1993. The area flooded by large floods has contracted by at least 40–50% during the last 50 years (1944–1993). Water use has progressively increased upstream in the period, depriving the Macquarie Marshes of water: 51% of all water passing Dubbo each year, a gauge 100 km upstream, reached the Macquarie Marshes in the period 1944–1953, but by 1984–1993 this had declined to 21%. Numbers of species and density of waterbirds on the northern part of the Macquarie Marshes declined between 1983 and 1993. Three other wetlands, not affected by water abstractions, showed no declines. We believe the decline was due to wetland degradation as a result of decreased flooding. We estimated more than 88,000 waterbirds in the Macquarie Marshes in October 1984, establishing the site as an important wetland site in Australia. The extent and viability of this wetland will depend on maintaining or increasing the water supply.

Dams and canals mostly supplying water for irrigated agriculture and for generating electricity regulate many of the world's rivers (Allan and Flecker 1993). Often this regulation has reduced the area of downstream wetlands (Turner 1991, Hollis and Jones 1991, Scott 1991), sometimes devastating their fauna (Scott 1991, Bildstein and others 1991). Wetlands in arid parts of the world are particularly vulnerable because water is so scarce (Hollis 1990). This process has seldom been reported in Australia, where the focus has been submergence of natural wetlands by dams (Finlayson 1991) and altered seasonality and frequencies of river flow (Walker 1985, Bren 1988, Lake and Marchant 1990).

The Macquarie River is a regulated river that supports a large irrigation industry and flows into arid Australia (see Stafford Smith and Morton 1990) to form the Macquarie Marshes (Figure 1A), an impressive wetland of waterways, aquatic vegetation, and flooded grassland. Except during large floods, the Macquarie River ends in the Macquarie Marshes (Paijmans and others 1985), which are renowned for their waterbirds (Cooper 1954, Hyem 1957, Braithwaite and others 1986, Brooker 1992). The Macquarie Marshes provide habitat for more than 60 species of waterbirds, including 42 species that breed in the area (Brooker 1992). These include significant breeding colonies of glossy ibis *Plegadis falcinellus* (800), Australian white ibis *Threskiornis mollucca* (2000), straw-necked ibis *Threskiornis spinicollis* (>12,000), intermediate egrets *Egretta intermedia* (17,000), and rufous night herons *Nycticorax caledonicus* (3000)(Carrick 1962, Jones 1983, Marchant and Higgins 1990, Magrath 1991, Brooker 1992, Johnson 1992, Johnson personal communication.) The conservation importance of the Macquarie Marshes was recognized early this century as a bird and animal sanctuary (Paijmans 1981). In 1955 they became a faunal reserve and 18,000 ha was dedicated as a nature reserve in 1971 (see Figure 1C). This area was recognized as a wetland of international importance in 1986 under the RAMSAR Convention (Michaelis and O'Brien 1988).

Despite the conservation importance of the Macquarie Marshes, development of the Macquarie River has undergone a long history of regulation, following construction of the first weir in 1896. There are now nine large dams with greater than 5000 Ml capacity (Ml = 10^6 liters), five major weirs (and several minor ones), a water-transfer scheme (14,000 Ml/yr), and an

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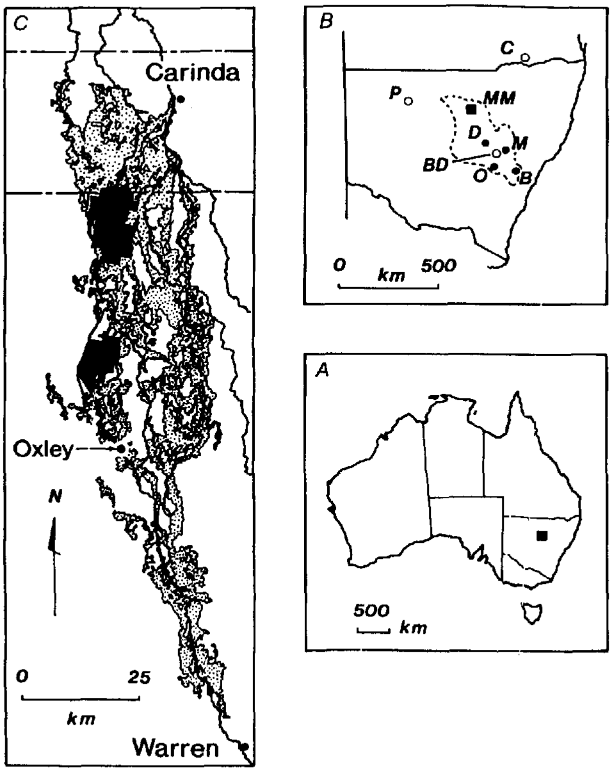

Figure 1. **(A)** Site of Macquarie Marshes; **(B)** locations of wetlands (open circles): Macquarie Marshes (MM), control wetlands (C, Coolmunda Dam; BD, Burrendong Dam; P, Paroo River Lakes), and towns (closed circles) in the catchment (enclosed by dotted line) for which rainfall data were used (B, Bathurst; D, Dubbo; M, Mudgee; O, Orange). **(C)** Stippling shows flooded area in the Macquarie Marshes (8 September 1990), digitized from Landsat imagery (MSS). Horizontal dashed and dotted lines mark the 30-km-wide survey band where waterbirds were surveyed in the Macquarie Marshes and the filled in area signifies the Nature Reserve.

extensive system of canals, regulators, pumps, and off-river storages throughout the catchment (DWR 1991). Burrendong Dam, finished in 1967, is the main regulatory structure, with a capacity 70% larger than any other storage in the catchment (1,189,000 Ml). An 18-km bypass channel installed before 1970 (WCIC 1975) now diverts some water from the Macquarie River around the northern part of the Macquarie Marshes. In 1984, Windamere Dam (353,000 Ml) was built on the Cudgegong River (an upper tributary of the Macquarie River), and increased annual water allocations (10,400 Ml/yr each) were granted for two irrigation schemes off the Macquarie River (Narromine, Trangie) (B. Gardoll, personal communication). These changes have resulted in the expansion of the irrigation industry from about 17,500 ha between 1965 and 1969 (SKPPL 1984) to 85,577 ha in 1990 (DWR 1991).

