Floodplain development & vegetation health on the Macquarie River floodplain of the Murray-Darling Basin

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Executive Summary

The Macquarie River in the Murray-Darling Basin has a large complex floodplain that includes the Macquarie Marshes, a wetland of international importance under the Ramsar Convention. The Macquarie Marshes supports some of the larger waterbird breeding colonies in Australia and complexes of different floodplain communities, including river redgum *Eucalyptus camaldulensis*. Environmental flows to this wetland are affected by dams and abstractions upstream but also potentially by earthworks on the floodplain. We investigated the distribution and type of earthworks on the floodplain of the Macquarie River, between the towns of Warren and Carinda, using satellite imagery (SPOT 2005).

There were 338km levees, 1,648km channels, 54 off-river storages and 664 tanks or farm dams on the floodplain area of 4,793km². A further 119km levees were classified uncertain, requiring further ground truthing, making an upper estimate of 2,320km of earthworks. Most levees and channels (72%) were in the southern part (max. density 3,400m km⁻²) and two northern areas, where there was irrigation development. Outside these areas, curvilinear levees and channels were built to move water around the floodplain and also for erosion control. More than half (62%) of channels were between 0.5 - 1m, a third were < 0.5m in height and the rest (5%) were greater than 1m in height (n= 55). Most levees (65%) were less than 0.5m high (n=20), except those that bounded off-river storages (1 - 5m in height). Based on 12 randomly selected irrigated and non-irrigated quadrats (10x11km) tracked from 1949-2005, most development of earthworks occurred between the 1980s and 1990s. In irrigated areas, the density of earthworks doubled from 284m km⁻² in 1949 to
577m km\(^{-2}\) in 1981, then tripled by 1994 (864m km\(^{-2}\)) and by 2005 had increased by four times (1182m km\(^{-2}\)) the 1949 density. Levees in irrigated areas were three times the density of non-irrigated areas in 1994 (245m km\(^{-2}\)), and twice the density of non-irrigated areas in 2005 (562m km\(^{-2}\)). There was evidence for increased development subsequent to the implementation of the Murray-Darling Basin Cap in 1995, designed to halt further diversion of water. Growth rate of earthworks was initially slow (<10m km\(^{-2}\) yr\(^{-1}\) before 1967), but increased to 26m km\(^{-2}\) yr\(^{-1}\) by 1995. There were 101km of levees, 368km of channels and 16 off-river storages built within the precluded area defined by government guidelines (1978/82), designed to protect the connected floodways from development. Revised guidelines developed in 2006 by government, shifted boundaries so that the revised precluded area included 88km of levees, 338km of channels and 8 off-river storages.

Over half the original floodplain (61.5\%) has not been inundated for over 28 years in Landsat Spring - Summer imagery. The most severe reduction in flooding occurred in the southern section (73\%) compared to the northern section where the floodplain was reduced by about half (53\%). Earthworks alienated large parts of the original floodplain and affected the health of river redgums. All river redgums were dead at 9.1\% of 55 randomly surveyed sites (225x150m) and half of the river redgums were dead at 21.8\% of sites, some within the internationally significant wetland. River redgums were healthy where river flows were channelled through the dense southern area of earthworks but also in this area some river redgum stands were isolated from river flows by earthworks. Levees exacerbated the natural tendency for the floodplain to become dry distally from the channel. In the northern part of the Macquarie Marshes, one third of river redgum sites were dead due to upstream river
regulation, abstraction and drought, even though they were well-connected to the river.

This is the first comprehensive analysis of floodplain development of any river in the Murray-Darling Basin and raises management issues in relation to the Murray-Darling Basin Cap and environmental flows. There is potential for increased access to water when rivers exceed bankfull. Water flowing on the floodplain may be captured by levees, redirected by channels, extracted from the river and not be accounted for or audited. This could include environmental flows, including the wildlife allocation for the Macquarie Marshes. Earthwork developments, such as those identified on the Macquarie River floodplain, are widespread on the rivers of the Murray-Darling Basin and have grown since 1993/1994 levels of development. Further growth has largely come because of lack of government policies, regulations or enforcement (see breach of guidelines). The extent of earthworks on the floodplains of rivers such as the Macquarie River could significantly affect ecological outcomes, necessitating increased government efforts to rehabilitate degraded ecosystems such as the Macquarie Marshes.
Introduction

Semi-arid and arid environments stretch across 47% of Earth’s terrestrial surface and experience less than 500mm of rainfall each year (Kingsford and Thompson, 2006). Rivers that traverse these environments, dryland rivers, sustain complex and rich biotic communities and many subsistence human communities and cultures. These cultural and conservation values are compromised by a growing demand for agriculture, irrigation, drinking water, electricity, transportation, industry, mediated through water resource development (Kingsford et al., 2006a). Dams, weirs, irrigation structures and flood mitigation barriers (Fig. 1 - 7) perturb the key intrinsic processes that drive dryland river systems: flow regime and hydrological connectivity.

‘Connectivity’ is the highly variable spatial linkage and pathway of water through the landscape (Freeman et al. 2007), defined by three variables: spatial dimension, temporal dimension and quality (Table 1). Hydrological connectivity mediates the transfer of energy, matter and organisms (Amoros and Roux, 1988) and shapes unique floodplain landscapes by redistributing sediments across the channel and floodplain, activating channel migration (Ward and Stanford, 1995).

Before 1988, fluvial ecological models were derived from temperate forest streams of the northern hemisphere (Bunn et al., 2006) where flows were stable, predictable and flooding rarely exceeded bankfull. Classical river models, based on fluvial data, primarily from within-channel gauges and rarely from the floodplain and wetlands, focused on longitudinal channel gradients (Vannote et al., 1980) and in-channel
productivity (Thorp and Delong, 1994). These models inadequately incorporated floodplain connectivity and productivity. Junk et al. (1989) responded to these shortcomings by proposing the Flood Pulse Concept incorporating floodplain dynamics and hydrological extremes. Dynamic models followed in Australia (Thoms and Sheldon, 2000), accounting for non-equilibrium, climatic variability, and lateral floodplain connectivity, intrinsic mechanisms of dryland rivers.

Hydrological connectivity and disconnection are major drivers of patterns and processes for biodiversity (Freeman et al., 2007; Brock et al., 2006; Boulton et al., 2000; Bunn et al., 2000). Water transfers inorganic and particulate organic matter including phosphates, nitrates, salts, seeds, spores and aquatic plants (Young and Kingsford, 2006) between otherwise disconnected areas. This dispersion balances geochemistry and nourishes soils (Jenkins and Boulton, 2003), stimulating survival, reproduction, growth and recruitment of biodiversity.

