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## **Changing water regimes and wetland habitat on the Lower Murrumbidgee floodplain of the Murrumbidgee River in arid Australia.**

R.T. Kingsford and R.F. Thomas

New South Wales National Parks and Wildlife Service, P.O. Box 1967, Hurstville, NSW 2220, Australia



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## **Executive Summary**

The Lower Murrumbidgee floodplain has joined a growing list of wetlands around the world, that exhibit symptoms of ecological collapse, as a result of water resource development on the 1,690 km long Murrumbidgee River that supplies the wetland. The Lower Murrumbidgee floodplain covered more than 303,781 ha at the beginning of the 20<sup>th</sup> century. After over 140 years of water resource development (1855-1998), at a catchment and local scale, at least 76% of the wetland disappeared or degraded. Twenty-six storages in the catchment allowed diversion of 2,122,000 ML in 1998/1999, predominantly (95%) for irrigation, making the Murrumbidgee River one of Australia's more developed river. Diversion of water reduced the amount of water reaching the Lower Murrumbidgee floodplain by at least 60%. Also, levees cut-off the western parts of the floodplain in the early 1900s from the river. We estimated that water resource development caused the loss of 26% of the floodplain area before 1975. Then, we analysed wetland flooding in the Lower Murrumbidgee floodplain over a period of 23 years, 1975-1998, using Landsat satellite imagery. An additional 32% of the original wetland area was lost during this period. Of the remaining wetland area (42%) of the Lower Murrumbidgee floodplain, 44% of the perennial flood dependent vegetation was in poor health or dead and this area was defined as degraded. Long-term declines in health and distribution of floodplain vegetation are predicted because of reduced river flows, including the loss of flood dependent vegetation in Yanga Nature Reserve. Only one area on the Lower Murrumbidgee floodplain, the Redbank stratum, remained in reasonably good condition as a wetland. The building of about 394 km of channels and 2,145 km of levee banks have caused most of the destruction of wetland in the middle of the Lower Murrumbidgee floodplain (Nimmie-Caira stratum) where there was a 60% reduction in the wetland area present in 1975 by 1998. This was the habitat for most waterbirds. Waterbird numbers estimated using aerial surveys, every year between 1983 and 2000, collapsed by more than 80% and total numbers of species probably declined on the Lower Murrumbidgee floodplain. One reference site, Fivebough Swamp, exhibited similar changes but the other two (Menindee Lakes and Paroo River overflow lakes) did not. Changes on the Lower Murrumbidgee floodplain occurred across all functional groups, piscivores, herbivores, duck and small grebe species, large wading birds and small wading birds. Comparing the period at the beginning of the aerial surveys

(1983-1986) to the period at the end of the surveys (1997-2000), there were declines in numbers of piscivorous waterbird species from about 12,000 to 2,500; large wading birds from about 30,000 to about 4,000; duck and small grebe species from about 55,000 to 11,000; and small wading waterbirds from about 20,000 to 1,000. These reductions indicated a similar collapse in other aquatic biota that formed the food of these waterbird groups. Maude and Redbank Weirs, built in 1939-1940, restored some of the flows to the floodplain, originally lost through diversions upstream, but the weirs were also catalysts to further development on the floodplain in the 1980s and 1990s. The environmental importance of the area was well known in the early 1990s, as were the impacts of water resource development. The Lower Murrumbidgee floodplain serves as an example of the ecological consequences of water resource development. Debates and water resource developments planned for other rivers around Australia and the world need to ensure that such ecological costs are clearly defined, based on growing knowledge of river systems.

## **Introduction**

With access to water, human communities have established along many of the world's rivers, even in arid regions (Agnew and Anderson 1992), despite unpredictable river flows (Kingsford 2000a). Water stored in dams and diverted for human use is predominantly water that flowed to sea, underground aquifers or onto a river's floodplains (Kingsford 2000b). These floodplain wetlands provided a large range of different habitats for microbes, plants and animals resulting from complex spatial and temporal changes in geomorphology and hydrology.

Diversion of river flows upstream of floodplain wetlands has serious ecological and social impacts that are almost insoluble because of the dependency of upstream human communities and industry on the water (Kingsford 1999a). Successional changes result as ecosystems and their processes change from aquatic to terrestrial, once denied of water, resulting in serious declines in abundances of many aquatic organisms (Allan and Flecker 1993, Comín and Williams 1994, Lemly et al. 2000).

Hydrological and ecological effects of river regulation and diversions are acute in arid regions where water is scarce (Kingsford 2000a). Australia is the world's most arid inhabited continent (70% receives less than 500mm of annual rainfall) and has invested considerable capital into water resource infrastructure and development over more than 100 years. Per capita, we have the highest storage 4.6 ML/person (Wasson

*et al.* 1996) of any country in the world. Australia has a relatively small population (19 million) but is a significant international primary producer of food and fibre. Much of this production is dependent on diversions of water from our rivers for irrigation. Irrigated agriculture covers 2.6 million ha and uses 15,000 GL each year, about 70% of the water diverted (Wasson *et al.* 1996). Most of this water comes from the 26 major rivers of the Murray-Darling Basin (Kingsford 2000b). The Murray-Darling Basin is the crucible of agricultural production with almost a third of its \$10 billion produced by irrigated agriculture (MDBMC 1995).

The Murrumbidgee River has the most water diverted of any river in the Murray-Darling Basin (Crabb 1997), predominantly for irrigation, accounting for about 22% of all annual flows diverted in the Murray-Darling Basin (MDBMC 1995). There is a long history of water resource development on the river because the Murrumbidgee River was one of the first rivers developed for irrigation in Australia (Lloyd 1988). It is now one of the more developed rivers in Australia, with 98% of its divertible flow diverted (Kingsford 2000b) to irrigate pastures, rice, grains, vegetables, citrus and grapes. About 50% of Australia's rice crop is grown in the Murrumbidgee valley (DWR 1993a). Periodic droughts, social development and perceptions that water that flows down river was wasted were primarily responsible for water resource development on the Murrumbidgee River. Without such development many of the irrigation towns and industries on the Murrumbidgee would not have been as established as they are today (e.g. Griffith, Leeton). Water from the Murrumbidgee River catchment also supplies Australia's capital, Canberra (300,000 people) and the other major towns of Wagga Wagga (58,000 people), Griffith (21,000 people) and Tumut (11,000 people) (Fig. 1).

Nearly all of the water resource development on the Murrumbidgee River lies upstream of the river's major wetland system, the Lower Murrumbidgee floodplain. This wetland is listed as one of 35 major wetlands in the Murray-Darling Basin (Crabb 1997) and one of the important wetlands in Australia (ANCA 1996). The main aim of this study was to determine what ecological changes had occurred to the floodplain as a result of water resource development. As ecological impacts of regulating rivers and diverting their water occur over long temporal scales, we used three long-term data sets. Annual hydrological data were available over more than 100 years (1888-1998) to investigate changes in river flows. We used Landsat satellite data on wetland flooding over 23 years (1975-1998) to examine changes in wetland

area. We also analysed aerial survey data of waterbirds over 17 years (1983-1999) to determine trends in waterbird numbers on the floodplain.

*Objectives*

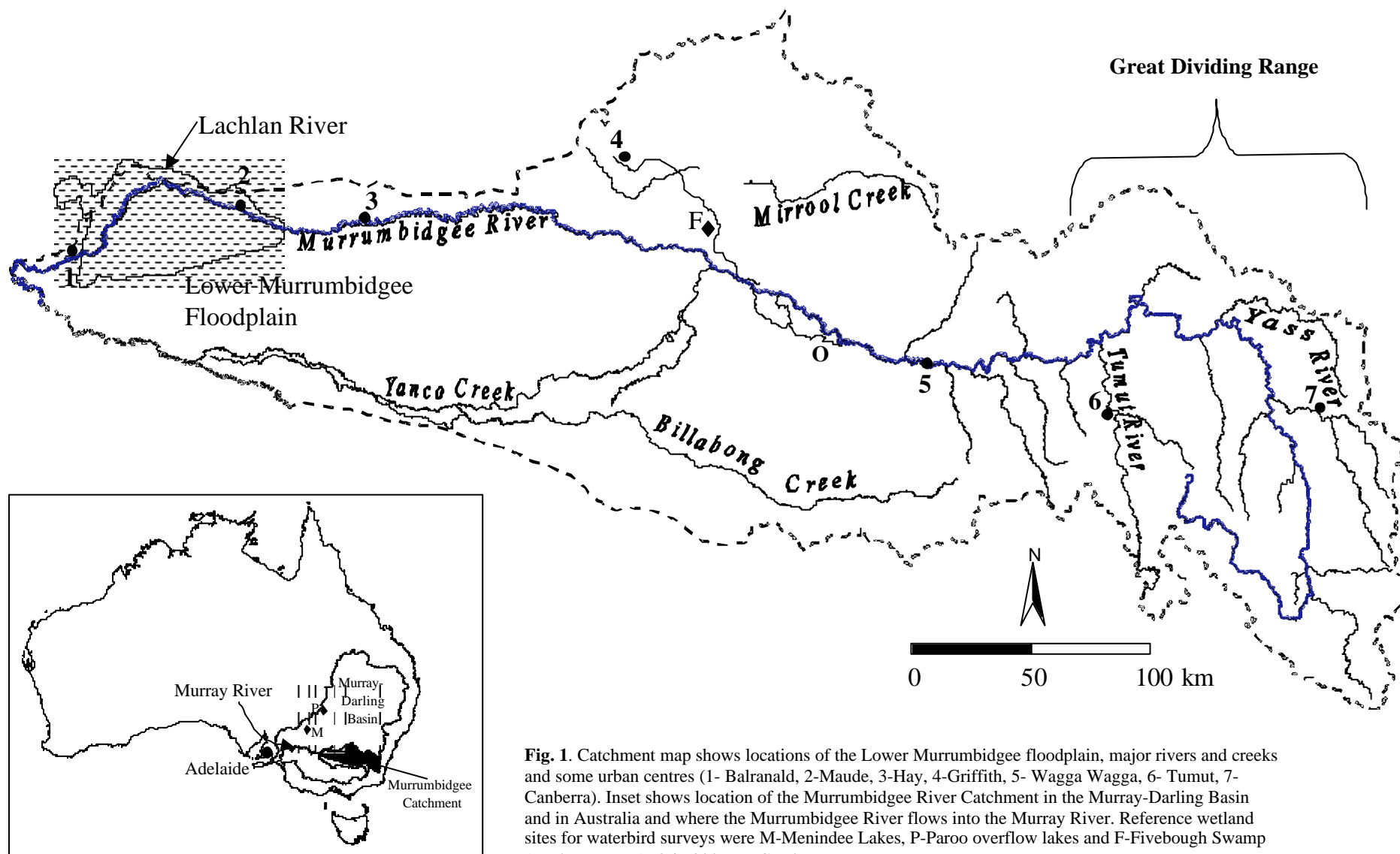
- a. To determine effects of altered water regime on wetland area in the Lower Murrumbidgee floodplain, at the confluence of the Murrumbidgee and Lachlan rivers.
- b. To determine how water management has modified wetland habitat.
- c. To determine the impacts of wetland changes on species and abundance of waterbirds.
- d. To determine impact of changes to wetland area in the Lower Murrumbidgee floodplain in the period 1975-1998.
- e. To analyse patterns of water flow to the Lower Murrumbidgee wetlands using hydrological data.

## **Methods**

### **Murrumbidgee River**

The Murrumbidgee River, 1,690 km long (Crabb 1997), is one of the more southerly catchments in the Murray-Darling Basin and it flows east to west in its 84,000 km<sup>2</sup> catchment (Fig. 1). Most of the river's flow comes from the Great Dividing Range, delivered by the main tributary rivers: Yass, Molongolo, Queanbeyan, Bredbo, Numeralla, Cotter, Goodradigbee and Tumut (Fig. 1). The Tumut River, although only occupying 5% of the catchment area, contributes about a third of the run-off in the river (WCIC 1972, p. 42). Highest rainfall in the catchment averages 1,500 mm per year, some of which is snow. Average annual rainfall in the lower catchment is about a fifth of this figure (DLWC 1996). River flows had a strong seasonal pattern, driven by reliable winter and spring rainfall and snow melt from the Great Dividing Range. The major tributary rivers join the Murrumbidgee River upstream of the town of Wagga Wagga (Fig. 1).

Seven smaller creeks (Jugiong, Adelong, Billabong, Hallas, Tarcutta, Kyeamba, and Hollaghans) also flow into the Murrumbidgee River. Mirrool and Billabong Creek, although within the Murrumbidgee River catchment, do not flow into the Murrumbidgee River (Fig. 1). The Murrumbidgee has one major distributary creek, Yanco Creek, and some smaller distributary creeks upstream of Maude (e.g. Old Man Creek, Gum Creek and Sandy Creek) (Fig. 1). As the Murrumbidgee River progresses to its lower end, distributary creeks take river flows to floodplain wetlands and lakes. Downstream of the town of Hay, the Murrumbidgee reaches the Lower Murrumbidgee floodplain, the most extensive wetland area in the Murrumbidgee River catchment (Fig. 1). The river then continues west to join the Murray River eventually flowing out to sea south of Adelaide (Fig. 1).



**Fig. 1.** Catchment map shows locations of the Lower Murrumbidgee floodplain, major rivers and creeks and some urban centres (1- Balranald, 2-Maude, 3-Hay, 4-Griffith, 5- Wagga Wagga, 6- Tumut, 7- Canberra). Inset shows location of the Murrumbidgee River Catchment in the Murray-Darling Basin and in Australia and where the Murrumbidgee River flows into the Murray River. Reference wetland sites for waterbird surveys were M-Menindee Lakes, P-Paroo overflow lakes and F-Fivebough Swamp (catchment map). O is Old Man Creek.

### **Lower Murrumbidgee floodplain**

The Lower Murrumbidgee floodplain is a wetland that lies on the semi-arid floodplain, where average maximum summer temperatures reach about 33°C and annual evaporation is 161.5 cm per year (WCIC 1972). Mean annual rainfall based on 107 years was 320mm at Balranald (Scott 1992). Most of the water for Lower Murrumbidgee floodplain comes from the upper catchment of the Murrumbidgee River.

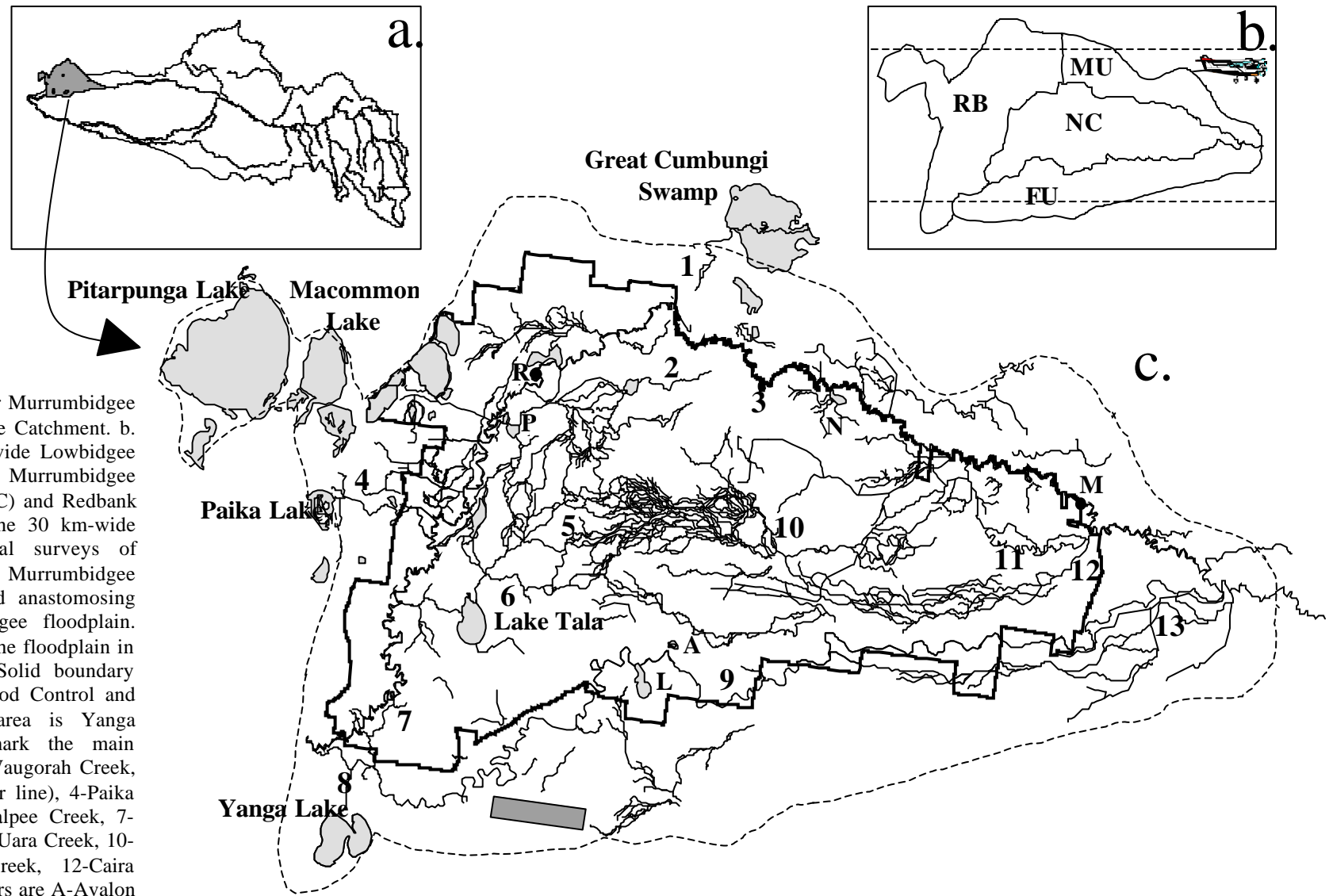
Floods are carried throughout the floodplain by a series of distributary creeks (Fiddlers, Uara, Cairra, Nimmie, Pollen, Waugorah, Talpee, Monkem, Kietta, Yanga and Paika) which form a highly complex interconnected network of anastomosing creeks on the Lower Murrumbidgee floodplain (Fig. 2) (Butler *et al.* 1973). Other smaller unnamed creeks also take water from the river to the floodplain. Most of these convey water to the south but some small creeks also take water to the north where the Lachlan River terminates in the Great Cumbung Swamp (Pressey *et al.* 1984). Flows from the Lachlan River (Fig. 2c) rarely reach the Murrumbidgee River (Pressey *et al.* 1984).

Flows leave the Murrumbidgee River first at Fiddlers Creek (previously known as Gum Creek) (Fig. 2c). This creek system is shallow and provided water to the south. The floodplain of this creek system includes Yanga Nature Reserve (1,772 ha), an area recognised for its stands of Black Box woodland (Fig. 2c). Anastomosing channels of Fiddlers Creek eventually form the Uara Creek that forms a channel and conveys water to Yanga Lake and the Murrumbidgee River near the town of Balranald (Fig. 2c).

The next creeks to leave the Murrumbidgee River are the Cairra and Nimmie Creeks that also convey water to the southwest (Fig. 2c). Neither has well defined channels from the river. The river used to flow over the banks to these systems of anastomosing channels. Water from the Cairra Creek flowed south before bifurcating to the north to form Pollen Creek and to the south to continue as Cairra Creek (DWR 1993b) (Fig. 2c). Nimmie Creek water joined up with Pollen Creek but also flowed to the northwest to inundate areas near the river. Between Nimmie Creek and Waugorah Creek, conveying water to the south, smaller channels take water to the floodplain. Waugorah Creek flows southwest to fill channels and floodplains and links up with Monkem and Talpee Creeks that similarly flow to the south to join up with the main channel of the Murrumbidgee River (Fig. 2c). The Murrumbidgee River also has

many small channels that convey water to the south. North and west of the Murrumbidgee River, the Redbank system is a large floodplain dissected by channels (Fig. 2c) with no defined distributary creeks. This area is primarily reliant on overbank flows caused by a constriction in the main channel capacity of the river. It is an area of primarily River Red Gum forests interspersed with swamps (Maher 1990, Eddy 1992, Scott 1992). There were also open water lakes greater than 50 ha (Maher 1990), including Piggery, Tala and Yanga Lakes (Fig. 2c). Black Box stands occur on the edges of the floodplain (Pressey *et al.* 1984). Further to the south, Paika Creek is a distributary flowing west from the Murrumbidgee River (Fig. 2c). When the Murrumbidgee River reaches Balranald, it loses some of its complexity and flows are primarily confined to the main channel before eventually flowing into the Murray River (Fig. 1).

Part of the Lower Murrumbidgee floodplain is now covered by a legislative boundary, the Lowbidgee Flood Control and Irrigation District (Fig. 2c). This is separated into two administrative systems for hydrological and natural resource management: Nimmie-Caira, which is south of the Murrumbidgee River and Redbank to the north and west of the Murrumbidgee River.



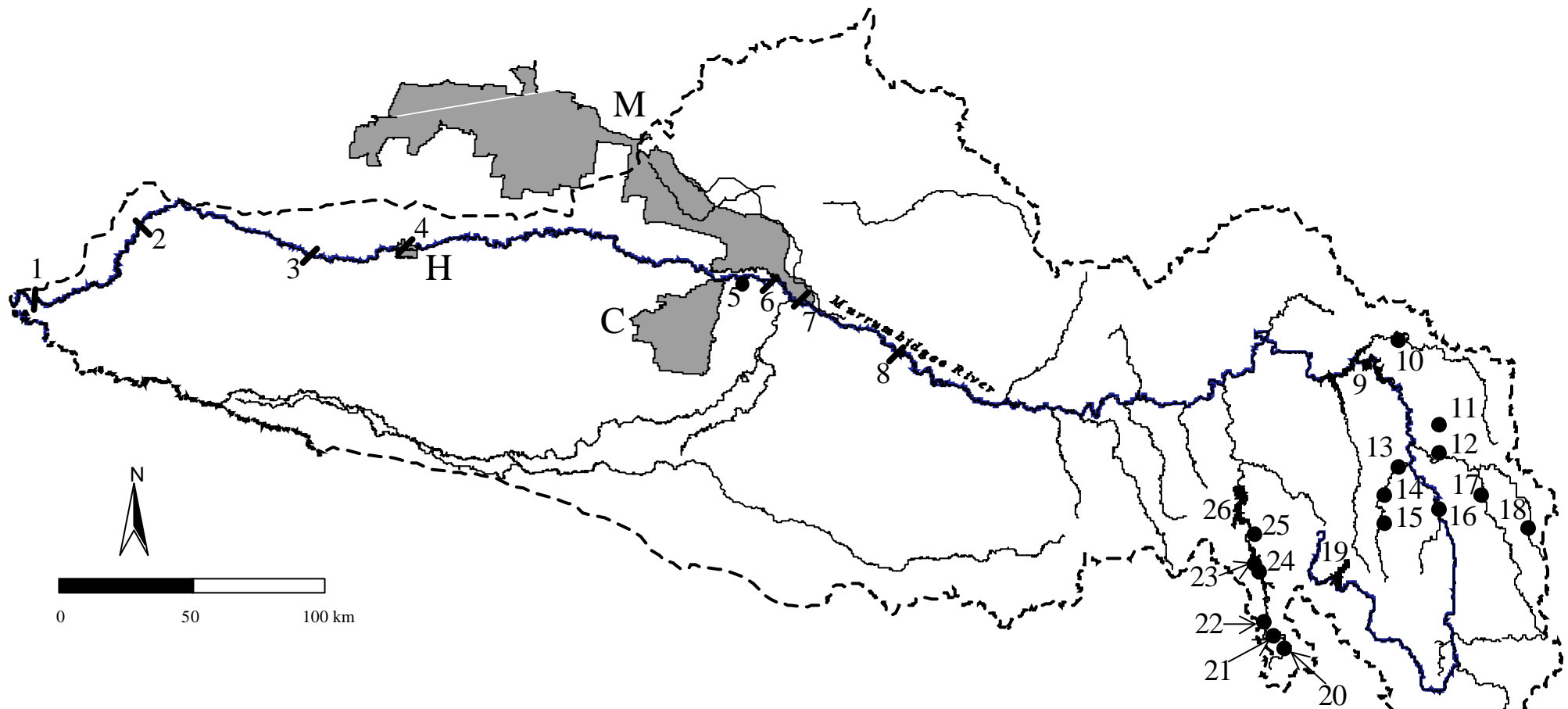
**Fig. 2** a. Location of the Lower Murrumbidgee floodplain in the Murrumbidgee Catchment. b. Hydrological strata used to divide Lowbidgee floodplain: Fiddlers-Uara (FU), Murrumbidgee River (MU), Nimmie-Caira (NC) and Redbank (RB). Dashed lines indicate the 30 km-wide survey band used for aerial surveys of waterbirds on the Lower Murrumbidgee floodplain c. Major lakes and anastomosing creek system in the Lowbidgee floodplain. Dashed line was the extent of the floodplain in 1902(South Australia 1902). Solid boundary line marks the Lowbidgee Flood Control and Irrigation District. Hatched area is Yanga Nature Reserve. Numbers mark the main streams: 1-Lachlan River, 2- Waugorah Creek, 3- Murrumbidgee River (darker line), 4-Paika Creek, 5-Monkem Creek, 6-Talpee Creek, 7- Kieta Creek, 8-Yanga Creek, 9-Uara Creek, 10-Pollen Creek, 11-Nimmie Creek, 12-Caira Creek, 13-Fiddlers Creek. Letters are A-Avalon Swamp, L-Loorica Lake, M-Maude Weir, N-Nap Nap Swamp, P-Piggery Lake and R-Redbank Weir

## River flows

We used annual river flow data (1888-1998) for four gauging stations on the Murrumbidgee River, Wagga Wagga, Hay, Maude and Balranald (Fig. 1) to investigate long-term changes in flow. Hydrological data were only available from 1937 to 1998 at Maude Weir. Most diversions for irrigation to the Murrumbidgee Irrigation Area and Colleambally Irrigation Area (Fig. 3), occur between Wagga Wagga and Hay (DWR 1993a). Also, the major tributary river systems join the Murrumbidgee upstream of the town of Wagga Wagga (Fig. 1) and there are relatively few diversions of water from the river upstream of this point (Ebsary 1992). The largest annual diversion upstream of Wagga Wagga is 35,000 ML, which supplies Canberra but there are also 263 extraction licences in the upper catchment, diverting about 30,000 ML per year (DLWC 1996).