An annual water allocation of 18,500 Ml was granted on request to the Macquarie Marshes in 1969 (McKenzie 1987a) to mitigate the effects of river regulation, particularly on waterbird breeding (DWR and NPWS 1986). The allocation was first granted in 1980 and again in 1983 (19,000 Ml) and then increased to 50,000 Ml (recommended in 1949) and supplied in 1985 (DWR and NPWS 1986, McKenzie 1987b). The allocation was not used in 1986 or 1990, partly supplied in 1987 (14,000 Ml), and fully supplied in 1988, 1989, and 1991–1993.

Changes in hydrology of the Macquarie River are reasonably well known (WRC 1979, TEC 1980, DWR 1991), but their impacts on the Macquarie Marshes and their fauna and flora are largely anecdotal (but see Brander 1987). We investigated the recent changes to the hydrology (1983–1993) on abundance, numbers of species, and density of waterbirds in part of the Macquarie Marshes over 11 years. Three wetlands were chosen as controls to separate induced variation from natural variation. We also investigated changes in the area flooded each year in relation to the amount of water supplied to the Macquarie Marshes. As long-term flow data were available, this allowed retrospective analysis of changes in water supply over a 50-year period (1944–1993) and their likely effects on the area flooded in the Macquarie Marshes.

Study Area

After the Macquarie River leaves the town of Warren, it forms an anastomosing channel pattern (Bora Channel, Buckiinguy Creek, Bulgeraga Creek, Gum Cowal, Marra Creek, Marthaguy Creek, Monkey Creek, Monkeygar Creek, Terrigal Creek, and the main channel of the Macquarie River) (Figure 1C). The complex habitat formed by these multiple creeks consists of scattered areas of open water, lignum *Muehlenbeckii florentula*, common reed *Phragmites australis*, cumbungi *Typha orientalis*, water couch *Paspalum paspalodes*, and floodplain eucalypts *Eucalyptus camaldulensis*, *E. microtheca*, and *E. largiflorens* (Paijmans 1981). To the west, tributaries of the Macquarie River (Crooked Creek, Duck Creek, Gunningbar Creek) join the Bogan River during extensive floods.

Median annual rainfall for the Macquarie Marshes is 300–400 mm and temperatures range from 4°C (average daily minimum temperatures) during winter months to 35°C (average daily maximum temperatures) during summer months (WRC 1979). Sheep and cattle grazing is the predominant land use around and within the Macquarie Marshes, although increasingly larger areas are being planted to irrigated crops, particularly cotton.

Methods

Waterbirds

We used waterbird data collected during annual aerial surveys (1983–1993) across eastern Australia each October (Braithwaite and others 1986). These aerial surveys were not designed specifically for this study, but the methodology remained the same among years. Three aerial survey bands, 30 km wide (see Braithwaite and others 1986), were centered on latitudes 28°30′S, 30°30′S, and 32°30′S, included four wetland areas (Figure 1C): part of the Macquarie Marshes (30°35′S, 147°32′E), the northern section (2592 ha) of Burrendong Dam (32°41′S, 149°08′E), Coolmunda Dam (28°27′S, 151°13′E), and three Paroo River Lakes (30°30′S, 143°49′E) (see Figure 1B). All wetlands were surveyed about the middle of October each year. Coolmunda Dam was not surveyed in 1988. The Paroo River Lakes (Tongo Lake, Mullawoolka Basin, and Yantabangee Lake) are natural wetlands of particular importance for waterbirds (Maher and Braithwaite 1992, Kingsford 1994). Their water supply was not subjected to river regulation over the period of this study. The two dams have altered little in the flooded area over the study period.

An observer on each side of a Cessna 206 high-winged aircraft estimated numbers of waterbirds of each species onto a mini-cassette recorder. Not all waterbirds could be identified to species (see Appendix 1). Counts were totaled for each observer to give either a total count for a wetland or a proportion count for the wetland.

Three methods were used to fly over the four wetlands. The three control wetlands were predominantly large open-water areas. The aircraft was flown within 150 m of the shoreline on these because this is where waterbirds usually congregate (Kingsford and Porter 1994). Either the whole wetland was circled or a population of the wetland (≥50%) counted at a height of 30–46 m and an airspeed of 167 km/h (90 knots). We extrapolated counts on proportions of wetlands to give estimates for the whole wetland.

There was no defined shoreline in the Macquarie Marshes, so waterbirds were counted in a 200-m-wide transect across the 30-km-wide survey band that crossed the northern part of the study area (Figure 1C). This was flown at a height of 46 m at 204 km/h (110 knots). We measured the proportion of the wetland surveyed each year and extrapolated counts of waterbirds to give an estimate of waterbirds within the area bounded by latitudes 30°22′S 30°38′S (Figure 1C).