Communities of flood-dependent vegetation are structured by their hydrological connectivity and disturbance (van Looy et al., 2003). Hydrological connectivity and flooding frequency decrease distally from the channel (Ward et al., 1999), producing an environmental gradient of flood-dependent vegetation, ranging from frequently flooded to terrestrial vegetation intolerant of flooding and influenced by runoff, groundwater and drying (Galat et al., 1998). Species have specific flooding regimes and flow envelopes. For example, health of river redgums Eucalyptus camaldulensis Dehnh is highly correlated with the frequency and regularity of overland flooding (Bacon et al., 1993). Flooding also stimulates flood-dependent fauna, including invertebrates and fish, to colonise new habitats (Boulton and Jenkins, 2003).
Figure 1. Spillway of Burrendong Dam on the Macquarie River operating since 1967. Burrendong Dam can store 1,188,000ML of water (NSW Government, 2007), but the dam was less than 5% in June 2007.
Figure 2. Marebone Weir on the Macquarie River (Fig. 10) controls flows for diversions (May, 2006).
Figure 3. A levee rising over 4m high surrounds an off-river storage on the Macquarie River floodplain (May, 2006).
Figure 4. Artificial channels on the Macquarie floodplain supply water from the river or floodplain to irrigated areas (May, 2007).
Figure 5. Water in this partially filled off-river storage comes from Bulgerga Creek, conveyed by more than four kilometres of channels (May, 2007).
Figure 6. Two tank drains (<1 m height) capture rainwater from the floodplain and channel it into a tank for livestock drinking water (May, 2007).
Figure 7. Levees and artificial channels on the floodplain of the Macquarie Marshes bordering flood-dependent vegetation (foreground and centre). These stop flows reaching the lateral areas cleared for irrigation. (Photo W. Johnson).

Table 1. Three variables can describe hydrological connectivity

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial</td>
<td>Three-dimensions of water flow through space: longitudinal</td>
<td>Ward and Stanford,</td>
</tr>
<tr>
<td></td>
<td>(upstream-downstream), lateral (channel-floodplain), vertical</td>
<td>1995; Freeman et al. 2007</td>
</tr>
<tr>
<td></td>
<td>(atmosphere-channel-subsurface)</td>
<td></td>
</tr>
<tr>
<td>Temporal</td>
<td>Frequency of inundation, rate of inundation</td>
<td>Freeman et al. 2007</td>
</tr>
<tr>
<td>Quality</td>
<td>The strength of the flow, including flow velocity, degree of</td>
<td>Ward et al. 1999</td>
</tr>
<tr>
<td></td>
<td>interactivity</td>
<td></td>
</tr>
</tbody>
</table>
The connectivity between the river and its floodplain can be severed by dams and water extractions that reduce flow frequency or by earthworks built directly on the floodplain (Kingsford, 2000). River regulation has modified the natural flow regime in over half of the world’s largest rivers, including 26% of Australasian rivers (Nilsson et al., 2005), with a significant global impact on ecosystem health (Lemly et al., 2000).

Most ecological research has focused on the regulatory effects of large, centralized structures like dams (Ward and Stanford, 1995) that significantly alter flow regimes, but hydrological connectivity of the world’s dryland rivers has also been affected (Kingsford et al., 2006a). Little is known about the distribution of floodplain earthworks or their cumulative ecological effects. The flat floodplain soils of dryland river floodplains are fertile for agriculture, but original vegetation removal is a process rarely documented (van Looy et al., 2003). Effects of river regulation on floodplain connectivity exist from some Northern Hemisphere floodplains (Galat et al., 1998; Gergel et al., 2002; van Looy et al., 2003) but little is known from floodplains in Australia.

Our aim was to investigate the extent and distribution of earthworks that may impact on flows to one of Australia’s more important wetlands systems, the Macquarie Marshes, a Ramsar-listed wetland in semi-arid Australia. This floodplain lies at the end of the highly regulated Macquarie River. Frequent and complex flooding across the large floodplain, including 72km² of semi-permanent wetlands, supports the largest community of river redgums (Fig. 8) in northern New South Wales and the largest beds of common reed *Phragmites australis* (Fig. 9) in New South Wales.
(Lemly et al., 2000). The wetland provides habitat for a diversity of waterbirds with 72 species recorded breeding, including seven threatened species in New South Wales (Kingsford and Auld, 2005). Flows greater than 200,000ML and of sufficient duration (Kingsford and Auld, 2005) trigger colonial waterbird breeding events (up to 80,000 nests of ibis, herons and cormorants).

The first weir in the Macquarie River System was constructed in 1890, marking the beginning of a century centered on regulating water for flood control and providing water to irrigation (Johnson, 2005). Today, nine major dams of the Macquarie catchment can capture and store 2,100,000 ML of water, regulating water supply to the floodplain. Extracted water is used largely for irrigated farming, predominantly cotton (Lemly et al., 2000). The total allocation for extractive use in the Macquarie is 738,793ML per year, in a river that yields 475,000ML annually (Johnson, 2005). This does not include the environmental allocation of 160,000ML per year, groundwater, unregulated licences and floodplain harvesting (Johnson, 2005). A small part of the Macquarie floodplain is a conservation reserve, with most (88%) privately owned (DWR, 1991).

This study addressed two main objectives: i) identification of the extent that earthworks alter the hydrological connectivity; and ii) the response of hydrological and ecological systems. To quantify changes to ecosystem integrity, we investigated whether river redgum mortality was affected by the density of earthworks, the distance from the river channel, and the frequency of inundation between 1979 and 2006. Finally, we evaluated the effectiveness of floodplain policies and regulations that govern the water resource development on the Macquarie floodplain.
Figure 8. A healthy river redgum *Eucalyptus camaldulensis* forest in the Macquarie Marshes Northern Nature Reserve (May 2006).

Figure 9. Beds of common reed *Phragmites australis* in Northern Nature Reserve of the Macquarie Marshes (May 2007).
Methodology

The Study Site

The Macquarie River in southeast Australia stretches over 460km in length and drains 73,000 km² (Johnson, 2005), a catchment bounded by the Great Dividing Range to the east and a 400km ridge to the south. The Macquarie River flows to Burrendong Dam then continues through the towns of Dubbo and Narromine in a well-defined channel before the entire valley opens out into the Macquarie floodplain from, Narromine downstream to Warren, then Oxley (WRC, 1978, WRC 1982) and Carinda (Fig. 10). This flat, alluvial floodplain receives only 436mm yr⁻¹ of rainfall and has a high evaporation rate of 1800mm yr⁻¹ (Kingsford and Auld, 2005).