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 annual index to water diversions. We calculated all flow data for the 12 month period November-October to coincide with survey data of waterbirds and wetlands.

After 1960, the storages of the Snowy-Mountains Hydroelectric Scheme were constructed which diverted river flows from the eastward flowing Snowy River into the Murray and Murrumbidgee River catchments (Davies *et al.* 1992). Water is diverted from Tantangara Reservoir in the Upper Murrumbidgee River (Fig. 3) into Lake Eucumbene in the Snowy River catchment and then down the Tumut River. Water can also be diverted from the southern Murray River catchment (Tooma Reservoir) into the Tumut River. Flow data were obtained to calculate the net annual amount of water diverted into the Murrumbidgee catchment each year. These were subtracted from annual flows at Wagga Wagga to ensure that relative analysis of changes in flow between Wagga Wagga and Hay were accounted for, without the influence of additional river flows from the eastern flowing rivers. We also analysed trends in annual quantity of water at Hay and Wagga Wagga over the 111 year period



**Fig. 3.** Locations of major dams (filled circles), weirs (diagonal bars) and irrigation areas (hatched) in the Murrumbidgee River catchment. Numbers refer to dams (reservoirs, pondages, lakes) or weirs: 1-Balranald Weir, 2-Redbank Weir, 3-Maude Weir, 4-Hay Weir, 5-Tombullen reservoir, 6-Gogeldrie Weir, 7-Yanco Weir, 8-Berembed Weir, 9-Burrinjuck Dam, 10-Yass Dam, 11-Lake Ginninderra, 12-Scrivener Dam, 13-Cotter Dam, 14-Bendora Dam, 15-Corin Dam, 16-Lake Tuggeranong, 17-Googong Dam, 18-Captains Flat Dam, 19-Tantangara Reservoir, 20-Happy Jacks Pondage, 21-Tumut Pond, 22-Tumut 2 Pondage, 23-Tumut 3, 24-Talbingo Reservoir, 25-Jounama Reservoir, 26-Blowering Dam,. Table 1 provides storage capacities and dates when storages were built. Letters refer to major irrigation areas: M- Murrumbidgee Irrigation Area, C-Coleambally Irrigation Area; H-Hay Irrigation Area.

(1888-1998) by dividing annual flow data for Wagga Wagga into three equal groups: low flows (<2,900,000 ML), medium flows (2,900,000 ML – 4,230,000 ML) and high flows (>4,230,000ML). Then trends in flows at Hay were analysed for these three flow categories.

Floods occur when flows exceed channel capacity of the Murrumbidgee River, which is comparatively low in the Lower Murrumbidgee floodplain compared to areas upstream: Redbank Weir (11,000 ML day<sup>-1</sup>), Maude Weir (20,000 ML day<sup>-1</sup>), Hay (35,000 ML day<sup>-1</sup>) and progressively higher upstream (Ebsary 1992). Daily flows do not exist for Maude or Redbank before regulation but daily flow data were available for Hay (1915-1998). We examined the frequency of different daily flows at Hay (<10,000 ML day<sup>-1</sup>; 10,000-20,000 ML day<sup>-1</sup>; 20,000-30,000 ML day<sup>-1</sup>; 30,000-40,000 ML day<sup>-1</sup>; 40,000-50,000 ML day<sup>-1</sup>; >50,000 ML day<sup>-1</sup>), for eight time periods from 1915 to 1998.

### **Wetland changes**

The Lower Murrumbidgee floodplain was mapped in 1902, before substantial water resource development in the catchment (South Australia 1902) (Fig. 2a). To determine original area of wetland on the Lower Murrumbidgee floodplain, we digitised the historical map drawn in 1902 of the area flooded on the Lower Murrumbidgee floodplain (South Australia 1902)(Fig. 2c). This was used as the basis of wetland area comparisons with satellite imagery. Part of the northern and eastern edges of this floodplain were not incorporated in our study area, which covered most (90%), of the original floodplain depicted on the map. The northern part was omitted because of the influence of the Lachlan River on flooding and only areas downstream of Fiddlers Creek were defined (eastern boundary). The floodplain is interspersed with dune formations and so we used a digital data layer of the geomorphology of the area (Butler *et al.* 1973) to define the extent of wetland area more precisely and remove non-wetland areas (e.g. dunes).

Two time periods were analysed separately: before 1975 and 1975-1998 (when satellite imagery was available). Wetland loss before 1975 was defined as the maximum area classified as wetland from satellite imagery (in the period 1975-1998) subtracted from the original wetland area from the historical 1902 map (South Australia 1902).

### *Index to wetland area*

Landsat satellite data, Multispectral Scanner (MSS) (average pixel size 50m) and Thematic Mapper (TM) (pixel size 30 m) sensors, provided data for an analyses of changes to wetland area over the Lower Murrumbidgee floodplain from 1975 to 1998. A 16-day periodicity allowed most images to be acquired at one time of year, during October. This coincided with maximum flooding (Pressey *et al.* 1984, DWR 1994), which gives the best definition of riverine wetland areas (Johnston and Barson 1993). It also coincided with aerial surveys of waterbirds.

Image dates selected from the MSS sensor were September 1975, October 1976, September 1979, October 1981-1986, November 1987, August 1988, July 1989, October 1990-1991, November 1992, October 1993, September 1994, November 1995-1996, and from the TM sensor were October 1993, 1997-1998 (Appendix 1). Closest images to October were acquired when cloud or poor data quality prevented choice of an October image.

***To avoid bias in comparisons of imagery, images were corrected for geometric distortion (Richards 1993). For MSS images, this was done using image-to-image registration with the finer pixel resolution of the 1993 TM image. The 1993 TM image was referenced initially to 1:100 000 scale scanned topographic maps and geocoded to the Australian Metric Grid (AMG zone 54) projection, in the AGD66 datum. Then, this image was warped using a first order linear polynomial and resampled to 25m by 25m pixels, using the nearest neighbour algorithm (Richards 1993, ERDAS 1999). The matching (same date) 1993 MSS image and the 1997-1998 TM images were then registered to the 1993 TM scene and to 1:100 000 topographic map sheets outside the boundary of the TM image. Each MSS image was then registered to the registered 1993 MSS scene.***

TM and MSS sensors have different pixel sizes (MSS-56 x 79m and 57 x 82 m; TM - 30 x 30m) (Appendix 1). To ensure valid comparisons among all images, data were resampled to a standard pixel size of 50 x 50m, using the nearest neighbour algorithm (Duggin and Robinove 1990, Avery and Berlin 1992, Richards 1993, Lillesand and Kiefer 1994). All images were then registered to a sub-pixel level (Root Mean Square Error (RMSE) < 1.0 pixel), giving an acceptable level of registration accuracy for images used in temporal analyses, particularly in sparsely vegetated semi-arid areas (Townshend *et al.* 1992).

Radiometric distortions resulting from atmospheric scattering and seasonal variations in sun angle illumination were corrected for using the dark pixel method (Chavez 1988; Richards 1993) and by normalisation (Richard 1993; Johnston and Barson 1993) respectively.

Images covered a greater area than the Lower Murrumbidgee floodplain and so the subset (741 by 1357 pixels), covering the Lower Murrumbidgee floodplain, was extracted from each geometrically corrected image. Some cloud remained over the floodplain area in nine image subsets but was only a problem for three images, covering the southern part of the floodplain. Southern data for these images were not analysed.

### *Stratification of the floodplain*

The Lower Murrumbidgee floodplain is spectrally complex, causing spectral confusion among land cover types. The reflectance of cultivated land is spectrally similar to actively growing species of ephemeral wetland vegetation (Houhoulis and Michener 2000) and flooded agricultural land is spectrally similar to shallow turbid open water lakes. To improve separation between different cover types, the Lower Murrumbidgee floodplain was subdivided into strata, based on hydrological regime, and on developed areas. Four hydrological strata, Fiddlers-Uara, Murrumbidgee, Nimmie-Caira, and Redbank were defined primarily by how water reached these different parts of the floodplain (Table 1, Fig. 2b). The boundaries of each stratum were digitised on screen as areas-of-interest with the aid of ancillary vector information that included a digital vegetation layer (Scott 1992, Porteners 1993) and drainage and infrastructure layers (AUSLIG 1994). Straight edges and levees defined developed land, regardless of the spectral signature. This was combined with a digital vector overlay of banks and levees (DLWC unpubl. data) so that areas of developed land were digitised on screen to create a binary thematic layer of developed land and non-developed land. This layer masked developed areas from classification of each image, improving its accuracy. A digital layer of channels was derived from three existing digital data sets (a channel layer and a banks layer of the Nimmie-Caira System, and channels of the Redbank System) (DLWC unpubl. data) and from visual interpretation of Landsat imagery for channels within the Fiddlers-Uara stratum. This derived layer was used to calculate the length of channel and levee systems in each of the strata.

### *Classification of wetland extent*

For each hydrological stratum (Table 1), a spectral classification delineated wetland extent, based on the presence of water. The complex mixture of vegetation, bare ground and inundation within cover types necessitated the use of an unsupervised classification (Townshend and Justice 1980, Jensen *et al.* 1987, Johnston and Barson 1993, Sheng *et al.* 1998). All four bands of MSS data were used in the classification of wetland extent. Only three bands of TM data (Bands 2-4), which represent the spectral wavelength range of MSS data, were used in the classification (Appendix 1). Where the MSS band 4 was not operable (Appendix 1), the highly correlated band 3 (Pickup *et al.* 1993) represented the NIR wavelength range. A standard unsupervised classification yielded 20 clusters using the ISODATA cluster algorithm (ERDAS 1999). Spectral classes were then merged into three broad groups: inundated wetland vegetation, open water and non-wetland areas. This was done so that cluster histograms had minimal overlap and represented one of the three broad classes.

Interpretation of derived classes from remotely sensed data should be done with ancillary data from existing geographical information systems (GIS) (Hutchinson 1982, Janssen *et al.* 1990, Welch *et al.* 1992). Hence, the GIS layer for structural vegetation (Scott 1992, Porteners 1993) was also used to merge clusters because the type of wetland vegetation is dependent primarily on the water regime (Pressey *et al.* 1984, Bren *et al.* 1988, Bren 1992). The binary layer of developed areas was added to the thematic layer of wetland extent for each stratum to create coverage of wetland (open water and inundated vegetation), developed areas and non-wetland areas.

Wetland area, developed area and non-wetland estimates of area were derived from the classification for each stratum and the area overall. In addition, a fragmentation index was derived. This was the ratio of the number of contiguous areas of wetland within each stratum, divided by the wetland area in that stratum. The denominator was

Table 1. Areas, flood dependent vegetation and descriptions of flow regime of hydrological strata used to subdivide the Lower Murrumbidgee floodplain (see Fig. 2c for locations).

Hydrological Strata	Vegetation <sup>a</sup>	Flow regime
Fiddlers-Uara (80,948 ha)	Lignum ( <i>Muelenbeckia florulenta</i> ), Blackbox ( <i>Eucalyptus largiflorens</i> ), and Nitre Goosefoot ( <i>Chenopodium nitrariaceum</i> ) grow along this creek system. This includes Yanga Nature Reserve (1,772 ha), recognised for its stands of Black Box woodland.	This was the first major distributary creek system of the Lower Murrumbidgee floodplain, from the Murrumbidgee River. It conveyed water to the southern edge of the Lower Murrumbidgee floodplain (Fig. 2c). Anastomosing channels of Fiddlers Creek eventually form Uara Creek which takes water to Yanga Lake and the Murrumbidgee (Fig. 2c). This stratum lies on either side of the Murrumbidgee River (Fig. 2).
Murrumbidgee River (42,723 ha)	This has River Red Gum Forest ( <i>Eucalyptus camaldulensis</i> ) and Lignum areas.	Water flooded whenever the Murrumbidgee River was sufficiently high, through a series of 'break-outs' along the river on both sides and also the distributary Waugorah Creek. It is separated from the Nimmie-Caira system in the south by elevated ground.
Nimmie-Caira (94,051 ha)	It had the largest expanse of Lignum on the Lower Murrumbidgee floodplain. Cumbungi ( <i>Typha orientalis</i> ), Common Watermilfoil ( <i>Myriophyllum variifolium</i> ), Water Primrose ( <i>Ludwigia peploides</i> ) and Eel-weed ( <i>Vallisneria gigantea</i> ) also grew in flooded areas.	Water entered from the Murrumbidgee River through two distributary creek systems, Nimmie and Caira Creeks (Fig. 2c). Neither had well defined channels. Maude Weir now raises water levels in the river to allow flows to be diverted down constructed channels. Water from Caira Creek flowed south before bifurcating to the north to form Pollen Creek (Fig. 2c) and to the south to continue as Caira Creek flowing west (now Caira Cutting). On the western edge, levee banks and levee banks now separate the Nimmie-Caira from the Redbank stratum. Development restricts natural flood flows that used to reach southwest to Tala Lake (Fig. 2c).
Redbank (93,136 ha)	River Red Gum forests are interspersed with swamps of Tall Spike Rush ( <i>Eleocharis sphacelata</i> ) and Common Reed ( <i>Phragmites australis</i> ). Small swamps of Common Spike Rush ( <i>Eleocharis acuta</i> ) and Pale Spike Rush ( <i>Eleocharis pallens</i> ) also occur. Red Azolla ( <i>Azolla filiculoides</i> ), Common Watermilfoil ( <i>Myriophyllum propinquum</i> ), Water Primrose ( <i>Ludwigia peploides</i> ) and Floating Pondweed ( <i>Potamogeton tricarinatus</i> ) grow in more open areas and Nardoo ( <i>Marsilea drummondii</i> ) grows around the edges of swamps. Southern areas have River Cooba ( <i>Acacia stenophylla</i> ) stands.	This stratum forms the western edge of the Lower Murrumbidgee floodplain and straddles the Murrumbidgee River, from the northern part of the Lower Murrumbidgee floodplain to Yanga Lake in the south (Fig. 2c). Levee banks separate the stratum from the Nimmie-Caira Creek in the east. Channels dissect this large floodplain that has no defined distributary creeks. The area is primarily reliant on overbank flows, through small channels, caused by a constriction in the main channel capacity of the river. Most water now reaches both sides of the stratum after diversion by Redbank Weir (Fig. 2c), of flows in the Murrumbidgee River.

<sup>a</sup>Maher 1990, Scott (1992), Porteners (1993)

used to remove the influence of any trends in wetland area on the number of contiguous wetland areas in the stratum.

#### *Field assessment and survey of vegetation health*

Reliability of wetland classification is dependent on an assessment of accuracy. We defined 147 random ground reference locations (about 50 m<sup>2</sup>), stratified by classification. Numbers of samples in each wetland category were adjusted according to size and heterogeneity (Congalton 1991). Eighty-five points were allocated to wetland, the largest and most spectrally variable group; 18 points were allocated to the non-wetland group (the least in area); and 44 points were allocated to the developed area. Each point on a classified image from August 1998 was surveyed on 25th June 1998 with a helicopter, at a height of about 30m. We independently identified the dominant vegetation community at each point from either side of the helicopter using hand-held tape recorders. The communities included River Red Gum, Black Box woodland, Lignum, and various chenopod shrublands. Some records were merged to represent associates (e.g. Lignum and chenopod shrubland associates), recognised in previous vegetation studies (Scott 1992; Porteners 1993). Areas of disturbance were also recorded as cleared, bare ground or open areas. Percentage vegetation canopy cover, vegetation health and percentage of inundation were also recorded. Health of flood dependent vegetation was assessed on a qualitative scale of dead, poor, moderate or good. Poor vegetation had more than no canopy but less than 30% of the canopy with leaves or growth; moderate had 30-60% and good health greater than 60% canopy cover on plants. Points recorded as cleared, bare ground and open water were not allocated a vegetation health attribute.

#### *Classification accuracy of wetland areas*

Vegetation results from both observers were collated and each point allocated a class: wetland (e.g. River Red Gum, Black Box, Lignum, Lignum and chenopod shrubland associates and open water), developed area (e.g. cleared, bare ground, open areas) or non-wetland (e.g. chenopod shrublands), based on the image classification. Error matrices were produced and analysed to provide a classification accuracy and Kappa statistic (Congalton 1991). The overall accuracy was the percentage correctly classified by remotely sensed data relative to aerial photography over all classes

(Congalton 1991) (see Appendix 2). The recommended Kappa coefficient of agreement (Rosenfield and Fitzpatrick-Lins 1986) was similar but accounted for the influence of confusions among classes, by incorporating non-diagonal elements of the error matrix. Accuracy for each class (e.g. wetland) had two measures: user's and producer's accuracy (Appendix 2). The user's accuracy for each class was the percentage of the remotely classified data that was correctly mapped according to the aerial photography while the producer's accuracy for each class was the percentage of the class that were correctly identified as the class using the reference data. The former used the total number of points classified as the denominator while the latter used the total number of reference points as the denominator (Appendix 2).

The overall accuracy of the mapping (75%) was average (Congalton 1991), compared to the aerial survey assessment (Appendix 2). The low Kappa statistic (0.59) indicated confusion between classes. The probability that each class was classified correctly was good (>90%) (wetland) to average (74%) (developed) to poor (< 50%) (non-wetland) (Appendix 2). The classification accuracy for wetland extent was high (91%) although the corresponding Kappa coefficient was of lower accuracy (0.79) (Appendix 2). Although 72% of the non-wetland points were correctly identified as non-wetland, the probability of being non-wetland on the ground was only 42%, which was reflected in the low Kappa coefficient (0.34). These figures probably reflect the temporal variability between the periods of field assessment (June) and the timing of satellite imagery (August). The results may also be confounded by the fact that the field assessment was during a non-flood period therefore only vegetation, rather than its combination with water, was used in the field assessment to define wetland areas. Discrimination of boundaries between wetland and non-wetland areas was the main problem. Two thirds of the reference points were on the wetland / non-wetland boundary hence the timing for determining which class these points fall into was crucial. Also the low number of sample points in the non-wetland class may have biased the result.

### **Aerial surveys of waterbirds**

Aerial surveys of waterbirds were flown over about 10% of eastern Australia each October between 1983-2000 (Braithwaite *et al.* 1986a, Kingsford *et al.* 1999). More than 1,500 wetlands greater than one hectare were surveyed, including most of the Lower

Murrumbidgee floodplain, between latitudes 34°22'S, 34°38'E (Fig. 2b). Three additional wetland areas were used as reference sites. These were Fivebough Swamp (34°32'S, 146°25'E), the Menindee Lakes system (32°22'S-32°37'S, 142°11'E-142°19'E), the lakes of the Paroo River overflow lakes (30°36'S-30°39'S, 143°42'E-143°44'E) (Fig. 1). The Menindee Lakes surveyed, Cawndilla, Menindee, Emu, Kangaroo and New, were mostly regulated wetlands where water was kept artificially high (Kingsford 1995a). The Paroo River overflow lakes surveyed, Mullawoolka Basin, Yantabangee Lake, Tongo Lake and the Paroo overflow floodplain, were at the end of a river with few diversions or regulatory structures (Kingsford *et al.* 1998). Fivebough Swamp relies on sewage effluent (two megalitres daily) (Taylor and Richardson 2000) and possibly some local rainfall.

All wetlands were surveyed about the middle of October each year. An observer on each side of a Cessna 206 high-winged aircraft recorded numbers of waterbirds of each species on a mini-cassette recorder. Not all waterbirds could be identified to species (see Appendix 3). Counts were totalled 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 reference 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 proportion of the wetland ( $\geq 50\%$ ) counted at a height of 30-46 m and a speed of 167 km/hr (90 knots). We extrapolated counts on proportions of wetlands to give estimates of an index to waterbirds for the whole wetland. This method was used to count waterbirds on the main open water lakes of the Lower Murrumbidgee floodplain. There was no defined shoreline in the Pollen Creek and Nimmie-Caira system so waterbirds were counted in 200-m wide transects across the floodplain areas (Fig. 2b), flown at a height of 46 m at 204 km/hr (110 knots) (Braithwaite *et al.* 1986b). We estimated the proportion of the wetland surveyed each year and extrapolated counts of waterbirds to give an index to total numbers of waterbirds within the Lower Murrumbidgee floodplain. Numbers of nests and broods of waterbirds were also estimated on the Lower Murrumbidgee floodplain.

For analyses, waterbirds were further divided into broad guilds, corresponding to different foods (Barker and Vestjens 1989) and where the birds usually forage (Kingsford 1991). The five guilds included piscivorous birds (e.g. cormorants, pelicans, terns), large wading birds (Morton *et al.* 1993), duck species (all duck species except herbivorous

species), herbivorous waterbirds (e.g. black swans, Australian wood duck) and small wading birds (Charadriiformes) (see Appendix 3).

### **Statistical 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 some data to improve normality (Zar 1984): abundance of waterbirds, wetland area on the Lower Murrumbidgee floodplain, developed area on the Lower Murrumbidgee floodplain and flow data (log); percentage flow data (arcsin) and numbers of species of waterbirds for wetlands (square root).

## Results

### River regulation

River regulation has affected the amount of flooding and its distribution on the Lower Murrumbidgee floodplain at the catchment and local scale over a period of more than 140 years, 1855-1998. River flows in the Murrumbidgee River have been regulated and diverted by pumps, dams and weirs across the river and a river cutting, upstream of the Lower Murrumbidgee floodplain (Table 2, Fig. 3). Large dams (e.g. Burrinjuck, Blowering, and Googong) and weirs (e.g. Berembred and Gogeldrie) were built to divert water to Canberra, towns, domestic use or irrigation areas (Table 2, Fig. 3). There are now 26 major dams or weirs that control flows in the river or its tributary streams (Fig. 3).

Catchment scale impacts on the Lower Murrumbidgee floodplain began in 1855 when some flow in the Murrumbidgee River was diverted down Yanco Creek (Table 2, Fig. 1). On completion of the river cutting, there were also 36 pumps diverting water from the river. The main regulation of the Murrumbidgee River occurred over two periods when large storages were built: 1910-1927 and 1956-1971 (Fig. 4). Dams and weirs in the Murrumbidgee River catchment can now store 4,241,852 ML of water (Fig. 4). 22.6% of this storage capacity was established before 1927 with the building of Burrinjuck Dam (Table 2, Fig. 4) which stored water for the Murrumbidgee Irrigation Area (Table 2, Fig. 3). The next major phase was between 1956 and 1971 when most (73%) of the remaining storage capacity in the catchment was established (Fig. 4). Augmentation of Burrinjuck Dam in 1956 increased its potential to store water for irrigation. In this period, the dams of the Snowy Mountains Scheme and most major dams to supply Canberra were also built (Figs 2 and 4, Table 2). Ninety-four percent of the water stored in the catchment's dams is for irrigation areas and the generation of hydroelectricity (Table 2). Nearly all the rest of the storage capacity (5.9%) is to provide Canberra with a reliable water supply and recreation areas (Table 2).

Most storage capacity is in the upper catchment of the Murrumbidgee River, with 98.7% located upstream of Wagga Wagga (Fig. 3). Regulation of the Tumut River with the Snowy Mountains Scheme, combined with appropriation of additional water diverted from eastern-flowing rivers, permitted the establishment of the other major irrigation area, the Coleambally Irrigation Area (Fig. 3) which accounts for about 30% of the water diverted from the river (Table 2). To further control flows in the early

1980s, Tombullen Lake, a natural wetland was converted into a storage and Hay Weir was built (Fig. 3, Table 2). The last major regulatory structure, upstream of the Lower Murrumbidgee floodplain, was built in 1988 (Table 2, Fig. 3).

