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Review

Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia

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Abstract Australian floodplain wetlands are sites of high biodiversity that depend on flows from rivers. Dams, diversions and river management have reduced flooding to these wetlands, altering their ecology, and causing the death or poor health of aquatic biota. Four floodplain wetlands (Barmah-Millewa Forest and Moira Marshes, Chowilla floodplain, Macquarie Marshes, Gwydir wetlands) illustrate these effects with successional changes in aquatic vegetation, reduced vegetation health, declining numbers of water-birds and nesting, and declining native fish and invertebrate populations. These effects are likely to be widespread as Australia has at least 446 large dams (>10 m crest height) storing 8.8×10^7 ML (10^6 L) of water, much of which is diverted upstream of floodplain wetlands. More than 50% of floodplain wetlands on developed rivers may no longer flood. Of all of the river basins in Australia, the Murray-Darling Basin is most affected with dams which can store 103% of annual runoff and 87% of divertible water extracted (1983–84 data). Some floodplain wetlands are now permanent storages. This has changed their biota from one tolerant of a variable flooding regime, to one that withstands permanent flooding. Plans exist to build dams to divert water from many rivers, mainly for irrigation. These plans seldom adequately model subsequent ecological and hydrological impacts to floodplain wetlands. To avoid further loss of wetlands, an improved understanding of the interaction between river flows and floodplain ecology, and investigations into ecological impacts of management practices, is essential.

Key words: Barmah-Millewa Forest, Chowilla, Gwydir, irrigation, Macquarie Marshes, Murray-Darling Basin, pumping, regulation, storage.

INTRODUCTION

Wetlands have disappeared or declined in many areas around the world (Hollis 1990, 1992; Hollis & Jones 1991; Jones *et al.* 1995; Sparks 1995; Wilen & Bates 1995; Foote *et al.* 1996), and water resource development is a major cause (Allan & Flecker 1993; Dynesius & Nilsson 1994; Ligon *et al.* 1995; Thomas 1996; Milliman 1997; Lemly *et al.*, 2000). Dams on many of the world's large rivers divert water, produce hydroelectricity, assist navigation and control floods (Walker 1985; Dynesius & Nilsson 1994; Power *et al.* 1995). Such changes have affected estuarine and coastal ecology (Milliman 1997), and reduced the amount of water reaching floodplain wetlands, affecting their ecology. The most notorious example, ecologically, is the Aral Sea, the floodplain terminus of the Amu-Darya and Syr-Darya Rivers in Uzebekistan and Kazakhstan. Over a 27-year period from 1960 to 1987, diversion of water for irrigation upstream caused water levels in this huge inland sea (68 000 km^2) to drop by 13 m, decreasing the wetland area by 40%, and having a severe impact on biodiversity (Micklin 1988). Water resource development, primarily driven by irrigated agriculture (Kingsford 1995a; Wasson *et al.* 1996), is also affecting floodplain wetlands in Australia (Lemly *et al.* 2000).

Reviews of literature regarding river ecology and impacts of water resource development on biota in Australia have generally focused on within-channel processes of rivers (Walker 1985; Lake & Marchant 1990; Barmuta *et al.* 1992; Bren 1993; Lake 1995), not on floodplain wetlands, which are perhaps most affected by water resource development. Australian floodplain wetlands are sites of extraordinary biological diversity with abundant and diverse populations of waterbirds (Morton *et al.* 1990a, b; Kingsford 1995b; Halse *et al.* 1998), native fish (Ruello 1976; Puckridge 1999), invertebrate species (Outridge 1987; Crome & Carpenter 1988; Shiel 1990; Boulton & Lloyd 1991), aquatic plants (Pressey 1990; Roberts & Ludwig 1991) and microbes (Boon *et al.* 1996).

This review begins with the natural behaviour of Australian rivers and their floodplains, and then

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examines how dams, diversions and river management have affected floodplain wetlands, focusing on four floodplain wetlands. The wide distribution and abundance of large dams and diversions provide a basis to record the extent of such ecological impacts in Australia, and to assess potential for future impact. Finally, I examine why interaction between water resource management and floodplain wetland management remains poor and how it may be improved.

RIVERS AND THEIR FLOODPLAIN WETLANDS

Naturally flowing floodplain rivers are among the more dynamic ecosystems on earth (Power *et al.* 1995), with enormous spatial and temporal complexity. River flows determine the distribution patterns of channels, backswamps, marshes and tributaries that make up the floodplain (Ward 1998). These floodplain wetlands also include freshwater and saline lakes, anabranches, billabongs, lagoons, overflows, swamps and waterholes in Australia. The flow regime of a river, and its connections to floodplain wetlands, govern biotic responses, channel formation and sediment transfer (Junk *et al.* 1989; Walker *et al.* 1995).

When Australian floodplain wetlands receive water from rivers, the flow carries organic matter (Outridge 1988). Other accumulated organic matter within the wetland may consist of eucalypt leaf litter (Briggs & Maher 1983; Boulton 1991), aquatic macrophytes from the last filling (Briggs *et al.* 1985), or terrestrial plants that colonise wetlands when they dry. Arrival of water in a floodplain wetland sets off dynamic ecological processes and interactions among a wide range of species. Methanotrophic bacteria and algae may drive complex food webs (Bunn & Boon 1993; Bunn & Davies 1999). Organic matter provides food for microbes (Outridge 1988; Boon *et al.* 1996), zooplankton shredders and scrapers (Lake 1995). Zooplankton emerge from newly flooded ‘seed banks’ of eggs and drought-resistant forms (Boulton & Lloyd 1992), and graze on microbes (Boon & Shiel 1990) and plants. Sedentary biota such as aquatic macrophytes also germinate from ‘seed banks’ (Britton & Brock 1994). Floodplain eucalypts use floodwater (Jolly & Walker 1996). Understorey aquatic plants, such as lignum *Muehlenbeckia florulenta*, grow (Craig *et al.* 1991). Burrowing frogs, buried in a water-filled sac after the last flood (Lee & Mercer 1967), emerge to feed and reproduce. Colonisers, such as fish larvae from the river, arrive (Geddes & Puckridge 1989; Gehrke *et al.* 1995), although initial high levels of tannins and low oxygen may limit habitat suitability (Gehrke *et al.* 1993). Abundant insects with rapid generation times also follow the flood sequence (Maher & Carpenter 1984; Maher 1984), sometimes months after flooding (Crome & Carpenter 1988). Aquatic macrophytes, invertebrates, frogs and fish provide food for water-birds (Kingsford & Porter 1994), which colonise the wetland from more permanent wetlands nearby (Kingsford 1996), and breed later (Crome 1986; Lawler & Briggs 1991). A variety of reptiles and the water rat *Hydromys chrysogaster* live in floodplain wetlands but knowledge of their ecology remains relatively poor. Flowering eucalypts, frogs, fish and water-birds may also attract terrestrial bird species such as honeyeaters and birds of prey (Kingsford & Porter 1999). When floodplains dry, they may also provide habitat for terrestrial animals (Briggs 1992).

The key drivers for these processes and subsequent high biodiversity are the lateral connectivity to the river of the floodplain wetland, and the unpredictable flows that are not well served by current models of river behaviour (Walker *et al.* 1995). The River Continuum Concept (Vannote *et al.* 1980) and the Riverine Productivity Model (Thorp & Delong 1994) adopt a riverine focus with little emphasis on floodplain wetlands. Even the Serial Discontinuity Concept, modelling impacts of dams, largely ignored floodplains initially (Ward & Stanford 1995). The Flood Pulse Concept (Junk *et al.* 1989) rightly established floods and lateral connections to the river as the drivers of ecological processes in many Australian rivers. However, predictability was considered important for biotic adaptations – a hypothesis that is increasingly questioned (Power *et al.* 1995; Walker *et al.* 1995). Unpredictable flows, a feature of Australian dryland rivers (Puckridge *et al.* 1998), create wide ranges of temporally and spatially different aquatic ecosystems for organisms (Power *et al.* 1995; Ward 1998). High abundance and diversity of biota occur after flooding on floodplain wetlands of rivers in arid Australia (Walker *et al.* 1997; Kingsford *et al.* 1998; Kingsford *et al.* 1999).

