DOI: 10.1007/s00267-004-0250-3

Destruction of Wetlands and Waterbird Populations by Dams and Irrigation on the Murrumbidgee River in Arid Australia

R. T. KINGSFORD*
R. F. THOMAS
NSW Department of Environment and Conservation
43 Bridge Street
Hurstville, NSW 2220, Australia

ABSTRACT / The Lowbidgee floodplain is the Murrumbidgee River's major wetland in southeastern Australia. From more than 300,000 ha in the early 1900s, at least 76.5% was destroyed (58%) or degraded (18%) by dams (26 major storages), subsequent diversions and floodplain development. Diversions of about 2,144,000 ML year^{-1} from the Murrumbidgee River come from a natural median flow of about 3,380,000 ML year^{-1} providing water for Australia's capital, hydroelectricity, and 273,000 ha of irrigation. Diversions have reduced the amount of water reaching the Lowbidgee floodplain by at least 60%, from 1888 to 1998. About 97,000 ha of Lowbidgee wetland was destroyed by development of the floodplain for an irrigation area (1975–1998), including building of 394 km of channels and 2,145 km of levee banks. Over 19 years (1983–2001), waterbird numbers estimated during annual aerial surveys collapsed by 90%, from an average of 139,939 (1983–1986) to 14,170 (1998–2001). Similar declines occurred across all functional groups: piscivores (82%), herbivores (87%), ducks and small grebe species (90%), large wading birds (91%), and small wading birds (95%), indicating a similar decline in the aquatic biota that formed their food base. Numbers of species also declined significantly by 21%. The Lowbidgee floodplain is an example of the ecological consequences of water resource development. Yanga Nature Reserve, within the Lowbidgee floodplain, conserved for its floodplain vegetation communities, will lose these communities because of insufficient water. Until conservation policies adequately protect river flows to important wetland areas, examples such as the Lowbidgee will continue to occur around the world.

Introduction

Many of the world's rivers are dammed (Dynesius and Nilsson 1994, Vörösmarty and others 1997, Graf 1999) and much of their water is diverted for human populations running out of fresh water (Postel 2000). Such water resource development destroys floodplain wetlands, particularly in arid regions of the world (Kingsford 2000a, Arthington and Pusey 2003) where hydrological and ecological effects of river regulation and diversions are acute. Diversion of water upstream of wetlands reduces flooding causing significant declines in biota (Micklin 1988, Lemly and others 2000, Bunn and Arthington 2002) and flood-dependent vegetation die with reduced flooding (Taylor and others 1996), which also exacerbates the impacts of salinization (Jolly and others 1993). Biodiversity tends to be more reduced in areas that are infrequently flooded, compared to those that experience moderate flooding (Boulton and Lloyd 1992) and eventually the landscape may become terrestrial (Ward 1998). Relatively few published examples of the impacts of water resource development on floodplain wetlands exist around the world, even though these are the areas most impacted by the building of dams and diversion of water. Governments and their development agencies continue to advocate development of water resources with poor cost–benefit analyses (Lemly and others 2000). In debates about further development of rivers, case studies of the ecological impacts of water resource development are essential (Kingsford 2000a).

Australia has a history of more than 100 years of water resource development (Kingsford 2000a, Kingsford 2000b, Kingsford 2003, Sheldon and others 2000, Arthington and Pusey 2003). Although our population of 20 million is relatively small, the country is a significant producer of food and fiber for international markets, and much of this comes from arid regions with diversions of water. Irrigated agriculture uses about 76% of the water (17,900 GL) diverted annually across the continent (National Land and Water Resources Audit 2001) and most (90%) was diverted from the rivers of the Murray-Darling Basin (Kingsford 2000a). The Murrumbidgee River has one of the longer histories of development—more than 100 years—of any of

Published online August 24, 2004.

*Author to whom correspondence should be addressed; *email:* richard.kingsford@npws.nsw.gov.au

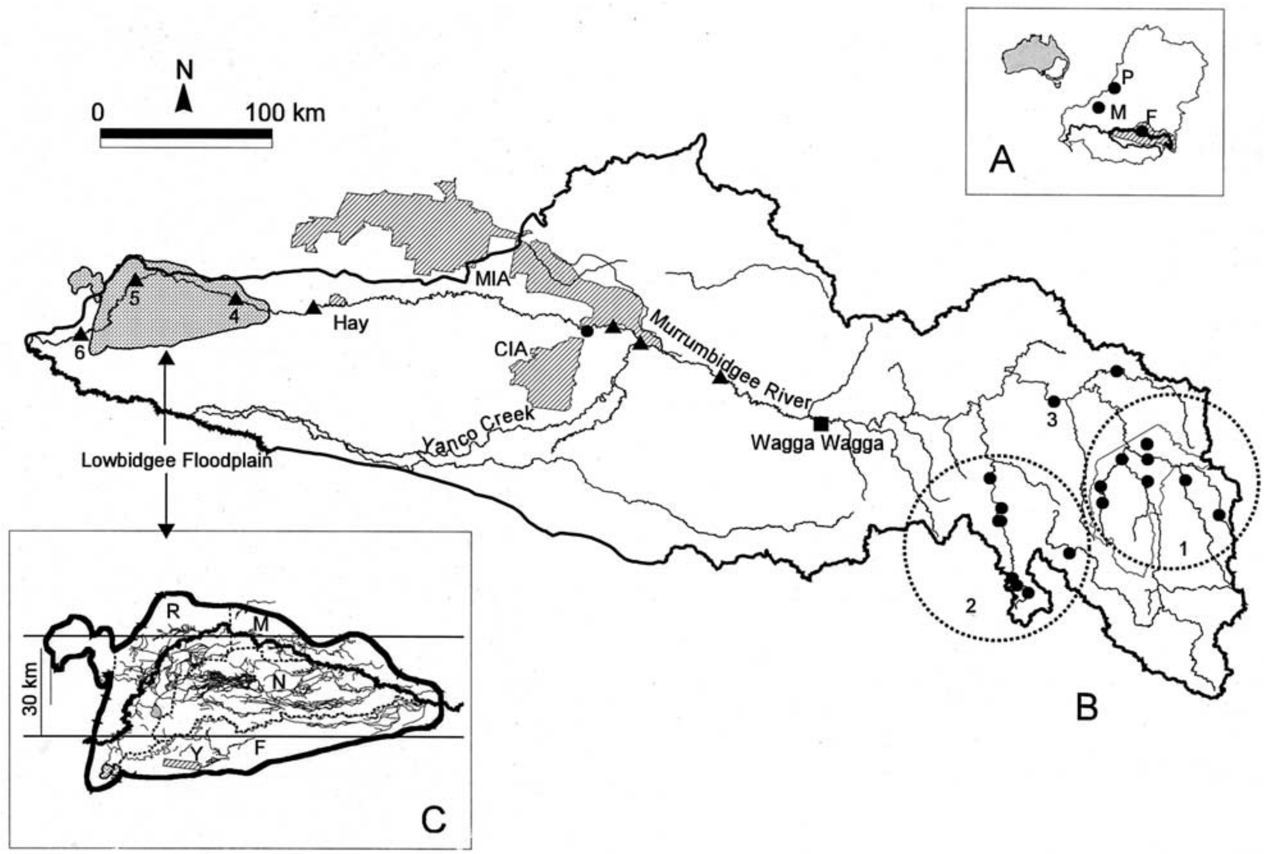

Figure 1. (**A**) Location of the Murrumbidgee River catchment within the Murray-Darling Basin in Southeastern Australia and three reference wetland sites for waterbird surveys: M— Menindee Lakes, P—Paroo overflow lakes, and F—Fivebough Swamp. (**B**) Location of the Lowbidgee floodplain, major watercourses, towns (■), major reservoirs (●), major irrigation areas (hatched area) (MIA—Murrumbidgee Irrigation Area, CIA—Colleambally Irrigation Area), and weirs (▲) in the Murrumbidgee River catchment. Numbers refer to Canberra's reservoirs (1), Snowy Mountains Hydro-electric Scheme (2), Burrinjuck Reservoir (3), Maude Weir (4), Redbank Weir (5), and Balranald Weir (6). (**C**) The extent of the core 90% of the Lowbidgee floodplain in 1902 (SA Government 1902). Dashed lines show hydrological strata (R—Redbank, M—Murrumbidgee, N—Nimmie-Caira, F—Fiddlers-Uara) and permanent lakes (shaded). Parallel lines indicate the aerial survey band for waterbirds and Y refers to Yanga Nature Reserve (hatched).

the rivers in the Murray-Darling Basin (Kingsford 2003). Nearly all of the water resource development on the Murrumbidgee River lies upstream of the river's major wetland system, the Lowbidgee floodplain (Figure 1), one of the major wetlands in the Murray-Darling Basin (Crabb 1997). This makes it particularly vulnerable to the impacts of water resource development. This area was a candidate for listing as a wetland of international importance under the Ramsar Convention in the early 1990s (DWR 1994) but was not carried out. Part of the floodplain, Yanga Nature Reserve (1772 ha) (Figure 1), is a conservation area for floodplain vegetation communities.