Stored water was released down the river to supply irrigation areas and urban communities downstream. As well as water stored in dams or weirs, river flows were also pumped directly from the river and accounted for about 36,000 ML each year in the period 1979-1990 (Table 2). About 2,433,000 ML of water was diverted each year from the Murrumbidgee River by 1994 (Table 2). Much of this water would have flowed to produce a range of floods on the Lower Murrumbidgee floodplain.

**Table 2.** History of water resource development in the Murrumbidgee catchment, upstream of the Lower Murrumbidgee floodplain. This includes dams, weirs, changes to flow regimes and diversions upstream that have reduced flows to wetlands on the Lower Murrumbidgee floodplain, 1850-1998. Fig. 3 shows locations of river regulatory structures and place names.

Time period	Regulatory or diversionary structures	Reference
1855-1902	Opening to Yanco Creek was deepened (Yanco Cutting) by 1.2-1.5 m to increase diversions of water from the Murrumbidgee River	(South Australia 1902, p. 261)
1880-1902	Six of 36 river pumps on the Murrumbidgee and tributaries were used to irrigate about 405 ha of fruit, vegetables and lucerne.	(South Australia 1902)
1902-present	River pumpers irrigate 40,000-145,600 ha annually and, in the period 1979-1990, diverted an average of 301,603±16,714 (SE) ML or 14% of diversions in the Murrumbidgee catchment.	(DWR 1993b)
1902-present	Water is pumped from the river to supply towns, livestock and domestic use. Mean annual diversions, in the period 1979-1990, averaged 35,929±4,374 (SE) ML or 1.7% of annual diversions from the river.	(DWR 1993b)
1910	Berembed Weir (3,100 ML) was built to divert water down the Main Canal to the Murrumbidgee Irrigation Area.	(DWR 1993b)
1915	Cotter Dam (4,700 ML) was built to provide water for Canberra.	
1924	The Main Canal (160 km) was completed and could divert 4,900 ML per day from the Murrumbidgee River.	
1907-1927	Burrinjuck Dam (951,900 ML) was completed to store water for diversion to the Murrumbidgee Irrigation Area. Water was first supplied to irrigation farms in 1912. Mean annual diversions, in the period 1979-1990, to this area averaged 1,143,512±33,450 (SE) ML, or 54% of total diversions upstream of the Lower Murrumbidgee floodplain.	DWR (1993b), WCIC (1971)
1927	Yass Dam (1,100 ML) was built to supply water to the town of Yass.	
1928	Yanko Weir (2,900 ML) was built to divert water (700 ML per day) from the Murrumbidgee River to irrigation areas and properties along Yanco Creek.	
1938	Captains Flat (820 ML) was built for Canberra's water supply.	
1956	Burrinjuck Dam was enlarged by 80,500 ML to store water for irrigation areas in Murrumbidgee Irrigation Area.	
1958	Tumut Pond (52,800 ML) was built to regulate water for the Snowy Mountains Hydroelectricity Scheme.	
1959	Golgeldrie Weir (7,400 ML) was built to divert water to Coleambally Irrigation Area via Coleambally Canal (potential flow capacity of 3,700 ML per day) and to Murrumbidgee Irrigation Area via Sturt Canal (potential flow capacity 1,200 ML per day). Happy Jacks Pondage (275 ML) was built to regulate water in the Snowy Mountains Hydroelectricity Scheme.	(DWR 1993b)
1960	Tantangara Reservoir (254,100ML) was built on the upper Murrumbidgee River for the Snowy Mountains Hydroelectricity Scheme. Water is diverted from the dam into Lake Eucumbene in the Snowy River Catchment and then into Tumut River in the Murrumbidgee River catchment.	

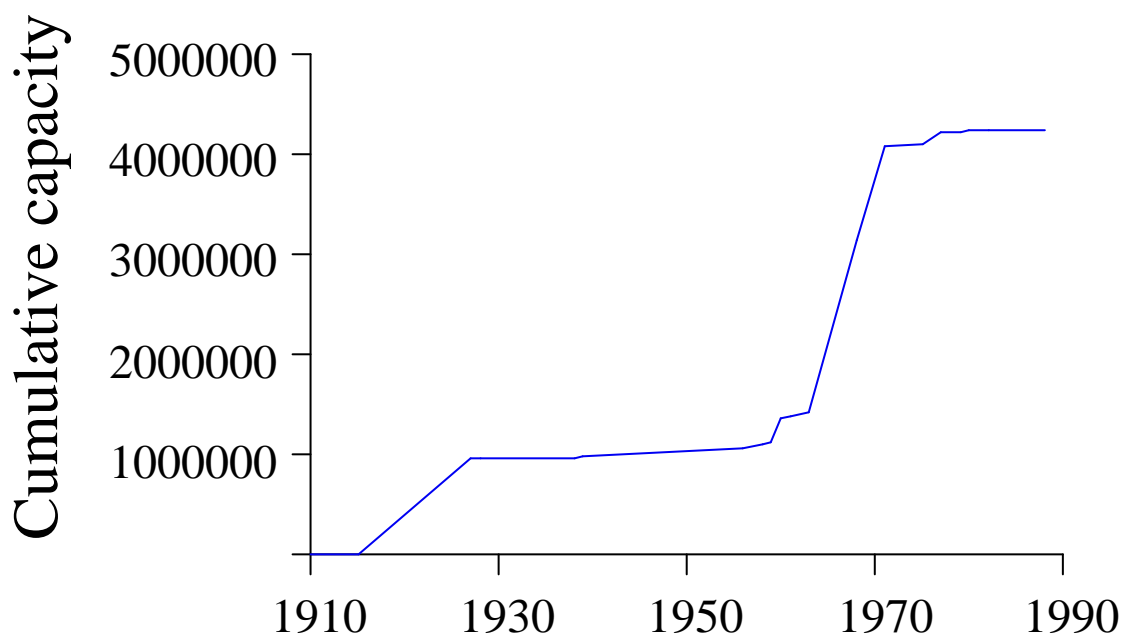
**Table 2** continued. History of water resource development in the Murrumbidgee catchment, upstream of the Lower Murrumbidgee floodplain. This includes dams, weirs, changes to flow regimes and diversions upstream that have reduced flows to wetlands on the Lower Murrumbidgee floodplain, 1850-1998. Fig. 3 shows locations of river regulatory structures and place names.

Time period	Regulatory or diversionary structures	Reference
1961	Tumut 2 Pond (2,700 ML) was built on the Tumut River for the Snowy Mountains Hydroelectricity Scheme and Bendora Dam (11,000 ML) to supply water to Canberra.	
1963	Scrivener Dam (27,700 ML) or Lake Burley Griffin was built in 1963 for Canberra to improve water quality.	
1968	Jounama Reservoir (43,800 ML) and Blowering Dam (1,600,000 ML) were built on the Tumut River for the Snowy Mountains Hydroelectricity Scheme. They store about 550,000 ML per year of water, diverted from eastern flowing rivers through Snowy Mountains Scheme, for Coleambally Irrigation Area. Mean annual diversions of water to Coleambally Irrigation Area, for the period 1979-1990, averaged $635,764 \pm 17,272$ (SE) ML or 30% of total diversions upstream of the Lower Murrumbidgee floodplain. Talbingo Reservoir (950,500 ML) was built as part of the Snowy Mountains Hydroelectricity Scheme in 1971. Corin Dam (76,000 ML) was built in 1968 to provide water to Canberra.	(DWR 1993b)
1975	Ginnindera Dam (3,700 ML) was built for Canberra to improve water quality.	
1977	Googong Dam (125,000 ML) was built to supply water to Canberra. Annual diversions from the Murrumbidgee to Canberra were 35,000 ML annually for the period 1985-2000.	
1980	Tombullen Lake (11,320 ML) was a natural wetland that had a bank built to hold water, downstream of main dams. This reduced uncontrolled flooding and artificial flooding and increased supply of regulated water for irrigation.	
1982	Hay Weir (13,500 ML) was built to reregulate water downstream of main dams and supply the Hay Irrigation Area (constituted in 1902). Mean annual diversions, in the period 1979-1990, to this area averaged $7,728 \pm 770$ (SE) ML or 0.4% of total diversions upstream of the Lower Murrumbidgee floodplain.	(DWR 1993b)
1988	Tuggernong Reservoir (1,837 ML) was built for Canberra to control floods, improve water quality and for recreation.	
1988-1993	An average of 2,443,000 ML was diverted annually from the Murrumbidgee River Catchment (99% for irrigation).	(MDBMC 1995)

At a local scale, within the Lower Murrumbidgee floodplain, levees, channels with regulators across the floodplain and weirs (Maude and Redbank) have changed the distribution of wetland flooding (Table 3). Such floodplain development was primarily for the planting of irrigated crops. There were three major periods over which this occurred: before 1912, 1939-1980 and 1980-present. The first channel cut in 1859 was an attempt to link the Lachlan River with the Murrumbidgee River and obtain more water (Table 3). A levee was constructed before 1902 to stop water flowing into Pitarpunga and Macommon Lakes (Table 3). This levee alienated western lakes (10,772 ha) from flows from the Murrumbidgee River. This was then followed by the building of the Paika Levee, which stopped water from reaching the western part of the floodplain and the western lakes (Table 3, Fig. 5a).

Maude and Redbank Weirs (Fig. 2c) were built in 1939-1940 to raise the level of the river so water could be diverted onto the Lower Murrumbidgee floodplain (Table 3). Small levee banks were constructed across the complex series of distributary channels in the Redbank system to stop flows that had been diverted by Redbank Weir from entering back into the main river channel (Table 3). A series of levees and dams were then constructed across the floodplain to redistribute floods. In 1966, the Government established a regulator in Cairra Creek and built the Cairra Cutting, a channel that efficiently conveyed flows to the Nimmie-Caira stratum (Table 3). Up until now the ill-defined Cairra Creek system had prevented rapid transmission of flows because floodwaters supplied the floodplain adjacent to the Murrumbidgee River. This development was followed by a period, up until the early 1980s, when landholders built levee banks, bypass channels to redistribute floodwaters and dams to store water for later use (Table 3).

The final period, after 1980 until the present, was when a series of major channels, levee banks and regulators were built by Government to constrict water flows to floodways and special habitat areas (Table 3, Fig. 5c). In 1981, the Government followed the Cairra Creek development with a similar development on Nimmie Creek and a channel for efficient transmission of floods to the stratum (Table 3). There are now 2,145 km of levee banks across the Lower Murrumbidgee floodplain and about 394 km of



**Fig. 4.** Cumulative storage capacity of dams and weirs in the Murrumbidgee Catchment for the period 1910-1990. Dams in the Snowy-Mountains Hydroelectric Scheme also store about 500,000 ML each year, diverted from eastern flowing rivers in the Snowy River catchment

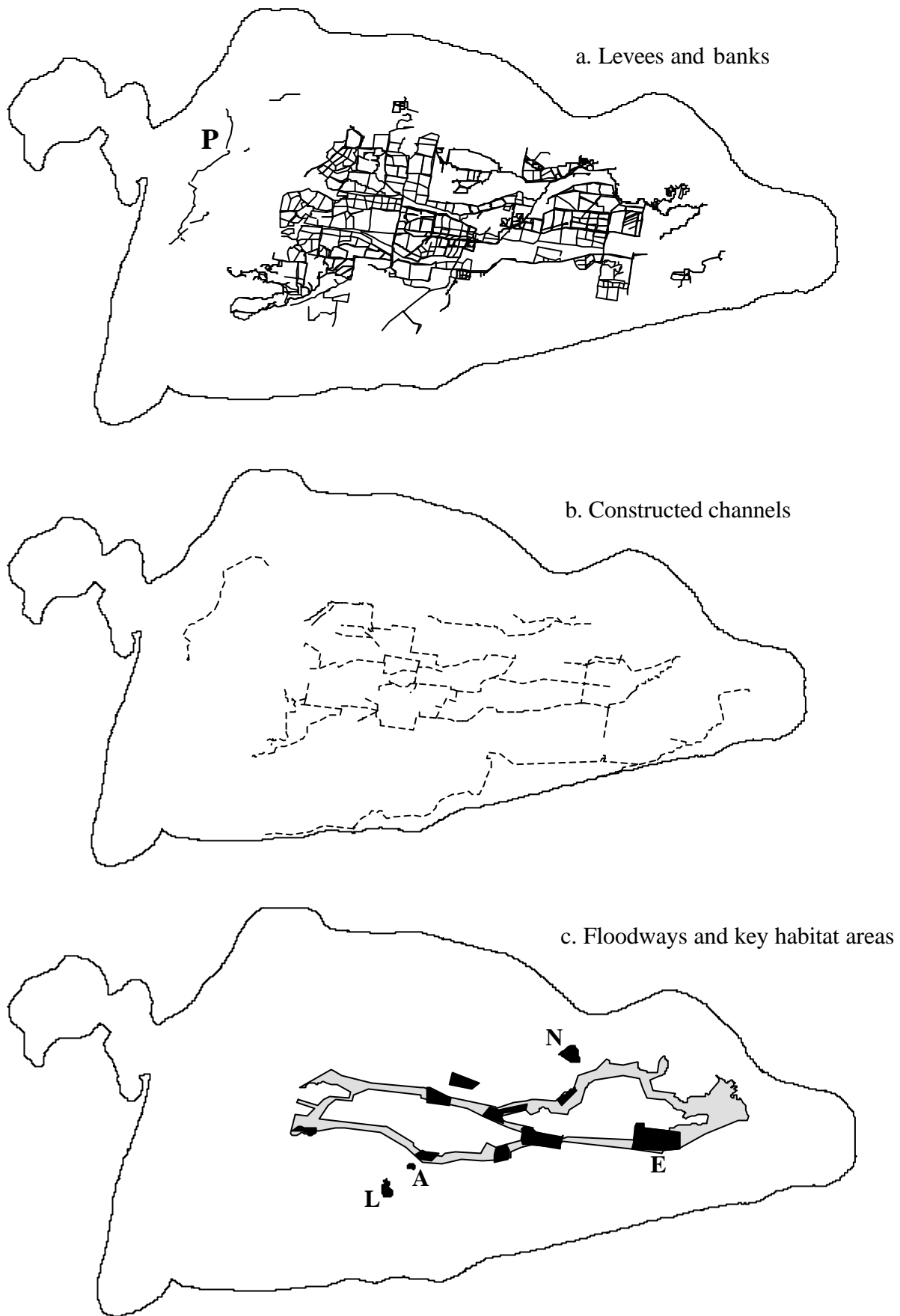
**Table 3.** River regulation structures and changes to flow regimes on the Lower Murrumbidgee floodplain that have affected flooding of wetlands on the Lower Murrumbidgee floodplain, 1850-1998. Figs 2, 5a,b shows locations of structures.

Time period	Regulatory or diversionary structures	Reference
1859	A channel (width 1.3 m and depth 1.2 m) was cut from Lachlan River to Paika Station to increase flows.	Jervis (1952)
1872	First diversion structure on the floodplain built to enhance natural pastures	Eddy (1992)
Before 1902	Levees were built across inflows into Pitarpunga, and Macommon lakes.	South Australia (1902)
1912	Paika Levee (23km) (Fig. 5b) cut off the western floodplain and lakes (Paika, Pitarpunga, and Macommon) from flows of the Murrumbidgee River.	
1840s-1920s	Macpherson Channel was built to convey water across the floodplain on the Redbank system.	
1939-1940	Maude (5,000 ML) and Redbank Weirs (5,500 ML) were built to compensate for reduced flow in the Lower Murrumbidgee floodplain, resulting from building of Burrinjuck Dam and subsequent diversions upstream (Fig. 2c).	
1940-present	Building of regulators <sup>a</sup> on open water lakes (e.g. Yanga Lake, Piggery Lake, Lake Tala), changing water regimes of these lakes from intermittent flooding to permanent flooding.	Pressey <i>et al.</i> (1984)
1940-1945	Middle levee constructed and Chastons cut constructed in the Redbank system to distribute floodwaters	pers. Comm Troy
1940s-present	Levee banks across small tributary channels to stopped flows returning to the Murrumbidgee River during artificial floods of the Redbank system. There was increased duration of artificial floods on the Redbank River system. Levee banks were built on the floodplain to redistribute floodwaters: Is-Y-Coed Long Bank, Yanga Station banks which direct water supply south to Kia Lake.	(DWR 1989)
1950s	Bank and bypass constructed across Talpee Creek and Pee Vee Creek which holds water back for about three kilometres	(DWR 1993a)
1955	Pollen Creek Dam was built to store water and redirect flow initially to the southern part of Pollen Creek and later to irrigation areas with building of channels.	(DWR 1994)
1960	Telephone Bank was built across Pollen Creek to spread the water across the floodplain and store water (1,000 ha) that was diverted later through the White Elephant Channel to the north and south and west through pipes.	(DWR 1993a)
1960	Littlewood Swamp (200 ha) was formed by a bank across Pollen Creek to store water. It was washed out in 1989 and later enlarged with new bank and road access to cover an area of 500 ha.	(DWR 1993a)
1966	The Caira regulator (capacity 2,000 ML/day) and Caira Cutting, a constructed channel of about 4km, were built to increase efficiency of flows in the anastomosing channels of Caira Creek. Levee banks on either side of the Caira Cutting reduced flows to the floodplain.	(DWR 1993a)
1968	A levee and cutting were built to supply water annually to Avalon Swamp from Caira Creek. It also controls regulated flows to Loorica Lake (Fig. 2c).	(DWR 1994)
1969	Suicide Bank was built across Caira Creek to divert some water that flowed north to Pollen Creek to the south, into Caira Creek. It created a storage of 600 ha that was later reduced to 300 ha. Development in the 1980s converted the bank into a road and irrigation channel.	(DWR 1993a)

<sup>a</sup>Regulators are engineered structures that allow regulation of the flow into a channel

**Table 3 continued.** River regulation structures and changes to flow regimes on the Lower Murrumbidgee floodplain that have affected flooding of wetlands on the Lower Murrumbidgee floodplain, 1850-1998. Figs 2, 5a,b shows locations of structures.

Time period	Regulatory or diversionary structures	Reference
1970s-1980s	Small levees about 500mm high (spreader banks) were built to spread water over extensive areas adjacent to minor creeks	
1975	North South Lees Bank was built across Cairra Creek which produced a storage of 700ha for distributing water to irrigation areas.	(DWR 1993a)
1980	Avalon North Bank was built across Cairra creek resulting in a storage of about 500ha. It also spreads water across the floodplain.	(DWR 1993a)
1980s-present	Flood dependent vegetation was cleared from the floodplain and irrigation bays (up to 250ha). Bays were built by landholders and had surrounding levees to retain water.	
1981	The regulator on Nimmie Creek (capacity 2,000 ML/day) and channel were built to increase efficiency of flows in the anastomosing channels of Nimmie Creek. The levee banks on either side of the channel leaving the regulator reduced flows to the floodplain.	(DWR 1993a)
1983	A levee bank was built on Nap Nap Swamp to raise water levels by two metres. It was breached later because red gums were dieing because of artificially high water levels.	(DWR 1993a)
1986	A bank and bypass channel were built on Yanga Station, about two kilometers downstream from Waugorah road, to hold water back after flooding.	(DWR 1993a)
1986	Eulimbah bank was built across the Cairra Creek to produce a storage (3,000 ML) (Fig. 5c) for water that could be distributed for irrigation areas through Tory Grand Channel to the south, and to the south on Uara Creek. A levee bank was also built on the Redbank System to split flows.	(DWR 1993a)
1988-present	Channels and levee banks were built and regulators located in the Nimmie-Caira stratum. Tory Grand Channel (capacity 400 ML/day) was built in 1988. The works constructed by Government (1993-1998) included Southern Cairra Channel (59.8 km of channel, 21 regulators), Northern Cairra Main Channels (28.7 km of channel, 21 regulators, 9.4 km levee bank) and White Elephant Channel (7 regulators, earthwork repairs). These confined waters to constructed channels for diversion later to irrigation bays, protected by levee banks.	(DWR 1993a)
1988-present	Channels and levee banks were built and regulators located in the Redbank stratum. Works constructed by Government (1993-1998) included raising height of Redbank Weir, channel construction (31.6 km), including Redbank North Canal, building of 12 regulators, refurbishment of other regulators, installation of power supply and bridge construction.	
1989-1994	Government proposed a plan for the sustainable development of the Lower Murrumbidgee floodplain through the development of controlled flooding and identification of key habitat areas that could be supplied by a system of floodways.	DWR (1989,1994)



**Fig. 5.** a. Levee banks – 2,145 km (includes banks around irrigation bays, along channels and across flood systems). P marks Paika Levee. b. Constructed channels on the Lower Murrumbidgee floodplain (394 km). c. System of floodways (patterned) designed to convey water to specific wetlands or key habitat areas and irrigation bays (DWR 1994). Letters refer to some of these areas: A-Avalon Swamp, E-Eulimbah storage, L-Loorica Lake. Data were only available for Lowbidgee Flood Control and Irrigation District (see Fig. 3).

constructed channels (Fig. 5, Table 6). Most (88%) of the levee banks and the channels (69%) are in the Nimmie-Caira stratum (Fig. 5, Tables 3 and 6). Levee banks surrounding irrigation bays were built by landholders. There was also recent development in the Redbank system (Fig. 5). The main channel of the Murrumbidgee River was not severely affected by channels or levees.

### **Changes to river flows**

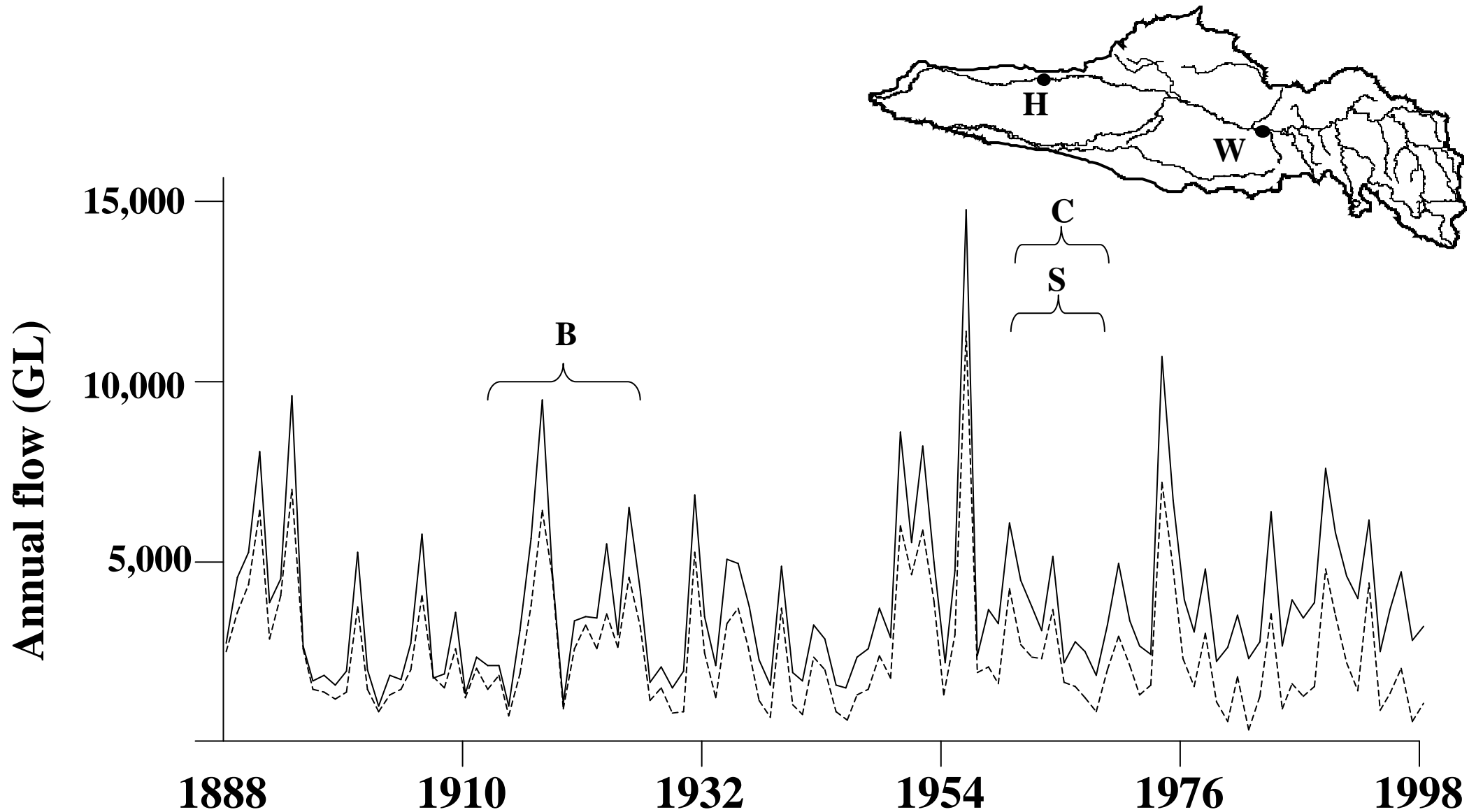
Flows to the Lower Murrumbidgee floodplain from the Murrumbidgee River have declined in volume, over time, 1898-1998 (Fig. 6). Before Burrinjuck Dam was built, annual flows at Hay followed a similar pattern of variability and quantity to annual river flows measured at Wagga Wagga (Fig. 6). After Burrinjuck Dam was built, the pattern of flows diverged in quantity although annual patterns of variability coincided. The second major regulation of the river, after 1955, occurred when Burrinjuck's storage capacity was increased, the building of the dams of the Snowy Mountains Scheme and dams to supply water to Canberra (Fig. 3). These changed the relationship between river flows at Wagga Wagga and Hay (Fig. 6). There were similar patterns of variability but there was a considerable difference in the quantity of water reaching Hay from Wagga Wagga, compared to before river regulation.