The floodplain relies primarily on spatially and temporally dynamic floods (Fig. 11) that pulse from the upper catchment in the Great Dividing Range, where rainfall reaches up to 1000mm yr⁻¹ (DWR 1991). As flows reach the flat, dry landscape beyond Warren, the floodplain transforms into a maze of interconnected streams, lagoons, distributary creeks and anabranching channels (Paijmans, 1981). Here, floodwaters have suspended and deposited non-calcareous brown and grey clays (Brander, 1987). During high floods, the Macquarie system connects with the Darling River system. Between flood events, the natural footprint of connectivity shrinks and low regulated flows are confined to channels, except during exceptionally dry periods when the channels run dry.
The Original Floodplain

First, we defined the spatial extent of the original floodplain and located engineered earthworks (levees, channels, off-river storages and tanks) that could affect connectivity of flows. Hydrologically, the floodplain is a continuous surface of gradients of varying flow frequencies delimited by recurrence (eg. 1 in 100 year flood). Also, the floodplain is a geomorphologically low-gradient sediment sink, carved by fluvial action with fluvial landforms (oxbow lakes, gilgai swamps, anabranching channels).

We defined the natural floodplain of the Macquarie using hydrological, geomorphological and flood-dependent vegetation data. The hydrological surface included a vector watercourse layer (GA, 2006) and the largest flood event in 1955 that inundated an estimated 3,744km$^2$ of the floodplain (SKP, 1984) (Fig. 12a). This 1955 flood map was based on interviews with landholders, aerial photography, and government records (SKP, 1984). It was scanned, digitised, georectified and projected into Geocentric Datum of Australia 1994 in the Map Grid of Australia Zone 55 (GDA 94 MGA Zone 55). The geomorphological surface (Fig. 12b) was a polygon extract from the Digital Atlas of Australian Soils (BRS, 2000), based on 1960’s mapping (scale of 1:2,000,000) (Northcote et al., 1960). The digitized extract depicted floodplains of grey and brown alluvial clays (Morgan and Terrey, 1992), active and non-active gilgais and low domes or rises that are probably artefacts of fluvially-formed levees (BRS, 2000). Finally, eight vegetation maps of the Macquarie Marshes (Table 2) were integrated to define 13 flood-dependent vegetation communities of the Macquarie Marshes floodplain (Fig. 12c).
Figure 10. Map showing the location of the Macquarie River catchment, major tributary rivers, distributary creeks, large dams, Macquarie Marshes floodplain (including the Nature Reserve) and some towns on the river downstream of storages in New South Wales, Australia. The river flows northwest.
Figure 11. Monthly flow at Oxley gauge (see Fig. 10) on the Macquarie River, Australia, between 1943 and 2005. The highest recorded flows occurred before 1967, prior to the development of Burrendong Dam.
Figure 12. Three datasets were used to define the Macquarie Marshes floodplain upstream of the town of Warren: (a) hydrological (watercourses (GA, 2006), 1955 flood boundary (BRS, 2000)); (b) geomorphological (soils and landforms (SKP, 1984)); and (c) available flood-dependent vegetation layers (See Table 3).
Table 2: Water requirements of major flood-dependent communities in the Macquarie River study area from different and sometimes conflicting vegetation mapping layers.

<table>
<thead>
<tr>
<th>Common name</th>
<th>Specific name</th>
<th>Alluvial specificity</th>
<th>Hydrological connectivity</th>
<th>Area (km²)a</th>
<th>GIS polygon dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumbungi</td>
<td><em>Typha orientalis</em></td>
<td>Frequently flooded areas</td>
<td>Well connected within channel or on streambanks</td>
<td>0.045</td>
<td>DLWC® Lower Macquarie Floodplain</td>
</tr>
<tr>
<td>Water couch</td>
<td><em>Paspalum distichum</em></td>
<td>Frequently flooded areas</td>
<td>Well connected within channel</td>
<td>3.2</td>
<td>DLWC® Lower Macquarie Floodplain</td>
</tr>
<tr>
<td>Common reed</td>
<td><em>Phragmites australis</em></td>
<td>Frequently flooded areas</td>
<td>Well connected on streambank and inner floodplain</td>
<td>7.9</td>
<td>Carinda Barwon DIPNR</td>
</tr>
<tr>
<td>River redgum association</td>
<td><em>Eucalyptus camaldulensis</em></td>
<td>Intermittently flooded areas</td>
<td>Well connected on streambank and inner floodplain</td>
<td>12.8</td>
<td>DLWC® Lower Macquarie Floodplain, Carinda Barwon DIPNR, Reconstructed vegetation, Wheatbelt</td>
</tr>
<tr>
<td>River redgum – river cooba</td>
<td><em>Eucalyptus camaldulensis</em> and <em>Acacia stenophylla</em></td>
<td>Intermittently flooded areas</td>
<td>Well connected on streambank and inner floodplain</td>
<td>1767.2</td>
<td>DLWC® Lower Macquarie Floodplain, Wheatbelt, Carinda Barwon DIPNR, Floodplain Vegetation 1995, MDBC Wetlands, Reconstructed vegetation, Wheatbelt</td>
</tr>
<tr>
<td>Mixed marsh and wetlands complex</td>
<td>unspecified</td>
<td>Intermittently flooded areas</td>
<td>Well connected on streambank and inner floodplain</td>
<td>107.2</td>
<td>DLWC® Lower Macquarie Floodplain, Floodplain Vegetation 1995</td>
</tr>
<tr>
<td>Floodplain shrubland</td>
<td>unspecified</td>
<td>Intermittently flooded areas</td>
<td>Well connected on streambank and inner floodplain</td>
<td>71.0</td>
<td>DLWC® Lower Macquarie Floodplain, Floodplain Vegetation 1995</td>
</tr>
<tr>
<td>Floodplain woodland</td>
<td>unspecified</td>
<td>Intermittently flooded areas</td>
<td>Well connected on streambank and inner floodplain</td>
<td>4.7</td>
<td>DLWC® Lower Macquarie Floodplain</td>
</tr>
<tr>
<td>Common name</td>
<td>Specific name</td>
<td>Alluvial specificity</td>
<td>Hydrological connectivity</td>
<td>Area (km²)(^a)</td>
<td>GIS polygon dataset</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------</td>
<td>--------------------------------------------------</td>
<td>---------------------------------------------</td>
<td>------------------</td>
<td>---------------------------------------------------------</td>
</tr>
<tr>
<td>River cooba</td>
<td><em>Acacia stenophylla</em></td>
<td>Intermittently flooded areas</td>
<td>Moderate connection on outer floodplain</td>
<td>1.0</td>
<td>DLWC Lower Macquarie Floodplain, Carinda Barwon DIPNR</td>
</tr>
<tr>
<td>Myall</td>
<td><em>Acacia pendula</em></td>
<td>Requires infrequent flooding</td>
<td>Moderate connection on outer floodplain</td>
<td>7.1</td>
<td>DLWC Lower Macquarie Floodplain, Carinda Barwon DIPNR</td>
</tr>
<tr>
<td>Black Box and</td>
<td><em>Eucalyptus largiflorens</em></td>
<td>Requires infrequent flooding</td>
<td>Moderate connection on outer floodplain</td>
<td>1204.8</td>
<td>DLWC Lower Macquarie Floodplain, Carinda Barwon DIPNR, Reconstructed vegetation</td>
</tr>
<tr>
<td>Association</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coolibah</td>
<td><em>Eucalyptus coolabah</em></td>
<td>Requires infrequent flooding</td>
<td>Moderate connection on outer floodplain</td>
<td>558.8</td>
<td>Carinda Barwon DIPNR, Reconstructed vegetation, Wheatbelt</td>
</tr>
</tbody>
</table>