CHANGING FLOWS TO FLOODPLAIN WETLANDS

Alienation of floodplain wetlands

The primary objective of river management and the delivery of water for human purposes, may be the antithesis of the provision of water to floodplain wetlands. This objective was to provide ‘. . . maximum supplies with minimum waste’ (Water Conservation and Irrigation Commission 1971; p. 64), meaning that the Murray-Darling Basin Commission must maximise the conservation of water (i.e. reduce losses) under the Murray-Darling Basin Agreement (Wettin *et al.* 1994). ‘Wasted’ water flows to either floodplain wetlands, aquifers or the sea. Even the language of river management extends this notion of waste. River catchments are 'drainage' divisions or basins (Australian Water Resources Council 1975), rivers supply 'effluent', creeks and floods are 'surplus flows' (Wettin *et al.* 1994), and high water losses occur in floodplain wetlands (e.g. Macquarie Marshes, see Water Conservation and Irrigation Commission 1971; p.61). However, effluent creeks, surplus flows and 'lost' water are the primary source of water for floodplain wetlands.

Temporary or permanent cut-off of the water supply to floodplain wetlands can be achieved by filling dams, diverting flows upstream, or river management on the river or floodplain (Table 1). Dams deny floodplain wetlands of flows as they fill. Burrendong Dam on the Macquarie River first filled after it was built in 1967 (Kingsford & Thomas 1995) and again in 1998, when it was 5% full, and most of these flows did not reach the Macquarie Marshes. Dams can eliminate flows to floodplains by capturing the flood pulse and then releasing this water for diversion, within the main river channel. Ecological attention has generally focused more on the regulatory effects of dams, not on the impacts of diversions. A cumulative synergy between dam building (including building of weirs and off-river storages) and diversion increasingly alienates floodplain wetlands by reducing the frequency and volume of flows to them. The initial impact of the Hume Dam on average annual flows in the Murray River was only 2% but, within 23 years, this had increased to 21% (Maheshwari *et al.* 1995), despite increased flows diverted from eastward-flowing rivers (Bevitt *et al.* 1998). Dams and diversions also affect the flow regime (Walker 1985), shifting flooding from a spring to summer pattern on southern rivers (Maheshwari *et al.* 1995) and affecting temperature (Walker 1985), channel stability (Thoms & Walker 1993; Walker & Thoms 1993) and salinity (Walker & Thoms 1993). Storage releases, weir operations, rainfall rejection releases and timing of pumping also affect natural flow variability.

After rainfall, dams and diversions of water upstream govern how much water reaches floodplain wetlands. Flows controlled by government-built dams or weirs and other river management structures (Table 1) are called 'regulated', while uncontrolled flows from tributaries, often downstream of dams, or overflows from dams are 'unregulated' (see Appendix, Table A1, for definitions). Most diversions are from regulated supplies, proportionally allocated each year from water held in dams and weirs but pumps on a river also divert 'unregulated' flows into off-river storages or ring tanks (up to 80 000 ML) (Table 1; Appendix 1, Table A1).

River management also alienates floodplain wetlands. Structures such as weirs, levees and block banks (Table 1) either stop or reduce flows to the floodplain through effluent channels or distributaries (Water Conservation and Irrigation Commission 1971; Kingsford, 1999c). Channels, levees and drains across the floodplain can divert water to storages, denying downstream floodplains of water. Also, water delivered at bank-full capacity (Thoms & Walker 1993) or with low flows erodes river channels, reducing overbank flows to floodplain wetlands.

Dams and weirs affect riverine fauna and flora (Bell *et al.* 1980; Harris 1984; Walker 1985; Chessman *et al.* 1987; Doeg *et al.* 1987; Marchant 1989; Walker & Thoms 1993) but ecological impacts on floodplain wetlands are poorly understood. Loss of connectivity to the river changes aquatic systems to terrestrial ecosystems. Aquatic plants, sedentary animals (burrowing frogs; aquatic invertebrates) and microbes adapted to unpredictable flood events eventually die, and are replaced by terrestrial vegetation. For long-lived floodplain species (e.g. eucalypts), this may not occur for 20 or more years. Seed banks of aquatic plants and invertebrate eggs have limited viability (Boulton & Lloyd 1992; Brock 1999). Habitat loss may have widespread impacts for native fish and water-birds. Regulation reduces the availability of floodplain habitat for young fish, which leads to declining fish populations (Geddes & Puckridge 1989; Gehrke *et al.* 1995, 1999; Harris & Gehrke 1997). Colonial water-birds (e.g. ibis, egrets and herons) breed on only a few large floodplain wetlands in Australia (Marchant & Higgins 1990), so reduced flooding may have an impact (Kingsford & Johnson 1999) on continental populations. Changes in the timing of flooding may also have long-term impacts. We know little of the lagged effects of reduced flooding on populations' capacities to respond to flooding (Boulton & Lloyd 1992; Walker *et al.* 1995). Rare large floods may maintain population abundance across landscapes for decades (Kingsford *et al.* 1999). Effects on food webs and other ecological processes are poorly known, but may be severe (Power *et al.* 1996).

Increased flows

Dams have submerged some wetlands, such as Lake St Clair, Great Lake, Lake Pedder and Lagoon of Islands, in Tasmania (Tyler 1976; Kirkpatrick & Tyler 1988), and turned other floodplain wetlands (e.g. Menindee Lakes on the Darling River, Lakes Brewster and Cargelligo on the Lachlan River, and Lake Victoria on the Murray River) into off-river storages with dam walls, regulators and channels (Table 1). Weirs and locks have the same impact although at a smaller scale (Walker & Thoms 1993). Increased low flows (Kingsford & Thomas 1995; Maheshwari *et al.* 1995) have meant some floodplain wetlands seldom dry out (e.g. 35% of wetlands along the Murray River; Pressey 1990).

Substitution of a variable-flooding pattern with a permanent one, and loss of wet-dry cycles, has lasting ecological effects. Seven species of macroinvertebrates

Table 1. The variety of structures and processes that affect river flows in Australia

River management structures	Description	Purpose[a]	Location	Time period
Block banks	Earth levees used to control water and stop flooding	Increased efficiency of water flow for irrigation	Main river	Early 1900s
Channels	Channels that transfer water to irrigation areas or storages, bypass natural floodplains or capture water flowing across floodplains	(i) Transfer of water to irrigation users (ii) Increased efficiency of water flow for irrigation (iii) Capture of floodplain flows	Established irrigation areas	
Cutting	Excavation to convey water through high ground or between bends in rivers	More efficient transfer of water		
Dredging/Desnagging	Estuaries and major inland rivers dredged to allow navigation of large vessels. Trees, aquatic macrophytes and rocks removed from rivers	(i) Navigation (ii) Increased efficiency of water flow for irrigation	Most estuaries and rivers with large dams	1800s–present
Farm dam	Small dams (usually < 1 ha)	(i) Water supply for livestock (ii) Water supply for human consumption (iii) Recreation	Rural areas	
Groyne	A bank or other structure built out into a channel or other water body	Modification of current flow and sediment deposition or erosion patterns	Main rivers	
Levees	(i) Earthen banks across floodplains (ii) Roads and railways can have similar effects	(i) Redirection of water flows to increase flooding or to harvest water to off-river storages (ii) Protection of towns, crops and homesteads		
Locks	Enclosed part of a river, with gates, for moving boats or barges	Navigation	Murray River	1850–1950
Pumps	Pump water from creeks or rivers to irrigation areas or off-river storages	(i) Industry (ii) Irrigation (iii) Mining (iv) Public water supply (v) Hydroelectricity		