The percentage of the volume of annual flows reaching Hay from Wagga Wagga decreased significantly over the 111 year period (1888-1998) ( $R^2=0.48$ ,  $p<0.001$ ,  $\arcsin(\text{percentage flow})=10.4-0.005 \text{ year}$ ) (Fig. 7a), resulting in about a fifty percent reduction. For the 20 years before river regulation (1888-1907),  $80\% \pm 2.1$  of the annual volume of water reached Hay from Wagga Wagga, compared to  $41.7\% \pm 3.3$  in the equivalent recent period (1979-1998). Average annual flows at Hay between 1888 and 1918 were considerably higher than average flows between 1979 and 1998 (Table 4). The twenty year period between 1979 and 1998 had the lowest range of annual flows at Hay and at Wagga Wagga than for any other period for which hydrological data were available (Table 4).

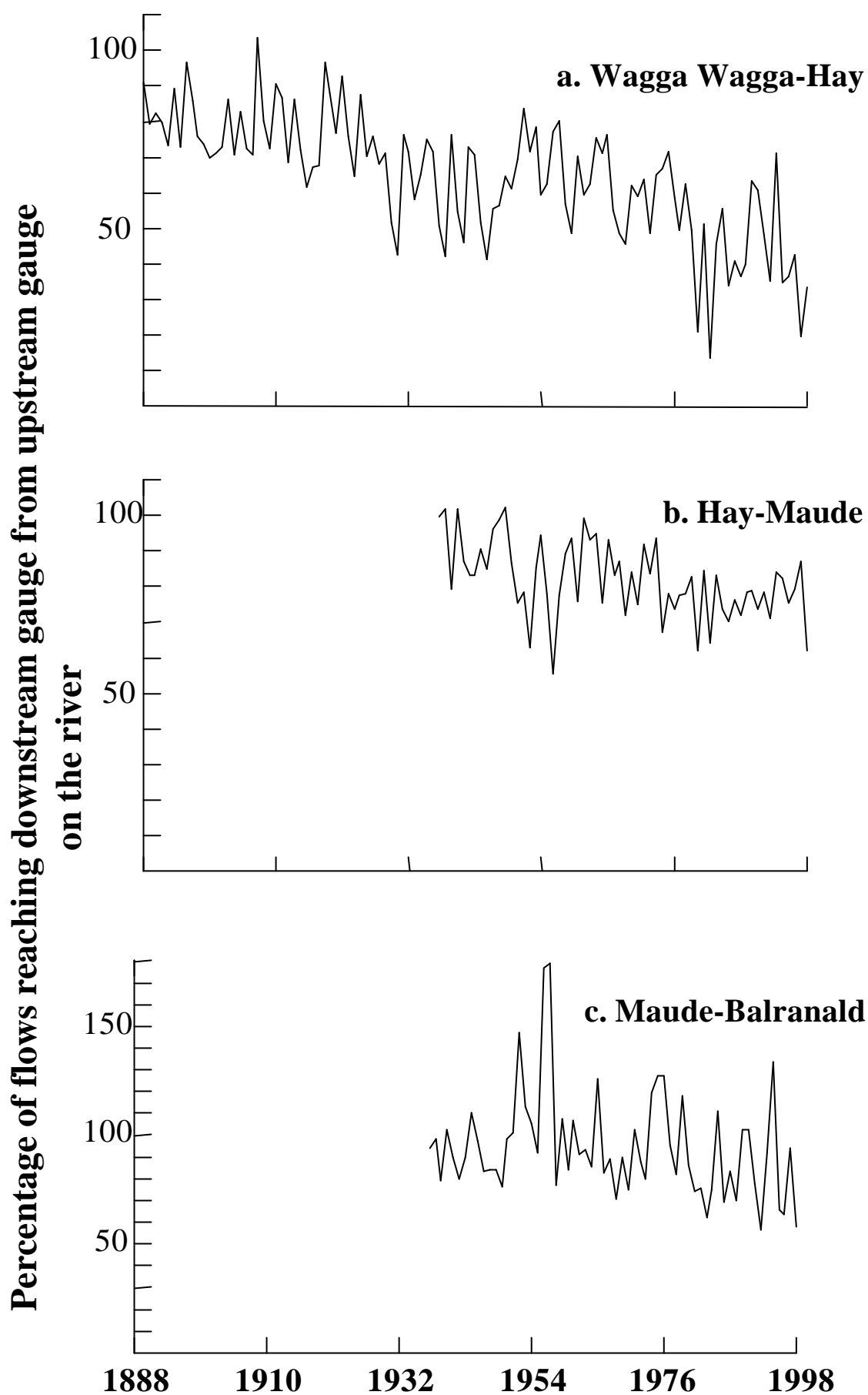
**Table 4.** Summary of annual flows (ML) at Wagga Wagga and Hay for different periods between 1888-1998. Annual flows were calculated from November to October each year.

Measure	Period	Mean	S.E.	Median	Range
Annual flows at Wagga Wagga	1888-1918	3471311	421188	2669334	8646584
	1919-1938	3381595	377986	3391506	5817070
	1939-1958	4205198	716155	3055006	13310085
	1959-1978	4048171	456360	3310035	8875325
	1979-1998	3936901	337579	3592382	5334107
Annual flows at Hay	1888-1918	2686643	421188	1977323	6312021
	1919-1938	2392848	298432	2588198	4577966
	1939-1958	2909818	571237	2034868	10773980
	1959-1978	2541537	335203	2211800	6342478
	1979-1998	1802201	285215	1374846	4478526
Annual flows reaching Hay from Wagga Wagga (%)	1888-1918	79%	0.018%	76%	61-103%
	1919-1938	69%	0.031%	71%	42-93%
	1939-1958	65%	0.027%	63%	41-84%
	1959-1978	61%	0.021%	61%	46-76%
	1979-1998	42%	0.033%	40%	14-71%

The amount of water reaching the Lower Murrumbidgee floodplain was further reduced with a reduction in the amount of water reaching Maude from Hay, after 1937 ( $R^2=0.24$ ,  $p<0.001$ ,  $\arcsin(\text{percentage flow})=11.9-0.006 \text{ year}$ ) (Fig. 7b). For the ten year period from 1937 to 1946,  $90.8\% \pm 2.69$  (SE) compared to  $77\% \pm 2.25$  (SE) for the last decade of data, 1989-1998 reached Maude from Hay. There was no trend ( $p=0.11$ ) for flows between Maude and Balranald in the period 1937-1998 (Fig. 7c).



**Fig. 6.** Annual flows (GL) in the Murrumbidgee River at Wagga Wagga (solid line-W) and Hay (dashed line-H). Most diversions from the river occur between these gauges. Flows at Wagga Wagga do not include the contribution from the Snowy Mountains Scheme. B, S and C indicate when Burrinjuck Dam, dams of the Snowy Mountains and Canberra supply dams were constructed.



**Fig. 7.** Percentage of annual river flows reaching downstream gauges from upstream river gauges (see Fig. 1 for locations of gauges) for the period 1888-1998. Percentage of annual river flow reaching Hay from Wagga Wagga (a); Maude from Hay (b) and Balranald from Maude (c). Data for Maude only exist for the period 1939-1998.

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:  $R^2=0.11$ ,  $p=0.027$ ,  $\log(\text{annual flows})=26-0.006 \text{ year}$ ; medium flows:  $R^2=0.5$ ,  $p<0.001$ ,  $\log(\text{annual flows})=40-0.013 \text{ year}$ ; high flows:  $R^2=0.13$ ,  $p=0.017$ ,  $\log(\text{annual flows})=24-0.005 \text{ year}$ ). In contrast, there were no trends in low ( $p=0.33$ ) or high ( $p=0.53$ ) annual flows at Wagga Wagga but there was a significant decline in medium flows at Wagga Wagga ( $R^2=0.11$ ,  $p=0.024$ ,  $\log(\text{annual flows})=19.6-0.005 \text{ year}$ ).

Daily flows at Hay showed a variable pattern over different decades (Table 5). The period between 1949 and 1958 had the highest frequency and percentages of high daily flows ( $>10,000 \text{ ML}$ ) and the lowest frequency and percentage of low daily flows ( $<10,000 \text{ ML}$ ). The 1979-1988 decade had the highest proportion and highest number of low daily flow ( $<10,000 \text{ ML}$ ). No daily flows of greater than 30,000 ML was recorded in this decade at Hay (Table 5). There were only 15 daily flows greater than 30,000 ML after 1979 (Table 5). The two latest decades had the lowest proportion and number of daily flows greater than 30,000 ML of any decades after 1915 (Table 5). The frequency of medium to large flood events was reduced.

### **Changes to wetlands**

There was an estimated 303,781 ha of floodplain in the Lower Murrumbidgee at the beginning of the 20<sup>th</sup> Century (Table 6). Wetland area varied among the different strata with the Nimmie-Caira and Redbank systems occupying the most extensive area of about 90,000 ha each. Before 1975, between 16% and 34% of wetland area, 6,625-30,947 ha, was estimated to have been lost in the four strata (Table 6) with the Fiddlers-Uara and Redbank strata losing the most, estimated to be about 34% of their original wetland area. Total wetland area lost from the Lower Murrumbidgee floodplain was estimated at 26%, or about 80,000 ha, before 1975.

There was a decrease in wetland area over the period 1975-1998 (Figs 8 and 9). There were significant decreases in wetland area overall and separately in three of the strata over the period, 1975-1998, Fiddlers-Uara, Murrumbidgee and Nimmie-Caira (Table 7). The greatest decline over this period was in the Nimmie-Caira stratum, followed by the Fiddlers and then the Murrumbidgee strata (Fig. 9). There was no **Table 5**. Frequencies and percentages, within a time period, of different daily flows (ML) at Hay for eight time periods between 1915 and 1998. Daily flows were only available from 1915.

Period	Daily flows											
	<10,000		10,000-20,000		10,000-20,000		20,000-30,000		30,000-40,000		>50,000	
	%	n	%	n	%	n	%	n	%	n	%	n
1915-1928 <sup>a</sup>	70.8	2584	16.2	593	8.9	323	2.4	86	1.29	47	0.49	18
1929-1938	82.8	3015	10.5	383	4.4	157	1.2	43	0.39	14	0.77	28
1939-1948	83.4	3184	9.8	374	5.9	226	0.5	20	0.29	11	0.13	5
1949-1958	63.8	2329	16.0	586	9.7	354	4.4	161	2.30	84	3.81	139
1959-1968	83.0	3032	12.2	446	2.6	96	1.5	56	0.52	19	0.16	6
1969-1978	78.0	2846	11.7	427	5.9	216	2.3	82	0.93	34	1.23	45
1979-1988	88.5	3274	8.3	305	2.2	80	1.1	39	0	0	0	0
1989-1998	79.7	2908	11.1	405	6.7	246	2.1	77	0.27	10	0.14	5

<sup>a</sup>Adjusted so comparable to other time periods

trend in wetland area lost in the Redbank stratum (Table 7, Fig. 9). Between 1975 and 1998, an additional 32% (96,309 ha) of the original wetland area was lost from the Lower Murrumbidgee floodplain (Table 6). Most of this was from the Nimmie-Caira stratum where an estimated 45,813 ha of wetland were lost (Fig. 9). Of the wetland remaining in the Nimmie-Caira stratum in 1975, the period between 1975 and 1998 resulted in the loss of 59% of wetland area in this stratum. There appeared to be a stabilisation in the amount of area lost in stratum after 1995 (Fig. 9).

Substantial areas, about 42%, of the original wetland remained (Table 6, Fig. 8). Among strata, the percentage of wetland remaining varied from 23%-49%. The Redbank system had the largest remaining percentage of wetland and the next most extensive was the Fiddlers-Uara Creek stratum (Table 6). Of this remaining wetland area of 127,688 ha, 43% (54,905 ha) of the perennial vegetation dependent on floods was in poor health or dead (Table 6). This was defined as degraded. The amount of wetland vegetation in poor health or dead in each of the stratum varied: Fiddlers-Uara (62%), Murrumbidgee (62%), Nimmie-Caira (43%), Redbank (27%) (Table 6). In total, we estimated that 76% of the wetland area defined by us on the original 1902

Table 6. Wetland area of the Lower Murrumbidgee floodplain and each of the hydrological strata present in 1902. Wetland areas lost before 1975, between 1975 and 1998 and total area lost. Estimate of remaining wetland and health of perennial flood dependent vegetation in remaining wetland for each stratum. Lengths of levee banks and constructed channels in each stratum.

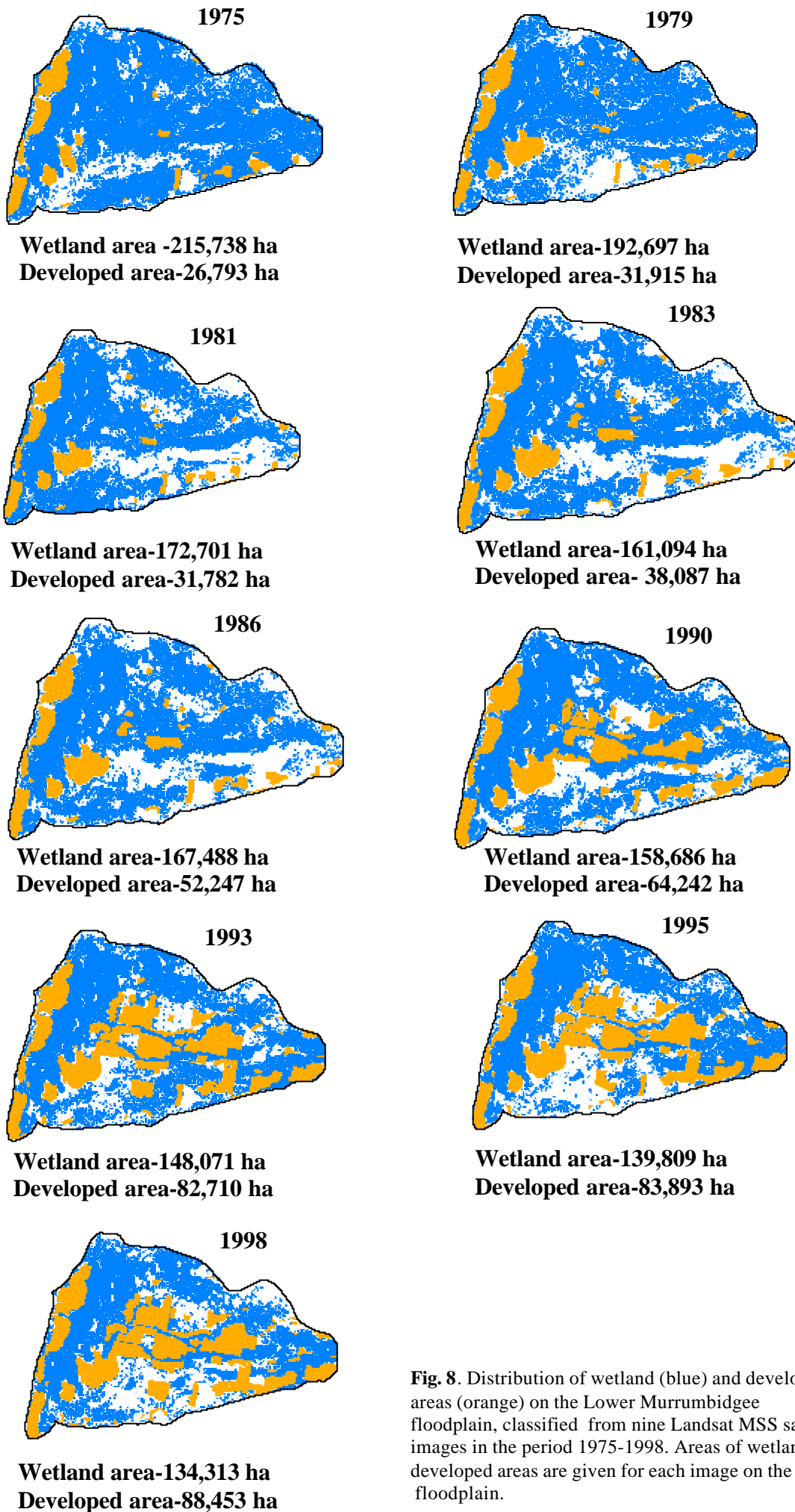
Stratum	Original <sup>a</sup> wetland (ha)	Wetland area lost						Remaining wetland					Levee banks <sup>c</sup> (km)	Channels <sup>d</sup> (km)	
		Before 1975		1975-1998		Total		Area (ha)	Health of riverine vegetation (%)						
		ha	%	ha	%	ha	%		Dead	Poor	Mod.	Good			n <sup>b</sup>
Fiddlers-Uara	77348	26178	34	25504	33	51682	67	25666	0	62	19	19	16	133.8	89.5
Murrumbidgee	41449	6625	16	18686	45	25311	61	16138	18	46	36	0	11	24.2	0.0
Nimmie-Caira	93355	16034	17	45813	49	61847	66	31508	0	43	9	48	21	1883.1	272.8
Redbank	91629	30947	34	6306	7	37253	41	54376	3	24	15	58	33	104.2	31.6
Lower Murrumbidgee (total)	303781	79784	26	96309	32	176093	58	127688	4	40	17	39	81	2145.3	393.9

<sup>a</sup>Estimated using 1902 map of floodplain (South Australia 1902) and geomorphological data layer of the area (Butler *et al.* 1973). This area covered 90% of the original wetland area.

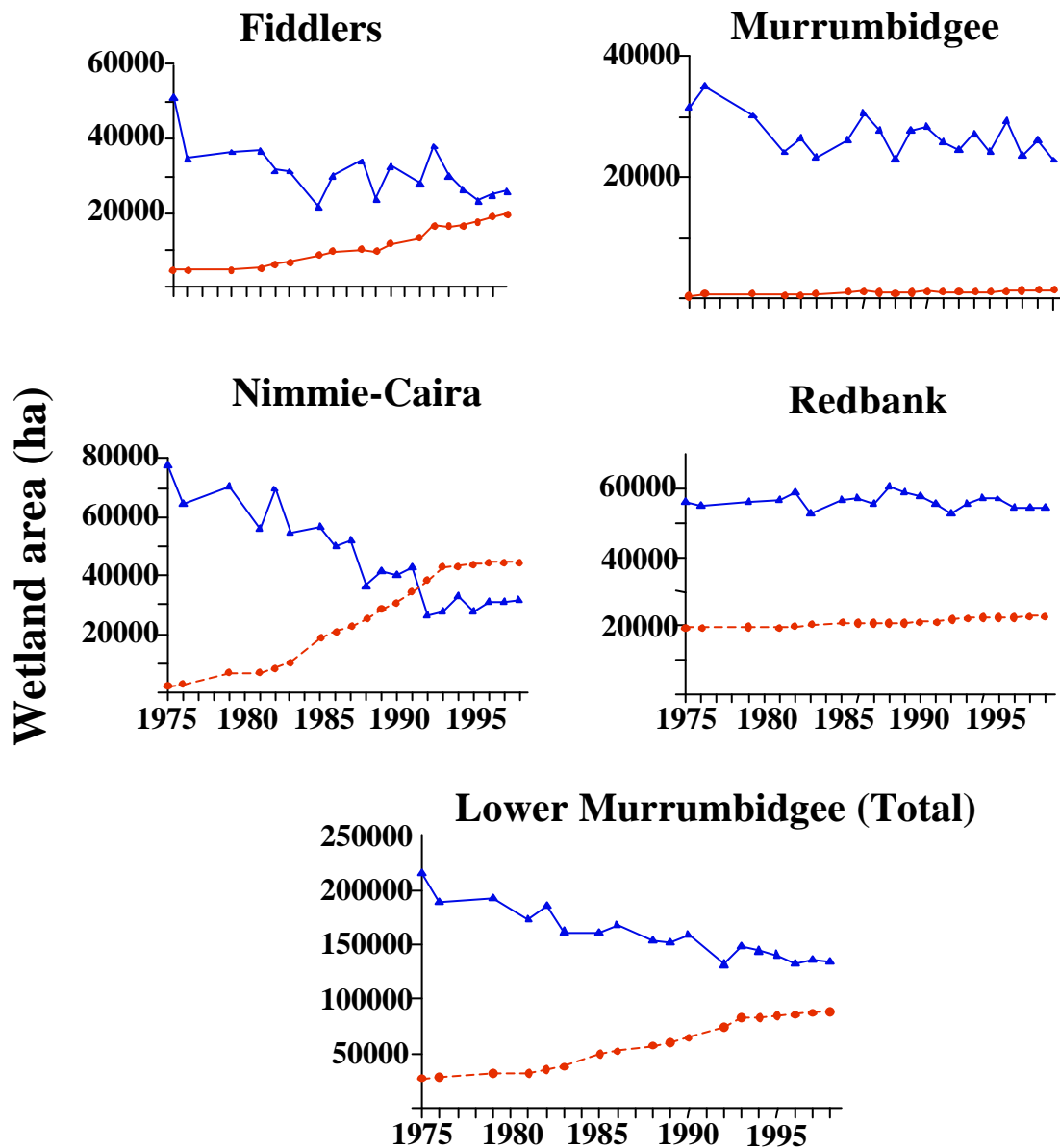
<sup>b</sup>Random points assessed on the floodplain as dead (no canopy), poor vegetation (<30% of canopy with leaves or growth); moderate (30-60% of canopy with leaves or growth) and good health (>60% canopy cover).

<sup>c</sup>Includes levee banks across the floodplain, levees bordering channels and banks bordering irrigation bays

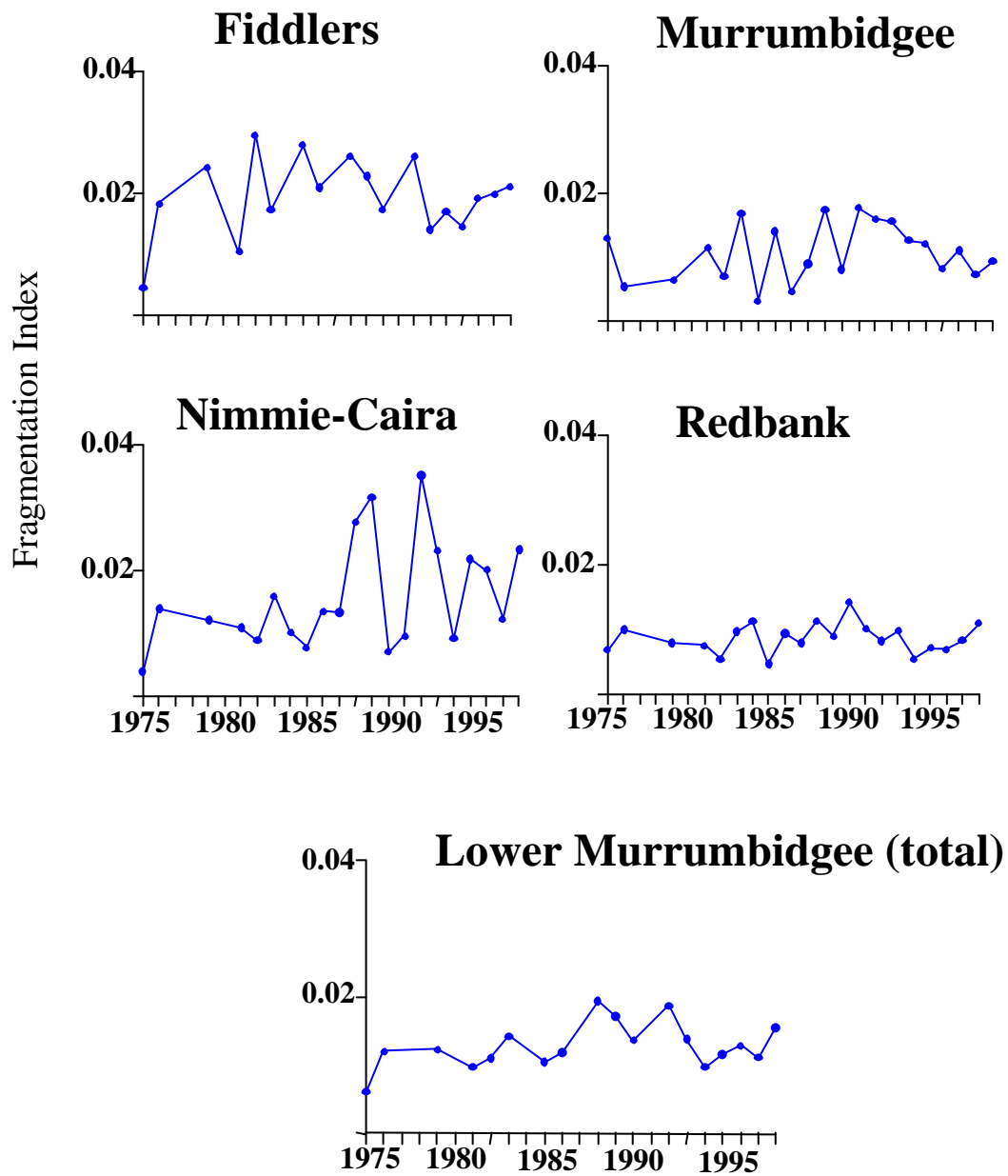
<sup>d</sup>Constructed channels within the Lower Murrumbidgee floodplain



**Fig. 8.** Distribution of wetland (blue) and developed areas (orange) on the Lower Murrumbidgee floodplain, classified from nine Landsat MSS satellite images in the period 1975-1998. Areas of wetland and developed areas are given for each image on the entire floodplain.