The aim of our study was to determine the ecological changes on the floodplain as a result of water resource development (dams, diversions, and floodplain development). We used three long-term data sets to measure the effects of water resource development on the floodplain. We investigated changes to 1) annual river flows using data that extended over more than 100 years (1888–1998), 2) wetland area using Landsat satellite data (1975–1998), and 3) waterbird populations using annual aerial survey data (1983–2001). Our paper ends with a discussion of the major consequences of these impacts for conservation of wetland systems and their dependent biota.

Methods

The Murrumbidgee River

Most of the Murrumbidgee River's runoff originates from the main tributary rivers of the upper catchment, upstream of Wagga Wagga (Figure 1), where mean annual rainfall is 1500 mm year^{-1} (DLWC 1996). Before river regulation, river flows were seasonal, driven by reliable winter and spring rainfall and snow melt, and much of the flow reached the Lowbidgee floodplain (Figure 1).

We used annual river flow data (1888–1998) for four river gauges on the Murrumbidgee River, Wagga Wagga, Hay, Maude Weir, and Balranald Weir (Figure 1) to investigate long-term changes in annual river flows. Hydrological data were only available from 1937 to 1998 for Maude Weir. Most diversions occur between Wagga Wagga and Hay (Ebsary 1992; DWR 1993), although about 35,000 ML for Canberra and 30,000 ML for 263 extraction licences is diverted upstream of Wagga Wagga each year (DLWC 1996), but this was not considered because annual data were not available. After 1960, the storages of the Snowy-Mountains Hydroelectric Scheme (Figure 1) stored most of the water from the eastward-flowing Snowy River and diverted this water into the Murray and Murrumbidgee River for irrigation (Davies and others 1992). We adjusted annual flows at Wagga Wagga, so these flows were not included because all of this interbasin transfer is diverted towards Colleambally Irrigation Area (Figure 1). These augmented flows particularly affect the upper part of the river but not the Lowbidgee floodplain downstream of Colleambally Irrigation Area. Inclusion of this additional flow would have biased assessment of changes in natural river flows between the upper and lower parts of the river.

Long-term (>50 years) historical data for diversions were not available, and so to determine the impacts of water resource development on Murrumbidgee River flows, we calculated the proportion of the total annual flow reaching a downstream river gauge from the gauge upstream, as an index to volumetric diversions. This provided an indirect assessment of reductions over time at the downstream gauge, as a result of diversions to the major irrigation areas, downstream of the upstream gauge of Wagga Wagga (Figure 1). We calculated these indices using all flow data for the 12-month period November to October to coincide with aerial survey data of waterbirds and the peak period for wetland flooding (Pressey and others 1984, DWR 1994, Johnston and Barson 1993). We analyzed long-term trends in flow percentages reaching Hay from Wagga Wagga over the 111-year period (1888–1998). We separated annual flows at Wagga Wagga into low flows (<2,900,000 ML), medium flows (2,900,000 ML–4,230,000 ML), and high flows (>4,230,000 ML) and analyzed flow percentages reaching Hay from Wagga Wagga.

Lowbidgee Floodplain

The Lowbidgee floodplain lies at the lowest part of the Murrumbidgee River catchment (Figure 1) where mean rainfall is 320 mm year^{-1} (n = 107) at Balranald (Scott 1992) (Figure 1), annual evaporation is 1615 mm year^{-1}, and mean maximum summer temperatures reach 33°C (WCIC 1972). The floodplain relies almost entirely on flows from the Murrumbidgee River. Channel capacity is low within the Lowbidgee floodplain, compared to upstream: Redbank Weir (11,000 ML day^{-1}), Maude Weir (20,000 ML day^{-1}), Hay (35,000 ML day^{-1}), and progressively higher upstream (Ebsary 1992) (Figure 1). The Lowbidgee floodplain is a complex system of interconnected creeks flowing east to west and including Fiddlers, Uara, Caira, Nimmie, Pollen, Waugorah, Talpee, Monkem, Kietta, Yanga, and Paika Creeks (Butler and others 1973). We divided the floodplain into four hydrological strata (Kingsford and Thomas 2002): Redbank, Murrumbidgee, Nimmie-Caira, and Fiddler-Uara (Figure 1). After Balranald Weir (Figure 1), the river loses its complexity and flows are confined to the main channel.

The major woody vegetation on the Lowbidgee floodplain (Scott 1992; Porteners 1993) depends on floods. Lignum (*Muelenbeckia florulenta*) and black box (*Eucalyptus largiflorens*) communities dominate the southern part of the floodplain, including Yanga Nature Reserve (Figure 1), whereas the western edge of the floodplain is predominantly river red gum (*E. camaldulensis*). There are also open water lakes greater than 50 ha (Figure 1), including Piggery, Tala, and Yanga Lakes.

Wetland Changes

We used Landsat satellite data, Multispectral Scanner (MSS) and Thematic Mapper (TM) to analyze changes to wetland area between 1975 and 1998 (n = 21 years; no imagery in 1977, 1978, 1980). All images were geometrically and radiometrically corrected, georeferenced, and resampled to a standard pixel size. A brief description is provided here (see details in Kingsford and Thomas 2002). Wetland and nonwetland areas were delineated from each satellite image using an unsupervised classification and an independently derived mask of developed areas. A temporal series of wetland, nonwetland, and developed areas was then created by merging the classification results with the mask. The final classes had an accuracy of 75% compared to reference data and most (two thirds) of this difference related to areas on the margins of wetland and nonwetland areas (Kingsford and Thomas 2002).

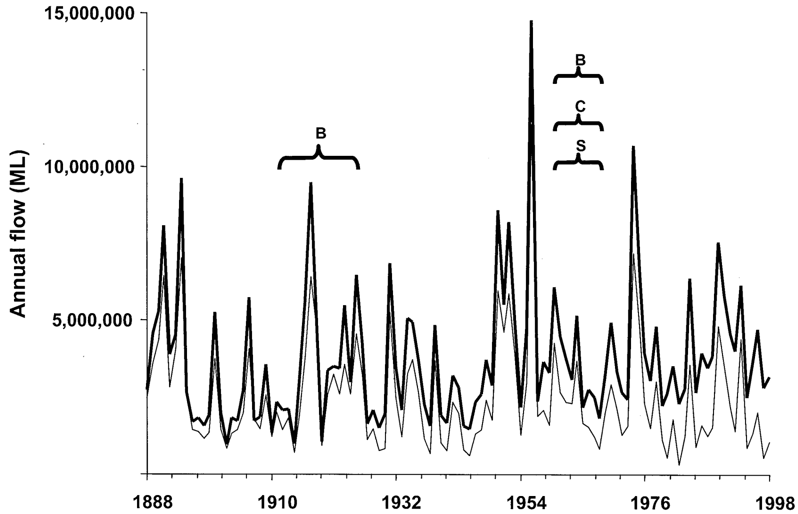

Figure 2. Annual flows (ML) in the Murrumbidgee River at Wagga Wagga (bold line) and Hay (thin line), 1888–1998. Flows at Wagga Wagga do not include the contribution from the Snowy Mountains Hydro-electric Scheme. Letters indicate when Burrinjuck Dam (B), dams of the Snowy Mountains (S), and Canberra dams (C) were constructed or enlarged.

This was likely to be consistent bias and unlikely to affect trend analyses.

The original wetland area of the floodplain was delineated from a 1902 map of the Lowbidgee floodplain (SA Government 1902) and a geomorphological digital coverage (Butler and others 1973) to remove nonwetland areas, including dunes (Kingsford and Thomas 2002). We separately analyzed wetland loss over two time periods: 1900–1975 and 1975–1998 (satellite imagery available). Wetland loss before 1975 was defined as the maximum area classified as wetland, using satellite imagery, in the period 1975–1998 subtracted from the original wetland area. We also calculated the current length of channel and levee systems across the Lowbidgee floodplain, from available digital data.

Vegetation health of the dominant woody vegetation communities, dependent on flooding, was assessed on a qualitative scale of dead, poor, moderate, or good from a helicopter at a height of about 30 m on June 25th, 1998 (Kingsford and Thomas 2002). This was done at 81 random ground reference locations, stratified by wetland classification. Dead vegetation had no canopy, vegetation in poor health had less than 30% of the canopy with leaves, moderately healthy vegetation had 30–60%, and good health equated to 60% canopy cover.