Total 4563.7

\(^a\)Refers to the study area (see Fig. 13)

\(^b\)DLWC – NSW Department of Land and Water Conservation

\(^c\)DIPNR - NSW Department of Infrastructure, Planning and Natural Resources
The hydrological, geomorphological and vegetation surfaces were overlayed to form a single polygon defining the original floodplain (Fig. 13). This map encompassed spatial and temporal flow variability and connectivity of the original floodplain before river regulation. While the entire original floodplain stretched from Narromine to beyond Carinda, our study area was the floodplain between Warren and Carinda (4,793km²), an area 150km long and no wider than 50km (Fig. 13). We divided this into two parts to compare floodplain characteristics and to align with the management and policy focus (Fig. 13): the Southern Section delineated by the 1978/82 Floodplain Guidelines (WRC, 1982) and the 2006 Draft Macquarie River Floodplain Management Plan (DNR, 2006); and the Northern Section including the 1985 designated floodplain (Millington, 1985), Macquarie Marshes Nature Reserves (NPWS, 1993) and the focus of the 1996 Macquarie Marshes Water Management Plan (DLWC and NPWS, 1996).

Satellite Image Analysis
To investigate the distribution of earthworks within the Macquarie floodplain, we used SPOT imagery (January and February 2005), with aerial photography for accuracy assessment. SPOT satellite imagery (resolution of 2.5m per pixel) is suitable for visually extracting spatial details (Wang et al., 1992) including linear engineered earthworks and mapping their distribution. Levees are physical earth barriers (0.1 - 5m high) designed to block water flows (Table 3). They control water for storage, protect agricultural land and infrastructure or redirect water to different parts of the landscape (within or outside the floodplain) (DNR, 2006). Tank drains are small levees used for channelling water across the floodplain. Artificial channels are open waterways that transport water from the river (and its distributaries) to
storages and irrigated cultivation or to bypass a wetland. The Bypass Channel in the Macquarie Marshes moves water efficiently around the wetland, minimising evaporation and other transmission losses. Channels can be below ground or bounded by levees and above ground level (Moorhouse and Noonan, 2001). Off-river storages store water diverted or pumped from a watercourse, rainfall or groundwater for irrigation, stock or domestic purposes. We differentiated large off-river storages (> 0.2km²) from tanks (< 0.2km²). Elevated gravel roads, paved roads and highways, bank stabilization, dredging and vegetation clearing were not identified. Earthworks on a designated floodplain, river or lake require development approval under Part 8 of the 1912 Water Act if they affect the flow or spread of water (DNR, 2006). The Northern Section of the Macquarie floodplain is a designated floodplain (Fig. 13).

The SPOT imagery was projected in the standard GDA 94 MGA Zone 55. Levees, channels, off-river storages and tanks were then classified and digitized as Geographic Information System (GIS) vector lines and polygons using the ArcGIS 9.2 software (ESRI, 2006). We used the spectral properties, shape, texture and placement in relation to surrounding cadastral features, such as irrigation fields and buildings, important characteristics for recognition (Gastellu-Etchegorry, 1990). We differentiated roads from linear channels using a road map (1:10,000 scale). The total length and density of earthworks in each section of the study area was calculated using a GIS length tool (ESRI, 2006).

A 100km² pilot study area (Fig. 13) was chosen in the Southern Section where earthworks had relatively high density. Earthwork sites (100) and undeveloped sites (2) were selected randomly across the pilot area. Earthworks identified from SPOT
### Table 3. Upstream and downstream river structures that regulate river flows and affect hydrological connectivity

<table>
<thead>
<tr>
<th>Structure</th>
<th>Location</th>
<th>Function</th>
<th>Structure</th>
<th>Cross sectional view&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dam or Weir</td>
<td>Main channel, usually in the upper catchment</td>
<td>To capture and store water then allow for release</td>
<td>Concrete structures usually within the main channel</td>
<td><img src="image" alt="Concrete structure" /></td>
</tr>
<tr>
<td>Artificial levee</td>
<td>Floodplain</td>
<td>To reduce or block flooding from towns and valuable agricultural land, control water for irrigation, to spread water to increase flooding of floodplain, to contain water within off-river storages, to reduce erosion and to drain swamps.</td>
<td>Physical earth barriers constructed with in-situ alluvium reaching between 0.1 and 5m in height.</td>
<td><img src="image" alt="Earth levee" /></td>
</tr>
<tr>
<td>Artificial channel</td>
<td>Floodplain</td>
<td>To transport water from the river to irrigation plots or storages, harvest water from the floodplain or redirect water around wetlands (e.g. Bypass Channel).</td>
<td>Channels are designed to be deep with a small surface area and minimise transmission losses due to evaporation.</td>
<td><img src="image" alt="Channel" /></td>
</tr>
<tr>
<td>Off-river storage</td>
<td>Floodplain</td>
<td>To store large reserves of water on the floodplain to be used as needed for crop irrigation. The water is pumped from a watercourse, rainfall or groundwater.</td>
<td>Off-river storages are large reservoirs of water between 0.2 and 2km² in area and contained within levees.</td>
<td><img src="image" alt="Off-river storage" /></td>
</tr>
<tr>
<td>Tanks and Farm Dams</td>
<td>Floodplain</td>
<td>To store water for livestock and domestic supplies. Water is pumped from a watercourse, drawn from a bore or harvested from the floodplain using tank drains.</td>
<td>Tanks and farm dams (&lt;0.2km²) are usually square, cut into the ground, and bound by levees.</td>
<td><img src="image" alt="Tank and farm dam" /></td>
</tr>
</tbody>
</table>

<sup>a</sup> Shaded areas indicate distribution of water and raised areas constructed levees or dam walls.
Figure 13. The original Macquarie River floodplain was produced by amalgamating hydrological, geomorphological and vegetation map layers. The focus of this study was the Northern and Southern Sections. It includes the following administrative areas: designated floodplain (Millington, 1985), Macquarie Marshes Nature Reserve, restricted zone (1996 Water Management Plan), designated floodplain (1986 Water Management Plan), floodplain guidelines 1978/82 (WRC, 1982) and draft floodway guidelines (DNR, 2006) are overlaid.
imagery were compared to those identified with high-resolution (0.0041m$^2$ per pixel) aerial photography captured from 2004 (DL, 2004), as there was no matching 2005 aerial photography data. Stereo-paired photographs allowed for clear identification. The accuracy of classification was determined using an error matrix (Congalton, 1991), with reasonable match ("good" Kappa statistic, $K_{HAT} = 0.6254$, Byrt, 1996). The main problem, ‘users’ error, was inflated because levees were constructed between the photography date (2004) and the aerial SPOT image capture (2005). Following the pilot assessment, the study area (Fig. 13) was divided into a 100km$^2$ grid and each cell processed systematically identifying all earthworks (levees, channels, off-river storages, tanks) in the Northern and Southern Sections.