Table 1. continued

River management structures	Description	Purpose[a]	Location	Time period
Off-river storages (on-farm storages or ring tanks)	Public or private water storages built away from river channels. They may have earthen walls (private) or be based on billabongs or temporary lakes that are modified with block banks or walls to contain water ((v)g. Lake Brewster, and Cargelligo and Menindee Lakes). Water is either channelled (major public off-river storages), or pumped into them.	(i) Store water for later use for irrigation (ii) Mining	see Table 2	1980s–present
Reservoirs or dams (Government built)	Concrete wall built across river or creek, resulting in a large storage of water upstream	(i) Ponding of water diverted for irrigation, human and livestock consumption, industry, cooling coal-fired power stations and mining (ii) Generation of electricity (hydroelectricity) (iii) Recreation	On nearly all major rivers	1900s–present
River transfers	Water pumped from one catchment to another	Augmentation of water resources in a catchment		
Siphon	A pipe which conveys water from a higher level to a lower level over an obstacle using atmospheric pressure only	Transfer of water between irrigation channels under natural channels		
Weirs	Barriers built across rivers (concrete). Smaller than dams but effectively act as small dams.	(i) Ponding of water enabling upstream extraction or diversion (ii) Recreation – sailing, water skiing, swimming (iii) Increased efficiency of water flows for irrigation by restricting flows down effluent creeks (iv) Control of further releases downstream	Throughout Australia	1850s–present
Wetland storages	Natural wetlands used to hold water permanently	(i) Public water supply (ii) Irrigation	Primarily restricted to the Murray-Darling Basin	1930s–1980s

[a] Structures can serve more than one purpose.

disappeared when Lake Pedder was flooded (McComb & Lake 1990; p. 139). Invertebrate communities become dominated by species adapted to lakes and standing water (Shiel 1990; Bennison *et al.* 1991) and may be less diverse or abundant than those in temporary billabongs (Boulton & Lloyd 1991). Unique 'islands' of floating vegetation supporting successional stages of aquatic and terrestrial vegetation have almost gone from the Lagoon of Islands (Tyler 1976). Floodplain eucalypts and lignum *Muehlenbeckia florulenta* die with prolonged flooding (Smith & Smith 1990; Walker & Thoms 1993; Thornton & Briggs 1994). Dead floodplain eucalypts around the edge of Menindee Lake on the Darling River mark remains of aquatic vegetation that covered the lake, probably changing a diverse water-bird community to one dominated by piscivores (Kingsford 1995a). Following permanent inundation of Tom Bullen Lake on the Murrumbidgee River, the abundance of 14 water-bird species declined, compared with only two species increased abundance. Egrets stopped breeding (Briggs *et al.* 1994). Loss of productivity from disturbance of wet-dry cycles may affect breeding and habitat use of water-birds. Prolonged flooding also reduces growth and survival of aquatic macrophytes (Brock & Casanova 1991). When Lake Mokoan on the Broken River was converted to an off-river storage, high turbidity destroyed submerged wetland vegetation (Casanova 1999). Where water levels are reasonably stable, cumbungi *Typha* spp. (Walker *et al.* 1994; Kingsford 1995a) and introduced water hyacinth *Eichornia crassipes* can become established (Pressey & Middleton 1982; McCosker R. O. & Duggin J. A. (1992; Gingham watercourse resource management issues, Gwydir River Basin, Moree NSW. Unpublished Report, Department of Ecosystem Management, University of New England, Armidale). Regulation of flows may also favour exotic fish species such as European carp *Cyprinus carpio* (Gehrke *et al.* 1995, 1999).

CASE STUDIES

For four floodplain wetlands in the Murray-Darling Basin, sufficient data exist showing the ecological impacts of dams, diversions and river management on floodplain wetlands and some of the associated biota.

Barmah-Millewa Forest and the Moira Marshes

The Barmah-Millewa Forest on the upper Murray River (Fig. 1) covers about 65 000 ha and is the largest river red gum *Eucalyptus camaldulensis* forest in Australia. Part of it is listed as a wetland of international importance under the Ramsar Convention (Australian Nature Conservation Agency 1996). Moira Marshes (25 000 ha) is a series of lakes that adjoin the southern part of the Barmah-Millewa Forest (Leslie 1995). Floods determine vegetation patterns, with rushes and sedges (*Juncus* spp., *Eleocharis acutus*) growing in the most frequently flooded areas, moira grass (*Pseudoraphis spinescens*) plains and red gums growing in the less frequently flooded areas, and black box *Eucalyptus largiflorens* communities existing in the least frequently flooded areas (Bren & Gibbs 1986; Chesterfield 1986; Bren *et al.* 1988; Bren 1992).

High evaporation rates and low annual rainfall (400 mm) mean that the floodplain wetland is dependent on river flows (Bren 1992) coming from the upper

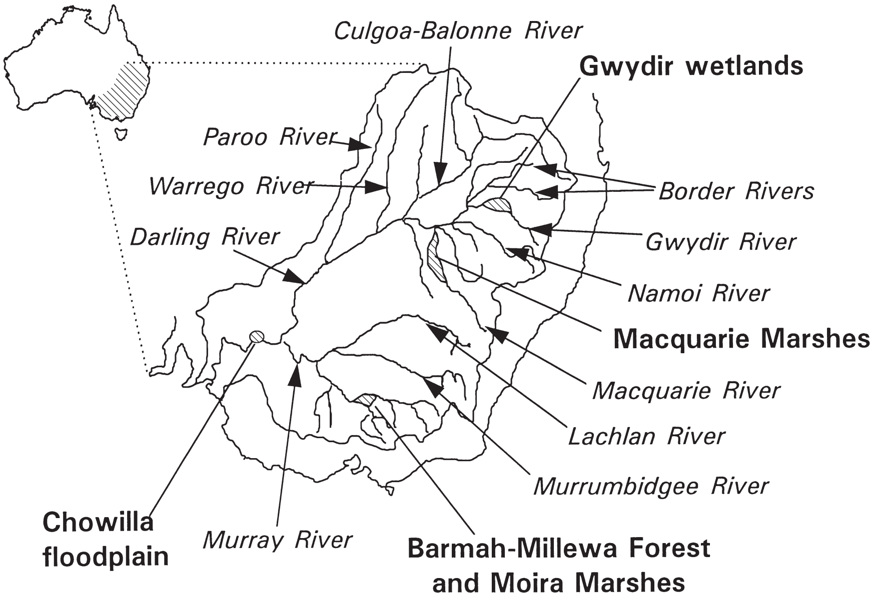

Fig. 1. Locations of the major rivers in the Murray-Darling Basin and four floodplain wetlands (shown in bold) used as case studies.

catchment of the Murray River. Hume (3 038 000 ML) and Dartmouth Dams (3 906 000 ML) regulate flows, permitting annual average diversion of 1 648 000 ML (1988/89–1992/93) (Murray-Darling Basin Ministerial Council 1995; Department of Land and Water Conservation, unpubl. data), mostly (98%) for irrigation (Murray-Darling Basin Ministerial Council 1995). This has more than halved natural average annual flows at Yarrawonga, about 100 km upstream of the Barmah-Millewa Forest (Maheshwari *et al.* 1995), and shifted the pattern of flows from spring to summer (Bren *et al.* 1987; Close 1990; Maheshwari *et al.* 1995).