Flooded Areas

We determined flooded areas in the surveyed area of the Macquarie Marshes (1983–1991) by digitizing floods on photographic images (1:250,000) from the Multispectral Scanner (MSS) on the Landsat satellite. The 16-day periodicity of the satellite and the availability of cloud-free images set dates for images (1983–1993). They were generally within two weeks of the aerial survey (dates for respective years, 1983–1993, were 29 September, 9 October, 28 October, 15 October, 31 August, 20 October, 5 September, 26 October, 13 October, 29 September, 18 October). To ensure consistency, only parts of the wetland that gave the false color of black were considered flooded (Richason 1978). We mapped flood boundaries for each year with the geographical information system ERMS (NPWS 1989). The 1986 image was digitized at the beginning and end of this process to estimate error in interpretation of the false color. The 3.3% difference between estimates was minor compared with annual differences. An MSS image was not available in 1992, so we used Thematic Mapper (TM) images from Landsat for this year. The TM sensor has a smaller pixel size (30 m) than the MSS sensor (80 m), resulting in improved accuracy (Johnston and Barson 1993). We compared the flood estimates of an MSS image with a TM image for 1986. The area estimate for the TM image was 12.6% higher than that for the MSS image, so we adjusted water area estimates from TM images down for 1992. We also determined the extent of the largest flood (8 September 1990) between 1983 and 1993 of the Macquarie Marshes, by digitizing flood boundaries between Warren and the town of Carinda from an MSS image. We estimated areas of the three control wetlands during each survey in relation to high water marks of the wetlands.

Rainfall

Annual rainfall data for the period 1944–1993 were used from four towns (Figure 1B), Bathurst (33°26′S, 149°34′E), Dubbo (32°13′S, 148°34′E), Mudgee (30°36′S, 149°35′E), and Orange (33°17′S, 149°05′E), which are spread across that part of the catchment that contributes 88% of the runoff to the Macquarie River (DWR 1991). Annual rainfall for all these towns was added together to give an index (RI) of the amount of water entering the Macquarie River system. Local rainfall data were collected at the town of Quambone, about 10 km southeast of Carinda (Figure 1C). We used annual rainfall data for the 12-month period November–October to coincide with survey data.

Flow and Water Use on the Macquarie River

We used annual flow data from Oxley (upstream of most of the Macquarie Marshes), Warren, and Dubbo, all in the Macquarie River (see Figure 1B and C), to determine long-term changes (1944–1993) in flow of the Macquarie River. Incomplete data for Oxley (1944, 1952), Warren (1948–1951), and Dubbo (1957, 1970, 1971) were omitted. The proportion of flows reaching downstream gauges from upstream gauges provided an annual index of water consumption on the Macquarie River between 1944 and 1993. We also compared the proportions of water reaching Oxley from Dubbo each year between the first (1944–1953) and last decades (1984–1993). The high flow in 1950 was omitted as large flows spread out and bypass the Oxley gauge (WRC 1979). New South Wales Department of Water Resources supplied annual data on water use from the Macquarie River and one of its tributaries, Bulgeraga Creek, for the period July 1982 to June 1993. As with annual rainfall data, we calculated all flow data for the 12-month period November–October to coincide with survey data.

Statistical Analyses

We used regression analyses to investigate the effects of time (years) on waterbird abundance, numbers of species, and waterbird density between 1983 and 1993. We included the area flooded as a second independent variable for the Macquarie Marshes analyses. The influences of local annual rainfall and annual flow on area flooded in the surveyed area each October were determined using linear regression.

Due to the variability of annual rainfall in the catchment, we split the flow data at Oxley into three data sets corresponding to low, medium, and high rainfall years in the catchment. Relationships between these and time were determined using linear regression for the period 1944–1993. We transformed some data to improve normality (Zar 1984): abundance of waterbirds, water area, rainfall, and flow data (log); percentage flow data (arcsin), and numbers of species and densities of waterbirds for some wetlands (square root). We used linear regression to investigate possible trends in rainfall, flow, and water use over time. Residuals from regressions were examined with Systat diagnostics to ensure that assumptions of analyses held (Wilkinson and others 1992).

Results

1983–1993

There was no significant linear trend in annual rainfall in the catchment between 1983 and 1993 ($P = 0.689$). The amount of water used for irrigation from the Macquarie River each year increased significantly over the period 1982/1983–1992/1993 ($R^2 = 0.50, P = 0.009$; 1982/1983: 267,649 Ml; 1992/1993: 421,165 Ml). Use was greatest in 1991/1992 (496,562 Ml). Even when the dry years of 1982/1983 and 1983/1984 were omitted from this analysis, there was evidence for an increase in water use ($R^2 = 0.27$, $P = 0.09$).

Numbers of waterbirds estimated in the surveyed area of the Macquarie Marshes were highly variable between 1983 and 1993, ranging between 2300 in 1991 and 88,600 in 1984, and included between eight and 26 species of waterbirds (Figure 2). All species seen during aerial surveys had been sighted before in the Macquarie Marshes (Appendix 1). Aerial surveys did not detect uncommon or cryptic species. The three more common species of waterbirds were grey teal, straw-necked ibis, and Australian white ibis (Figure 2). The trend over time for waterbird numbers in the Macquarie Marshes was negative but not significant ($P = 0.291$), although there was a significant decrease in numbers of species ($R^2 = 0.29$, $P = 0.052$) (Figure 2) and in densities of waterbirds ($R^2 = 0.30$, $P = 0.049$). Numbers of waterbirds increased significantly with area flooded in the Macquarie Marshes ($R^2 = 0.35, P = 0.034$).

Abundance of waterbirds, number of waterbird species, and density showed no significant trends on other wetlands: Paroo River Lakes ($P = 0.99$, $P = 0.17$, $P = 0.60$), Burrendong Dam ($P = 0.63$, $P = 0.59$, $P = 0.88$), or Coolmunda Dam ($P = 0.71$, $P = 0.22, P = 0.65$) (see Figure 2).