**Fig. 9.** Total changes in wetland (blue, triangles and solid lines) and developed areas (red, circles and dashed lines) on the Lower Murrumbidgee floodplain and each of the hydrological strata between 1975 and 1998, based on classification using Landsat MSS imagery.



**Fig. 10.** Fragmentation index (number of wetland clusters divided by wetland area) of wetland area in the four strata and on the entire Lower Murrumbidgee floodplain between 1975 and 1998.

**Table 7.** Results of trend analyses in wetland area (ha), developed area (ha) and fragmentation index on the Lower Murrumbidgee floodplain and the hydrological strata 1975-1998, using simple linear regression.

Stratum	Variable <sup>a</sup>	R <sup>2</sup>	Coeff.	Constant	Signif.
Fiddlers Creek	Wetland area	0.406	-0.019	47.88	0.004
	Fragmentation Index <sup>b</sup>	0.022	0	-2.390	0.55
	Developed area	0.967	0.071	-132.55	<0.001
Murrumbidgee	Wetland area	0.292	-0.009	28.41	0.012
	Fragmentation Index	0.027	0	-2.03	0.474
	Developed area	0.685	0.038	-68.00	<0.001
Nimmie-Caira	Wetland area	0.848	-0.047	103.47	<0.001
	Fragmentation Index	0.200	0.001	-1.100	0.042
	Developed area	0.915	0.133	-253.53	<0.001
Redbank	Wetland area	0.01	-0.001	12.02	0.66
	Fragmentation Index	0.012	0	-0.064	0.64
	Developed area	0.922	0.004	-5.19	<0.001
Lower Murrumbidgee (total)	Wetland area	0.895	-0.19	49.33	<0.001
	Fragmentation Index	0.147	0	-0.336	0.117
	Developed area	0.973	0.059	-106.97	<0.001

<sup>a</sup>log transformed

<sup>b</sup>Fragmentation index was the number of contiguous areas of wetland divided by wetland area each year.

map was either lost or degraded (Table 6). As well as decreasing wetland area in the Nimmie-Caira stratum, there was a significant increase in the fragmentation index for this stratum (Fig. 10, Table 7). No other strata showed any trend.

There was an increase in the developed area in all of the strata (Fig. 9) which was reflected in an increase over the whole Lower Murrumbidgee floodplain between 1975 and 1998 (Table 7, Fig. 8). Most of this development occurred in the Nimmie-

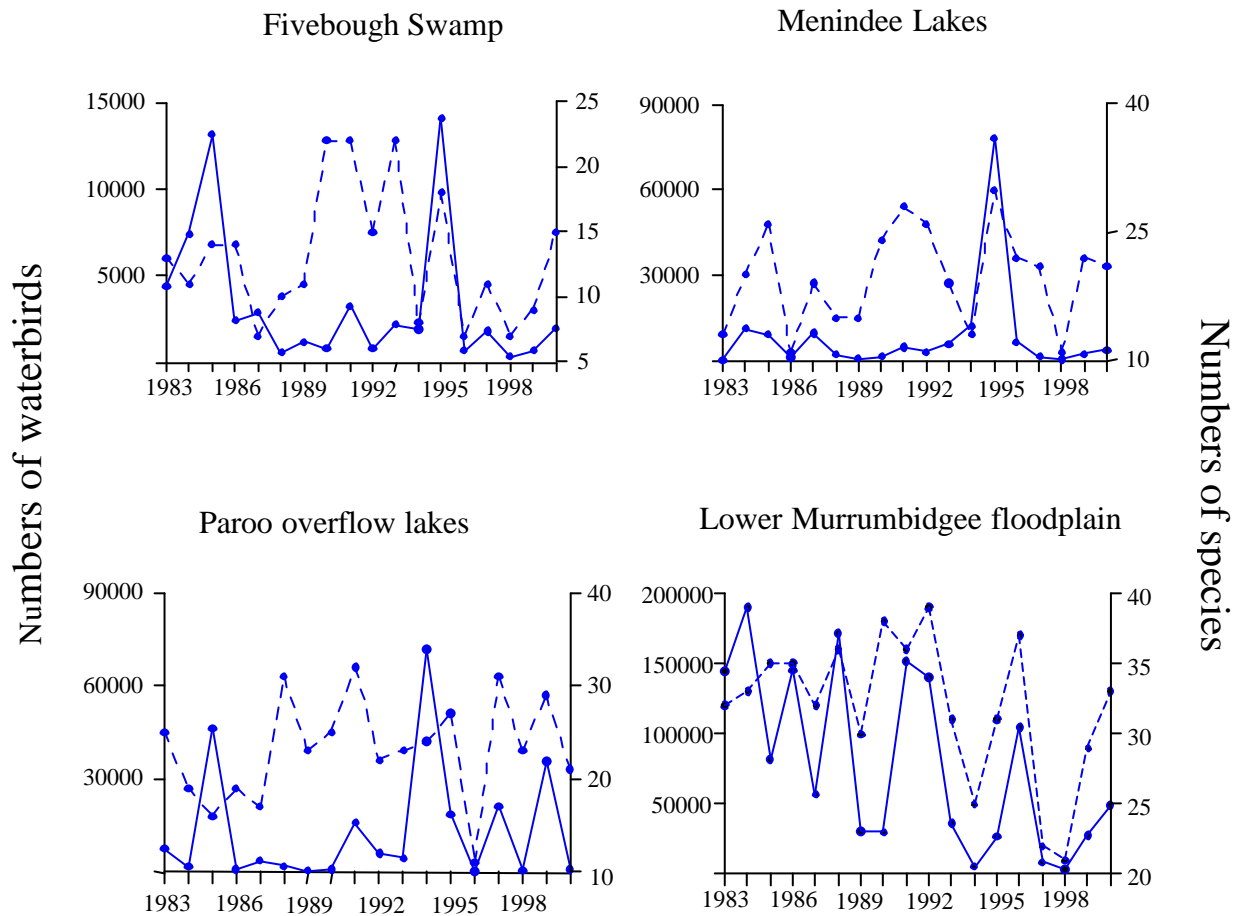
Caira system (Fig. 9). The area developed doubled in the period 1975-1998 from about 41,400 ha to 88,700 ha on the Lower Murrumbidgee floodplain. This area developed at a greater rate than all other strata with the Redbank system developing at the lowest rate (Fig. 9, Table 7). The area developed in the Nimmie-Caira was about 2,000 ha in 1975 and had reached about 44,500 ha by 1998 (Fig. 9). This showed some stabilisation by 1995 (Fig. 9).

### **Waterbirds**

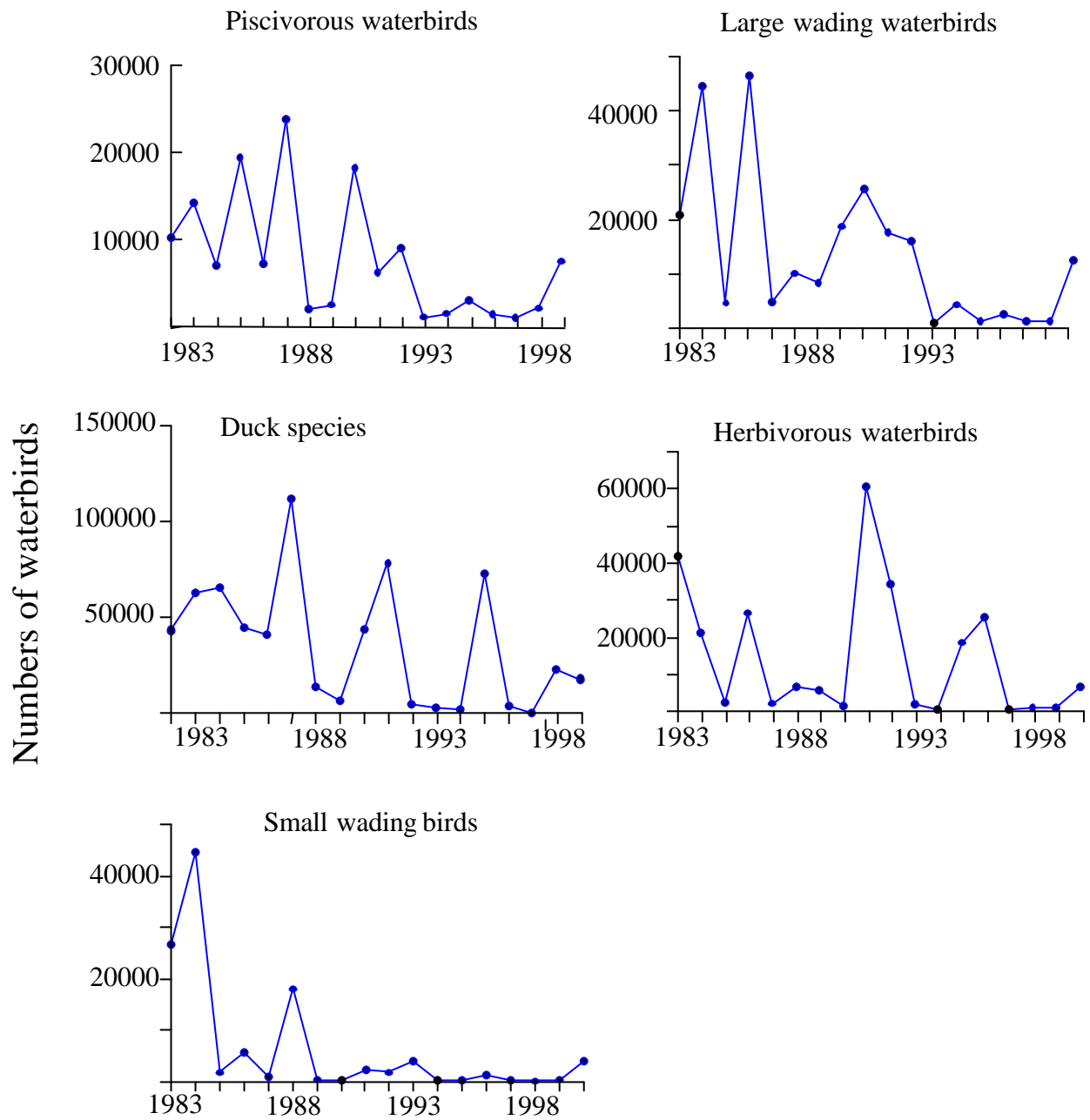
Most waterbirds occurred on the floodplain of the Nimmie-Caira stratum. Sixty species of waterbirds have been seen on the Lower Murrumbidgee floodplain and 41 of these species have bred on the wetland (Appendix 3). Most of these species were seen during aerial surveys (Appendix 3). There was a significant decline in total numbers of waterbirds with indications that numbers of species also declined ( $p=0.074$ ), in the 18 year period between 1983 and 2000 on the Lower Murrumbidgee floodplain (Table 8, Fig. 11), despite considerable variability. In comparison, only total numbers of waterbirds declined significantly on one of the three reference sites: Fivebough Swamp (Table 8, Fig. 11). Total numbers of waterbirds on Fivebough Swamp showed similar relative decline as on the Lower Murrumbidgee floodplain, between the two periods 1983-1986 and 1997-2000, although the rate of decline was not as high as on the Lower Murrumbidgee floodplain (Table 8). Numbers of species on the two other reference sites, Menindee Lakes and the Paroo overflow lakes, did not show any trends (Fig. 11, Table 8). In the period 1983-1986, total numbers of waterbirds on the Lower Murrumbidgee averaged about 139,900 compared to about 21,700 for the period 1997-2000 (Table 8), a reduction of 84% in abundance. The relative difference for total numbers of waterbirds on the Menindee Lakes was similar with a 74% decline between the two time periods, although there was no overall decline (Table 8). Numbers of waterbirds increased between the two time periods, on the Paroo overflow lakes, although this was not significant over time (Table 8).

Table 8. Average total numbers of waterbirds, numbers of species of waterbird and different groups for the periods 1983-1986 and 1997-2000, estimated during aerial surveys each year. Percentage (%) change was the difference between these averages. Results of trend analysis (simple linear regression) for these groups of waterbirds on the Lower Murrumbidgee floodplain, Fivebough Swamp, Menindee Lakes and the Paroo overflow lakes, using annual aerial survey data between 1983 and 2000.

Wetland	Waterbird group	1983-1986		1997-2000		% change	R <sup>2</sup>	Const.	Coeff.	Signif.
		Mean	SE	Mean	SE					
Lower Murrumbidgee floodplain	Total numbers of waterbirds	139927	22152	21677	10335.01	-84	0.372	294.5	-0.142	0.007
	Numbers of waterbird species	33.8	0.75	26.3	2.87	-22	0.186	856.1	-0.414	0.074
	Piscivorous waterbirds	12339	2685.78	2602	1514.27	-79	0.365	279.3	-0.136	0.008
	Large wading waterbirds	29732	10422.47	3994	2821.42	-87	0.373	347.8	-0.170	0.007
	Duck species	54522	5902.71	11009	5417.7	-80	0.288	367.6	-0.180	0.022
	Herbivorous waterbirds	23744	8194.91	2996	1503.01	-87	0.142	197.9	-0.095	0.124
Fivebough Swamp	Small wading waterbirds	19591	9953.87	1075	949.32	-94	0.334	88.19	-0.043	0.012
	Total numbers of waterbirds	6844	2345.26	1203	411.16	-82	0.201	185.60	-0.089	0.062
Menindee Lakes	Numbers of waterbird species	13.0	0.71	10.5	1.71	-20	0.009	189.86	-0.0089	0.716
	Total numbers of waterbirds	5495	2766.49	1518	533.69	-74	0.011	-43.46	-0.026	0.680
Paroo overflow lakes	Numbers of waterbird species	17.5	3.43	18.0	3.51	1	0.031	--362.49	0.192	0.484
	Total numbers of waterbirds	14224	10861.65	14744	8572.76	4	0.002	-19.30	0.014	0.859
	Numbers of waterbird species	19.75	1.89	26.0	2.38	24	0.043	-412.48	0.219	0.407



**Fig. 11.** Estimated numbers of waterbirds (continuous line) and numbers of species (dashed line), from aerial surveys each October of Fivebough Swamp, Menindee Lakes, Paroo overflow lakes and the Lower Murrumbidgee floodplain, in the period 1983-1999.

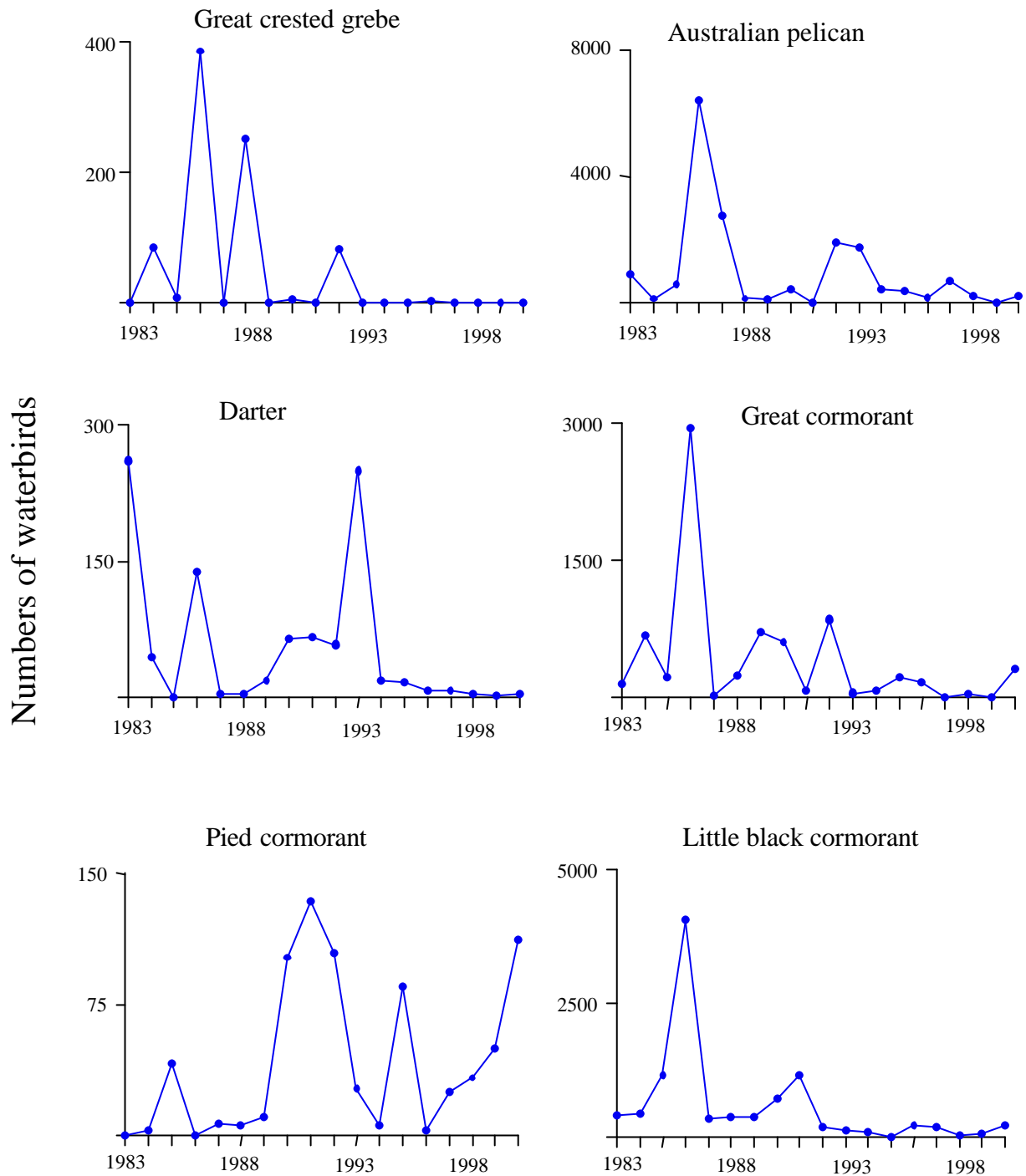


**Fig. 12.** Estimated numbers of five groups of waterbirds (see Appendix 1), piscivorous waterbirds, large wading birds, duck and small grebe species, herbivorous waterbirds and small wading birds from aerial surveys on the Lower Murrumbidgee floodplain each October of 1983-2000.

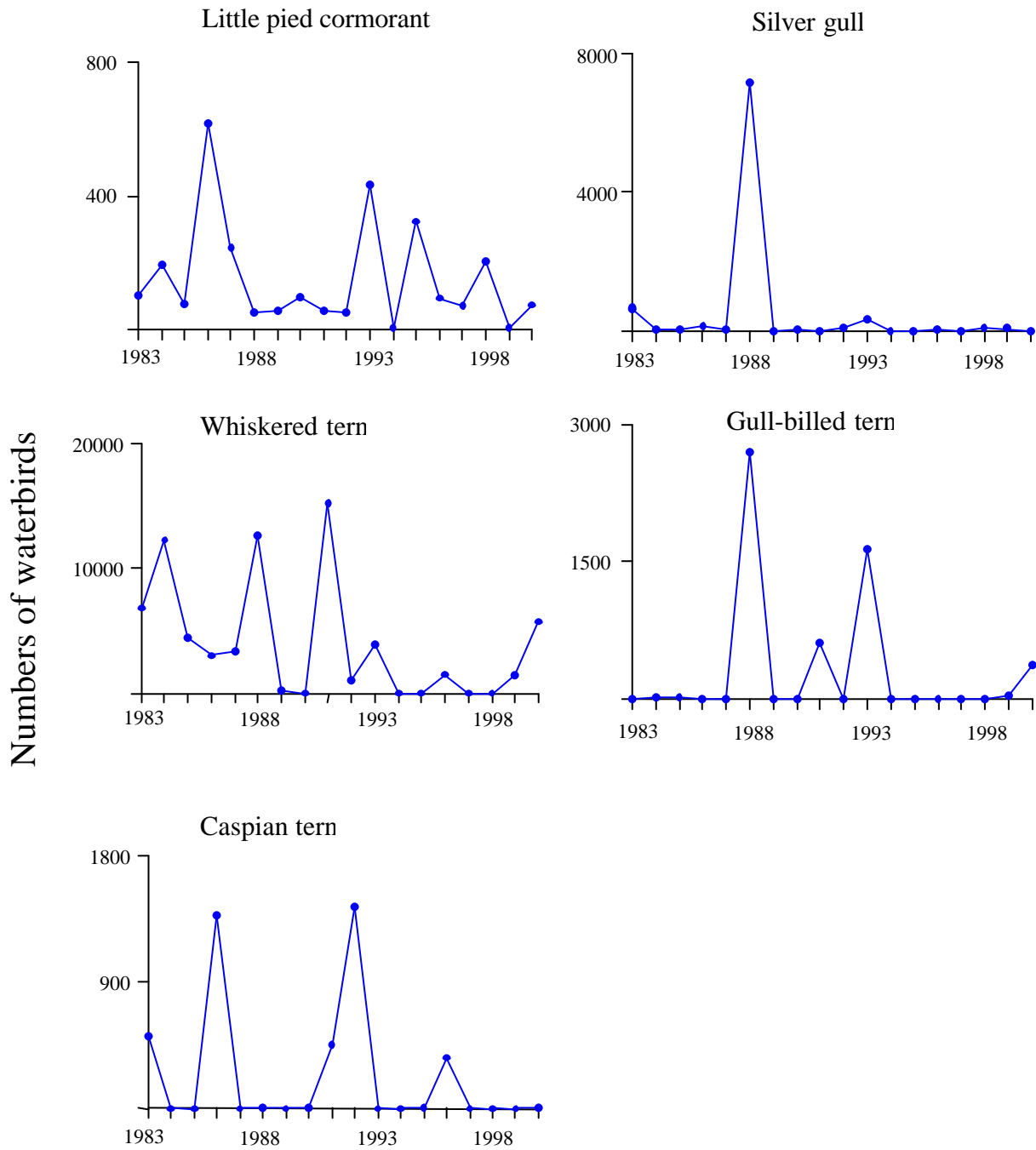
Total numbers of species declined by 22% on the Lower Murrumbidgee floodplain (Table 8). Numbers of species were reasonably stable until 1993 and then there was a rapid decline, particularly in the years 1997 (22 species) and 1998 (21 species) (Fig. 11). In 2000, numbers of species reached 33 species. There were no significant declines in numbers of species on the three reference wetlands (Table 8).

The pattern of decline of total numbers of waterbirds on the Lower Murrumbidgee floodplain was significant across all guilds of waterbirds, except herbivorous species (Table 8, Fig. 12). Even with herbivorous species, there was a negative slope and a probability of 0.12, indicating some evidence for a decline in numbers. Comparing the three years at the beginning of the surveys with the four years at the end of the surveys, there was about an 80% or more declines across all guilds of waterbirds (Table 8). Comparing average numbers in 1983-1986 and 1997-2000, there were declines in numbers of piscivorous waterbird species from about 12,000 to 2,500; large wading birds from about 30,000 to about 4,000; duck and small grebe species from about 55,000 to 11,000 (Table 8). Small wading waterbirds exhibited the greatest decline from about 20,000 to 1,000 (Table 8). Most species exhibited a similar pattern of decline although there was considerable variability at the scale of species (Figs 13-17). Estimates of total numbers of each piscivorous and large wading species were generally low in 1997 and 1998 for all species, except Australian pelicans and pied cormorants (Figs 13 and 14). Other species exhibited a similar pattern (Figs 15-17).