Aerial Surveys of Waterbirds

Aerial surveys of waterbirds were flown over about 10% of eastern Australia each October between 1983–1999 (Kingsford and others 1999), including the Lowbidgee floodplain (Figure 1). Three additional wetland areas were used as reference sites: Fivebough Swamp, Menindee Lakes system, and the overflow lakes of the Paroo River (Figure 1). All waterbirds were estimated on each wetland to species level, apart from some groups that could not be identified to species (Kingsford and Porter 1994). We analyzed annual trends in total numbers of waterbirds on each wetland and the numbers of species. Waterbirds were divided further into broad groups, corresponding to their use of different foods (Barker and Vestjens 1989) and where the birds usually forage (Kingsford and Porter 1994). The five groups included piscivorous birds (e.g., cormorants, pelicans, terns), large wading birds, duck species (all duck species except herbivorous species), herbivorous waterbirds (e.g., black swans, Australian wood duck), and small wading birds (Charadriformes).

Analyses

We used linear regression analyses to investigate the effects of time (years) on changes in hydrology between different parts of the river, waterbird abundance, wetland area, and numbers of waterbird species. Residuals from regressions were examined with SYSTAT diagnostics to ensure that assumptions of analyses held, including potential serial autocorrelation (SPSS 1999). We transformed data to improve normality (Zar 1984): abundance of waterbirds, wetland area on the Lowbidgee floodplain, developed area on the Lowbidgee floodplain and flow data (log); percentage flow data (arcsin) and numbers of species of waterbirds for wetlands (square root).

Results

River Flows

Annual flows to the Lowbidgee floodplain from the Murrumbidgee River have declined in volume over time, 1888–1998 (Figure 2). Before Burrinjuck Dam was built in 1927, annual flows at Hay followed a similar pattern of variability and quantity to annual river flows measured at Wagga Wagga (Figure 2) but afterwards, the pattern of flows diverged in quantity although annual patterns of variability coincided. After 1955, Burrinjuck's storage capacity was increased and the dams of the Snowy Mountains Hydroelectric Scheme and dams for Canberra were built (Figure 1). This changed the relationship between river flows at Wagga Wagga and Hay (Figure 2). There were similar patterns of variability but considerable differences in the quantity of water reaching Hay from Wagga Wagga, compared to before river regulation.

The percentage volume of annual flows reaching Hay from Wagga Wagga decreased significantly over the 111-year period (1888–1998) (arcsin (*percentage flow*) = 10.4 – 0.005 *year*, $R^2 = 0.48$, $p < 0.001$)) (Figure 3A) by about 50% (Table 1). For the 20 years before river regulation (1888–1907), 80% ± 2.1 (SE) of the annual volume of water reached Hay from Wagga Wagga, compared to 42% ± 3.3 (SE) in the 20 most recent years (1979–1998) (Table 1). Annual flows at Hay between 1888 and 1907 were significantly higher than annual flows between 1979 and 1998 (two-sample *t* test: $t = 2.31$, $df = 37.1$, $p = 0.027$). In contrast, comparison of annual flows for the two periods at Wagga Wagga were not significantly different (two-sample *t* test: $t = -1.48$, $df = 30.4$, $p = 0.149$). The percentage volume of water reaching Hay from Wagga Wagga in 1979–1998 was the smallest of any period (Table 1).

The amount of water reaching the Lowbidgee floodplain was further reduced with a reduction in the amount of water reaching Maude from Hay, after 1937 (arcsin (*percentage flow*) = 11.9 – 0.006 *year*, $R^2 = 0.24$, $p < 0.001$) (Figure 3B). For the 10-year period from 1937 to 1946, 91% ± 2.7 (SE) compared to 77% ± 2.3 (SE) for the last decade of data, 1989–1998 reached Maude from Hay. There was no significant trend (arcsin (*percentage flows*) = 5.368 – .002 *year*, $R^2 = 0.027$, $p = 0.11$) for flows between Maude and Balranald in the period 1937–1998 (Figure 3C).

There were significant declines in low, medium, and high annual flows at Hay, defined by annual high, medium and low flows measured at Wagga Wagga (low flows: log (*annual flows*) = 26 – 0.006 *year*, $R^2 = 0.11$, $p = 0.027$; medium flows: log (*annual flows*) = 40 – 0.013 *year*, $R^2 = 0.50$, $p < 0.001$; high flows: log (*annual flows*) = 24 – 0.005 *year*, $R^2 = 0.13$, $p = 0.017$). In contrast, there were no trends in low ($p = 0.33$) or high ($p = 0.53$) annual flows at Wagga Wagga but a significant decline in medium flows (log (*annual flows*) = 19.6 – 0.005 *year*, $R^2 = 0.11$, $p = 0.024$).

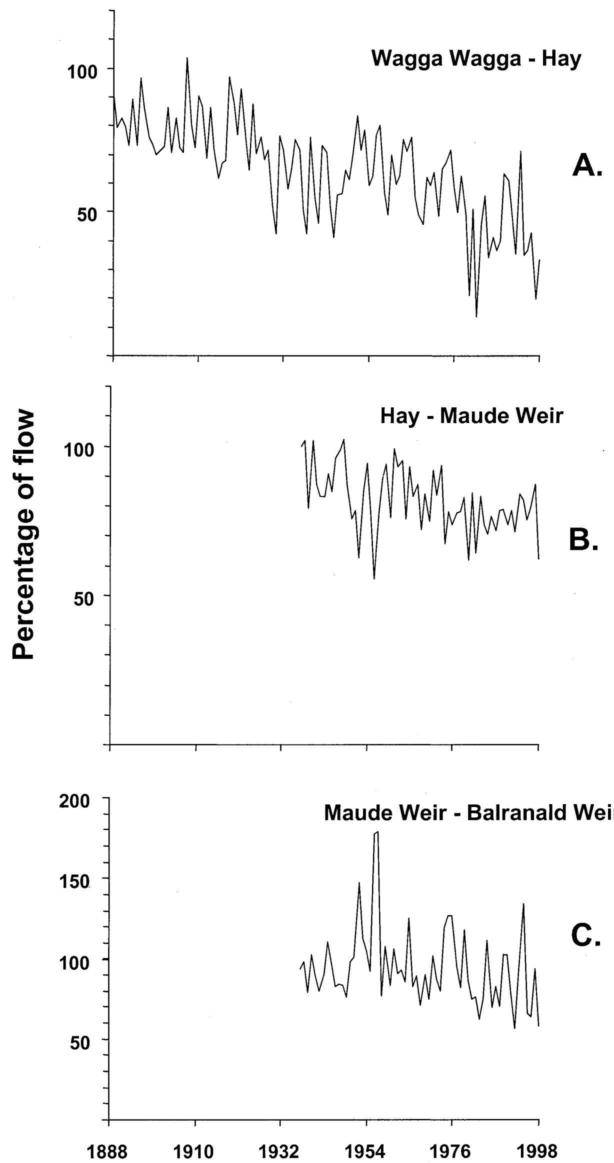

Figure 3. Percentage of annual river flows, 1888–1998 between river gauges, Hay from Wagga Wagga (**A**), Maude from Hay (**B**), and Balranald from Maude (**C**). Data for Maude only existed from 1939.

Lowbidgee Floodplain

There was an estimated 303,781 ha of floodplain in the Lowbidgee at the beginning of the 20th century (Table 2). Wetland area varied among the different strata with the Nimmie-Caira and Redbank systems, occupying about 90,000 ha. Before 1975, between 16% and 34% of wetland area (6,625–30,947 ha) was lost in the four strata (Table 2) with the Fiddlers-Uara and Redbank strata losing the most (34%). Total wetland area lost before 1975 from the Lowbidgee floodplain was estimated at 26% or about 80,000 ha (Table 2).

Table 1. Annual flows of the Murrumbidgee River at Wagga Wagga and Hay[a]

Measure	Period	Mean (± SE)	Median	Range
Wagga Wagga (ML)	1888–1907	3,517,606 (522,188)	2,700,472	8,646,584
	1908–1918	3,387,139 (746,321)	2,329,918	8,515,011
	1919–1938	3,381,595 (377,986)	3,391,507	5,817,070
	1939–1958	4,205,198 (716,155)	3,055,006	13,310,085
	1959–1978	4,048,171 (456,360)	3,310,035	8,875,325
	1979–1998	3,936,901 (337,579)	3,592,382	5,334,107
Hay (ML)	1888–1907	2,764,818 (391,463)	2,229,830	6,178,633
	1908–1918	2,544,506 (520,014)	1,880,702	5,720,405
	1919–1938	2,392,848 (298,432)	2,588,198	4,577,966
	1939–1958	2,909,818 (571,237)	2,034,868	10,773,980
	1959–1978	2,541,537 (335,203)	2,211,800	6,342,478
	1979–1998	1,802,201 (285,215)	1,374,846	4,478,526
Wagga Wagga–Hay (%)	1888–1907	80 (2.0)	78	70–100
	1908–1918	77 (3.5)	72	62–97
	1919–1938	69 (3.1)	71	42–93
	1939–1958	65 (2.7)	63	41–84
	1959–1978	61 (2.1)	61	46–76
	1979–1998	42 (3.3)	40	14–71

[a]Mean (± SE), median, and range of annual flows (ML) at Wagga Wagga and Hay with percentage of flows reaching Hay from Wagga Wagga for periods between 1888 and 1998. Annual flows were calculated from November to October each year.