The pilot assessment iteratively informed the large scale classification (Congalton 1991). Two new categories, small water storage tanks or farm dams and an ‘uncertain’ category, were added to explicitly account for classification ambiguity. Accuracy assessment for the entire study area was essential to provide rigour (Congalton, 1991). The large extent of the floodplain and inaccessibility meant that a helicopter survey provided effective unbiased ground-truthing of the SPOT classification. We identified 116 ground control points, randomly stratified across earthwork categories (17 levees, 28 channels, 6 storages, 5 tanks, 11 uncertain levees and 49 areas without development), spaced at least 500m apart to minimize effects of spatial autocorrelation. The helicopter hovered over each point at 500 feet (152.4m), while the GPS location and earthwork category (levee, channel, off-river storage tank) were recorded on digital voice recorders and digital cameras. The locations were independently classified and compared to their counterpart SPOT classification
to produce an error matrix. Subsequently we adjusted the methodology for the 11 uncertain sites based on the ground-truthed data.

**Temporal Development**

We sampled 12 random quadrats to estimate growth patterns of earthworks between 1949 and 2005 across the irrigated and non-irrigated areas of the floodplain (10x11km quadrats). The ground-truthed map of the 2005 earthworks extent was overlayed with 1994 Landsat TM imagery (resolution of 25m per pixel), and any features not present in the Landsat imagery removed to produce an estimate of total length of earthworks within each quadrat calculated for 1994. The process continued by comparing the 1994 earthworks map with available black and white aerial photography from July 1981 (scale of 1:50,000), September 1972 (scale of 1:84,350) and November 1949 (scale of 1:30,000) followed by calculation of the length of the earthworks present at each date. Narrow and low earthworks (<1m) in the Northern Section (Fig. 13) were difficult to identify from satellite imagery, so we used local information to approximate date of construction.

To calculate the growth rate of earthworks, mixed effects models were used for fixed (temporal) and random (spatial) variables. Earthworks were assumed to be permanent features of the floodplain and therefore autocorrelated over time (Zeger et al., 1988). The variability among quadrats was normal according to a Shapiro-Wilks test (W = 0.98, p = 0.63).

**Connectivity**

We tested whether the surface area of dry ground was different between the inner
(river-side) and outer sides of levees during Spring-Summer flooding. Paired 500x100m quadrats were placed on either side of 25 randomly chosen levee sites and 29 randomly chosen control (undeveloped) sites (Fig. 14). At levee sites, the inner and outer quadrats were aligned parallel with the straight edge, and at control sites, the two quadrats were aligned parallel with the nearest river channel to account for the natural drying patterns that increase distally from the channel. Dry ground was derived from an inundation frequency map (resolution 30m² per pixel) for the study area, where every pixel showed how often it was flooded, based on annual (Spring to Summer) inundation from Landsat satellite imagery (MSS and TM) for a 28 year period (1979 - 2006) (Thomas et al., unpublished data). These paired quadrats were spaced less than 50m apart to minimise confounding effects of spatial variation that increase with distance. All tests relied on differencing the surface area of dry ground (zero flow), of the inner quadrat from the outer quadrat, to yield the dependent variable of difference in dry surface area between paired quadrats.

The Shapiro-Wilk normality test (Shapiro and Wilk, 1965) showed the data were not normal (W = 0.897, p < 0.001), so we used the non-parametric Kruskal-Wallis on all data because log and power transformations failed to normalise data. This test assumes underlying populations are continuous with the same shape. A two-tailed test was chosen because the direction of flooding was not known and water pooled behind the levee (Fig. 14a).

We examined overall hydrological connectivity by comparing the extent of recent inundation (1979 – 2006) in Spring - Summer with the extent of the original Macquarie floodplain in the study area. The 28-year inundation map (Thomas et al.,
unpublished data) captured inundation extent and frequency for each part of the floodplain after many earthworks were established. Inundated areas were calculated separately for the Northern and Southern Sections using GIS area tools.

*River Redgums*

To determine if earthworks potentially affected health in river redgums, we modelled mortality of river redgums in relation to hydrological connectivity. River redgums are a subset of flood-dependent vegetation in the Macquarie Marshes (Brander, 1987; Paijmans, 1981). Without adequate flows, river redgums experience atypical leaf shed and leaf discolouration (MDBC, 2003) and reduced tree growth rate, accelerated senescence, increased mortality and minimal regeneration (Fig. 15) (Bacon *et al.*, 1993). Conversely, river redgums dependent on an intermittent flooding regime do not tolerate permanent submergence (Fig. 16) (DLWC, 2000; Lemly *et al.*, 2000; Bray, 1994).

The leaf area index (LAI) correlates strongly with vegetation condition (Benger, 1997), however extensive coverage of the Macquarie floodplain using an LAI sensor was not possible. The Grimes rating system (Grimes, 1987) is faster but difficult to apply because of subjectivity in variable systems (RMCWMB, 2002) such as the Macquarie. Instead, we used high-resolution aerial photographs to assess river redgum mortality. These data could be collected using unbiased samples assessed during helicopter surveys in May 2007. Sixty-four random river redgum sites (225x150m, 50mm focal length, 150m height) were selected across a range of inundation frequencies over the entire original floodplain in the study area. To ensure sites were independent, they were spaced more than 500m apart. Colour photographs
Figure 14. Examples of where the effects of levees on flooded areas were tested: (a) levee site and (b) undeveloped control site. The flooded area (red) within paired quadrats at 54 sites was clipped from an inundation map (shaded blue and compiled for the period 1979 – 2006) (Thomas et al., unpublished data) and the difference in non-flooded area between each 50,000m² quadrat was calculated over the period 1979 - 2006. Note how water has pooled behind the levee in (a.).
Figure 15. River redgums that are dead or critically stressed in the Northern Section of the study area due to reduced flows (May, 2007). River redgum communities are being displaced by vegetation species that tolerate lower flow frequencies.
Figure 16. River redgums in an off-river storage in the Northern Section of the study area on the Macquarie floodplain have been killed due to increased flood frequency and inadequate drying phases (May, 2007).