The area flooded in the Macquarie Marshes over the 11 years (1983–1993) was highly variable (Figure 3). The largest flood was in 1990 when about 18,750 ha were flooded in the surveyed area (Figure 3). The peak of this flood was 8 September 1990 (Figure 1C) when there was 130,996 ha flooded between Warren and Carinda; 32,750 ha was within the surveyed area. The flooded area 48 days later (see Figure 3) was smaller, covering only 57% of the area flooded on 8 September 1990. Area flooded in the surveyed area (Figure 3) was significantly related to total annual flow of water measured at Oxley over the previous 12

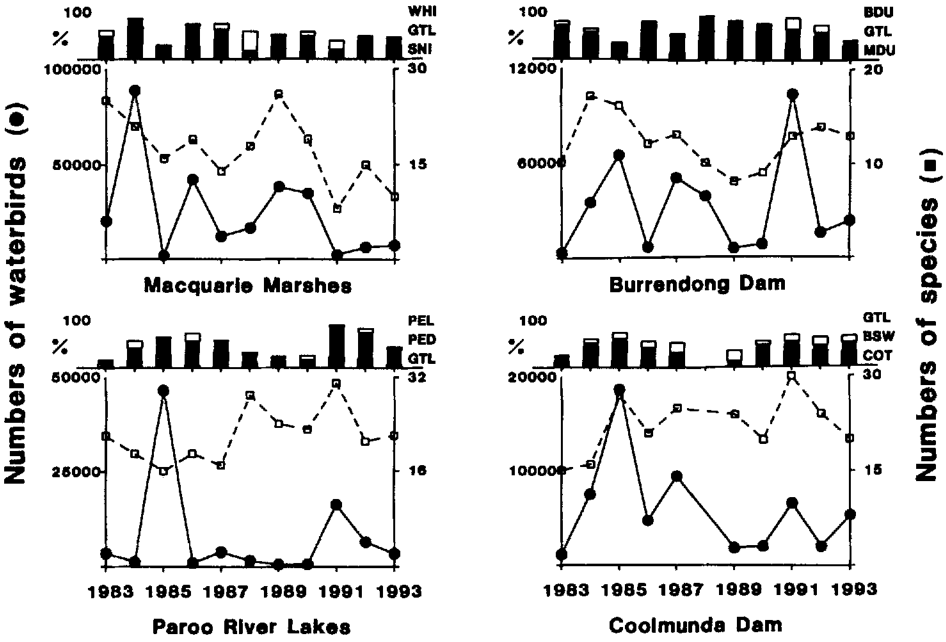

Figure 2. Abundances (filled circles, solid lines) and numbers of species of waterbirds (open squares, dotted lines) in the study region of the Macquarie Marshes, the Paroo River Lakes, Burrendong Dam, and Coolmunda Dam, 1983–1993. Histograms give percentage composition of the three most abundant species on each wetland. BDU, Pacific black duck; BSW, black swan; COT, Eurasian coot; GTL, grey teal; MDU, maned duck; PED, pink-eared duck; PEL, Australian pelican; SNI, straw-necked ibis; and WHI, Australian white ibis.

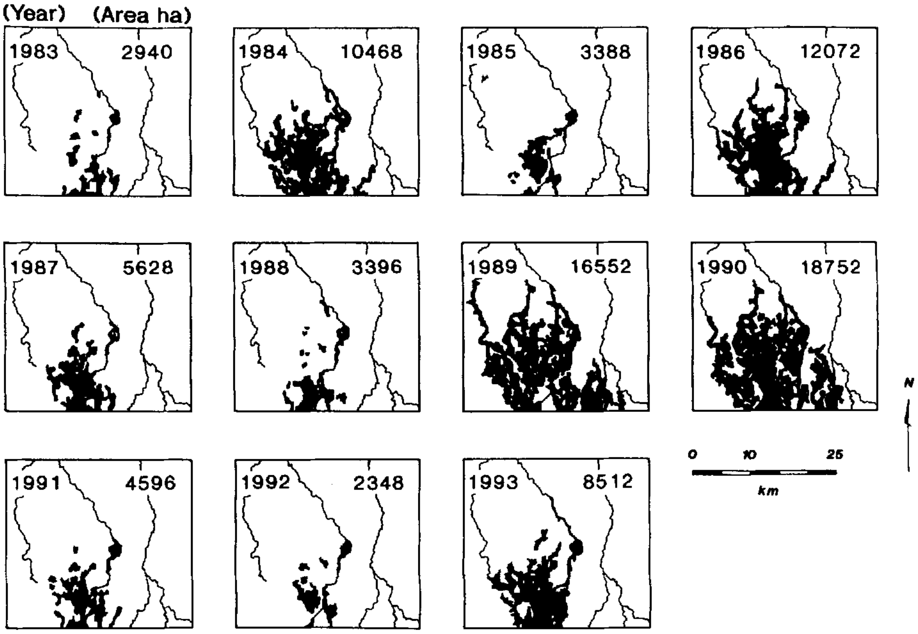

Figure 3. Flooded areas in the study region of the Macquarie Marshes during October, 1983–1993, digitized from Landsat imagery. Estimates of inundated areas (hectares) are in top right-hand corners of each map.

months [log (area, hectares) = −8.47 + 1.39 log (flow, megaliters per year), $R^2 = 0.859$, $P < 0.001$; see Figure 4] but not to local rainfall ($P = 0.497$).