Table 2. Changes in wetland area on the Lowbidgee floodplain of the Murrumbidgee River[a]

		Wetland area lost (%)		Remaining wetland		Total[e]			
Stratum	Original (ha)[b]	1902–1975	1975–1998	Area (ha) (%)[c]	% Degraded[d]	(ha)	%	Levee (km)	Constructed channels (km)
Total	303,781	26	32	127,688(42)	44(81)	232,276	76.5	2145	394
Fiddlers-Uara	77,348	34	33	25,666(33)	62(16)	67,595	87.4	134	90
Murrumbidgee	41,449	16	45	16,138(39)	64(11)	35,639	85.9	24	0
Nimmie-Caira	93,355	17	49	31,508(34)	43(21)	75,395	80.8	1883	273
Redbank	91,629	34	7	54,376(59)	27(33)	51,935	56.7	104	32

[a]Wetland area (ha) lost and degraded on the Lowbidgee floodplain and lengths of levee banks on floodplains, bordering channels and irrigation bays and constructed channels in each of the strata (Figure 5) and total floodplain, 1902–1998.
[b]1902 map of floodplain (SA Government 1902) and geomorphological data layer of the area (Butler and others 1973) covered 90% of the core mapped area.
[c]Percentage of original wetland.
[d]Random points (sample size in parentheses) assessed as degraded where vegetation was dead (no canopy) or poor (<30% of canopy with leaves or growth).
[e]Total wetland area lost or degraded.

There was a further significant decrease in wetland area over the Lowbidgee floodplain 1975–1998 (log (wetland area) = 49.333 – 0.019 year, $R^2 = 0.888$, $p < 0.001$, Figure 4). An additional 32% (96,309 ha) of the original wetland area was lost from the Lowbidgee floodplain (Table 2) and most of this was from the Nimmie-Caira system where an estimated 49% (45,813 ha) of wetland was lost (Table 2). There appeared to be a stabilization in the amount of area lost on the floodplain after 1995 (Figure 4).

Substantial areas, about 42% (127,688 ha), of the original wetland remained (Table 2, Figure 4). Of this remaining wetland area, 44% (56,183 ha) was degraded (Table 2). Among strata, the percentage of wetland remaining varied: 33%–59%. The Redbank system had the greatest extent of wetland and least degradation (27%) (Table 2). The Murrumbidgee and Fiddlers-Uara strata had similar degradation of remaining wetland areas (Table 2). In total, we estimated that 76.5% of the wetland area defined on the original 1902 map was either lost or degraded (Table 2).

There was a significant increase in the developed area for irrigation across the whole Lowbidgee floodplain between 1975 and 1998 (log (*developed area*) =

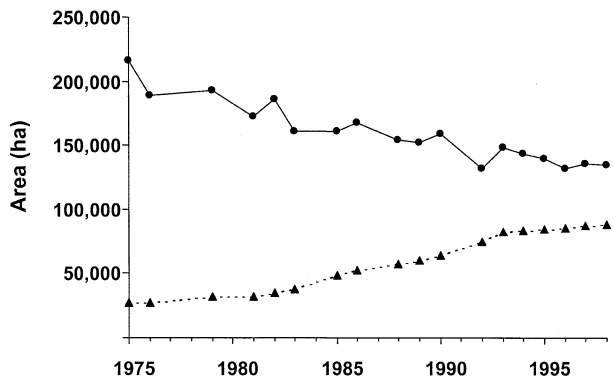

Figure 4. Total changes in wetland (●) and developed areas (▲) on the Lowbidgee floodplain between 1975 and 1998, based on classification using Landsat MSS imagery.

0.059 *year* – 106.966, $R^2 = 0.971$, $p < 0.001$, Figure 4) and most of this occurred in the Nimmie-Caira system. The area developed doubled in the period 1975–1998, from about 41,400 ha to 88,700 ha (Figure 4).

Levees, channels with 61 regulators and weirs (Maude and Redbank), were built across the floodplain, primarily for irrigated crops. These changed the distribution of wetland flooding. By 1998, there was 2145 km of levee banks and 394 km of constructed channels (Figure 5, Table 2). Most (88%) of the levee banks and the channels (69%) were in the Nimmie-Caira system (Figure 5, Table 2).

Waterbirds

Most waterbirds occurred on the floodplain of the Nimmie-Caira stratum. There was a significant decline in total numbers of waterbirds and some evidence for a decline in numbers of species 1983–2001 on the Lowbidgee floodplain, despite considerable variability (Table 3, Figure 6). Mean numbers of waterbirds on the Lowbidgee averaged about 139,900, 1983–1986, compared with about 14,200 at the end of the survey 1998–2001, a reduction of 90% in abundance (Table 3). Only total numbers of waterbirds declined significantly on one of the reference sites: Fivebough Swamp (Table 3, Figure 6). Total numbers of waterbirds on Fivebough Swamp showed similar decline as on the Lowbidgee floodplain, although the rate of decline was not as high (Table 3). The decline in abundance on Menindee Lakes at the beginning of the survey compared to the end of the survey (Table 3) was not significant because of high abundance in the middle of the survey (Figure 6).

Mean numbers of species declined by about 21% from 34 to about 27 species on the Lowbidgee floodplain from the beginning to the end of the surveys (Table 3; Figure 6). Also, there was relatively little variability in numbers of species 1983–1993, but a considerable increase in variability afterwards, with the lowest numbers on record occurring in 3 of the last 5 years (Figure 6). There were no significant declines in numbers of species on the three reference wetlands (Table 3; Figure 6).

The pattern of decline of total numbers of waterbirds on the Lowbidgee floodplain was significant across most functional groups of waterbirds; herbivores also appear to decline (Table 3; Figure 7). Comparing the beginning with the end of the surveys, there was an 80% or more decline in abundance across all groups of waterbirds (Table 3). Piscivorous waterbird species declined from about 12,300 to about 2,200, whereas large wading birds dropped from 29,700 to about 2,700. There were declines in numbers of duck species from about 54,500 to 5,200, herbivorous waterbird numbers dropped from 23,700 to 2,900 (Table 3) while small wading waterbirds exhibited the greatest decline from about 19,600 to 900 (Table 3).

Discussion

The Murrumbidgee River is one of the more agriculturally important river catchments in Australia, particularly for irrigation (National Land and Water Resources Audit 2001), but this development has come at a high ecological cost to the river's main wetland, the Lowbidgee floodplain (Figure 1). The floodplain has joined a growing list of wetlands exhibiting symptoms of ecological collapse from water resource development (Micklin 1988, Wiens and others 1993, Stanley and Warne 1998). Few global or Australian estimates of wetland loss or degradation (Lemly and others 2000) match that of the Lowbidgee floodplain, where about 76% of the area was lost or degraded over 140 years, 1855–1998 (Table 2). Historical accounts of the area described an extensive wetland, frequently flooding from the Murrumbidgee River (SA Government 1902), but dams and diversions of water upstream and development of the Lowbidgee floodplain considerably reduced the size of the wetland (Tables 1 and 2, Figures 3 and 4).