Figure 17. Photographs were subsampled (100 random points) and classified into four categories: dead, live, soil and water to estimate river redgum mortality.
were subsampled by visually assigning 100 random points into one of four categories: live (leaves/live branches); dead (leafless dead branches); water; or soil (Fig. 17). River redgum mortality was calculated as the percentage of dead trees (dead/[live+dead]).

As a comparison, a visual classification of river redgum mortality was also done from the helicopter hovering at a height of 150m using a digital recorder. The observer estimated the proportion of dead trees over the photographed 500x100m quadrat, with five tree mortality categories: 0 – 24% dead, 25 – 49% dead, 50 – 74% dead, 75 – 99% dead and 100% dead. These data were compared to the binary tree mortality data to produce an error matrix.

Three independent variables were used to measure connectivity: spatial dispersal of flow; frequency of connectivity; and development density. The spatial dispersal of flow was calculated from the shortest distance water could travel from the river corridor to each river redgum site. Where a levee interfered, the shortest route was modelled around each earthwork. The second independent variable was inundation frequency, approximating the temporal element of hydrological connectivity. Inundation frequency between 1979 and 2006 (28 years) was derived from unsupervised spectral classification of wetted areas in Landsat imagery (Thomas et al., unpublished data). Earthwork density (m km⁻²) at each 10x10m pixel was based on the development within a 3km radius, smoothing local variation while retaining sufficient detail of development clusters. A kernel function weighted central features more heavily than earthworks at the circumference, accounting for the non-uniform spatial distribution of earthworks within the neighbourhood (Fig. 18).
the edge of the study area, kernel radius underestimated the density of earthworks (Fig. 19) as earthworks were not mapped beyond the boundaries and the kernel function assumed zero development.

We used a multivariate generalised linear model to determine whether the river redgum mortality was correlated with the three continuous variables: proximity to river channel; frequency of inundation; and density of earthworks. Data were homoscedastic (variance decreased as the probability approached zero and one) and the independent and dependent variables were not necessarily linearly related, requiring use of binomial logistic regression, an s-shaped function. Interaction effects were implicitly incorporated into the logistic model, with no interaction constant but an instantaneous rate of change that varies with every possible combination of predictors (DeMaris, 1990). The fit of the logistic regression was assessed in two ways. The $D^2$ statistic estimated the goodness-of-fit for the logistic regression, by dividing the null deviance (variability of the dataset) by the residual deviance and subtracting from one (Rossiter and Loza, 2006). Further, Akaike’s Information Criterion (AIC) was used to assess models. It adjusts the residual deviance for the number of predictors, favouring less complex models (Rossiter and Loza, 2006). We quantified the likelihood of river redgum mortality with the independent variables using odds ratios (OR), calculated as the exponential of the logistic regression coefficient (DeMaris, 1990).

Geographically Weighted Regression (GWR) was used to determine whether the derived global relationship from the logistic regression exhibited geographic trends or spatial autocorrelation. The GWR produced a local statistic disregarding sites
Figure 18. A three kilometre radius used to investigate spatial distribution of levees within two circular neighbourhoods. Earthworks closer to the neighbourhood centre exert more influence on the central point than those earthworks near the circumference. The overall development densities within two neighbourhoods (a., b.) can be similar, but the kernel function emphasizes the spatial distribution of earthworks, resulting in a higher overall density in neighbourhood (a.) (kernel density, 1.97m km⁻²) compared to (b.) (kernel density, 0.99m km⁻²).

Figure 19. Areas outside the entire study area (see Fig. X) were not analysed and so they underestimated densities of ‘edge’ neighbourhoods such as this example.
greater than 5km away and weighting sites within the 5km radius according to a
gaussian distribution. The 5km bandwidth eliminated the problem of having too few
sites (most sites > 1km apart), but small enough to capture local processes. The local
relationships were interpreted by looking at the parameter values with an estimate of
significance such as the $t$-value or the goodness-of-fit (Mennis, 2006).

**Floodway Network**

In 1978/82, the Government water agency developed guidelines for development of
the Macquarie floodplain from Narromine to Oxley (Southern Section) (WRC, 1978,
WRC, 1982). These guidelines confined floods to designated pathways for efficient
flow transmission (WRC, 1982) and allowed for agricultural development of the
floodplain outside the floodways (Johnson, 2005). In 2006, the water agency released
the 2006 floodway network to replace the 1978/82 guidelines (DNR, 2006). We
evaluated how the 1982 floodplain guidelines and 2006 floodway network
maintained flow connectivity, with respect to the map of 2005 earthworks. The two
sets of guidelines (raster data) were digitised into floodway polygons and projected
into GDA 1994 zone 55. The western edge of the 1982 floodway was undefined, so it
was assumed to have the same boundary as the 2006 floodway. These polygons were
overlain with the map of 2005 earthworks to identify the extent of earthworks within
flow corridors.
Results

Extent and Distribution of Earthworks

A total of 2,320km of earthworks were distributed across the study area (Table 4; Fig. 20) including 338km levees, 1,648km channels, enclosing 54 off-river storages spanning 19km² (enclosed by 129km of levees) and 664 tanks and farm dams (enclosed by 86km of levees). There were 119km of levees classified uncertain and requiring further ground truthing. Most levees and channels (72%) were in the Southern Section (max. density 3,400m km⁻²), arranged as enclosed regular shapes (rectangles, triangles, prisms) tessellated in compact grid-like clusters or rings (Fig. 20). By contrast, earthworks in the Northern Section were isolated curvilinear features across the landscape positioned at irregular angles and less dense than the Southern Section, with the exception of two clusters of earthworks (Fig. 20). A total of 55 channels were selected randomly across the study site and more than half (62%) were between 0.5m and 1m in height, a third were less than 0.5m and the remainder (5%) were 1 - 3m in height. Twenty levees were randomly surveyed from the air and most (65%) were less than 0.5m high. Levees bounding off-river storages were 1 - 5m in height.