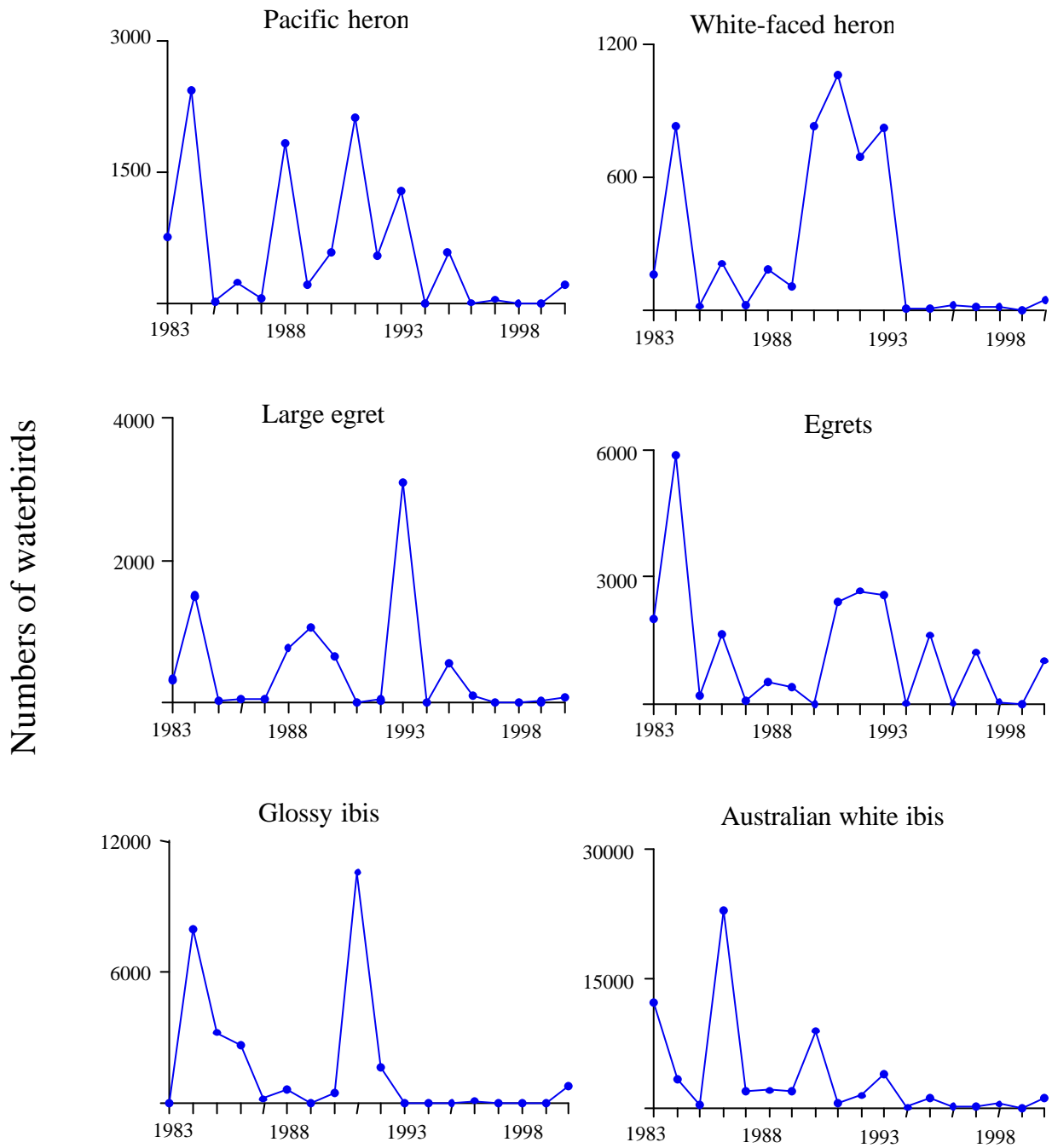
There were three peak years of breeding activity, 1986, 1990 and 2000 (Fig. 18). More than 10,000 nests or broods were estimated on the Lower Murrumbidgee floodplain in 1986 and 1990. There were also some nests and broods recorded in 1983, 1984, 1985, and 1989 (Fig. 18), averaging 682 (range 40-1469). There were no broods or nests seen in 1987. After 1990, numbers of nests and broods seen during aerial surveys were reduced (Fig. 18). No broods or nests were seen in 1991, 1994 and 1997 while an average of 151 nests or broods (range 2-258) were estimated each year in other years after 1990, except for 2000.



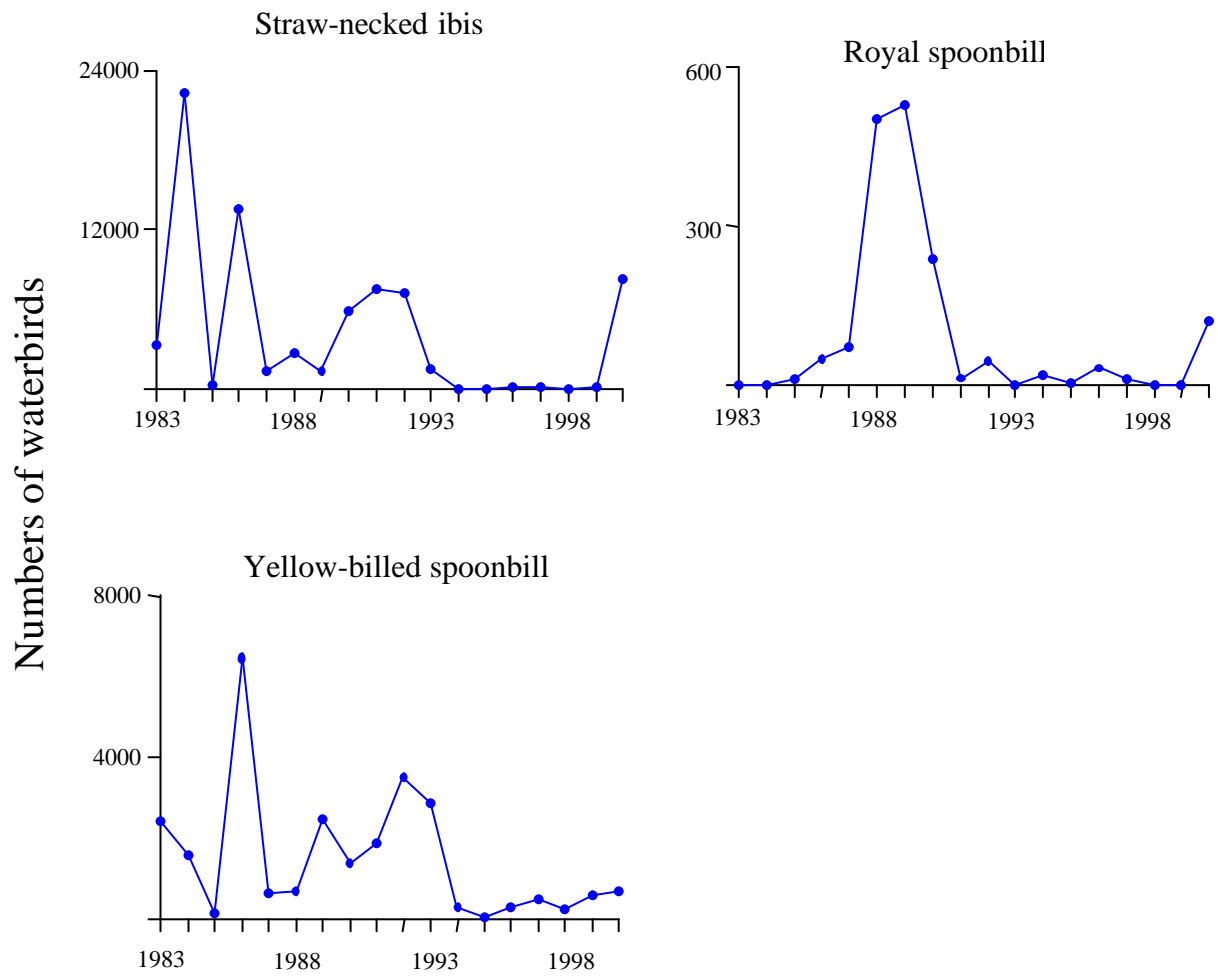
**Fig. 13.** Estimated numbers of each piscivorous species of waterbird, from aerial surveys on the Lower Murrumbidgee floodplain each October of 1983-2000.



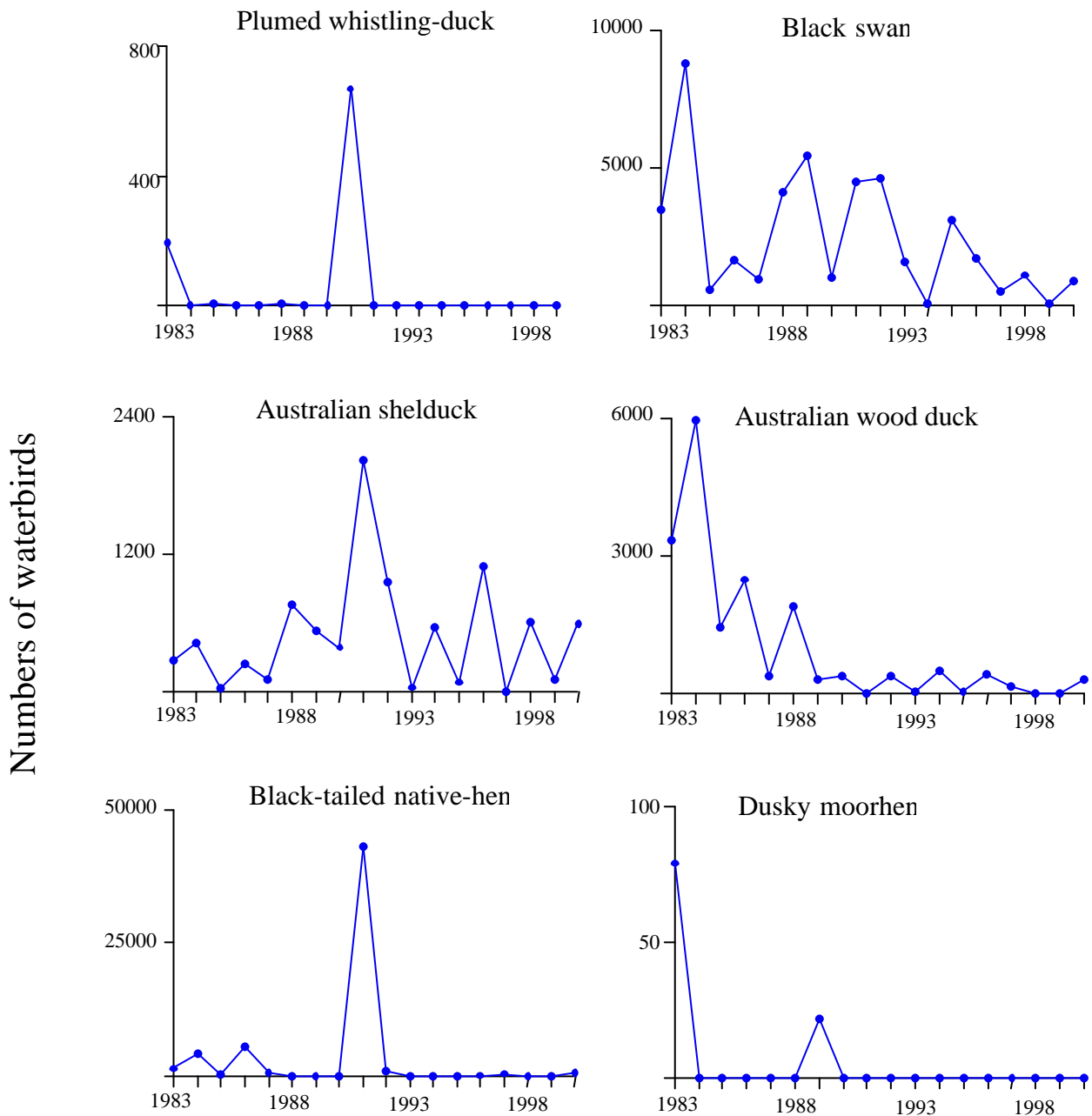
**Fig. 13.** Continued - Estimated numbers of each piscivorous species of waterbird, from aerial surveys on the Lower Murrumbidgee floodplain each October of 1983-2000.



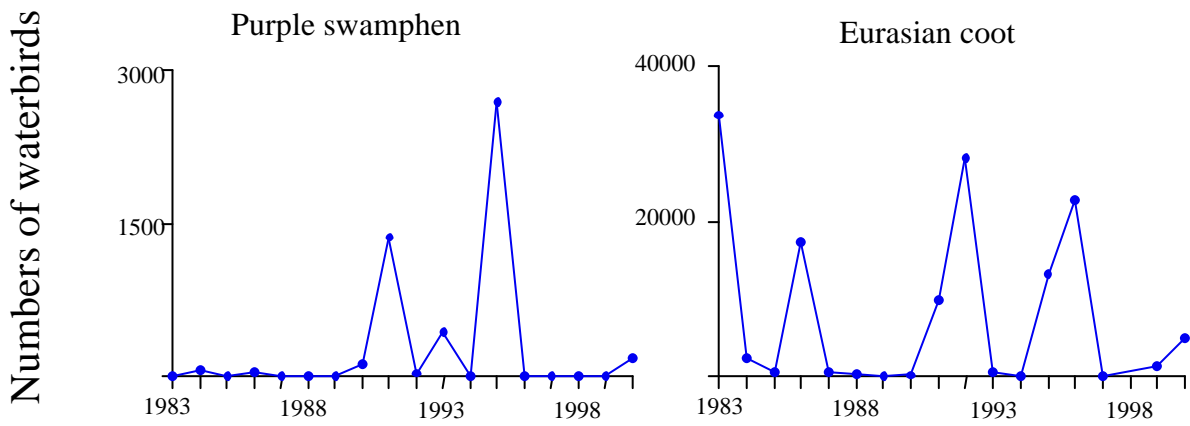
**Fig. 14.** Estimated numbers of each large wading species of waterbird, from aerial surveys on the Lower Murrumbidgee floodplain each October of 1983-2000.



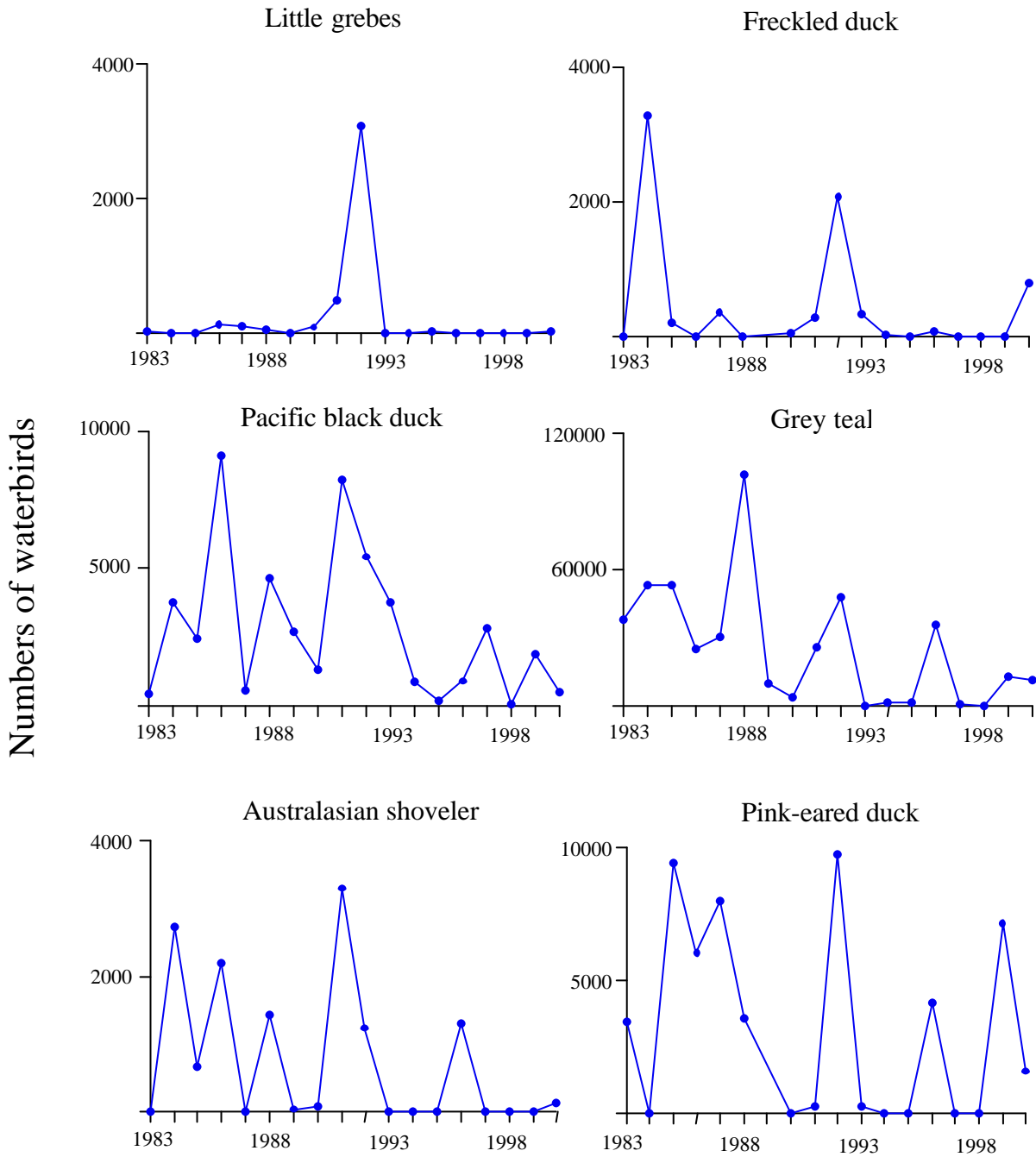
**Fig. 14.** Continued - Estimated numbers of each large wading species of waterbird, from aerial surveys on the Lower Murrumbidgee floodplain each October of 1983-2000.



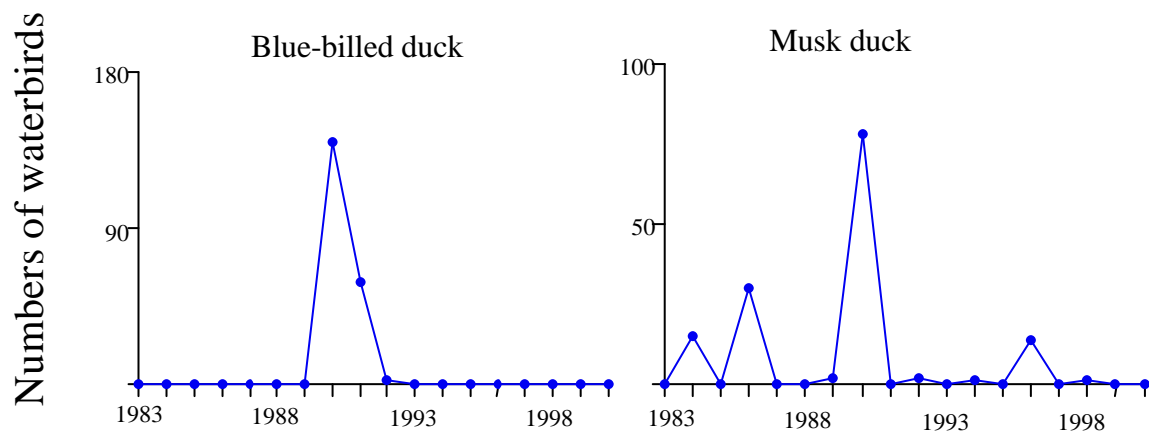
**Fig. 15.** Estimated numbers of each herbivorous species of waterbird, from aerial surveys on the Lower Murrumbidgee floodplain each October of 1983-2000.



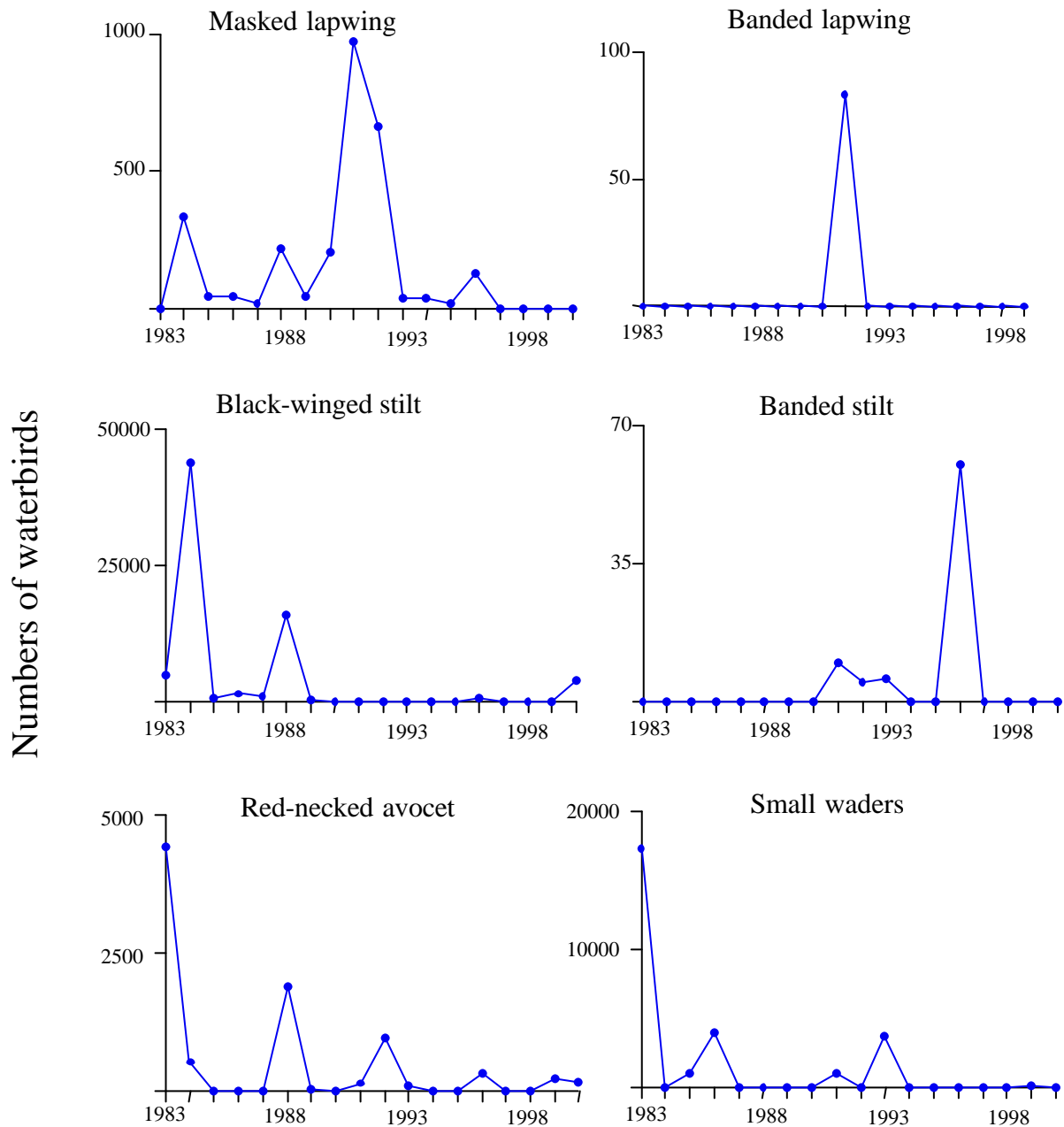
**Fig. 15.** Continued - Estimated numbers of each herbivorous species of waterbird, from aerial surveys on the Lower Murrumbidgee floodplain each October of 1983-2000.



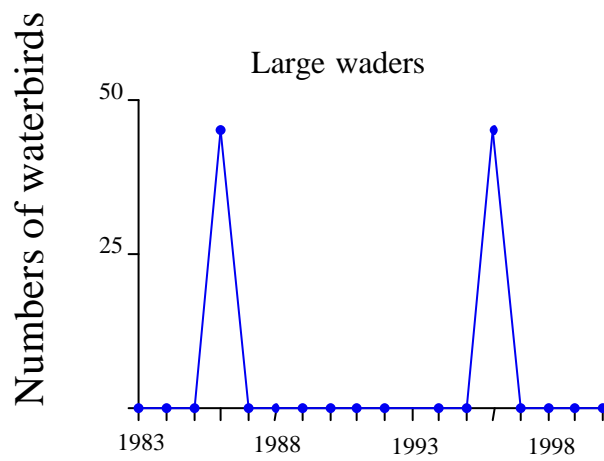
**Fig. 16.** Estimated numbers of each duck and small grebe species, from aerial surveys on the Lower Murrumbidgee floodplain each October of 1983-2000.