Areas with high flood frequency are most affected (Bren 1988). The percentage of years that the Barmah-Millewa Forest used to flood has declined from 80% to 35% (Close 1990). Flows that water key parts of the forest of 550 000 ML month^{-1} and 912 000 ML month^{-1} have declined by 48% and 62%, respectively (Murray-Darling Basin Ministerial Council 1995). In the period 1895–1929, there were only two years of no flooding compared with 13 in the period 1935–84 (Bren *et al.* 1987). Levees on the riverbank, block banks and regulators, alienate the floodplain and increase the efficiency of the river in the transmission of water downstream through the naturally constrictive Barmah and Millewa Chokes. Before dams and diversions, these chokes forced moderate to high flows into the wetland (Bren 1990).

Reduced flooding has changed the composition, growth and regeneration of the vegetation community (Bren *et al.* 1988; Bren 1991). Plants such as the common reed *Phragmites australis*, cumbungi and moira grass, which depend on frequent flooding, have declined in abundance (Chesterfield 1986), and red gums are replacing the moira grass plains (Bren 1992). Black box, tolerant of longer periods without floods, is replacing red gums on the margins (Chesterfield 1986). For the trees, reduced growth, crown condition and regeneration and increased mortality and susceptibility to insect attack have accompanied these changes (Bacon *et al.* 1993; Stone & Bacon 1994). Such changes may affect the threatened superb parrot *Polytelis swainsonnii*, which breeds in large, healthy and mature red gums (Webster 1988).

Populations of fish, water-birds, snakes and leeches have declined (Leslie 1995). Murray cod *Maccullochella peeli*, rarely caught in the river, no longer live in Moira Lake and only 106 native fish were captured during intense sampling (Gehrke *et al.* 1995) in an area that supported a major commercial native fishing industry for 45 years, 1855–1900 (Leslie 1995). Brolgas *Grus rubicundus* are locally extinct and glossy ibis *Plegadis falcinellus*, little egrets *Ardea garzetta* and whiskered terns *Chlidonias hybrida* regularly bred in the forest before the 1970s, but no longer do so (Leslie 1995). Cormorants *Phalacrocorax* sp., great egrets *Ardea alba*, intermediate egrets *Ardea intermedia* and rufous night herons *Nycticorax caledonicus* still breed but in declining numbers (Leslie 1995). Snakes, rarely seen in the Moira Marshes today, were killed in numbers of 50 per day in the 1860s and leeches (*Hirudo* spp.), gathered in the 1930s for Victorian hospitals (per 25 000–60 000 per year), were seldom seen after the 1970s (Leslie 1995).

Low flows have increased to a small central part of the Barmah-Millewa Forest (Bren 1993; Maheshwari *et al.* 1995) that is permanently connected to the river or filled during regulated flows during summer (Pressey 1990). Here red gums have died (Bren 1992) and *Myriophyllum propinquum* has replaced moira grass (Bren 1992).

Chowilla floodplain

The Chowilla floodplain (17 700 ha) has lakes, billabongs, islands and more than 100 km of anabranch creeks (Sharley & Huggan 1995; p. 81), 5–10 km either side of the lower Murray River, downstream of its junction with the Darling River (Fig. 1). It is the largest floodplain forest on the lower Murray River and encompasses aquatic vegetation communities (Roberts & Ludwig 1991). Chowilla is listed as a wetland of international importance under the Ramsar Convention (Taylor *et al.* 1996).

Average rainfall is low (250 mm year^{-1}) so the floodplain depends on upstream flows from the Murray and Darling Rivers, which naturally averaged 13 400 000 ML year^{-1}, with variability and absence of seasonality driven by inflows from the Darling River (Maheshwari *et al.* 1995). Dams and river management permitted an average of 9 801 000 ML to be diverted each year (1988/89–1992/93) upstream, mostly (about 97%) for irrigation (Murray-Darling Basin Ministerial Council 1995). Some of this water would have supplied floodplain wetlands and aquifers upstream, but now median natural flows to the Chowilla floodplain are half of natural flows (Maheshwari *et al.* 1995; Murray-Darling Basin Ministerial Council 1995). Within the wetland, nine embankments stop water flowing down anabranch creeks to the floodplain, maintaining high water levels in Lock 6 (Sharley & Huggan 1995; p. 87). As well, channel cross-sectional area is enlarged in many sites, reducing the potential for flooding (Thoms & Walker 1993). Water used to reach the floodplain about every 1.2 years but now reaches it every 2.5 years (Thoms & Walker 1993). The area of the floodplain inundated every second year has declined from 33 to 5%, and the area inundated every 10 years has declined from 77 to 54% (Jolly *et al.* 1992). Flows that used to flood about 30% of the floodplain (50 000 ML day^{-1}) now occur every three years and last half as long (Sharley & Huggan 1995; p. 93). Large floods of

100 000 ML day^{-1} which previously inundated the floodplain every three years, lasting for three months, now occur every 10 years and last for two months (Sharley & Huggan 1995; p. 93).

Reduced flooding has affected vegetation health. Saline groundwater previously flowed underneath the floodplain into the Murray River before the lock was built, but the creeks now intercept it (Jolly *et al.* 1992; Taylor *et al.* 1996). Floods used to leach salt from the soils but now saline groundwater is discharged in the floodplain by evapotranspiration, and it is killing black box trees (Jolly *et al.* 1993). Black box trees flooded one year in 10 remain healthy (Taylor *et al.* 1996), but they have died in areas not flooded for 35 years (Jolly *et al.* 1992). Red gums, restricted to the margins of the watercourses (Roberts & Ludwig 1990), take water from creeks and groundwater (Thorburn *et al.* 1994). Reduced flooding of the wetland has probably affected other plants such as lignum, where foliage cover is positively correlated with soil moisture and flooding (Craig *et al.* 1991).

Low frequency flooding (one year in 22) on the Chowilla floodplain resulted in only protozoans hatching and lower abundance and biomass of invertebrates compared to more frequent inundation (Boulton & Lloyd 1992). The temporary wetland habitats have the highest invertebrate biodiversity (Boulton & Lloyd 1991). Populations of 18 species of gastropod snails in the lower Murray River have declined in the last 50 years (Sheldon & Walker 1993). Such reductions will affect survival of native fish species and the many waterbirds that feed on invertebrates (Boulton & Lloyd 1992). Native fish populations in the Murray River have declined with the increase in storage capacity after the 1950s (Walker & Thoms 1993). Low flows have increased in the river and have contributed to the establishment of dense littoral plants, reeds *Phragmites australis* and cumbungi *Tyhpa* spp., in weir pools (Maheshwari *et al.* 1995). Species richness of riparian vegetation was lowest in areas exposed to current and wave action and highest in the billabongs and backwaters of the floodplain (Roberts & Ludwig 1991).

Gwydir wetlands

The Gwydir River usually terminates in the Gwydir floodplain wetlands (Fig. 1), the Lower Gwydir (to the south) and Gingham (to the north) watercourses. Annual rainfall is less than 450 mm (Keyte 1994), so the wetlands rely on water from the upper catchment, 300 km to the east. The network of wetlands of varying persistence is surrounded primarily by coolabah *Eucalyptus coolabah* and river cooba *Acacia stenophylla*, with lignum on low parts of the floodplain (McCosker & Duggin, 1992, unpubl. report; Keyte 1994). The Lower Gwydir watercourse supports about 24 000 ha of wetland that includes 7500 ha of water couch *Paspalum distichum* and 700 ha of marsh club-rush *Bolboschoenus fluviatilis* (Keyte 1994). The wetlands were declared a Bird and Wildlife Sanctuary in 1921 (Keyte 1994) for their waterbirds, and part is to be listed as a wetland of international importance under the Ramsar Convention.