Hydrology, 1944–1993

In decreasing order, the five wetter years in the catchment between 1944 and 1993 were 1950, 1956, 1969, 1973, and 1990, as measured by the rainfall index (Figure 5). The 1990 flood was ranked only ninth and probably was the tenth highest flood at Oxley over the 50-year period (see Figure 5). Data for 1952 flows at Oxley were missing but flow at Warren indicated 1952 was a larger flood than 1990. The eight floods at Oxley larger than the 1990 flood [annual flow (AF) = 569,695 Ml; RI = 3922 mm) were in 1950 (AF = 1,188,789 Ml; RI = 5536 mm), 1956 (AF = 1,153,895 Ml; RI = 5085 mm), 1951 (AF = 898,384 Ml; RI = 3062 mm), 1974 (AF = 850,136

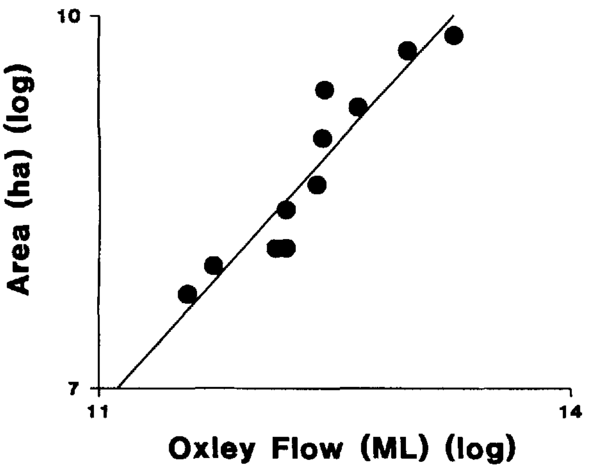

Figure 4. Relationship between area flooded in the Macquarie Marshes (see Figure 2) and annual flow at Oxley, 1983–1993 [log(area, hectares) = 8.47 + 1.39 log(flow, Ml/year); R^2 = 0.859, $P < 0.001$].

Ml; RI = 3786 mm), 1955 (AF = 798,338 Ml; RI = 3896 mm), 1948 (AF = 676,555 Ml; RI = 3481 mm), 1963 (AF = 669,844 Ml; RI = 3537 mm), and 1973 (AF = 572,693 Ml; RI = 4258 mm). The 1948 and 1963 flows, with lower rainfall indices than in 1990, would have flooded an estimated 28,100 ha and 27,700 ha, respectively, in October. This was based on the relationship between flow at Oxley and area flooded. Burrendong Dam reduced the flood in 1969, which had the third highest rainfall index (RI = 4023 mm), to a small flood, ranked 20th (AF = 355,681 Ml). Correlation between flows at Oxley and the rainfall index were high for the first decade, 1944–1953 (0.85), but decreased to 0.567 in the last decade (1983–1993). The gap between rainfall in the catchment and annual flow at Oxley has progressively widened with few exceptions (Figure 5).

Flows at Oxley corresponding to high rainfall years (RI = 3205–5536 mm) declined over time (R^2 = 0.438, P = 0.003, N = 16), but the amount of high rainfall in the catchment also declined over time (R^2 = 0.162, P = 0.07, N = 16). This decline in high rainfall was due to the two wet years of 1950 and 1956. When these data were removed from rainfall and flow, there was no trend in rainfall over time (P = 0.75), but the decrease in annual flow over time remained (R^2 = 0.261, P = 0.036, N = 14). For medium rainfall years (RI = 2728–3124 mm), annual flow also declined (R^2 = 0.231, P = 0.034, N = 16), although the rainfall for these flows did not (P = 0.141). There were no trends for low rainfall years (RI = 1364–2681 mm) (P = 0.929) or for the corresponding flows (P = 0.482, N = 16). The floods of 1948 and 1963, with 10% lower rainfall indices than the 1990 flood, would have flooded areas at least 40% larger than the 1990 flood, based on the relationship between area flooded and flow at Oxley.

Reduced high and medium flows have decreased the variability of total annual flows on the Macquarie River at Oxley. Ranges of annual flows for the five decades 1944–1953, 1954–1963, 1964–1973, 1974–1983, and 1984–1993 were, respectively, 1,178,540 Ml, 880,510 Ml, 525,280 Ml, 772,690 Ml, and 464,080 Ml.

The amount of water reaching Warren from Dubbo each year has declined significantly (R^2 = 0.29, $P < 0.001$, N = 43) (Figure 6). There was an indication of a decline after establishment of Burrendong Dam, but it was not significant (P = 0.147, N = 23). The proportion of water reaching Oxley from Warren each year has also decreased over the past 50 years (R^2 = 0.218, P = 0.001, N = 42) (Figure 6). This decrease was marked in the period after Burrendong Dam was established (R^2 = 0.384, $P < 0.001$, N = 26). In the first decade of the study, 1944–1953, 51% (±2.9 SE, N = 6) of the total amount of water passing through Dubbo made its way through to Oxley. By the last decade, 1984–1993, only 21% (±2.4 SE, N = 10) of the total annual flow Dubbo reached Oxley. There was no significant difference ($t_{14} = -1.33$, P = 0.204) between the rainfall indices for the first decade (2596 ± 250.5 SE, N = 6) and the last decade (3006 ± 187.7 SE, N = 10).

Discussion

The Macquarie Marshes are justifiably a wetland of international importance. Few wetlands in Australia have as diverse a wetland bird fauna as the Macquarie Marshes (Appendix 1). In 1984, the Macquarie Marshes supported at least 80,000 waterbirds (Figure 2). This was considerably more waterbirds than any of the other wetlands included in this study (Figure 2). It establishes the Macquarie Marshes among the more important wetlands in Australia for waterbirds (Braithwaite and others 1986, Morton and others 1990a,b, Kingsford 1994). Our surveyed area in the Macquarie Marshes covered about 25% of the total flooded area at the peak of the 1990 flood (Figure 1C). Thus, between 10,000 and 300,000 waterbirds use the Macquarie Marshes each October, assuming this was a typical flood distribution. These estimates are probably underestimates as aerial transects of waterbirds are usually negatively biased (Stott and Olson 1972, Johnson and others 1989, Bayliss and Yeomans 1990, Morton and others 1990a,b). While not a

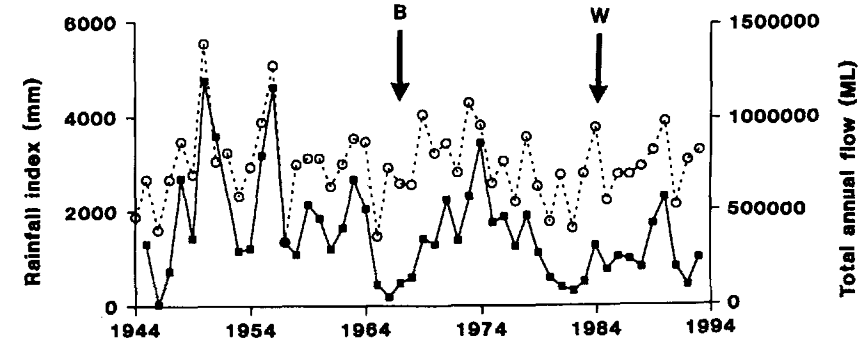

Figure 5. Annual rainfall index (dotted line) and annual flow (continuous line), measured by Oxley for the period 1944–1993. Arrows show when Burrendong (B) and Windamere (W) dams were built.