There were 54 off-river storages on the Macquarie floodplain (Table 4). Assuming a depth of two metres, off-river floodplain storages in the study area could hold up to 37,896ML of water, however in May 2007 they were partially filled or dry. Eighteen off-river storages on the floodplain were within or adjacent to a natural floodplain channel and the remaining 36 were 0.1 - 4km from the nearest river channel. Seventy-eight percent of all off-river storages for irrigation are in the Southern
Table 4. Lengths, areas enclosed and densities of earthworks (levees including uncertain ones, channels, off-river storages and tanks) within the original Macquarie floodplain in the Northern and Southern Section of the study area (4307.8km²)

<table>
<thead>
<tr>
<th>Earthworks</th>
<th>Section</th>
<th>Length (km)a</th>
<th>Total length km (%)</th>
<th>Quantity</th>
<th>Enclosed Water Storage Area (km²)b</th>
<th>Average density (m km⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&lt;0.5m</td>
<td>0.5 – 1m</td>
<td>&gt;1m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Levees</td>
<td>North</td>
<td>70</td>
<td>38</td>
<td></td>
<td>108 (32%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>150</td>
<td>80</td>
<td></td>
<td>230 (68%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>220</td>
<td>118</td>
<td></td>
<td>338</td>
<td></td>
</tr>
<tr>
<td>Uncertain levees</td>
<td>North</td>
<td>41</td>
<td>22</td>
<td></td>
<td>63 (53%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>36</td>
<td>20</td>
<td></td>
<td>56 (47%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>77</td>
<td>42</td>
<td></td>
<td>119</td>
<td></td>
</tr>
<tr>
<td>Channels</td>
<td>North</td>
<td>277</td>
<td>148</td>
<td>22</td>
<td>447 (27%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>745</td>
<td>396</td>
<td>60</td>
<td>1,201 (73%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>1022</td>
<td>544</td>
<td>82</td>
<td>1,648</td>
<td></td>
</tr>
<tr>
<td>Off-river storages</td>
<td>North</td>
<td></td>
<td></td>
<td></td>
<td>37c (28%)</td>
<td>12 (33%)</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>92c</td>
<td>92c</td>
<td></td>
<td>92c (72%)</td>
<td>42 (67%)</td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>129c</td>
<td>129c</td>
<td></td>
<td>129c</td>
<td>54</td>
</tr>
<tr>
<td>Tanks</td>
<td>North</td>
<td>51c</td>
<td>51c</td>
<td></td>
<td>51c (59%)</td>
<td>402 (62%)</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>35c</td>
<td>35c</td>
<td></td>
<td>35c (41%)</td>
<td>262 (38%)</td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>86c</td>
<td>86c</td>
<td></td>
<td>86c</td>
<td>664</td>
</tr>
<tr>
<td>Total Development</td>
<td>North</td>
<td>388</td>
<td>208</td>
<td>110</td>
<td>706</td>
<td>414</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>931</td>
<td>496</td>
<td>187</td>
<td>1,614</td>
<td>304</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1,319</td>
<td>704</td>
<td>297</td>
<td>2,320</td>
<td>718</td>
</tr>
</tbody>
</table>

aHeights estimated from sample where: 65% of levees were less than 0.5m and 35% were 0.5 - 1m; 62% of channels were less than 0.5m and 33% were 0.5 - 1m and 5% were 1 – 3m. Off-river storages and tanks were enclosed by levees greater than 1m.
bArea enclosed on all sides by earthworks
cLevees bounding off-river storages or tanks
Figure 20. The distribution of earthworks (levees, channels, off-river storages, tanks) on the original Macquarie floodplain within the study area. Most irrigation development is in the Southern Section, with the exception of two clusters of irrigation development, (A) and (B).
Section (Table 4). Additionally, there were 664 tanks uniformly dispersed across the Northern and Southern Sections (Fig. 21), primarily used for stock and domestic water supplies.

Within the 1978/82 floodplain guidelines (WRC, 1982), there were 101km of levees, 368km of channels, 16 off-river storages and 69 tanks (Table 5; Fig 22a). The 2006 floodway network (DNR, 2006) included 88km of levees, 338km of channels, 8 off-rivers storages and 84 tanks (Fig. 22b). The 2006 floodway network (DNR, 2006) excludes 13km of levees, 30km of channels and 8 off-river storages that were in the 1978/82 floodplain guidelines.

The classification and location of earthworks’ for the complete study yielded a Kappa statistic ($K_{HAT}$) of 0.661, an improvement (>4%) on the pilot study (Table 6; Table 7). Errors arose from falsely classifying channels as levees, with reclassification of 33.8km of levees as channels. The comparison provided an estimate for the omission error of 82.5%, a commission error of 81.6%, and overall accuracy of the final classification of more than 77%.

Temporal Development

The growth of earthworks on the Macquarie floodplain was initially slow (<10m km$^{-2}$ yr$^{-1}$ before 1967), but rose at an increasing rate (26m km$^{-2}$ yr$^{-1}$ by 1995). The growth of irrigated areas was significantly greater ($t = -5.69$, $p < 0.01$) than non-irrigated areas in the mixed effects model. For irrigated areas, there were an estimated 284m km$^{-2}$ of earthworks in 1949. By 1981, the number of earthworks doubled (577m km$^{-2}$), then tripled in 1994 (864m km$^{-2}$) and in 2005 there were over
four times more earthworks (1182 m km\(^{-2}\)) than 1949 (Fig. 23). Irrigated areas were three times more dense than non-irrigated areas in 1994 (245 m km\(^{-2}\)), and twice as dense in 2005 (562 m km\(^{-2}\)).

The growth curve for irrigated (a) and non-irrigated (b) quadrats was described by the following quadratic equations:

(a) \(L = 0.2865t^2 + 283.4\)  
(b) \(L = 0.2865t^2 - 335.9\)

where \(L\) = length of earthworks and \(t\) = year.

The time coefficient was significant (\(t = 7.454, p < 0.001\)) as was the constant (\(p = 0.0057\)).

*Connectivity Analysis*

The extent of flooding between 1979 and 2006 was 61.5\% (2,950 km\(^2\)) less than the original floodplain flooded during Spring - Summer (Table 8; Fig. 24). The most severe reduction in flooding occurred in the Southern Section (73.04\%), and the extent of flooding in the Northern Section floodplain reduced by about half (53.2\%). Levees exacerbated the natural tendency for the floodplain to become dry distally from the channel. The outer quadrats of surveyed sites had a reduced flooded area and were drier than inner quadrats for the period 1979 to 2006 (Fig. 25). Floodplain sites with levees were significantly drier than control sites (Mann-Whitney \(U = 508, p = 0.012\)).
Figure 21. Distribution of off-river storages and tanks along a South to North vector of the floodplain. Most off-river storages were situated in the Southern Section, but tanks were distributed homogenously across the floodplain.

Table 5. Extent of earthworks within the 1978/82 floodplain guidelines and the 2006 floodway network.

<table>
<thead>
<tr>
<th>Category of development within flow corridor</th>
<th>1978/82 guidelines(^a)</th>
<th>2006 floodway network(^b)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levees (km)</td>
<td>101</td>
<td>88</td>
<td>-13</td>
</tr>
<tr>
<td>Channels (km)</td>
<td>368</td>
<td>338</td>
<td>-30</td>
</tr>
<tr>
<td>Off-river Storages</td>
<td>16</td>
<td>8</td>
<td>-8</td>
</tr>
<tr>
<td>Tanks</td>
<td>69</td>
<td>84</td>
<td>15</td>
</tr>
<tr>
<td>Total flow corridor area ((km^2))</td>
<td>705.05</td>
<td>753.1</td>
<td>48.1</td>
</tr>
</tbody>
</table>

\(^a\)WRC, 1982
\(^b\)DNR, 2006
Figure 22. Earthworks (101km of levees and 368km of channels) within the 1978/82 floodplain guidelines (WRC, 1982) (a.), and (b.) earthworks (88km of levees and 338km of channels) in the 2006 draft floodway network (DNR, 2006).