Copeton Dam (1 360 000 ML) built in 1976, regulates 55% of the total inflow to the Gwydir River (Keyte 1994); most of the rest flows down the unregulated Horton River. Government-built weirs at Tareelaroi, Boolooroo, Tyreel and Combadello in the 1970s and 1980s directed water down the southern part of the river system where there was a defined channel (McCosker & Duggin, 1992, unpubl. report). 86 000 ha of irrigation licences (530 000 ML year^{-1}) were issued (Keyte 1994) exceeding natural median annual flow (520 000 ML) in the Gwydir River about 60 km upstream of the wetlands (Environment Protection Authority 1997; p. 25). The region of the catchment irrigated mostly for cotton expanded rapidly from 1976 until 1990/91.

The irrigation industry rapidly increased the capacity of off-river storages in the 1980s in order to divert unregulated flows from the Horton River (Fig. 2). On average, 301 000 ML of water was diverted annually from the river in the period 1988/89–1992/93 (Murray-Darling Basin Ministerial Council 1995), coming from regulated flows stored in Copeton Dam and unregulated flows pumped into off-river storages.

Diversions have reduced flooding of the wetlands. The core wetland area (20 000 ha) would have flooded naturally 17% of the time over 93 years, but flooding now occurs only 5% of the time because of diversions, a 70% reduction in flows large enough to reach the Gwydir wetlands (Keyte 1994). Graziers within the wetlands report livestock production losses of 10–80% (McHugh 1996; p.56). Channels and levees within the wetland have further reduced flooding. A channel cut in the early 1980s to carry water to livestock and households has deepened and widened, further draining

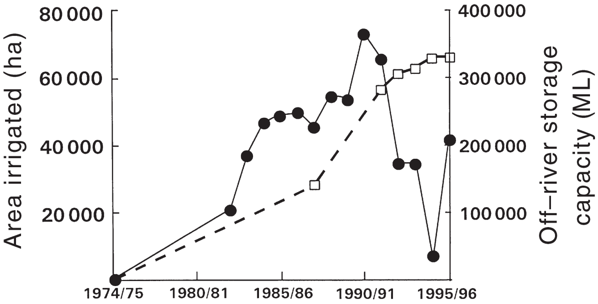

Fig. 2. Establishment of off-river storages (- - □- -) and area irrigated (—●—) on the Gwydir River in northwestern New South Wales (Bevitt 1998; Dowling 1997).

wetland areas and reducing flows onto the floodplain (McCosker & Duggin, 1992, unpublished report). Another elevated (2 m) irrigation channel, licensed in 1986, crosses the Lower Gwydir watercourse and stops water from flowing to parts of the wetland (Keyte 1994). Other levees, about 0.5 m high, redirect water within the wetlands to maximise grazing benefits (Keyte 1994).

Cover by marsh club-rush in the Lower Gwydir watercourse has contracted to one-third of its original area: 2200 ha to 700 ha (Keyte 1994). In parts of the Lower Gwydir and Gingham watercourses, terrestrial vegetation has established where aquatic vegetation lived (McCosker & Duggin, 1992, unpublished report; Keyte 1994), and lignum communities in the Lower Gwydir are degraded (Keyte 1994). There are no published accounts of the impacts of these changes on other fauna and flora.

Macquarie Marshes

The Macquarie Marshes are major floodplain wetlands at the end of the Macquarie River (Fig. 1). They covered about 130 000 ha during the 1990 flood (Kingsford & Thomas 1995). Flooding depends on flows from the upper catchment of the Macquarie River (Kingsford & Thomas 1995), more than 460 km to the southeast. During large floods, water flows through the Macquarie Marshes to reach the Darling River. The Macquarie Marshes are recognised for their conservation importance with 18 000 ha proclaimed as a Nature Reserve in 1971 and listed as a wetland of international importance under the Ramsar Convention. They have the largest reed beds, the largest northern area of red gums, and the most southerly occurrence of coolabah in New South Wales (Environmental Protection Authority 1995). Seventy-two species of water-birds, including 43 breeding, have been recorded within the marshes (Kingsford & Thomas 1995). They are also one of the more important sites for colonially breeding water-birds in Australia (Marchant & Higgins 1990).

Burrendong Dam, built in 1967 with a storage capacity of 1 678 000 ML, regulates most river flow (70%). Nine large dams, including Windamere Dam (353 000 ML), eight weirs, four bypass channels, a river transfer scheme and a system of 12 block banks, cuttings, groynes, regulators and siphons help supply water to irrigation, industry and towns. Most water (89%) diverted is for irrigation (Department of Water Resources 1991), which also takes unregulated flows with pumps and off-river storages. Consequently, their storage capacity rose from 15 000 ML in 1986 to 41 000 ML in 1992 (Kingsford & Thomas 1995). Two hundred thousand megalitres of unregulated flows in 1991/1992 were diverted by refilling off-river storages (Kingsford 1999b). A cap of 50 000 ML now applies to diversions of these flows (Department of Land and Water Conservation and National Parks and Wildlife Service 1996). An average of 471 000 ML year^{-1} was diverted from the river, predominantly upstream of the Macquarie Marshes, in the period 1988/89–1992/93 and reached a maximum in 1993/94 (543 000 ML). Before regulation and diversions, about 51% of the water passing the town of Dubbo (about 100 km upstream) reached the Macquarie Marshes, but by the late 1980s and early 1990s this had declined to about 21% (Kingsford & Thomas 1995). This has reduced the Macquarie Marshes to at least 40–50% of their original size (Kingsford & Thomas 1995). Reduced large flows and increased small flows have also decreased flow variability (Kingsford & Thomas 1995).

Low flows have eroded river channels, further reducing flows to the floodplain (Bell *et al.* 1983). An 18-km long channel, the northern bypass channel, was dug by government before 1970 to efficiently deliver water to downstream users (Water Conservation and Irrigation Commission 1975). Excavated soil formed a levee that alienated the adjacent eastern part of the floodplain from the river and retained floodwater on the western side for periods of more than 12 months (W. Johnson, 1999, personal communication). Other levees have been erected on the floodplain to redistribute flood flows.

Such changes have affected the biota. Abundance and species richness of water-birds in the northern part of the Macquarie Marshes declined over an 11-year period (Kingsford & Thomas 1995). Reduced flooding has resulted in smaller colony sizes and less frequent breeding of colonial water-birds than would have occurred naturally (Kingsford & Johnson 1999). In the core of the Macquarie Marshes, the area of river red gum has declined by about 14% (Brereton 1994) and in some areas mature trees are in poor health (Bacon P. 1996; Relationships between water supply, water quality and the performance of *Eucalyptus camaldulensis* in the Macquarie Marshes of NSW. Unpublished Report to Macquarie Marshes Unit, NSW Department of Land and Water Conservation, Dubbo). Halving of the area growing red gums occurred between 1934 and 1981, and of the area growing reed beds between 1963 and 1972 (Brander 1987). Water couch in the core of the Marshes declined by 40% between 1949 and 1991 and was replaced by dryland vegetation (Brereton 1994). Constant small supplies of water down some of the channels have killed floodplain eucalypts. The levee on the bypass channel retains floodwaters and has killed several hundred hectares of coolabahs 1970s (Johnson, W. J., pers. comm.).