Development of the Murrumbidgee River

With few major distributaries upstream (Figure 1), most water (76% median, Table 1) in the Murrumbidgee River from Wagga Wagga reached Hay each year and most (85%) then flooded the Lowbidgee floodplain (Cross and others 1991, DWR 1994). Effects of river regulation began in 1855 when flow was diverted down Yanco Creek, followed by construction of dams

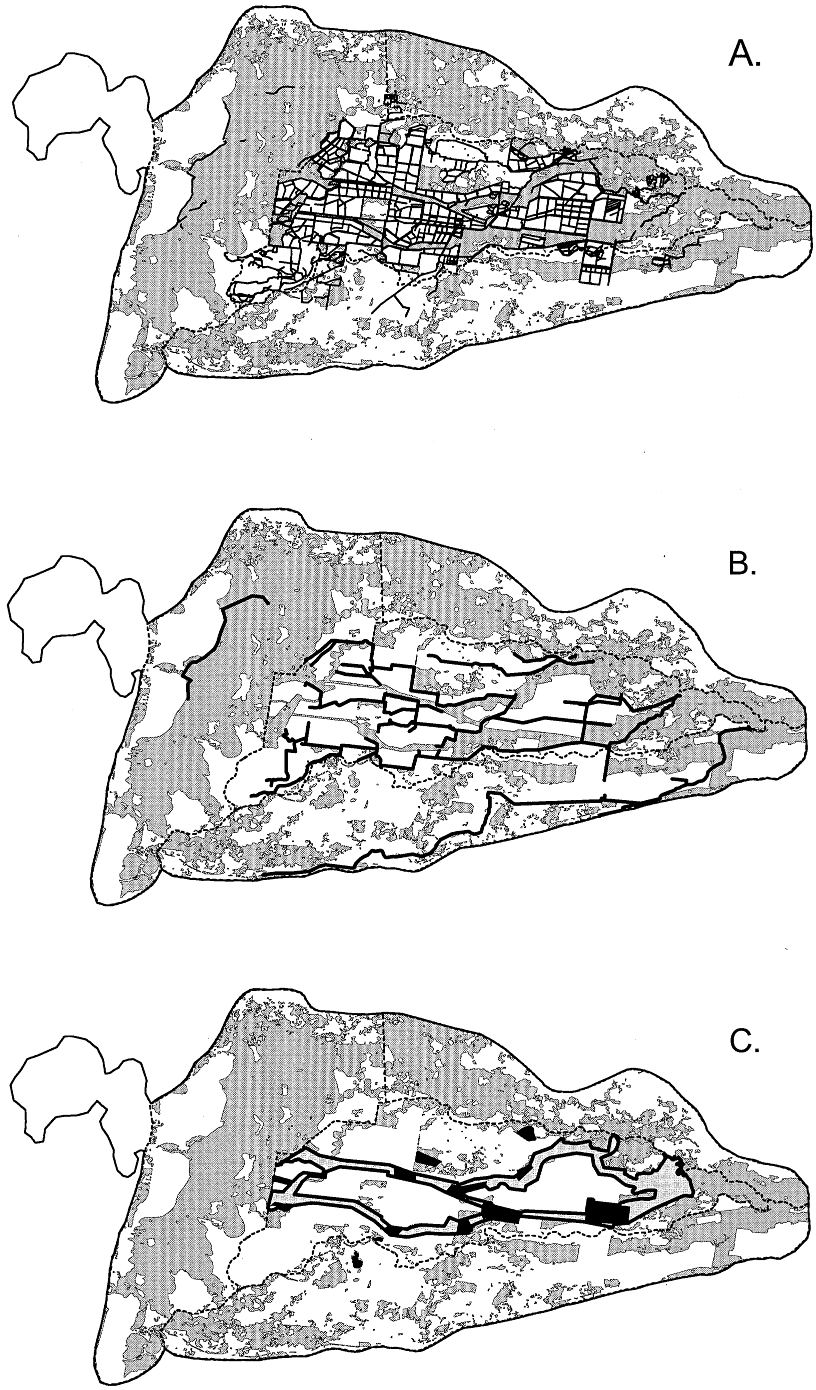

Figure 5. Original Lowbidgee floodplain, 1998 wetland coverage from satellite imagery (gray) and four strata. Distribution of 2145 km of levee banks around irrigation bays, along channels and across flood system (**A**), 394 km of constructed channels (**B**), and floodways (enclosed by thick boundary) used to convey water to specific wetlands or key habitat areas (solid) and irrigation bays (**C**).

for major irrigation areas, the Snowy-Mountains Hydroelectric Scheme and the city of Canberra (Kingsford 2003). We estimated that annual volumes to the Lowbidgee floodplain were reduced by about 60%: 48% reduction between Wagga Wagga and Hay and about a 13% reduction between Maude and Hay (Table 1, Figure 3B). There was evidence of some decline in flows from Maude to Balranald after the 1950s (Figure 3C), supplemented by additional water from the Lachlan River, which has also had about a 50% reduction in flows (EPA 1997). This did not account for diversions of about 65,000 ML upstream of Wagga Wagga for use in Canberra and irrigation (DLWC 1996). Our estimate was probably conservative. The Integrated Quality and

Table 3. Annual trends in waterbird abundance in four wetland systems, including the Lowbidgee[a]

Wetland	Waterbirds[b]	1983–1986 Mean (±SE)	1998–2001 Mean (±SE)	Change[c] (%)	R^2	Const.	Coeff.	Signif.
Lowbidgee	Numbers of species	34 (0.8)	27 (2.5)	–21	0.205	81.7	−0.038	0.051
	Abundance	139,939 (22,153.2)	14,170 (10,626.5)	–90	0.472	362.8	−0.177	0.001
	Piscivores	12,343 (2,686.6)	2,235 (1,620.9)	–82	0.392	298.5	−0.146	0.004
	Large waders	29,732 (10,422.6)	2,707 (2,366.2)	–91	0.483	462.4	−0.228	0.001
	Ducks	54,528 (5,895.3)	5,256 (4,187.7)	–90	0.413	406.5	−0.199	0.003
	Herbivores	23,745 (8,194.4)	2,968 (1,598.9)	–87	0.197	262.0	−0.127	0.057
	Small waders	19,591 (9,953.9)	1,003 (970.9)	–95	0.463	548.2	−0.272	0.001
Fivebough	Abundance	6,844 (2345.3)	911 (372.2)	–87	0.244	194.0	−0.094	0.031
	Number of species	13 (0.7)	12 (2.1)	–8	0.004	19.5	−0.008	0.788
Menindee Lakes	Abundance	47,698 (24,122.1)	2,369 (68.1)	–95	0.131	204.0	−0.100	0.128
	Number of species	22 (4.5)	18 (2.5)	–18	0.007	24.7	−0.01	0.732
Paroo Overflow	Abundance	14,224 (10861.7)	18,616 (10,280.7)	31	0.023	–82.4	0.046	0.532
Lakes	Number of species	20 (1.9)	23 (2.2)	15	0.012	–18.6	0.012	0.652

[a]Results of trend analysis (1983–2001) and mean (±SE) numbers of species, abundance, and different waterbird groups estimated during annual aerial surveys in October (1983–2001) across the Lowbidgee floodplain, Fivebough Swamp, the Menindee Lakes system, and the Paroo overflow lakes. Means were calculated for the 4 years at the beginning of the survey period (1983–1986) and the end (1998–2001).

[b]Waterbirds were divided into broad foraging groups: piscivorous birds (e.g., cormorants, pelicans, terns), large wading birds (herons, egrets, spoonbills, ibis), duck species (most duck species except herbivores), herbivorous waterbirds (e.g., black swans, Australian wood duck), and small wading birds (Charadriformes) (see Kingsford and Porter 1994).

[c]Percentage change was the percentage difference between means, 1983–1986 and 1998–2001.