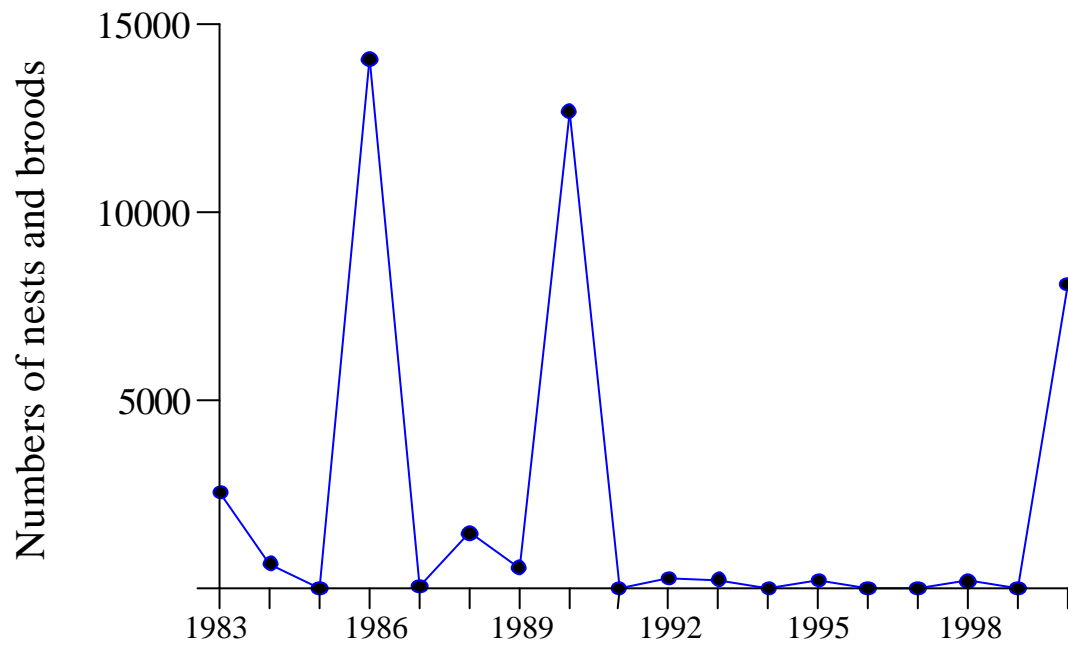
**Fig. 16.** Continued - Estimated numbers of each duck and small grebe species, from aerial surveys on the Lower Murrumbidgee floodplain each October of 1983-2000.



**Fig. 17.** Estimated numbers of each small wading species of waterbird, from aerial surveys on the Lower Murrumbidgee floodplain each October of 1983-2000.



**Fig. 17.** Continued - Estimated numbers of each small wading species of waterbird, from aerial surveys on the Lower Murrumbidgee floodplain each October of 1983-2000.



**Fig. 18.** Estimated numbers of waterbirds breeding (nests and broods), using aerial surveys, on the Lower Murrumbidgee floodplain each October of 1983-2000.

## Discussion

The Lower Murrumbidgee floodplain on the Murrumbidgee River in arid Australia (Fig. 1) has joined a growing list of wetland ecosystems that exhibit symptoms of ecological collapse, as a result of water resource development on the 1,690 km long Murrumbidgee River that supplies the wetland. Dams and water diversions have lowered river flows and reduced flooding of downstream wetlands around the world. In North America, about 90% of the wetlands in California's Central Valley have gone (Lemly *et al.* 2000) and the amount of water in Mono Lake in California has halved (Wiens *et al.* 1993). Water levels in the Aral Sea dropped by 13 m between 1960-1987 because of about an 80% reduction in flow, reducing wetland area by 40% (Micklin 1988, Ferrari *et al.* 1999). More than 20 dams upstream and diversions have reduced floods to the wetlands of the Hadejia-Nguru Wetlands in Africa by as much as 50% in dry years (Lemly *et al.* 2000). Dams and water diversions have reduced sediment loads by 90% in the Nile delta, leading to high erosion rates on promontories ( $>50\text{m year}^{-1}$ ), virtual elimination of floods and a 70% loss of wetland areas over 200 years (Stanley and Warne 1998).

About 76% of the Lower Murrumbidgee wetland was lost or degraded over the last 140 years, 1855-1998. This was probably a conservative estimate because our analysis covered only the core 90% of the original floodplain (South Australia 1902) and the remaining 10% of the floodplain, around the periphery of the floodplain, was also likely to have been affected. Also, most of the remaining wetland area in the Nimmie-Caira stratum (31,508 ha –Table 6), the floodways and key habitat areas, are affected by too much flooding, which is producing changes in aquatic vegetation. Also most of the open water lakes have changed flooding regimes. These changes were not incorporated in our assessment.

There are few estimates of wetland loss in Australia that match the estimate for wetland loss on the Lower Murrumbidgee floodplain. Most studies have not estimated area lost but area affected. Other wetland areas affected by human impacts include 96% of the wetlands on the Macleay River on the east coast of Australia affected by drainage (Pressey 1989) and 70% of wetlands on the Swan Coastal Plain in Western Australia altered or destroyed by drainage (Halse 1989). For the Gwydir wetlands, there was a 70% reduction in river flows causing loss of wetlands (Keyte 1994). Ninety-eight percent of the Carrum swamplands were drained for agriculture (Norman and Corrick 1988). Our estimate of wetland loss and degradation on the Lower

Murrumbidgee floodplain ranks among the higher estimates reported for wetlands in the world (Lemly *et al.* 2000). A previous estimate, based on little analysis, that about 20% of the Lower Murrumbidgee floodplain was lost (MDBMC 1995), was a considerable underestimate.

The Lower Murrumbidgee floodplain is the main wetland area of the Murrumbidgee River and covered more than 300,000 ha (Table 6). Much of the water in the Murrumbidgee River used to reach the Lower Murrumbidgee floodplain because the river has few major distributaries upstream of the Lower Murrumbidgee floodplain, apart from Yanco Creek (Fig. 1). Historical accounts in 1902 described an extensive wetland, frequently flooded by overbank flows (South Australia 1902), supplied by a complex system of anastomosing creeks and river channels (Fig. 2c, Butler *et al.* 1973). A wide range of biota (Pressey *et al.* 1984, Maher 1990, Scott 1992, Porteners 1993), sometimes occurred in large numbers and reflected this hydrological complexity. In the early 1990s, the Lower Murrumbidgee floodplain satisfied four criteria for listing as a wetland of international importance under the Ramsar Convention (Davis 1994). It had particularly good examples of two wetland types (Lignum swamps, fringing River Red Gum forests); habitat for plants and animals at a critical stage of their biological cycles (breeding areas); 20,000 individual waterbirds and one percent of the population of Straw-necked Ibis (DWR 1994).

The waterbird community included 60 species, inclusive of all functional feeding groups (Fig. 12) that feed on fish, invertebrates and aquatic plants. More than half (68%) of these species bred in the area (Appendix 3). The Lower Murrumbidgee floodplain had the third largest breeding colony of Glossy Ibis (>2,000 pairs in 1984) and the seventh largest breeding colony of Straw-necked Ibis (40,000 pairs in 1981), ever recorded in Australia (Lowe 1983, Marchant and Higgins 1990). In the early 1980s, there were about 139,000 waterbirds using the area but estimates collapsed by more than 80% to about 22,000 by the late 1990s (Table 8, Fig. 11). The causes of wetland loss and the collapse in waterbird populations were directly attributable to loss of habitat caused by water resource development at a catchment and local scale, over more than 140 years (1855-1999).

### **Catchment Impacts**

River regulation through the building of dams and diversion of water upstream changed the natural flow patterns in the Murrumbidgee River, particularly to the

lowest part of the river, the Lower Murrumbidgee floodplain. Terminal wetlands and floodplains are most sensitive to reductions in river flows and river regulation (Kingsford 2000b).

The Murrumbidgee River supplies water to two of Australia's larger irrigation schemes, the Murrumbidgee Irrigation Area and the Colleambally Irrigation Area and Australia's capital, Canberra (Figs 1 and 2). River flows are also influenced by the largest water resource project in Australia, the Snowy Mountains Hydroelectric Scheme (Davies *et al.* 1992, DWR 1993a). Most of the storage capacity in the Murrumbidgee Catchment (98%) is upstream of Wagga Wagga where 26 major dams store and control the flow of the Murrumbidgee River (Fig. 3). In 1998/1999, 2,122,000 ML of water was diverted from the Murrumbidgee River catchment (MDBMC 1999). Most of the water (95%) stored in the dams is released later to irrigation areas downstream; the same water that would have supplied floodplain wetlands, like the Lower Murrumbidgee floodplain (Kingsford 2000b). The Snowy Mountains Hydroelectric Scheme diverts water from the eastward flowing rivers in the Snowy River catchment into the Murrumbidgee catchment, after generating hydroelectricity (Davis *et al.* 1992) but none of this additional flow reaches the Lower Murrumbidgee floodplain because most is used by the Colleambally Irrigation Area (Table 2). The Murrumbidgee River is the most developed major river system in the Murray-Darling Basin and possibly Australia, with 98% of divertible flow now diverted (Kingsford 2000b).

Before most river regulation in the catchment, between 1888 and 1918, a median of 76% of annual flows from Wagga Wagga reached Hay each year (Table 4). Apart from evaporation, the difference in flows supplied the distributary creek systems (e.g. Old Man Creek), underground aquifers and floodplain wetlands along the river (Fig. 1). Between Hay and Wagga Wagga, there are 174,700 ha of wetland (Thornton and Briggs 1994). Of the flows that reached Hay, most (85%) flowed onto the Lower Murrumbidgee floodplain (Cross *et al.* 1991, DWR 1994) because the main river channel only has a capacity to carry 15% of flows (DWR 1989). Between 1979 and 1998, a median of 40% of the annual flow from Wagga Wagga reached Hay (Table 4, Fig. 7), which was a reduction of 48% compared to the period 1888-1918. Flows to the Lower Murrumbidgee floodplain were further reduced by about 13% in the amount of water reaching Maude from Hay each year, possibly water that supplied Hay Irrigation Area (Table 2, Fig. 3). There was also some evidence of a decline in

flows from Maude to Balranald after the 1950s (Fig. 7c). The increase in flows between Maude and Balranald (Fig. 7c) was due to the contribution of the Lachlan River that provides about 10% of the flow volume (Pressey *et al.* 1984). The contribution of the Lachlan River is reduced by about 50% because of a reduction in flows (EPA 1997), as a result of diversions and river regulation upstream. There was also an unaccounted reduction in our analyses in flows to the Lower Murrumbidgee floodplain resulting from diversion upstream of Wagga Wagga (Fig. 1). About 65,000 ML is diverted to Canberra and to irrigation each year (DLWC 1996).

We estimated that river flows to the Lower Murrumbidgee floodplain have been reduced by at least 60% by diversions upstream. Two independent hydrological models indicate this is a conservative estimate. One model estimated that median outflows at the junction of the Murrumbidgee and Murray Rivers (Fig. 1) were only 25% of natural levels and dry years, which occurred naturally in 5% of years, now occurred in 57% of years (MDBMC 1995). The other model estimated that median annual flows at Balranald were naturally 3,200,000 ML but are now only 20% of this level at 645,000 ML (EPA 1997).

There was also evidence that the range of annual flows was reduced (Table 4). River regulation can reduce the size of mid to large flows and increase low flows (Kingsford and Thomas 1995, EPA 1997, Thoms and Sheldon 2000). The Murrumbidgee River is managed to a flow target of 125 ML day<sup>-1</sup> at Balranald (Ebsary 1992) which means that dry years no longer occur and this reduces the potential for overbank flows, for a given volume. In the last two decades (1979-1988 and 1989-1998), only 15 daily flows have exceeded 30,000 ML at Hay (Table 5). Floods occur when flows exceed channel capacity, which varies from 11,000 ML day<sup>-1</sup> at Redbank Weir, 20,000 ML day<sup>-1</sup> at Maude Weir to 35,000 ML day<sup>-1</sup> at Hay (Ebsary 1992). The only other period where flows were similarly low was between 1939 and 1948 but this was probably due mostly to a dry period (Fig. 6). The period from 1989 to 1998 had good total annual flows at Wagga Wagga (Fig. 6). In the past two decades, there has been less opportunity for the river to flow over its banks onto the Lower Murrumbidgee floodplain, as a result of reduced daily flows. Major reductions in total volumes of flows and magnitude of daily flows have reduced flooding of the Lower Murrumbidgee floodplain. Cross-sectional area could have increased in the main river channel, as on the lower end of the Murray River (Thoms and Walker 1993), further reducing the frequency of overbank flows.

The impact of catchment development on flooding on the Lower Murrumbidgee floodplain was recognised first when the opening to the Yanco Creek was deepened (Table 2). Landholders estimated that floods to the Lower Murrumbidgee floodplain were reduced, based on river heights at Wagga Wagga (South Australia 1902, p. 161-162). Next, the engineer's report accompanying the introduction of the legislation for Burrinjuck Dam predicted the consequences of this dam: *"There is no doubt that by the diversion of water for irrigation, and the necessary storing of flood-waters for that purpose, the levels of floods on the lower river will be reduced, with a consequent reduction in the spreading of flood-waters over the country and adjoining the river, but to what extent it is difficult to say precisely."* (NSW Legislative Assembly 1905). Maude and Redbank Weirs (Fig. 2c) were built in the late 1930s (Table 3) specifically to compensate for reduced flows to the Lower Murrumbidgee floodplain as a result of water stored in Burrinjuck Dam for the Murrumbidgee Irrigation Area (Gibson 1974, Eddy 1992). The weirs raised the level of the river, lowered by diversions upstream, so floods reached the floodplain (WCIC 1971).

Based on flooding distribution between 1975 and 1998, we estimated that reduced flows as a result of catchment development destroyed about 34% of the floodplain in the Fiddler-Uara stratum (Table 6). Similarly, we estimated that about 16% and 17% respectively of the Nimmie-Caira and Murrumbidgee strata were lost because of reduced flows and possibly some of the Redbank stratum (Table 6). The greatest impact of catchment water resource development was probably on the Fiddlers-Uara and the Murrumbidgee strata that predominantly relied on overbank flows and benefited little from the building of Maude and Redbank Weirs. The health of perennial flood dependent vegetation in these strata indicated the problem. There was no flood dependent vegetation in good health found in random samples in the Murrumbidgee stratum and only 20% of samples in the Fiddlers-Uara stratum were in good health (Table 6). Further, the impact of reduced flooding was probably underestimated because some wetland areas reflected a spectral water signature on Landsat imagery that could have resulted from local rainfall. This would be unlikely to sustain wetland areas on the Lower Murrumbidgee floodplain that relied primarily on river flows. The area is semi-arid with low rainfall.

The Lower Murrumbidgee floodplain was not the only wetland area along the Murrumbidgee River to be affected by river regulation. There were also impacts of reduced flooding on the 174,700 ha of floodplain between Wagga Wagga and Hay.

Red gums (570 ha) have died from increased flooding in places such as Tombullen Reservoir (Thornton and Briggs 1994). Water is also stored in many wetland areas as part of river regulation. Local hydrological controls such as pumping of water, drainage, blocking of flows by levees or weirs, have affected 51% of open water wetlands (2,005 ha) between Hay and Wagga Wagga (Thornton and Briggs 1994). Also, rising groundwater and river regulation have affected Black Box wetlands (DWR 1993a). In addition to the impacts of reduced flows, levee banks were also built by private landholders and the Government which alienated parts of the floodplains of Old Man Creek and other distributary systems downstream between Hay and Maude, to protect irrigation areas from flooding (WRC 1974, 1979, DWR 1993a). Little is known of the impact of water resources on floodplain areas downstream of the Lower Murrumbidgee floodplain but they are likely to be considerable. These areas were flooded in large flood events (South Australia 1902, p. 108).

Other changes to river flows have occurred. River flows into the dams are usually highest during the spring, from June until October and lowest in late summer but river regulation has changed this seasonal nature by capturing winter and early spring flows for release during the summer irrigation period (EPA 1997). Such a change affects temperature (Walker 1985), channel stability (Thoms and Walker 1993, Walker and Thoms 1993) and salinity (Walker and Thoms 1993) with likely ecological effects on processes such as breeding of aquatic organisms. Another problem for the Murrumbidgee River was the riparian condition along the river. It declined significantly with grazing intensity (Jansen and Robertson in press). This followed loss of many of the reed beds in the Riverina from grazing in the 19<sup>th</sup> Century, leaving only the ones on the Lower Murrumbidgee floodplain (Williams 1962).

The Murrumbidgee River could be described to be in a mature phase of water resource development with relatively few opportunities to further regulate river flows. The two largest dams Burrinjuck Dam (1,032,400 ML) and Blowering Dam (1,631,400 ML) regulate 70% of river flows upstream, providing the means to control run-off in most of the catchment. Despite the completion of most storages by the early 1980s (Fig. 4), pressure on use of water resources, upstream of the Lower Murrumbidgee floodplain grew in the 1990s. In 1995, the Governments of the Murray-Darling Basin (Federal Australian Government, New South Wales, Queensland, South Australia, Victoria, Fig. 1) capped water diversions at 1993/1994

levels of development in all rivers in the Murray-Darling Basin (MDBMC 1996). The cap target for the Murrumbidgee River was 1,970,000 ML year<sup>-1</sup>, but this was exceeded by about 7.7% in 1998/1999 (MDBMC 1999). The increase in area of irrigated rice planted, the main consumer of water in the catchment, is another indicator of water use. In 1998/1999, there were 87,671 ha of rice, corresponding to a 23% increase in area since 1993/1994 (MDBMC 1999, DLWC unpubl. data). Also, areas for rice growing expanded from 400 ha in 1991-1992 to about 10,000 ha in 1994-1995 around Hay (Crabb 1997, p. 83-84). Canberra could also grow and place additional pressure on water resources and the amount of water reaching the Lower Murrumbidgee floodplain.

### **Local changes to the Lower Murrumbidgee floodplain**

The development of the Lower Murrumbidgee floodplain with the building of levees, channels, weirs and regulators over more than 100 years disrupted the distribution of flows and destroyed and degraded wetland areas (Tables 3 and 6, Fig. 9). The first levees stopped river flows reaching the western floodplain and lakes (Pitarpunga, Paika and Macommon) (Table 3, Fig. 2c). Most of the 34% of wetland lost in the Redbank stratum was due to these levees (Table 6) which occurred at the same time Burrinjuck began to lower flows in the river (Table 3).

The building of Maude and Redbank Weirs by the Murray-Darling Basin Commission in 1939-1940, allowed the river height to be raised and compensated for some of the lost flows resulting from water resource development upstream. Redbank Weir diverted water down the eastern and western sides of the Murrumbidgee River on the Redbank stratum and Maude Weir diverted water through the Nimmie and Cairra Creeks to the floodplain in the Nimmie-Caira stratum (Fig. 2c). Controlled flooding occurred subsequently in most years (Pressey *et al.* 1984, Eddy 1992), although there were some initial problems when the first flood created by Redbank Weir in the dry year of 1940 did not reach the floodplain. The many distributary channels downstream of the weir allowed the water to flow back into the main channel of the river and so these were subsequently closed with levees (Table 3, Eddy 1992).

The building of the weirs increased the frequency of flooding to parts of the Lower Murrumbidgee floodplain but only to previous natural levels, according to advocates at the time (Gibson 1974). This was probably optimistic. Flows could not be diverted

down Fiddlers Creek (Fig. 2c), which like most high level distributaries from rivers were affected by declining river flows (Kingsford 1999b). Lignum shrubs in Fiddlers Creek compared to the Nimmie-Caira stratum reflected this problem. The spatial distribution and density in the two strata were similar but the shrubs were considerably smaller in the Fiddlers Creek (DWR 1989). There was further evidence that floods were not restored to their original levels. Pressey *et al.* (1984) estimated that daily flows sufficient for overbank flows failed in about 20% of years before 1940 but subsequently failed in 30% of years. And, floods that lasted for more than three months, defined as 'natural', occurred about once every three years, after the building of Redbank Weir (Eddy 1992). Before river regulation in 1902, the manager of Paika Station near Paika Lake in the Redbank stratum (Fig. 2c), a resident of 30 years, observed that every second year was a flood year (South Australia 1902, p.64-65). On Yanga Station on the other side of the Murrumbidgee River in the Redbank stratum, flooding was usually every year (South Australia 1902, p. 67).

Maude and Redbank Weirs probably restored the amount of water reaching the Nimmie-Caira stratum and the core of the Redbank stratum. But the weirs and subsequent water resource development ultimately resulted in the loss of about 96,000 ha of wetland on the Lower Murrumbidgee floodplain over the 23 year period, 1975-1998 (Figs 8 and 9, Table 6). About half of this loss occurred on the Nimmie-Caira system where about 60% of the wetland area, present in 1975, disappeared (Table 6, Fig. 9). Most of this loss was directly due to development of the area for irrigation (Fig. 5).

Soon after the building of Maude Weir, the regular and predictable flooding of the Nimmie-Caira stratum encouraged landholders to build levee banks (Table 3) to redistribute floodwaters, presumably to enhance the growth of pastures for livestock. While the quantity of water may have been the same as natural flows, it was predictable. In 1966, the Government built the Caira Creek cutting and installed a regulator that further controlled river flows to the Nimmie-Caira stratum (Table 3). The levee banks on either side also stopped flood flows reaching the floodplain adjacent to the Murrumbidgee River (DWR 1989, Table 3). The regular supply of water produced by this development stimulated a change in land use from livestock grazing to irrigation. In the late 1960s, the first irrigation (400 ha) was established and irrigation of cereals soon followed in 1975 (DWR 1989). Regular flooding also stimulated growth in Lignum that covered about 40% of the Nimmie-Caira stratum,

making it difficult to manage livestock and control feral pigs *Sus scrofa* (DWR 1989). The change in land use to irrigation and need to control Lignum prompted widespread clearing which was not subject to any controls initially (DWR 1994). By 1988, 60% of the estimated 40,000 ha of Lignum was cleared (Cross *et al.* 1991). By 1996, 39,000 ha of land were developed for irrigated cropping of wheat, barley and safflower (Parmenter 1996). Much of this development was in the Nimmie-Caira stratum, with some development in the Murrumbidgee and Fiddlers-Uara strata (Fig. 9).

As well as the Paika levee, some structures were built on the Redbank stratum to control flows. Most of the major Spike Rush swamps had levee banks that retained water and banks on the eastern side of the stratum diverting water into areas that were not usually flooded (Maher 1990). During large floods, four “outlet regulators”, three on the western side of the river, and one on the east, allowed water to be diverted back into the river. The north-east corner of the Redbank stratum was a focus of recent development (Fig. 9). Some of the development on the Redbank stratum (5,900 ha) was based on water licences to irrigate from the river and occurred on the floodplain and lakes that were originally alienated by the Paika levee (Table 3).

In the developed area of the Lower Murrumbidgee floodplain, irrigation bays and agricultural areas were protected by about 2,100 km of levee banks and supplied by water conveyed by about 394 km of constructed channels (Table 6, Fig. 5). These fragmented wetland area in the Nimmie-Caira stratum (Table 7, Fig. 10). The number of structures now controlling flows of water means that natural flows may not reach some floodplain areas in this stratum unless directly connected by a channel. The development plan for the Lower Murrumbidgee floodplain (DWR 1989, 1994) was based on identifying special habitat areas or rookeries (Fig. 5c) that were protected or provided with water by floodways, while development was permitted elsewhere on the floodplain (Fig. 5c). The floodways were to provide hydrological continuity for aquatic animals such as fish and waterbirds and nutrients (Cross *et al.* 1991) but allowed development of the floodplain and wetland areas were confined to a narrow distribution of floodways and isolated rookeries (Fig. 5c). A narrow definition for wetlands as rookeries or key habitat areas was applied.

More frequent flows down the floodways changed the distribution and abundance of aquatic vegetation, favouring colonisation by Cumbungi, which restricted water flows (Eddy 1992, DWR 1994, DLWC 1997). The Southern Caira Channel was built

to bypass the floodway and allow more efficient transmission and increased flexibility in water management to irrigated areas downstream and key habitat areas (DLWC 1997). The bank on this channel also alienated the southern part of the floodplain from flood flows because it was constructed above the estimated 1956 flood level at the site and did not allow passage of floods so it needed to be breached during floods (DWR 1994).