EXTENT OF ECOLOGICAL IMPACTS ON FLOODPLAIN WETLANDS

The locations of 446 large dams and the distribution of diversions in river basins (Fig. 3, Table 2) provide a map for ecological impacts on floodplain wetlands in Australia. The greatest impacts are predicted within the Murray-Darling Basin, which has (i) most of its annual run-off diverted, (ii) the second greatest number of dams, with storage capacity exceeding mean annual runoff, and (iii) 87% of divertible resources extracted (Tables 2 and 3). The levels of impact will vary depending on the numbers of large dams, off-river storages, diversions and river management structures with floodplain wetlands on some rivers unaffected (e.g. Paroo River; Table 3). Increased numbers of off-river storages (see Fig. 2) compound the impacts of government-built dams (Table 3), as do increasing diversions in the Murray-Darling Basin (Murray-Darling Basin Ministerial Council 1995, 1998). Large proportions of divertible flow are extracted from most major rivers in the Murray-Darling Basin (Table 3). Natural flows at the end of the river are reduced by 45–77% (Close 1990; Maheshwari *et al.* 1995; Environment Protection Authority 1997; Thoms & Cullen 1998), with similar effects to flows to major wetlands such as Cumbung Swamp on the Lachlan River (Environment Protection Authority 1997); Narran Lake on the Narran River (Department of Primary Industries 1994); Hattah Lakes on the Murray River (Murray-Darling Basin Ministerial Council 1995); and floodplain wetlands of the Darling River (Thoms & Cullen 1998). Reductions in river flows are probably an underestimation of impacts on floodplain wetlands because small decreases in flood volumes can result in large reductions in area flooded (Taylor *et al.* 1996).

Dams in the northeast coast, southeast coast, South Australian Gulf, southwest coast and Timor Sea Basins are situated where humans live in capital cities (Fig. 3). River diversions provide water for drinking and industry (Table 2). The ecological impacts of these dams and diversions on floodplain wetlands are not well known, possibly because urban and agricultural development has already destroyed many floodplain wetlands (Goodrick 1970; Halse 1989; Pressey 1993; Blackman *et al.* 1996).

Impacts vary within and across river basins, according to the level of storage and diversion. At one extreme, diversion of nearly all flows (99%) in the Snowy River to the Murray-Darling Basin, through the Snowy Mountains Hydroelectricity Scheme, has reduced channel width and affected downstream floodplains (Bevitt *et al.* 1998). And for some rivers, full impacts of dams may not have registered because diversions are low. The capacity of Lake Argyle on the Ord River was recently raised from 5 797 000 to 10 700 000 ML. This accounts for 93% (based on original capacity) of the storage in the Timor Sea basin but only nine percent of mean annual runoff is diverted (Table 2). Diversions will increase when irrigation expands from 14 000 to 78 000 ha (Anon 1997a),

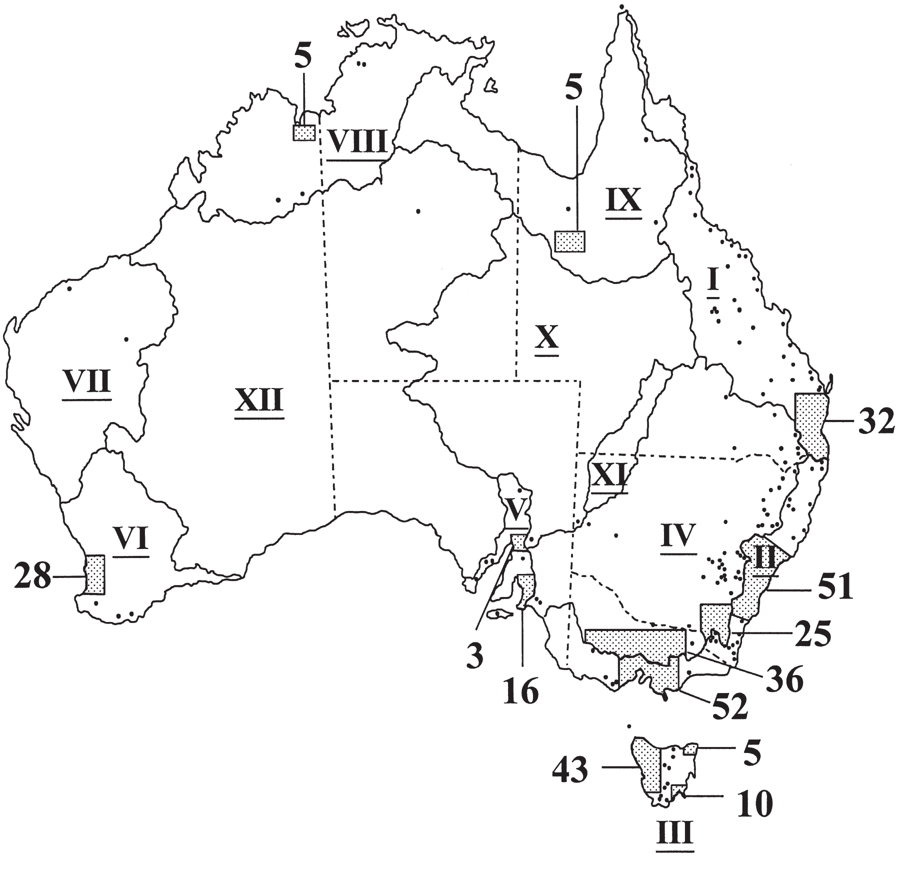

Fig. 3. Locations of 446 large dams, with a crest greater than 10 m in height (Australian National Committee on Large Dams 1990), within river basins of Australia. Numbers for shaded areas indicate numbers of dams. Roman numerals identify river basins (Australian Water Resources Council 1987); I, North-east Coast; II, South-east Coast; III, Tasmania; IV, Murray-Darling; V, South Australian Gulf; VI, South-west Coast; VII, Indian Ocean; VIII, Timor Sea; IX, Gulf of Carpentaria; X, Lake Eyre; XI, Bulloo-Bancannia; XII, Western Plateau (see Table 2).

Table 2. Location, number of storages and total storage capacity of large river basins in Australia

River Basin	Land area (km^2)	Mean annual runoff (ML)[a]	Divertible (ML)[b]	Developed (percentage of divertible flow) (ML)[c]	Number of storages	Total storage capacity (ML)	Storage capacity as percentage of mean annual	Population	Irrigation diversion (ML)	Urban and industrial diversion (ML)
North-east Coast	450 700	83 900 000	22 900 000	3 540 000 (16)	63	9 128 610	11	2 160 000	966 000	542 000
South-east Coast	273 600	41 900 000	15 100 000	4 280 000 (28)	128	13 188 656	32	8 180 000	1 020 000	1 360 000
Tasmania	68 200	52 900 000	10 900 000	1 020 000 (9)	70	32 609 321	62	415 000	96 700	66 000
Murray-Darling	1 062 530	24 300 000	12 400 000	10 000 000 (81)	107	24 968 566	103	1 800 000	7 650 000	327 000
South Australian Gulf	82 300	877 000	269 000	118 000 (44)	25	265 434	30	1 160 000	75 600	198 000
South-west Coast	314 090	6 670 000	2 914 000	385 000 (13)	31	1 040 015	16	1 210 000	267 000	382 000
Indian Ocean	518 570	3 960 000	296 000	27 000 (9)	2	95 800	24	94 200	8660	47 700
Timor Sea	547 050	80 700 000	22 000 000	1 980 000 (9)	9	6 232 935	8	106 000	70 300	41 500
Gulf of Carpentaria	638 460	92 500 000	13 200 000	78 000 (1)	8	496 798	1	83 700	74 200	57 100
Lake Eyre	1 170 000	6 310 000	204 000	26 000 (13)	2	13 175	0	47 100	3500	18 600
Bulloo-Bancannia	100 570	1 090 000	41 000	0	0	0	0	2230	0	460
Western Plateau	2 455 000	1 580 000	102 000	0	1	250	0	73 300	480	21 000
Total	7 681 070	396 687 000	100 326 000	21 454 000 (21)	446	88 039 560	22	15 331 530	10 232 440	3 061 360

Mean annual runoff, divertible and developed water resources, population, and irrigated area based on 1983/1984 data, Australian Water Resources Council (1987). Numbers of storages and total storage capacity data from Australian National Committee on Large Dams (1990).