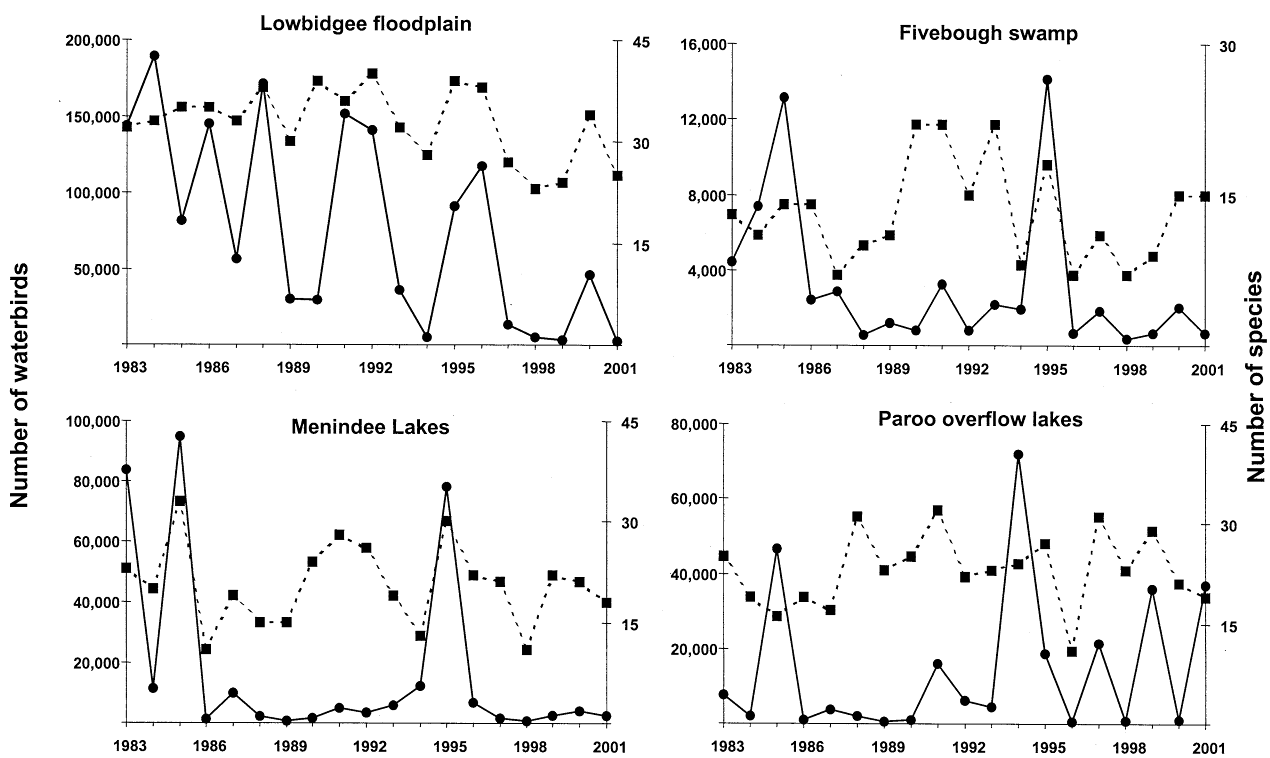

Figure 6. Estimated numbers of waterbirds (●) and numbers of species (■), using aerial surveys, on the Lowbidgee floodplain, Paroo overflow lakes, Menindee Lakes, and Fivebough Swamp, 1983–2001.

Quantity Model (IQQM), used to manage river flows, produced estimates of median outflows of the Murrumbidgee River that were only 20–25% of natural levels with dry years occurring in 57% of years, compared to

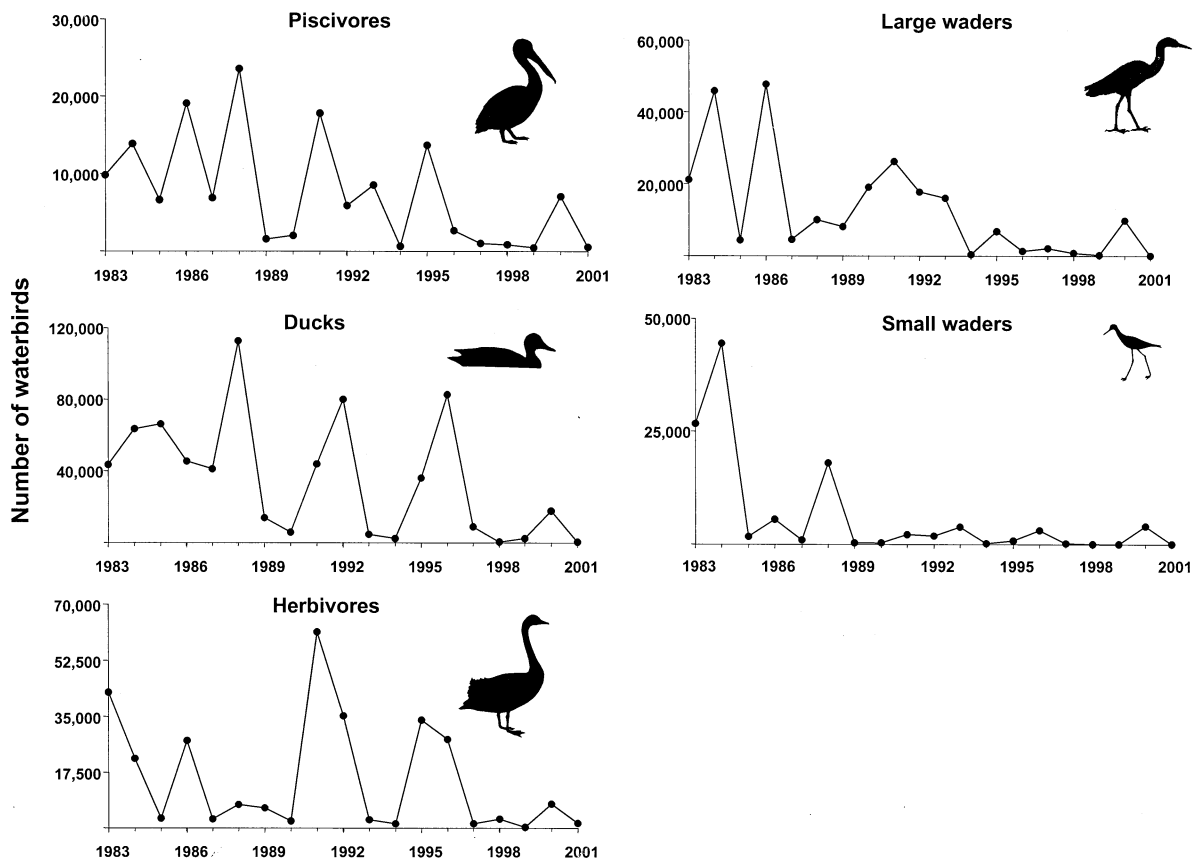

Figure 7. Estimated numbers of five groups of waterbirds: piscivorous waterbirds, large wading birds, duck and small grebe species, herbivorous waterbirds, and small wading birds from aerial surveys on the Lowbidgee floodplain each October between 1983 and 2001.

a natural frequency of 5% (MDBMC 1995, EPA 1997). These reductions occurred in the main river, but reductions in flows were potentially much higher on the floodplain.

Development of the Lowbidgee Floodplain

Our estimate of wetland degradation and loss on the Lowbidgee floodplain significantly revises a previous estimate of about 20% (MDBMC 1995). It is also an underestimate because we focused on the core 90% of the original floodplain (SA Government 1902) and the periphery was probably destroyed from upstream diversions. Also, we did not include remaining wetland area altered by increased flooding: floodways, key habitat areas (Figure 5C), and open water lakes (Figure 1).

Diversions upstream and levees (1902–1975) began the destruction of the floodplain, particularly in the peripheral areas of the Fiddler-Uara and Murrumbidgee strata (Table 2). Most flood-dependent vegetation was either dead or degraded in the Murrumbidgee and Fiddlers-Uara strata, respectively (Table 2). We probably underestimated the impact of reduced flooding because some wetland areas reflected a spectral water signature on Landsat imagery, resulting from local rainfall. The small size of lignum bushes in the Fiddler-Uara compared to the Nimmie-Caira (DWR 1989) provided further evidence of reduced flooding, despite their similar distribution on the floodplain.

Maude and Redbank Weirs, built in 1939–1940, raised the river height, restoring some flooding to the floodplain in most years (Eddy 1992) but not to natural levels. There was a 10% reduction in annual frequency of flooding post 1940 (Pressey and others 1984), with floods occurring about once every 3 years (Eddy 1992) compared to every 1 or 2 years (SA Government 1902, p. 64–65, 67). Because water could be controlled, the weirs were catalysts for subsequent water resource development within the floodplain (Kingsford 2003), subsequently destroying or degrading about 32% of the original floodplain (Table 2; Figure 3).

About half of this loss was in the Nimmie-Caira system, where about 60% of the wetland area present in

1975 (Table 2) was converted into irrigation bays (Figure 5) for wheat, barley, and safflower (Parmenter 1996). Irrigation bays and agricultural areas were protected by levee banks, supplied by water through constructed channels (Table 2, Figure 5). These fragmented wetland area (Figure 5), reducing the ability of flows to reach floodplain areas unless directly connected by a channel.

An "engineering" approach was adopted for development of the floodplain, beginning with identification of special habitat areas or rookeries (Figure 5C) that could be provided with water by floodways of hydrological continuity for biota and nutrients (DWR 1989, Cross and others 1991). This narrow definition for wetlands (i.e., rookeries or key habitat areas) allowed widespread development of the floodplain (Figure 5C) and increased flows down the floodways, changing the distribution and abundance of aquatic vegetation and favoring colonisation by cumbungi (*Typha* spp.) (Eddy 1992, DWR 1994, DLWC 1997). Lignum died in key habitat areas (e.g., Eulimbah, Figure 5) because of permanent flooding.

Waterbirds

The size of the Lowbidgee floodplain and its hydrological complexity (Butler and others 1973, Kingsford and Thomas 2002) provided habitat for a large range of biota (Pressey and others 1984, Scott 1992, Porteners 1993), including waterbirds (Maher 1990). Sixty species of waterbirds (68% breeding), including all functional feeding groups (Figure 7), occurred in the area in the late 1980s (Maher 1990). The floodplain had the third largest breeding colony of Glossy Ibis (*Plegadis falcinellus*) (>2000 pairs in 1984) and the seventh largest breeding colony of Straw-necked Ibis (*Threskiornis spinicollis*) (40,000 pairs in 1981) recorded in Australia (Lowe 1983, Marchant and Higgins 1990).