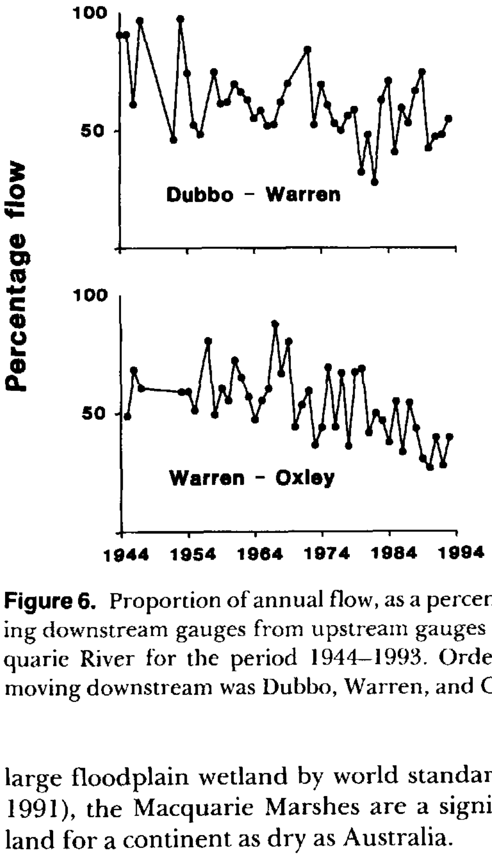

Figure 6. Proportion of annual flow, as a percentage, reaching downstream gauges from upstream gauges on the Macquarie River for the period 1944–1993. Order of gauges moving downstream was Dubbo, Warren, and Oxley.

large floodplain wetland by world standards (Maltby 1991), the Macquarie Marshes are a significant wetland for a continent as dry as Australia.

The future of the Macquarie Marshes is not assured given past management of their water supply, the Macquarie River. The Macquarie Marshes depend on water from the Macquarie River (Figure 4), not on local rainfall. River regulation has decreased the streamflow variability of the Macquarie River and the amount of water reaching the Macquarie Marshes (Figure 5). The river had the most variable flow of 18 selected rivers in the Murray-Darling Basin of Australia, with annual flows ranging from 2% to 940% of the mean (MDBMC 1987). The range has now decreased to about 300% of the mean (1984–1993). The influence of highly variable rainfall in the catchment is less than it used to be (Figure 5).

The proportion of water reaching Oxley each year from Dubbo has more than halved in 50 years. Declines in annual flows at Oxley for high and medium rainfall events on the Macquarie River (Figure 5) document a process of reduction in the flooded area in the Macquarie Marshes over a 50-year period. Such a pattern could be attributed to regulation, providing compensatory water in dry years. Our data showed no corresponding increase in flows corresponding to low rainfall. The proportion of rainfall entering the Macquarie River may have even increased over time because of widespread clearing of trees that might have otherwise taken up the water (Walker and others 1993).

Burrendong Dam is often cited as the cause of reduced flows to the Macquarie Marshes (Carrick 1962, WRC 1979, Turner 1981, DWR 1991, Brooker 1992). Certainly, the dampening effects of Burrendong Dam and Windamere Dam on flow at Oxley were noticeable as each dam filled (Figure 5), corroborating hydrological predictions (WRC 1979). Burrendong Dam reduced the 1990 flood from 560,000 Ml/day inflow to 165,000 Ml/day outflow and nullified the effects of a major flood in Bathurst in August 1986 (DWR 1991); however, this water is not lost but stored, predominantly for irrigation (DWR 1991). It is the continued loss of water from the Macquarie River before it reaches the Macquarie Marshes, particularly after completion of the dams, which is of most concern. Water use for irrigation has increased since closure of Burrendong Dam (Figures 5 and 6).

The amount of water used between 1982 and 1993 increased as the proportion of water reaching Oxley from Warren declined (Figure 6). This trend is reflected in nearly a 400% expansion in the area sown to irrigated cotton in the Macquarie River Valley over the period 1981–1992 (data in CYB 1992). Increasing trends in water use do not equate with assurance that water used for irrigation remained relatively stable during 1977–1990 in the Macquarie Valley (DWR 1991). Irrigation licenses that were issued but have not been activated until recently are probably contributing to this increased water use. Irrigators can also access water during flood periods by pumping water from the river into off-river water storages (Wettin and others 1994). There is a nominal upper limit of 50,000 Ml for the Macquarie River of water that may be pumped from the river during floods, but under so-called "wet conditions" (not defined), it may be lifted (DWR and NPWS 1986). In 1986, there were about 18 storages upstream of the Macquarie Marshes, ranging in capacity from 50 to 2000 Ml with a total capacity of 15,000 Ml (DWR and NPWS 1986). By 1992, storage capacity had reached 41,000 Ml (Kingsford 1995). This does not even measure maximum use, as water may be used and the storage refilled within an irrigation season (Wettin and others 1994). Access to these flows and increasing use of licensed allocations probably accounted for increased use of water from the Macquarie River during 1983–1993 (Figure 6). The impact on the Macquarie Marshes is clear.