[a] Outflow from basins where flow is greatest at the mouth of the river basin or combined mean annual runoff at points where flow is greatest in each major catchment of a river basin, excluding runoff from upstream basins.

[b] Average annual volume of water that could be removed using available technology.

[c] The portion of divertible resource currently available for use, estimated for exisiting storages or those under construction, and including licensed diversions.

increasing the level of ecological impacts that are already evident on downstream floodplain wetlands (Lane & Mccomb 1988). Similarly, increasing diversions from the Burdekin Dam (1 860 000 ML) on the Burdekin River in the northeast coast basin to ultimately irrigate 50 000 ha (Water Resources Commission) will have cumulative impacts on downstream floodplain wetlands. For other basins (Indian Ocean, Gulf of Carpentaria, Lake Eyre and Bulloo-Bancannia, Western Plateau), there has been either little annual runoff or little development of water resources (Table 2). Impacts of dams and diversions on floodplain wetlands would therefore be few. The Tasmania Basin has a high number of dams, and the highest storage capacity, storing 62% of mean annual runoff but diverting only 9% of this (Table 2). This is a consequence of the main purpose, to generate hydroelectricity, but regulation of flows can destabilise stratification of downstream wetlands and eliminate micro-organisms (Hodgson & Tyler 1996).

There is the potential to develop water resources with dams and diversions that will increase the loss of floodplain wetlands in Australia. Only 10% of divertible water from the tropics and 16% across other river basins is currently utilised, mainly for irrigated agriculture (77%; Table 2). We have developed the mechanisms to use 2% of divertible water across Australia (Table 2). Diversions increase in number, even in the Murray-Darling Basin, possibly fuelled by the expectation that licensed allocations should be met (Table 3), and despite the Murray-Darling Basin Cap (Murray-Darling Basin Ministerial Council 1998). Plans exist to spend $2 billion on new dams, weirs, channels and potential areas for irrigation on many river systems in the northeast coast basin (Department of Natural Resources 1997; Fig. 4). A 1985 survey provided possible locations for 73 water storages in Victoria where surface water could be harvested (Department of Conservation and Environment 1991; p. 82). Many other potential sites for water resource developments exist (Fig. 4). Pumping of flows into off-river storages means dryland rivers in the inland basins (e.g. Paroo River or Cooper's Creek) can be diverted (Walker *et al.* 1997; Kingsford *et al.* 1998; Kingsford 1999a).

LINKING WATER RESOURCE DEVELOPMENT AND MANAGEMENT TO ECOLOGY OF FLOODPLAIN WETLANDS

Water resource development in Australia has caused the loss of floodplain wetlands and dependent biota. Until ecological costs to floodplain wetlands are well defined, ecological science will continue to have a limited role in decisions on dams and diversions. Theoretical models of river ecology recognise the importance of floodplain wetlands (Ward & Stanford 1995;

Table 3. Storage capacities and water diversion amounts from large Government-built dams and private off-river storages in major catchments of the Murray-Darling Basin diverted

River system	Catchment area (km²)	Mean annual runoff (ML)[a]	Divertible resource (ML)[a]	Annual volume of water licensed for irrigation (ML)[b]	Average annual volume of water diverted 1988–93 (ML)[b]	Percentage of divertible resource diverted		
Upper Darling	115 880	106 000	404 000	549 000	189 000[c]	47	27 500	162 000
Lower Darling	58 800	446 000	20 000	255 000	213 000	48	2 285 000	0
Border Rivers	65 300	1 222 000	342 000	411 000	303 000	89	645 400	190 000
Condamine–Balonne	158 770	1 490 000	286 000	317 680[d]	162 000	57	320 190[e]	950 000
Gwydir	25 930	860 000	435 000	511 000	300 000	59	1 366 400	386 000
Lachlan	84 670	1 270 000	680 000	639 150	225 000	33	1 428 800	0
Macquarie-Bogan	90 200	1 560 000	713 000	642 500	471 000	66	1 646 100	65 000
Murrumbidgee	84 985	3 860 000	2 505 000	2 670 000	2 443 000	98	3 184 200	not known[e]
Murray	230 560	11 029 000	6 580 000	9 547 000	6 183 000	94	13 251 900	0
Namoi	43 050	1 000 000	342 000	260 000	244 000	71	878 800	118 000
Paroo	76 200	717 000	51 000	0	0	0	0	0
Warrego	72 800	750 000	37 000	1 500[f]	0	0	0	0
Total	1 107 145	24 310 000	12 395 000	15 803 830	10 733 000	87	25 034 290	1 315 900

[a] Australian Water Resources Council (1987).

[b] Murray–Darling Basin Ministerial Council (1995) and Environment Protection Authority (1997).

[c] Estimate may be high; actual diversion estimated to range 57 000–126 000 ML for the period 1989/90–1993/94 (B. Fitzgerald, 1999, personal communication).

[d] Includes floodplain harvesting.

[e] Off-river storages (10–20) on the Hay Plain, New South Wales.

[f] Diversion of 1500 ML per day in Queensland. Agreement for 36 000 ML shared equally between NSW and Queensland (yet to be developed).

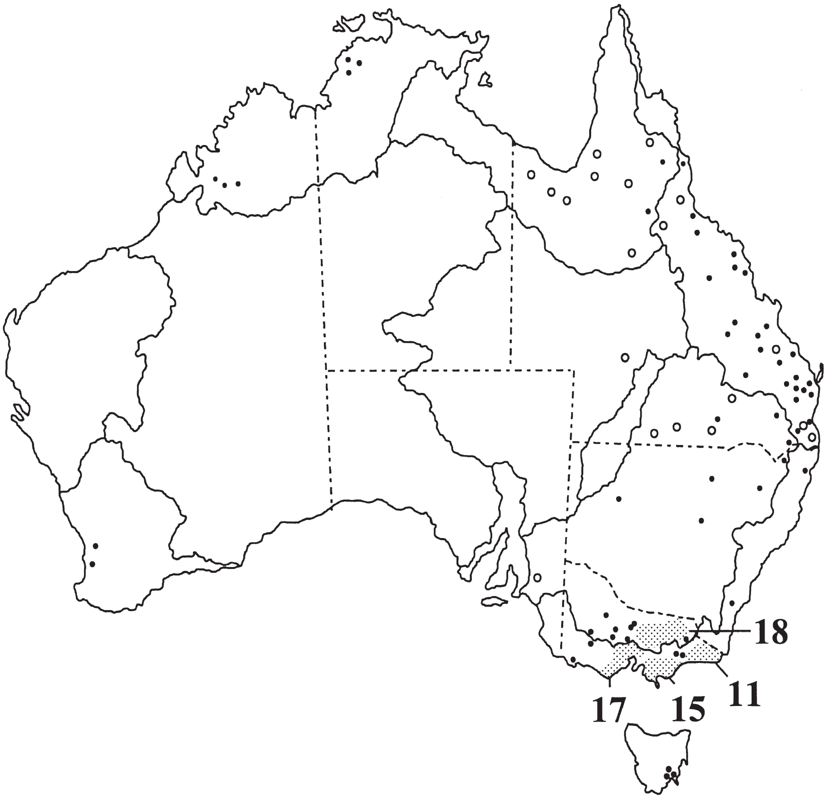

Fig. 4. Potential dam or weir sites (●) and areas where irrigation and water diversions are planned or will be investigated (○). Sources: Northern Territory Department of Lands and Housing (1990); Department of Conservation and Environment (1991); Department of Environment and Natural Resources (1995); Stokes *et al.* (1995); Department of Natural Resources (1997, and unpubl. data for New South Wales and Tasmania).

Ward 1998). In practice, river managers focus on the hydrology of the river channel, while conservation managers concentrate on the ecology of floodplain wetlands.