There were about 140,000 waterbirds regularly on the floodplain in October in the early 1980s, but numbers had collapsed by 90% to about 14,200 and number of species reduced by 21% by 1998–2001 (Table 3, Figure 6). The Lowbidgee wetlands were among the highest ranked 4 to 10 wetlands for waterbird abundance and diversity in 10% of eastern Australia in 1983–1993 and 1995, but it failed in 1994 and 1997–1999, 2001 (Kingsford and others unpublished data). Most of the decline on the Lowbidgee occurred in floodplain areas, even though many waterbirds still fed in cropped areas (Maher 1990, Magrath 1992, DWR 1994). Some of the decline was also due to reduced flows as a result of upstream diversions and poor rainfall. Changes also occurred on the open water lakes (e.g., Yanga Lake) used to store and regulate water where flocks of more than 10,000 waterbirds occurred in the 1960s (Hobbs 1961), but now seldom support more than a few hundred waterbirds (Pressey and others 1984), probably with reduced potential for breeding of waterbirds (Briggs and others 1997). Significant declines occurred across most major functional waterbird groups (Table 3, Figure 7). Because waterbird abundance and composition generally reflect abundance of potential food (Kingsford and Porter 1994), other aquatic biota probably experienced similar declines in abundance. Native fish populations have declined considerably in the Murrumbidgee River (Brown 1992, Gehrke and others 1995, Harris and Gehrke 1997), contributing to the listing of this area and adjacent other parts of the river as an endangered fish community under the New South Wales Fisheries Management Act 1994.

Effects of channels and levees impacted after 1990 (Kingsford 2003), isolating key habitat areas and rookeries from the contracting floodplain (Figure 5C). Breeding waterbirds probably need to forage over large floodplain areas when breeding (Butler 1994, Kingsford and Johnson 1999, Leslie 2001). Ground surveys of colonies indicated declining colony size. Waterbird colonies in 1989 and 1990 were less than in the previous years (Maher 1990, Magrath 1992) while the estimate of 40,000 pairs of breeding waterbirds (Lowe 1983) has not been reached in the subsequent 20 years (Maher 1990).

Conservation

The decline of the Lowbidgee floodplain illustrates a major problem for protection of wetlands of high conservation importance. Conservation legislation is primarily designed to protect areas of biological significance as reserves (e.g., National Parks and Nature Reserves) (Margules and Pressey 2000). When policies for river flows, the key factor for wetland health and the distribution and abundance of biota, are determined outside a reserve's boundaries, conservation may not be achieved (Barendregt and others 1995). On the Lowbidgee floodplain, two areas have protection: Yanga Nature Reserve (Figure 1) for its black box community and 23,800 ha of lignum protected from clearing (Cross and others 1991). The long-term prospects for these flood-dependent communities are poor because flooding now rarely occurs. Terrestrial vegetation will eventually take over these areas, with much of the lignum and black box either dead or in poor condition and depending on groundwater, rainfall, or occasional large floods (Table 2). Long-lived floodplain vegetation may experience long lag effects of water resource development (Kingsford 2000b, Taylor and others 1996).

Effective protection of floodplains must involve legislation and policy controlling threatening processes upstream or within the floodplain, including protection of remaining flows and floods and restoration of flows in the future. Options of listing an area such as the Lowbidgee floodplain as a threatened ecological community now exist, but effectiveness is still tied to provision of adequate flows. In 1995, Governments capped water diversions at 1993/1994 levels of development in all rivers in the Murray-Darling Basin (MDBMC 1996), including the Murrumbidgee River. This was followed by implementation of environmental flow rules (Kingsford 2003). These form part of a statutory water-sharing plan and include three main aspects: increased variability for the upper river outside the irrigation season, a relatively small environmental allocation in storage (60,000 ML), and a seasonally variable low flow target at the end of the river (Balranald). Irrigated agricultural demands upstream still exert considerable pressure on water policy and management in the Murrumbidgee River. Management of diversions remains difficult, with the cap target exceeded by about 7.7% in 1998/1999 (MDBMC 1999) and an increase of 23% in the area of rice sown between 1998/1999 and 1993/1994 (MDBMC 1999, DLWC unpublished data).

Conclusions

Water resource development and wetland decline are intertwined (Lemly and others 2000, Kingsford 2000b, Bunn and Arthington 2002, Arthington and Pusey 2003). The Murrumbidgee River is one of the more graphic examples with its long history of water resource development (Kingsford 2003). Diversions of about 2,144,000 ML year^{-1} from the Murrumbidgee River (National Land and Water Audit 2001) come from a natural median flow of about 3,380,000 ML year^{-1} (EPA 1997). Most of this water (94%) was diverted for irrigation, mostly upstream of the Lowbidgee floodplain. Much of this water would have reached the floodplain, sustaining a floodplain of more than 300,000 ha with complex flood-dependent biota and processes (Ward 1998). Institutional and economic factors for water resource development held primacy in decision-making to the ecological detriment of the floodplain (Kingsford 2003). Of the four criteria that made the Lowbidgee floodplain a potential wetland of international importance in the early 1990s (DWR 1994), only river red gum areas are in reasonable condition (Eddy 1992). Evidence exists that other parts of the river are also in ecological decline (Sheldon and others 2000).

There are three main lessons to be learned for the conservation of rivers. First, conservation of floodplain communities and their biota in reserves is insufficient without policies and processes that protect the flood regimes on which they depend. Second, case studies such as the Lowbidgee, showing the scale of the ecological impact, are essential for cost–benefit analyses on river systems that still remain the focus for development (Kingsford and others 1998). Third, rehabilitation of the Lowbidgee floodplain will only be possible if sufficient water is provided, but this will come at a high economic price for the irrigation industry that has developed the area, predominantly encouraged by Government (Kingsford 2003). These issues are germane to water resource development and wetland conservation around the world. Until there is good implementation of protection policies and legislation for river management, the example of the demise of the Lowbidgee floodplain will be repeated and we will continue to lose some of the most biodiverse ecosystems of the world.

Acknowledgments

Funds for this project were supplied by grants from Environment Australia and Land and Water Research Development Corporation through their wetlands program. The Natural Heritage Trust also provided funding. Hydrological data were provided by the New South Wales Department of Land and Water Conservation and the Snowy Mountains Hydroelectric Authority. We thank those who assisted with aerial surveys. The New South Wales National Parks and Wildlife Service provided support for this project. Views expressed by the authors do not necessarily reflect the views and policies of Environment Australia, the Land and Water Research Development Corporation, the Commonwealth Government, or the New South Wales Government.

Literature Cited

Arthington, A. H., and B. J. Pusey. 2003. Flow restoration and protection in Australian rivers. *River Research and Applications* 19:377–395.

Barendregt, A., M. J. Wassen, and P. P. Schot. 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., and W. J. M. Vestjens. 1989. The food of Australian birds. I, non-passerines. CSIRO Division of Wildlife and Ecology. Parchment Press, Melbourne 738.

Boulton, A. J., and L. N. Lloyd. 1992. Flooding frequency and invertebrate emergence from dry floodplain sediments of the River Murray, Australia. *Regulated Rivers* 7:137–151.

Briggs, S. V., S. A. Thornton, and W. G. Lawler. 1997. Relationships between hydrological control of river red gum wetlands and waterbird breeding. *Emu* 97:31–42.

Brown, P. 1992. The Murrumbidgee River fishery—a historical perspective J. Roberts R. Oliver The Murrumbidgee, past and present. A forum on past and present research on the lower Murrumbidgee River held at CSIRO Division of Water Resources, Griffith, New South Wales CSIRO Division of Water Resources Griffith 20 26.

Bunn, S. E., and A. H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30:492–507.

Butler, R. W. 1994. Population regulation of wading Ciconiiform birds. *Colonial Birds* 17:189–199.

Butler, B. E., G. Blackburn, J. M. Bowler, C. R. Lawrence, J. N. Newell, and S. Pels. 1973. A geomorphic map of the riverine plain of south-eastern Australia. Australian National University Press, Canberra. pp 39.

Crabb, P. 1997. Murray-Darling Basin Resources. Murray-Darling Basin Commission, Canberra 300.

Cross, H. C., P. D. Wettin, and F. M. Keenan. 1991. Corridors for wetland conservation and management? Room for conjecture D. A. Saunders R. J. Mobbs Nature conservation 2: the role of corridors Surrey Beatty and Sons Sydney 159 165.