The Macquarie Marshes that stopped the westward progress of the explorer Oxley in 1818 (Oxley 1820) were probably at least twice the size they are today. In 1863, a newspaper reported that "The whole of the country between the Merri Merri [Creek, 24–41 km east of the Macquarie River] and the Macquarie [River] was one sea of water, with scarcely a dry foot of ground" (Dormer and Starr 1979). The flood of 1874 was purportedly even bigger but not as big as the record flood of 1955 (Dormer and Starr 1979). Five large floods between 1870 and 1955 broke the banks of the Talbrager River, a tributary of the Macquarie River, but none did so in the next 29 years (SKPPL 1984).

Estimates for the area flooded in the Macquarie Marshes in major floods were published only recently but with no quantitative analyses: >200,000 ha (Goodrick and others 1991), >250,000 ha (Paijmans 1981), ≥300,000 ha (Johnson 1992, DWR and NPWS 1986), and 320,000 ha (WRC 1979). The largest flood of 1955 extended over about 1,280,000 ha downstream of Warren (SKPPL 1984). These estimates were probably based on distribution of wetland plants and anecdotal information about the extent of major floods. The 1990 flood was a major flood with a rainfall index ranked fourth highest in 50 years (Figure 5). More water flowed into Burrendong Dam in August 1990 than at any other month in the 105 years of record (DWR 1991), and the rainfall index for the 1990 flood was about the same as in the 1955 flood, 77% of the 1956 flood, and 70% of the 1950 flood (Figure 5), but the 1990 flood only inundated about 131,000 ha at its peak (Figure 1C) compared with 478,280 ha over the same area in the mid-1950s (calculated from flood maps in SKPPL 1984), a possible reduction of 73%. The 1948 and 1963 floods, with rainfall indices 10% lower than 1990, would have flooded 40% more area than was flooded in 1990. These underestimate flooded areas because they are based on the present hydrological environment, where flooding is restricted by the northern bypass channel, levee banks, roads, and extensive erosion of channels (WCIC 1975, WRC 1979, Brander 1987, Goodrick and others 1991, Johnson 1992). Similarly, the extent of the 1966 and 1967 floods were underestimated when modeled on recent data because of recent erosion of channels (Bell and others 1983). The 1978 flood, although only 83% of the total flow in 1990 (Figure 5), flooded about 150,000 ha (Brooker 1992), so the extent of flooding, for a given flow at Oxley, may have decreased. Reduced flooding has probably also affected the traditional grazing industry, which is usually detrimentally affected by irrigation (Turner 1991). This is true in the Macquarie Marshes (P. McClellan, personal communication).

Decreased flooding has affected the fauna and flora of the Macquarie Marshes. The area occupied by wetland vegetation has contracted since 1934 (Goodrick and others 1991). Extensive reed beds in the Macquarie Marshes halved in area between 1963 and 1972 and other wetland vegetation was replaced with dryland chenopods (Brander 1987). Many river red gums, *Eucalyptus camaldulensis*, have also died (B. Johnson, personal communication). There were also declines in density and numbers of waterbird species (1983–1993) (Figure 2). There were no significant changes on control wetlands (Figure 2). We failed to detect a significant decline in total numbers of waterbirds in the Macquarie Marshes, but this result should be treated with caution. With only 11 data points, there was a high probability of making a type II error—accepting the null hypothesis (no trend) when it was wrong.

The plight of the Macquarie Marshes is not simply due to decreased water. Small areas of the Macquarie Marshes have received too much water, killing floodplain trees (Brander 1987, Johnson 1992, Wettin and others 1994). Watercourses that were dry up to six months (WRC 1979) now seldom dry out as they carry promised water to irrigators. Floodplain trees also have been ring-barked (Brander 1987) and lignum cleared (DWR 1991, Magrath 1991) as the Macquarie Marshes have contracted and irrigated agriculture has expanded.

Only about 14% of the current Macquarie Marshes (1990 flood) are represented in a conservation reserve. The nature reserve includes none of the ibis breeding colonies and only three of the seven intermediate egret colonies (B. Johnson, unpublished data). The remaining area may be vulnerable to land use changes, and the whole of the Macquarie Marshes, including the reserve, is vulnerable to hydrological impacts. The water supply upstream remains the most critical management issue affecting the Macquarie Marshes. For many years, the Macquarie Marshes were the only wetland in Australia with guaranteed rights to water: 50,000 ml each year (MDBMC 1987). Governments, industry groups, and environmental groups have lauded this initiative, but it has encouraged the view that the allocation is sufficient to sustain the environmental value of the Macquarie Marshes. Inadequate hydrological analyses, based on this assumption, have contributed to the misapprehension that increased allocations of water for irrigation would not affect conservation values (WRC 1985). Such an argument is wrong. The Macquarie Marshes would be considerably smaller than they are now if they relied solely on their allocation of 50,000 Ml each year; as acknowledged by water managers (Geering and others 1988, Wettin and others 1994). The wildlife allocation is currently measured at Marebone Weir, 31 km upstream of Oxley, so when it reaches Oxley it is considerably less. Yet the smallest flood of our study in 1992 covered 2386 ha (Figure 3) and was produced by a total flow of 105,600 Ml, measured at Oxley (Figure 5). The 50,000 Ml of water passing Oxley would flood less than half this area. In the past 50 years, only two floods have been less than the 1992 flow through Oxley and both have been followed by large floods (Figure 5). These flows must be protected, either through an increased water allocation to the Macquarie Marshes or through restrictions on access to flood waters by an expanding irrigation industry. The latter would be more effective and more ecologically sound as it allows for high annual variability in flows.