Hydrological models have been primarily developed for delivering water for human purposes. Their flow data comes from the river channel and seldom from floodplain wetlands. The integrated water quantity and quality model, IQQM (Department of Water Resources 1995), used to manage rivers in New South Wales and Queensland, has a series of diversion nodes mainly for human use (e.g. towns and irrigation industries). Climate data and runoff models provide input variables for simulated modelling of natural flows versus current flows, usually based on 100 years of data. The relevance of these to the inundation of floodplain wetlands is unknown, but their ecological simplicity fails to model the complex connectivity and flow patterns that occur. Despite this, the model was used to determine the hydrological impacts of diversions on the 100 000-km^2 floodplain at Cooper's Creek, using inadequate flow data (Thoms & Cullen 1998; Puckridge 1999). Potential ecological impacts (Walker *et al.* 1997; Kingsford *et al.* 1998) were ignored and increased diversion recommended on the basis of hydrological analyses (Department of Natural Resources 1998). Similarly, a proposal to build Nathan Dam (1 100 000 ML) on the Dawson River in Queensland was recommended after ecological and social impact assessment (Hyder Environmental 1997). Only 7.5% of the assessment dealt with downstream impacts (51 pages out of 291), and there was no reference to peer-reviewed studies of impacts of dams and water diversions.

Decisions to divert water from rivers remain the prime responsibility of water managers and there are few opportunities to review the predictive power of hydrological models (Thoms & Cullen 1998), or their ecological relevance. Complex jargon compounds the problem (see Appendix, Table A1), and policies for allocation, off-allocation, floodplain harvesting, the Murray-Darling Cap, and sleeper allocation, interact with and govern river flows and diversions. These policies ultimately determine how much water reaches floodplain wetlands, but conservation strategies for floodplain wetlands are often independent of river flows. Wetland reserves, listing of Ramsar sites (Davis 1994), and identification of important wetlands (Australian Nature Conservation Agency 1996), are conservation measures focused on wetland sites not water. Even wetland policies (e.g. in New South Wales and Western Australia, and Commonwealth policies) deal poorly with the importance of river flows to floodplain wetlands because they fail to identify trade-offs between flows to wetlands and diversions to humans. This lack of integration is exacerbated by funding frameworks that separate the wetland from the river (e.g. Wetlands and Rivercare programs in the Natural Heritage Trust). Conservation measures seldom deal adequately with protection of flows upstream (Barendregt *et al.* 1995).

Three areas exist for urgent ecological research on floodplain wetlands. First, long-term ecological impacts of water resource development on biota, ecological processes and hydrology of floodplain wetlands need to be investigated. This will allow the ecological costs of proposed water resource developments to be defined. Second, hypotheses about relationships between hydrology and floodplain ecology (states and processes) need to be tested, using floods as landscape-scale experiments (Sparks *et al.* 1990; Power *et al.* 1996). Few studies have investigated the impacts of regulation on connectivity of floodplains (Ward & Stanford 1993). Such analyses will be relevant to river management decisions. Finally, for rivers with little or no development, an understanding of the ecological importance of natural flood events and their periodicity may provide a basis on which to assess future impacts (e.g. Kingsford *et al.* 1999; Puckridge 1999).

Extended time scales are necessary for research because flows of Australian rivers are amongst the most variable in the world (McMahon *et al.* 1992; Puckridge *et al.* 1998). The conceptual framework of 'control sites' and BACI designs (Green 1993; Underwood 1993; Osenberg *et al.* 1994), and analyses of long-term trends, can provide deeper insights and greater statistical power. Floodplains exist on some rivers (e.g. Paroo River and Cooper's Creek) that are not affected by dams and diversions, and may therefore be used for comparison. Three historical sources of data are useful: rainfall, water flow and satellite data. Rainfall stations over much of Australia measure climatic changes and more than 50 years of flow data exists for many rivers in the eastern states. There are almost 20 years of satellite data offering continuous data on flooding at large spatial scales (Roughgarden *et al.* 1991). Relationships between flows and flooding of wetlands, combined with historical flow data, can help determine the impacts of dams and water diversions on floodplain wetlands (Kingsford & Thomas 1995). Landscape measurement of biota in a floodplain wetland is difficult but possible with robust and rapid techniques (Taylor *et al.* 1996). Processes such as recruitment are more difficult to measure, but may ultimately determine a population's capacity to respond (Walker *et al.* 1995).

Hydrological models must predict flooding and drying patterns of floodplain wetlands and be linked to ecological processes and biotic life cycles. Scientists need to work with management by proposing and testing hypotheses about flooding and ecological responses and testing predictive power of hydrological modelling, and feeding these back into improving management practices (Walters & Holling 1990).

CONCLUSIONS

Reduced flooding to large areas of floodplain wetlands have been caused by the building of dams and the cumulative impact of diversions and river management upstream. Floodplains have turned into terrestrial ecosystems. This effect is not well studied, and data exist only for a fraction of potentially affected biota, even for four large floodplain wetlands (Fig. 1). Nevertheless, the range of biota affected by reduced flooding testifies to the generality of this problem. The ubiquity of large dams, diversions (Fig. 3; Tables 2 and 3), and the solely hydrological principles used in decision-making models, means that ecological impacts are probably widespread in Australia, although few river systems have been investigated. Hydrological models need to incorporate connectivity of the floodplain so that ecological costs can be adequately estimated for future water resource developments (Fig. 4).

Floodplain wetlands are sites of extraordinary biodiversity and their loss will continue until there is a widespread understanding of the long-term ecological effects of dams and diversions. We need to recognise that flows to floodplain wetlands serve an ecological function and are not lost or wasted.

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APPENDIX

Table A1. Definitions for terms used to manage rivers in Australia

Term	Definition
Allocation (annual)	Allocations for water users based on a river's yield from its catchment
Allocation (announced)	The percentage of water entitlement declared for diversion from a regulated stream during a season (usually the same as financial year)
Bulk water entitlement	Perpetual entitlement to water granted to water authorities by the Crown of Victoria under the Water Act 1989
Dozer allocation	An entitlement that is under-used or sometimes inactive
Entitlement	All users are given an entitlement (usually volumetric), which is their licence on a river
Floodplain harvesting	Capture of water using levees and channels across the floodplain, away from the river channel
Flow rules	A set of rules based on principles of flow for releasing water from storages, in order to manage river flows in regulated systems
High security entitlements	Entitlements that do not vary except in exceptional droughts (e.g. town-water supplies, permanent plantings)
Low security entitlements	Entitlements that vary with climatic conditions and storage capacities of dams
Murray-Darling Basin Cap	Annual volume of water diverted under 1993/1994 levels of development
Off-allocation	When unregulated tributary inflows or dams spills exceed downstream obligations, irrigators may pump flows once an 'off-allocation' period is declared by water resource managers. This water is not counted against the irrigator's announced allocation
On-farm storage	Privately owned dams that are used to store water pumped from the river. Also known as off-river storages or ring tanks
Rainfall rejection flows	Releases from dams for irrigation purposes, which are not diverted because local rainfall events satisfy crop demands
Regulated rivers	River flows and releases that are determined by managing storages or dams
River pumpers	Irrigators (predominantly) who extract water from rivers
Sleeper allocations	Entitlements that have no history of use
Unregulated rivers	River or tributary flows that are largely uncontrolled by Government-built dams or weirs
Volumetric allotment	An individual's licence to take water in South Australia
Water right	An individual's licence to take water in Victoria
Water harvesting	Diversions of water from an unregulated river in Queensland (similar to off-allocation).
Contingency allowance	A parcel of water kept in storage for release in order to deal with blue-green algae or other water quality problems, and for bird breeding

'Rivers' also refers to creeks and streams.