Davies, B. R., M. Thoms, and M. Meador. 1992. An assessment of the ecological impacts of inter-basin water transfers, and their threats to river basin integrity and conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems* 2:325–349.

DLWC (NSW Department of Land and Water Conservation) 1996. Murrumbidgee Catchment, 1994–1995. State of the rivers report. Vols 1 and 2. NSW Department of Land and Water Conservation, Parramatta.

DLWC 1997. Draft Land and Water Management Plan for Nimmie/Caira system. Vegetation management. NSW Department of Land and Water Conservation, Murrumbidgee Region, Leeton.

DWR (Department of Water Resources) 1989. Lowbidgee management plan: stage one: Protected lands and floodway scheme. NSW Department of Water Resources, Sydney.

DWR (Department of Water Resources) 1993. Water resources of the Murrumbidgee Valley. NSW Department of Water Resources, Sydney.

DWR (Department of Water Resources) 1994. Lowbidgee management plan: Stage two: land and water management 1991–96. NSW Department of Water Resources, Sydney.

Dynesius, M., and C Nilsson. 1994. Fragmentation and flow regulation of river systems in the northern third of the world. *Science* 266:753–762.

Ebsary, R. 1992. Regulation of the Murrumbidgee River J. Roberts R. Oliver The Murrumbidgee, past and present. A forum on past and present research on the lower Murrumbidgee River held at CSIRO Division of Water Resources, Griffith, New South Wales CSIRO Division of Water Resources Griffith 49 59.

Eddy, V. 1992. The Lowbidgee experience: Simulated natural flooding and river red gum. Pages 149–156 *in* Catchments of green—a national conference on vegetation and water management. Vol. B. Greening Australia, Adelaide.

EPA (Environment Protection Authority) 1997. Proposed interim environmental objectives for NSW Waters. Environment Protection Authority, Chatswood, Sydney.

Gehrke, P. C., P. Brown, C. B. Schiller, D. B. Moffatt, and A. M. Bruce. 1995. River regulation and fish communites in the Murray-Darling River system, Australia. *Regulated Rivers* 11:363–375.

Graf, W. L. 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research* 35:1305–1311.

Harris, J. H., and P. E. Gehrke. 1997. Fish and rivers in stress: The NSW River Survey. NSW Fisheries Office of Conservation and the Cooperative Research Centre for Freshwater Ecology, Cronulla, Sydney.

Hobbs, J. 1961. Birds of south-western New South Wales. *Emu* 61:21–55.

Johnston, R. M., and M. M. Barson. 1993. Remote sensing of Australian wetlands—an evaluation of Landsat TM data for inventory and classification. *Australian Journal of Marine and Freshwater Research* 44:235–252.

Jolly, I. D., G. R. Walker, and P. J. Thorburn. 1993. Salt accumulation in semi-arid floodplain soils with implications for forest health. *Journal of Hydrology* 150:589–614.

Kingsford, R. T. 2000a. Protecting or pumping rivers in arid regions of the world. *Hydrobiologia* 427:1–11.

Kingsford, R. T. 2000b. Review: Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology* 25:109–127.

Kingsford, R. T. 2003. Ecological impacts and institutional and economic drivers for water resource development—a case study of the Murrumbidgee River, Australia. *Aquatic Ecosystem Health and Management* 6(1):69–79.

Kingsford, R. T., A. J. Boulton, and J. T. Puckridge. 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* 8:361–378.

Kingsford, R. T., and W. J. Johnson. 1999. The impact of water diversions on colonially nesting waterbirds in the Macquarie Marshes in arid Australia. *Colonial Waterbirds* 21:159–170.

Kingsford, R. T., and J. L. Porter. 1994. Waterbirds on an adjacent freshwater lake and salt lake in arid Australia. *Biological Conservation* 69:219–228.

Kingsford, R. T., and R. F. Thomas. 2002. Use of satellite image analysis to track wetland loss on the Murrumbidgee River floodplain in arid Australia, 1975–1998. *Water Science and Technology* 45:45–53.

Kingsford, R. T., P. S. Wong, L. W. Braithwaite, and M. T. Maher. 1999. Waterbird abundance in eastern Australia, 1983–1992. *Wildlife Research* 26:351–366.

Lemly, A. D., R. T. Kingsford, and J. R. Thompson. 2000. Irrigated agriculture and wildlife conservation: conflict on a global scale. *Environmental Management* 25:485–512.

Leslie, D. J. 2001. Effect of river management on colonially-nesting waterbirds in the Barmah-Millewa forest, south-eastern Australia. *Regulated Rivers: Research and Management* 17:21–36.

Lowe, K. W. 1983. Egg size, clutch size and breeding success of the glossy ibis. *Plegadis falcinellus. Emu* 83:31–34.

Magrath, M. J. L. 1992. Waterbird study of the lower Lachlan and Murrumbidgee valley wetlands in 1990/01. Prepared for the NSW Department of Water Resources. Unpublished.

Maher, P. N. 1990. Bird survey of the Lachlan/Murrumbidgee confluence wetlands. Report to NSW National Parks and Wildlife Service.

Marchant, S., and P. J. Higgins. 1990. Handbook of Australian, New Zealand and Antarctic birds. Volume 1 Ratites to ducks. Oxford University Press, Melbourne 1400.

Margules, C. R., and R. L. Pressey. 2000. Systematic conservation planning. *Nature* 405:243–253.

MDBMC (Murray-Darling Basin Ministerial Council). 1995. An audit of water use in the Murray-Darling Basin. Murray-Darling Basin 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.

MDBMC (Murray-Darling Basin Ministerial Council). 1999. Review of cap implementation 1998/99. Report of the Independent Audit Group. Murray-Darling Basin Ministerial Council, Canberra.

Micklin, P. P. 1988. Desiccation of the Aral Sea: a water management disaster in the Soviet Union. *Science* 241:1170–1176.

National Land and Water Resources Audit. 2001. Australian Water Resources Assessment 2000. Commonwealth of Australia, Canberra.

Parmenter, M. 1996. Lowbidgee Land and Water Management Plan Agricultural Zone. District Summary. Department of Land and Water Conservation, Hay.

Postel, S. L. 2000. Entering an era of water scarcity: the challenges ahead. *Ecological Applications* 10:941–948.

Porteners, M. F. 1993. The natural vegetation of the Hay Plain: Booligal-Hay and Deniliquin-Bendigo 1:250 000 maps. *Cunninghamia* 3:1–121.

Pressey, R. L., F. C. Bell, J. Barker, A. S. Rundle, and C. A. Belcher. 1984. Bio-physical features of the Lachlan-Murrumbidgee confluence, south-western New South Wales. NSW National Parks and Wildlife Service, Sydney.

SA (South Australian) Government. 1902. Report of the Inter-State Royal Commission on the River Murray. Government Printer, Adelaide.

Scott, J. A. 1992. The natural vegetation of the Balranald-Swan Hill area. *Cunninghamia* 2:597–652.

Sheldon, F., M. C. Thoms, O. Berry, and J. T. Puckridge. 2000. Using disaster to prevent catastrophe: Referencing the impacts of flow changes in large dryland rivers. *Regulated Rivers: Research and Management* 16:403–420.

Stanley, D. J., and A. G. Warne. 1998. Nile Delta in its destruction phase. *Journal of Coastal Research* 14:794–825.

SPSS. 1999. Systat 9. Statistics I and II. SPSS Inc., Chicago.

Taylor, P. J., G. R. Walker, G. Hodgson, T. J. Hatton, and R. L. Correll. 1996. Testing of a GIS Model of *Eucalyptus largiflorens* health on a semiarid, saline floodplain. *Environmental Management* 20:553–564.

Vörösmarty, C. J., K. P. Sharma, B. M. Fekete, A. H. Copeland, J. Holden, J. Marble, and J.A. Lough. 1997. The storage and aging of continental runoff in large reservoir systems of the world. *Ambio* 26:210–219.

Ward, J. V. 1998. Riverine landscapes: biodiversity patterns, disturbance regimes and aquatic conservation. *Biological Conservation* 83:267–278.

WCIC (Water Conservation and Irrigation Commission) 1972. Water Resources of the Murrumbidgee Valley. Survey of thirty two N.S.W. river valleys, report no. 24. Water Conservation and Irrigation Commission, Sydney, New South Wales.

Wiens, J. A., D. T. Patten, and D. B. Botkin. 1993. Assessing ecological impact assessment: Lessons from Mono Lake, California. *Ecological Applications* 3:595–609.

Zar, J. H. 1984. Biostatistical analysis. 2nd edition. Prentice-Hall Inc, Englewood Cliffs, NJ 718.