### **Ecological impacts of water resource development**

Of the four criteria that made the Lower Murrumbidgee floodplain a potential wetland of international importance in the early 1990s, characteristic habitat types and three related to waterbirds (DWR 1994), only part of one remains. River Red Gum areas in the Redbank stratum are in reasonably good condition, particularly where floods are redirected through the forests (Eddy 1992). For Lignum communities, the other characteristic wetland type, most have disappeared, become fragmented or are in poor health. Extensive Lignum areas in the Nimmie-Caira stratum have been cleared (Cross *et al.* 1991) or fragmented (Fig. 10). The irrigation bays that replaced Lignum areas occasionally support *Eleocharis* species but are predominantly covered by cereal crops and some grasses in shallow areas (Maher 1990).

Lignum in the floodways (Fig. 5c) is predominantly in good health but this is unlikely to be sustainable with the increased flow regime. Lignum shrubs have died in the areas of the floodway, used as water storages (e.g. Eulimbah, Fig. 5c), and Cumbungi and Common Reed have established (Maher 1990, Eddy 1992, DWR 1994). The floodway system in the Nimmie-Caira stratum had about 3530 ha of Cumbungi and 36% of Eulimbah storage (Fig. 5c), with little Cumbungi in 1989, was covered by three metre high Cumbungi in April 1997 (DLWC 1997). Similarly Cumbungi colonised areas around Redbank Weir, on the north side of the Murrumbidgee River (Maher 1990). Stable water levels encourage colonisation by Cumbungi and Common Reed (Walker *et al.* 1994, Maheshwari *et al.* 1995). River regulation within the floodways has changed the composition of flood dependent vegetation in these areas from plants tolerant of less frequent flooding (e.g. Lignum, River Red Gum) to those equipped for perennial flooding (Maher 1990). All of the open water lakes (Piggery, Tala and Yanga) are used to store and regulate of water (Pressey *et al.* 1984) and so hold water more often than they did naturally. Most duck species do not breed on such wetlands where flows are highly controlled (Briggs *et al.*

1997). In the 1960s flocks of more than 10,000 birds, Eurasian coot, black swans blue-billed ducks and cormorants, used to occur on Yanga Lake (Hobbs 1961), but recent observations of waterbirds on Lakes Tala and Yanga, indicated that they were poor waterbird habitat (Pressey *et al.* 1984).

Flood dependent vegetation, Lignum and Black Box, on the periphery of the Lower Murrumbidgee floodplain, Fiddlers-Uara, Redbank and Murrumbidgee strata, was in generally poor health (Table 6). In the Fiddlers-Uara stratum, terrestrial plants interspersed flood dependent communities (Maher 1990) that now consisted primarily of long-lived Black Box that were in poor health. There were similar areas of Black Box, north of Redbank Weir, that were only reached by large natural floods (Maher 1990). Also there are Black Box and River Red Gum in areas of the Lower Murrumbidgee floodplain where no floods had occurred in the landholders' memories (Pressey *et al.* 1984). Presence of Black Box communities in some parts of the Lower Murrumbidgee floodplain probably reflected past flow regimes, with their present survival dependent on groundwater, rainfall or occasional large floods. On the Chowilla floodplain on the Murray River, Black Box died in areas that were not flooded for 35 years (Jolly *et al.* 1993). Ultimately Black Box will not survive because the flow regime to these parts of the floodplain has changed so much from when they were recruited. Long-lived floodplain vegetation may experience lag effects of water resource development over long periods (Kingsford 2000b). Aquatic vegetation also tends to decline in area when denied of floods (e.g. Gwydir wetlands, Keyte 1994).

River regulation, reduced flooding as a result of less water in the river or reduced connectivity to the floodplain has probably considerably affected the amount of carbon released from floodplains (Robertson *et al.* 1999). Aquatic invertebrates and plants have limits on the viability between floods (Boulton and Lloyd 1992, Brock 1999). Reductions in availability of floodplains may also reduce populations of native fish that breed in these habitats (Gehrke *et al.* 1995, Harris and Gehrke 1997). On these inland rivers increased regulation of rivers is linked to declining populations of native fish (Walker and Thoms 1993, Gehrke *et al.* 1995).

Over 17 years (1983-1999), waterbird abundance declined by more than 80% and numbers of species seen during aerial surveys probably declined on the Lower Murrumbidgee floodplain (Table 8, Fig. 11). Only one other reference site, Fivebough Swamp, registered a similar decline but the cause of decline on this wetland was not

clear. Other reference sites showed no significant changes (Fig. 11, Table 8). Habitat loss is a major cause of decline for many aquatic species of plants and animals (Allan and Flecker 1993). A 60% decline in the wetland area in the Nimmie-Caira stratum over 23 years (Table 6) was the main cause for the decline in waterbirds numbers on the Lower Murrumbidgee floodplain (Table 8). This was the area used by most waterbirds in the early 1980s, before water resource development. Maher (1990) assessed, using six sources of information, that the Lower Murrumbidgee floodplain was of national importance for nine species (large egrets, little egrets, intermediate egrets, glossy ibis, straw-necked ibis, little bittern, Australian bittern and freckled duck). For the six of these species for which data were available, there was evidence that numbers have declined, particularly after 1995 (Figs 14 and 16). Most other individual waterbird species also declined in numbers over the 18 year period (Figs 13-17).

Significant declines in all but herbivorous waterbirds ( $p=0.12$ ) showed that loss of wetland area affected all functional groups of waterbirds (Table 8, Fig. 12). Even herbivorous waterbirds exhibited evidence of decline, apart from large numbers in 1991 and 1992 (Fig. 12). Waterbird abundance and composition generally reflects abundance of potential food (Kingsford and Porter 1994). Abundance of other aquatic biota, invertebrates, fish, frogs and macrophytes, that were food for waterbirds, probably experienced similar declines in abundance and distribution because large areas of their wetland habitat were developed. This has occurred in the Barmah-Millewa Forest on the Murray River (Leslie 1995) and probably other floodplain wetlands (Kingsford 2000b). Native fish populations were already in decline in the Murrumbidgee River (Brown 1994). The replacement of wetland habitat by cropped areas did not convert to an equivalent loss of waterbird habitat. Waterbirds fed in cropped areas that were flooded (Maher 1990, Magrath 1992, DWR 1994), presumably on wasted grain and invertebrates. Irrigation bays were flooded for periods of up to six months (Maher 1990). Aerial survey data showed that there were large concentrations of waterbirds in some of these areas that offer important replacement habitat. Whether such areas will continue to provide feeding habitat in the long-term will depend on the water and land management practices adopted. Further efficiencies in use of water may mean less inundation of areas and reduced habitat for waterbirds. Increasing salinity could also be a problem as the groundwater table rises, reducing the period over which these areas offer habitat.

Loss of wetland area also affected breeding of waterbirds. There were three major breeding events recorded during aerial surveys, in 1986, 1990 and 2000, and some breeding also occurred in all but one year before 1990 but there was only one major breeding of waterbirds after 1990 and this was less than previous large breeding events (Fig. 18). Much of the channelisation and building of levees on the Lower Murrumbidgee floodplain and its subsequent effects resulted after 1990 (Table 3, Figs 5 and 8). Key habitat areas, the rookeries (Fig. 5c), isolated from the floodplain, failed to provide for the continuation of large scale breeding events for waterbirds that had occurred before the 1990s. Breeding waterbirds probably need to forage over large floodplain areas when breeding. Waterbirds in the Macquarie Marshes only bred when floods were of sufficient magnitude to produce extensive flooding (Kingsford and Johnson 1999). Generally, herons, egrets, spoonbills and ibis require extensive flooded areas for breeding (Butler 1994).

Little is known of the frequency or abundance of breeding colonies on the Lower Murrumbidgee floodplain before water resource development. There was evidence that the storing of water in the Nimmie-Caira stratum favoured the breeding of colonial waterbirds because most sites were established where water was artificially stored (Maher 1990, Magrath 1992, DWR 1994). Colonial waterbirds usually breed in areas where water is likely to remain for sufficient periods that ensure that eggs are laid and young hatched before nests are exposed. This occurs on unregulated river systems such as Cooper Creek and the Paroo River. As flows were only restored to parts of the Lower Murrumbidgee floodplain, the increased waterbird breeding may have only replaced natural frequencies and abundance of breeding. The challenges of managing artificial breeding sites were reflected in the abandonment of colonies by royal spoonbills, Australian white ibis and straw-necked ibis when water receded quickly from storages that had levees breached (Maher 1990). Storing of water in wetlands ultimately results in declines of breeding populations of most species (Briggs *et al.* 1994). There was independent evidence for such a trend on the Lower Murrumbidgee floodplain. The size of waterbird colonies in 1989, 1990 and 2000, from ground surveys, was less than in the previous ten years (Maher 1990, Magrath 1992). Estimates of 40,000 pairs of a range of species in 1981 on the Nimmie-Caira stratum (Lowe 1983) have not been reached in the subsequent 20 years (Fig. 18, Maher 1990). A colony near Redbank Weir in 1989/1990 was smaller than large colonies that occurred between 1940 and 1970 (Maher 1990). A colony further south

in the Redbank stratum, cormorant colonies on Tala Lake and mixed waterbird colonies on Uara Creek were all larger in the 1980s than during ground surveys of the colonies in 1989 and 1990 (Maher 1990). A few species bred in small numbers on developed areas but most did not (Maher 1990).

The Lower Murrumbidgee floodplain was among the highest ranked four or five and sometimes ten wetlands for waterbirds during aerial surveys of 10% of eastern Australia, 1983-1993 and 1995, but it failed in 1994, 1998 and 1999 (Braithwaite *et al.* 1985, 1986b, 1987, Kingsford *et al.* 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1997, 2000). Many of the waterbird species that qualified the Lower Murrumbidgee floodplain as an area of national, state and regional importance had declined in number (Figs 13-17). The rookeries that qualified as critical habitat areas for breeding waterbirds had a diminished function.

There is little opportunity for ecological restoration of the Nimmie-Caira or the Fiddlers-Uara creek strata but the Redbank stratum still holds some of the most important River Red Gum communities on the Murrumbidgee River (Eddy 1992). It is the area least affected by impacts of water resource development although changes have occurred. River Red Gum invaded open grassland and Lignum swamps between 1950 and 1983, where there was adequate flooding (Eddy 1992). It is not clear what successional changes resulted in the distribution of other vegetation throughout the Redbank stratum with changing water regimes. In the Barmah-Millewa Forest, a River Red Gum forest, reduced flooding affected growth and regeneration of vegetation (Bren *et al.* 1988, Bacon *et al.* 1993). River Red Gums have invaded areas that were more frequently flooded in the past (Bren 1992) while Black Box is replacing River Red Gum areas where there was insufficient flooding (Chesterfield 1986). The challenge for the management of the Redbank stratum will be to supply the area with sufficient water for long-term sustainability of the floodplain ecological communities. Recent further development with a major constructed channel to the area provides some opportunity to supply water to these areas but there will also be pressure to supply water to expanding irrigation areas to the west of the Paika Levee bank (Fig. 5a). The changes can be generalised (Table 9) and related to the different impacts on aquatic fauna and flora on the margins of the floodplain and the core. Such changes occur on many river systems whose floodplains have been affected reduced flows and floodplain development (Kingsford 2000).

The scale of ecological change, particularly on the Nimmie-Caira stratum, is similar or greater than other examples of where water resource development has affected wetlands around the world (Lemly *et al.* 2000). The Murrumbidgee River and its water resource represents one of the longer histories of water resource development of any river in Australia (Table 2).

Table 9. Generalised patterns of change on the Lower Murrumbidgee Floodplain for hydrological variables and biological variables in remaining wetland areas and developed areas.

Variable	Wetland areas		Developed areas
	Margins	Core	
River flows	Considerably reduced in volume and probably absent in a number of areas. Frequency also reduced	Reduced flows except for floodways where there is increased flows to supply developed areas	Changed in seasonality to supply cropping areas. Reduced flooding during crop growth but increased flooding during wetting phase
Extent of flooding	Considerably reduced in volume and probably absent in a number of areas. Frequency also reduced from natural.	Reduced flooding except for floodways where there is increased flows to supply developed areas. Frequency also reduced from natural levels.	Changed in seasonality to supply cropping areas. Reduced flooding during crop growth but increased flooding during wetting phase
Terrestrial vegetation	Increase in range and density	Mostly absent	Apart from crops, mostly absent
Aquatic vegetation dependent on flooding	Reduced health with poor canopy growth. Aquatic macrophytes unlikely to establish except during extreme events	Reduced health with poor canopy growth, apart from along the floodways. Aquatic macrophytes such as cumbungi well established on floodways in response to increased flows. Correspondingly lignum in poor health in floodways because of increased flooding	Some aquatic macrophytes remain in seed bank and germinate during flooding. Perennial aquatic vegetation (e.g. Lignum, Black Box) cleared.
Waterbirds	Reduced in numbers and diversity because of reduced habitat. Also long-term reduction in breeding expected.	Waterbirds still occur in reasonable numbers where there is flooding, utilising key habitat areas and floodways	Waterbirds found in large numbers on flooded irrigation bays but absent during dry periods.
Frogs <sup>a</sup>	Likely reduced in numbers and diversity because of reduced habitat. Also long-term reduction in breeding expected.	Likely to still occur in reasonable numbers where there is flooding, utilising key habitat areas and floodways	Frogs likely to be absent or in low numbers on flooded irrigation bays and absent during dry periods.
Aquatic invertebrates <sup>a</sup>	Likely reduced in numbers and diversity because of reduced habitat. Also long-term reduction in breeding expected.	Likely to still occur in reasonable numbers where there is flooding, utilising key habitat areas and floodways	Invertebrates likely to be present in large numbers on flooded irrigation bays and reduced in numbers during dry periods.
Fish <sup>a</sup>	Likely reduced in numbers and diversity because of reduced habitat. Also long-term reduction in breeding expected.	Likely to still occur in reasonable numbers where there is flooding, utilising key habitat areas and floodways	Fish likely to be in low numbers on flooded irrigation bays and absent during dry periods.

<sup>a</sup>No data exist for these groups and so assessments are based on changes to waterbird numbers.

### **Protected areas**

Waterbirds relied on much greater areas of wetland than those covered by such protected areas. The Lower Murrumbidgee floodplain illustrates a problem for protection of wetland areas under conservation legislation and policy. Conservation legislation is primarily designed to protect areas of significance as reserves (e.g. National Parks and Nature Reserves). Two examples from the Lower Murrumbidgee floodplain illustrate how this can fail. Yanga Nature Reserve lies in the Fiddlers-Uara stratum (Fig. 2c) and was primarily conserved for its Black Box woodland vegetation community. Similarly 23,800 ha of the Lower Murrumbidgee floodplain was protected in the Lower Murrumbidgee floodplain from clearing by legislation which it achieved (Cross *et al.* 1991). But the long-term prospects for flood dependent vegetation in both areas are probably poor because the flooding regime may not be sufficiently frequent to sustain the flood dependent vegetation that established in these areas. The areas were already in poor health with terrestrial vegetation becoming established. Legislation and policy measures usually protect actual sites of wetlands from development but do not control threatening processes upstream (Barendregt *et al.* 1995). To protect wetland areas, policies and legislation for wetland conservation need to be applied to flow regimes. This necessitates the interaction of policies applied to the floodplain with legislation that governs the management of water. Until there is protection of the flow regimes that define wetlands and their biota, their long-term future, even if they have reserve status, cannot be guaranteed.

### **Conclusions**

The case of the Lower Murrumbidgee floodplain demonstrated impacts of water resource development operating at a catchment scale and local scale. These issues are germane to all water resource developments in Australia and around the world. The development route taken for the Lower Murrumbidgee floodplain is one that has been repeated on many rivers around the world (Lemly *et al.* 2000). Such knowledge needs to be applied to further debates about water resources on rivers yet to be exploited (Kingsford 2000a). The drivers of water resource development need to be addressed and there should be an understanding of the ecological consequences to develop water resources.

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## Appendix 1

Characteristics of image data acquired from different Landsat satellites and sensors (Richards 1993, Avery and Berlin 1992, Lillesand and Keifer 1994).

Sensor <sup>a</sup>	Date	Ground Sampling Interval	Bands Used	Geometric Rectification RMSE <sup>b</sup>
MSS	11 Sep 1975	56 x 79 m	4,5,6,7	± 0.141
MSS	29 Oct 1976	56 x 79 m	4,5,6,7	± 0.224
MSS	08 Sep 1979	56 x 79 m	4,5,6,7	± 0.500
MSS	30 Oct 1981	56 x 79 m	4,5,6,7	± 0.283
MSS	07 Oct 1982	56 x 79 m	4,5,6,7	± 0.283
MSS	13 Oct 1983	57 x 82 m	1,2,3,4	± 0.224
MSS	07 Oct 1984	57 x 82 m	1,2,3,4	± 0.283
MSS	26 Oct 1985	57 x 82 m	1,2,3,4	± 0.283
MSS	29 Oct 1986	57 x 82 m	1,2,3,4	± 0.224
MSS	17 Nov 1987	57 x 82 m	1,2,3,4	± 0.224
MSS	15 Aug 1988	57 x 82 m	1,2,3,4	± 0.316
MSS	17 Jul 1989	57 x 82 m	1,2,3,4	± 0.224
MSS	24 Oct 1990	57 x 82 m	1,2,3,4	± 0.141
MSS	11 Oct 1991	57 x 82 m	1,2,3,4	± 0.283
MSS	30 Nov 1992	57 x 82 m	1,2,3,4	± 0.224
MSS	16 Oct 1993	57 x 82 m	1,2,3,4	± 0.283
TM	16 Oct 1993	30 x 30 m	2,3,4	± 0.424
MSS	01 Sep 1994	57 x 82 m	1,2,3,4	± 0.224
MSS	07 Nov 1995	57 x 82 m	1,2,3 <sup>c</sup>	± 0.224
MSS	25 Nov 1996	57 x 82 m	1,2,3 <sup>c</sup>	± 0.224
TM	27 Oct 1997	30 x 30 m	2,3,4	± 0.640
TM	14 Oct 1998	30 x 30 m	2,3,4	± 0.894
TM	27 Aug 1998	30 x 30 m	2,3,4	± 0.424

<sup>a</sup>Landsat Satellite 2 for 1975-1979; Landsat satellite 5 for 1981-1998. MSS (Multispectral Scanner), TM (Thematic Mapper).

<sup>b</sup>RMSE based on a 50m x 50m pixel for MSS and a 25m x 25m pixel for TM.

<sup>c</sup>Band 4 not operational

## Appendix 2

Error matrix and accuracy totals showing classification accuracy, based on comparison of remotely sensed data from Landsat MSS or TM imagery (classified data) and classification from a helicopter survey (reference data) of 147 points on the floodplain.

Table A21. Error matrix for classification

Classified Data	Reference Data			Classified Totals
	Developed	Non-wetland	Wetland	
Developed	37	3	10	50
Non-wetland	3	13	15	31
Wetland	4	2	60	66
Reference Total	44	18	85	147

Table A22. Accuracy totals for classification. Overall classification accuracy was 74.83% and overall Kappa statistic was 0.59.

Class	Reference Totals	Classified Totals	Number Correct	Producers Accuracy (%)	Users Accuracy (%)	Conditional Kappa
Developed	44	50	37	84.09	74.00	0.6289
Non-wetland	18	31	13	72.22	41.94	0.3383
Wetland	85	66	60	70.59	90.91	0.79
Totals	147	147	110			

### Appendix 3

Waterbird species and their breeding status (B) recorded on the Lower Murrumbidgee floodplain (source primarily Maher (1990) and aerial surveys). Letters after specific names signify whether birds seen during aerial surveys were categorised as piscivores (P), large wading birds (W), herbivorous waterbirds (H), ducks and small grebe species (D) and small wading birds (S).

Waterbirds	Specific name
Great-crested grebe(B)	<i>Podiceps cristatus</i> (P)
<sup>b</sup> Little grebes	(D)
Hoary-headed grebe(B)	<i>Poliiocephalus poliocephalus</i>
Australasian grebe(B)	<i>Tachybaptus novaehollandiae</i>
Australian pelican(B)	<i>Pelecanus conspicillatus</i> (P)
Darter(B)	<i>Anhinga melanogaster</i> (P)
Great cormorant(B)	<i>Phalacrocorax carbo</i> (P)
Pied cormorant	<i>Phalacrocorax varius</i> (P)
Little black cormorant(B)	<i>Phalacrocorax sulcirostris</i> (P)
Little pied cormorant(B)	<i>Phalacrocorax melanoleucos</i> (P)
Pacific heron(B)	<i>Ardea pacifica</i> (W)
White-faced heron(B)	<i>Ardea novaehollandiae</i> (W)
Great egret(B)	<i>Ardea alba</i> (W)
<sup>b</sup> Egrets*	(W)
Intermediate egret(B)	<i>Ardea intermedia</i>
Little egret(B)	<i>Ardea garzetta</i>
Cattle egret(B)	<i>Ardea ibis</i>
Rufous night heron(B)	<i>Nycticorax caledonicus</i> (W)
Little bittern <sup>a</sup>	<i>Ixobrychus minutus</i>
Australasian bittern <sup>a</sup>	<i>Botaurus poiciloptilus</i>
Glossy ibis(B)	<i>Plegadis falcinellus</i> (W)
Australian white ibis(B)	<i>Threskiornis aethiopica</i> (W)
Straw-necked ibis(B)	<i>Threskiornis spinicollis</i> (W)
Royal spoonbill(B)	<i>Platalea regia</i> (W)
Yellow-billed spoonbill(B)	<i>Platalea flavipes</i> (W)
Plumed whistling-duck	<i>Dendrocygna eytoni</i> (H)
Black swan(B)	<i>Cygnus atratus</i> (H)

<sup>a</sup>Waterbirds not seen during aerial surveys

<sup>b</sup>Species that could not be separated during aerial surveys

<sup>c</sup>A group of species classified as large waders that were not discriminated during aerial surveys. Only black-tailed godwits were seen during ground surveys.

Waterbirds	Specific name
Freckled duck(B)	<i>Stictonetta naevosa</i> (D)
Australian shelduck(B)	<i>Tadorna tadornoides</i> (H)
Pacific black duck(B)	<i>Anas superciliosa</i> (D)
Grey teal(B)	<i>Anas gracilis</i> (D)
Chestnut teal(B)	<i>Anas castanea</i> (D)
Australasian shoveler(B)	<i>Anas rhynchotis</i> (D)
Pink-eared duck(B)	<i>Malacorhynchus membranaceus</i> (D)
Hardhead(B)	<i>Aythya australis</i> (D)
Australian wood duck(B)	<i>Chenonetta jubata</i> (H)
Blue-billed duck(B)	<i>Oxyura australis</i> (D)
Musk duck(B)	<i>Biziura lobata</i> (D)
Buff-banded rail <sup>a</sup> (B)	<i>Rallus philippensis</i>
Baillon's crake <sup>a</sup>	<i>Porzana pusilla</i>
Australian crake <sup>a</sup>	<i>Porzana fluminea</i>
Spotless crake <sup>a</sup>	<i>Porzana tabuensis</i>
Black-tailed native-hen(B)	<i>Gallinula ventralis</i> (H)
Dusky moorhen(B)	<i>Gallinula tenebrosa</i> (H)
Purple swamphen(B)	<i>Porphyrio porphyrio</i> (H)
Eurasian coot(B)	<i>Fulica atra</i> (H)
Painted snipe <sup>a</sup>	<i>Rostratula benghalensis</i>
Masked lapwing	<i>Vanellus miles</i> (S)
Banded lapwing	<i>Vanellus tricolor</i> (S)
Black-winged stilt(B)	<i>Himantopus himantopus</i> (S)
Banded stilt	<i>Cladorhynchus leucocephalus</i> (S)
Red-necked avocet	<i>Recurvirostris novaehollandiae</i> (S)
<sup>b</sup> Small waders	(S)
Red-kneed dotterel	<i>Erthrogonyx cintus</i>
Black-fronted plover	<i>Charadrius melanops</i>
Sharp-tailed sandpiper	<i>Calidris acuminata</i>
Greenshank	<i>Tringa nebularia</i>
Marsh sandpiper	<i>Tringa stagnatilis</i>
Latham's snipe	<i>Gallinago hardwickii</i>

<sup>a</sup>Waterbirds not seen during aerial surveys

<sup>b</sup>Species that could not be separated during aerial surveys

<sup>c</sup>A group of species classified as large waders that were not discriminated during aerial surveys. Only black-tailed godwits were seen during ground surveys.

Waterbirds	Specific name
<sup>b</sup> Large waders	(S)
Black-tailed godwit	<i>Limosa limosa</i>
Silver gull(B)	<i>Larus novaehollandiae</i> (P)
Whiskered tern(B)	<i>Sterna hybrida</i> (P)
Gull-billed tern(B)	<i>Sterna nilotica</i> (P)
Caspian tern	<i>Hydroprogne caspia</i> (P)

<sup>a</sup>Waterbirds not seen during aerial surveys

<sup>b</sup>Species that could not be separated during aerial surveys

<sup>c</sup>A group of species classified as large waders that were not discriminated during aerial surveys. Only black-tailed godwits were seen during ground surveys.