Water use and its management around the world have generally been dominated by agriculturists and irrigation engineers (Hollis 1990). Unless measures are implemented for managing water in the Macquarie Marshes that are more effective for creating wetland habitat, the reputation of the Macquarie Marshes as an important breeding and feeding area for waterbirds, especially during major floods (Brooker 1992) will continue to decline. Commenting on the Macquarie Marshes, Carrick (1962) concluded: "It is flood prevention measures and the control of natural waters for mainly agricultural purposes that threaten the breeding of ibises and waterfowl. . . ." It is a sharp reminder of the inadequacies of water management for conservation that this conclusion remains as true today as it was more than 30 years ago.

Appendix 1. Waterbirds seen in the Macquarie Marshes[a]

Waterbirds[b]	Specific name	Aerial surveys
Great-crested grebe (B)	*Podicepts cristatus*	M B C
Little grebes[c]		M P B C
Hoary-headed grebe (B)	*Poliocephalus poliocephalus*	
Australasian grebe (B)	*Tachybaptus novaehollandiae*	
Australian pelican	*Pelecanus conspicillatus*	M P B C
Darter (B)	*Anhinga melanogaster*	M P B C
Great cormorant (B)	*Phalacrocorax carbo*	M P B C
Pied cormorant	*Phalacrocorax varius*	M P B C
Little black cormorant (B)	*Phalacrocorax sulcirostris*	M P B C
Little pied cormorant (B)	*Phalacrocorax melanoleucos*	M P B C
Pacific heron (B)	*Ardea pacifica*	M P C
White-faced heron (B)	*Ardea novaehollandiae*	M P B C
Great egret (B)	*Ardea alba*	M P B C
Egrets[c]		M P B C
Cattle egret (B)	*Ardea ibis*	
Little egret (B)	*Ardea garzetta*	
Intermediate egret (B)	*Areda intermedia*	
Rufous night heron (B)	*Nycticorax caledonicus*	M C
Little bittern (B)	*Ixobrychus minutus*	
Australasian bittern	*Botaurus poiciloptilus*	
Black-necked stork	*Xenorhynchus asiaticus*	
Glossy ibis (B)	*Plegadis falcinellus*	M P C
Australian white ibis (B)	*Threskiornis aethiopica*	M P C
Straw-necked ibis (B)	*Threskiornis spinicollis*	M P B C

Appendix 1. *Continued*

Waterbirds[b]	Specific name	Aerial surveys
Royal spoonbill (B)	*Platalea regia*	M P C
Yellow-billed spoonbill (B)	*Platalea flavipes*	M P B C
Wandering whistling-duck	*Dendrocygna arcuata*	
Plumed whistling-duck (B)	*Dendrocygna eytoni*	M C
Black swan (B)	*Cygnus atratus*	M P B C
Freckled duck (B)	*Stictonetta naevosa*	M P C
Cape Barren goose	*Cereopsis novaehollandiae*	
Australian shelduck	*Tadorna tadornoides*	M
Pacific black duck (B)	*Anas superciliosa*	M P B C
Grey teal (B)	*Anas gracilis*	M P B C
Chestnut teal	*Anas castanea*	
Australasian shoveler (B)	*Anas rhynchotis*	M P B C
Pink-eared duck (B)	*Malacorhynchus membranaceus*	M B P C
Hardhead (B)	*Aythya australis*	M P B C
Maned duck (B)	*Chenonetta jubata*	M P B C
Cotton Pygmy goose	*Nettapus coromandelianus*	
Blue-billed duck (B)	*Oxyura australis*	M
Musk duck (B)	*Biziura lobata*	M
Buff-banded rail	*Rallus philippensis*	
Australian crake	*Porzana fluminea*	
Spotless crake	*Porzana tabuensis*	
Black-tailed native-hen (B)	*Gallinula ventralis*	P
Dusky moorhen (B)	*Gallinula tenebrosa*	M
Purple swamphen (B)	*Porphyrio porphyrio*	M
Eurasian coot (B)	*Fulica atra*	M P B C
Brolga (B)	*Grus rubicundus*	M P
Painted snipe	*Rostratula benghalensis*	
Masked lapwing (B)	*Vanellus miles*	M
Black-winged stilt (B)	*Himantopus himantopus*	M P B C
Banded stilt	*Cladorhynchus leucocephalus*	P
Red necked avocet	*Recurvirostris novaehollandiae*	M P C
Small waders[c]		P B C
Red-kneed dotterel (B)	*Erthrogonys cintus*	
Red-capped plover	*Charadrius ruficapillus*	
Black-fronted plover (B)	*Charadrius melanops*	
Wood sandpiper	*Tringa glareola*	
Common sandpiper	*Tringa hypoleucos*	
Greenshank	*Tringa nebularia*	
Marsh sandpiper	*Tringa stagnatilis*	
Sharp-tailed sandpiper	*Calidris acuminata*	
Red-necked stint	*Calidris ruficollis*	
Curlew sandpiper	*Calidris ferruginea*	
Latham's snipe	*Gallinago hardwickii*	
Large waders[c]		C
Black-tailed godwit	*Limosa limosa*	
Bar-tailed godwit	*Limosa lapponica*	
Silver gull	*Larus novaehollandiae*	M P B C
Whiskered tern (B)	*Sterna hybrida*	M P B C
Whiskered tern (B)	*Sterna hybrida*	M P B C
Gull-billed tern	*Sterna nilotica*	P C
Caspian tern	*Hydroprogne caspia*	M P C

[a]Sources: Cooper (1954) and Brooker (1992). Letters indicate waterbirds seen during October 1983–1993 aerial surveys. M, Macquarie Marshes; P, Paroo River Lakes; B, Burrendong Dam; C, Coolmunda Dam.

[b]Waterbirds recorded breeding by Brooker (1992) are followed by (B).

[c]Species that could not be separated during aerial surveys.

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