<table>
<thead>
<tr>
<th>Category</th>
<th>Levee</th>
<th>Channel</th>
<th>Storage</th>
<th>No development</th>
<th>Total</th>
<th>Commission error</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pilot</strong></td>
<td>4</td>
<td>8</td>
<td>0</td>
<td>10</td>
<td>22</td>
<td>18.18%</td>
</tr>
<tr>
<td>Levee</td>
<td>0</td>
<td>54</td>
<td>0</td>
<td>5</td>
<td>59</td>
<td>91.53%</td>
</tr>
<tr>
<td>Channel</td>
<td>0</td>
<td>0</td>
<td>19</td>
<td>0</td>
<td>19</td>
<td>100.00%</td>
</tr>
<tr>
<td>Storage</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>100.00%</td>
</tr>
<tr>
<td>No Development</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>100.00%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>4</td>
<td>62</td>
<td>19</td>
<td>17</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>Omission Error</td>
<td>100%</td>
<td>87.10%</td>
<td>100%</td>
<td>11.76%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>Levee</th>
<th>Channel</th>
<th>Storage</th>
<th>Tank</th>
<th>No development</th>
<th>Unsure</th>
<th>Total</th>
<th>Commission error</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Complete</strong></td>
<td>2</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>17</td>
<td>11.76%</td>
</tr>
<tr>
<td>Levee</td>
<td>0</td>
<td>27</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>28</td>
<td>96.43%</td>
</tr>
<tr>
<td>Channel</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>100%</td>
</tr>
<tr>
<td>Storage</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>100%</td>
</tr>
<tr>
<td>Tank</td>
<td>0</td>
<td>49</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>49</td>
<td>100%</td>
</tr>
<tr>
<td>No Development</td>
<td>1</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>11</td>
<td>0.00%</td>
</tr>
<tr>
<td>Unsure</td>
<td>3</td>
<td>42</td>
<td>6</td>
<td>5</td>
<td>60</td>
<td>0</td>
<td>116</td>
<td></td>
</tr>
<tr>
<td><strong>Omission Error</strong></td>
<td>66.67%</td>
<td>64.29%</td>
<td>100%</td>
<td>100%</td>
<td>81.67%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7. Comparison between errors and accuracy of the pilot study and the complete study.

<table>
<thead>
<tr>
<th></th>
<th>Pilot Assessment</th>
<th>Complete Study Assessment</th>
<th>Difference a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Size</td>
<td>102</td>
<td>116</td>
<td></td>
</tr>
<tr>
<td>Average Omission Error</td>
<td>74.72%</td>
<td>82.52%</td>
<td>+7.8%</td>
</tr>
<tr>
<td>Average Commission Error</td>
<td>77.05%</td>
<td>81.64%</td>
<td>+4.59</td>
</tr>
<tr>
<td>Overall Accuracy</td>
<td>77.45%</td>
<td>76.72%</td>
<td>-0.73</td>
</tr>
<tr>
<td>$K_{HAT}$</td>
<td>62.54%</td>
<td>66.06%</td>
<td>+3.52</td>
</tr>
</tbody>
</table>

a Shows improvement of complete study
Figure 23: Growth curves for length of earthworks (1949 – 2005) within each quadrat (10x 11km; n = 12) for irrigated and non-irrigated areas; lines represent the growth curves for the length of floodplain earthworks over time.

Table 8. The area of original floodplain within the study area (see Fig. 13) compared with the extent of the floodplain inundated at least once between 1979 and 2006 during Spring - Summer.

<table>
<thead>
<tr>
<th>Section</th>
<th>Original floodplain (km²)</th>
<th>Floodplain inundated between 1979 and 2006 (km²)</th>
<th>Percentage (%) of original floodplain inundated between 1979 and 2006</th>
<th>Reduction in floodplain size (km²) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern</td>
<td>2775</td>
<td>1299</td>
<td>46.8</td>
<td>-1476</td>
</tr>
<tr>
<td>Southern</td>
<td>2018</td>
<td>544</td>
<td>27.0</td>
<td>-1474</td>
</tr>
<tr>
<td>Total</td>
<td>4793</td>
<td>1843</td>
<td>38.4</td>
<td>-2950</td>
</tr>
</tbody>
</table>

*(Thomas et al. Unpublished data)*
Figure 24: Between 1979 and 2006, 61.5% of the original floodplain was disconnected from flows in the defined study area during Spring – Summer. Inundated areas were connected by flooding at least once between 1979 and 2006.
Figure 25. A comparison of non-flooded areas on either site of control (undeveloped) and levee sites. A negative difference indicated the outer quadrat is drier than the inner quadrat; a difference of zero indicated paired quadrats experience a similar degree of flooding, and a positive difference indicated the outer quadrat was wetter than the inner quadrat.
River Redgum Mortality Assessment

River redgum mortality ranged between 0% and 100% at 55 surveyed sites (225x150m) (Fig. 26; Table 9). At 9.1% of the sites, all the trees were dead (Fig. 27). At 21.8% of the sites, over half of the trees were dead. Patterns in redgum mortality were tested for correlation with the path distance from the river (Fig. 28a), the inundation frequency (Fig. 28b), and density of earthworks (Fig. 28c). The logarithm of the odds depended linearly on the independent variables and the equation describing the relationship was:

\[
\text{Logit}(P) = \log\left(\frac{P}{1-P}\right) = 0.000234a - 0.0476b - 0.6535c - 0.1387
\]

where \(P\) = probability of a dead tree, \(a\) = path distance from nearest river channel, \(b\) = inundation frequency between 1979 and 2006 and \(c\) = density of earthworks. All regression coefficients of independent variables were significantly different from zero, except the constant (Table 10). The logistic model explained 58.6% of the variation (\(R^2 = 0.586\)). AIC values were calculated for all combinations of the three variables and the model with all three variables (path distance, inundation frequency and density) emerged as the better model with the lowest AIC value (Table 11).

The density of earthworks was a key factor for determining where river redgum death occurred (Table 12). Path distance was not a strong explanatory variable for river redgum mortality (OR = 1.0002; where OR = 1 is an equally likely chance of live or dead river redgums) with all other variables held constant. Every unit increase in density of earthworks increased the odds of a river redgum death by half (OR = 0.52; where OR < 1 is a reduced likelihood of dead river redgums), with inundation
frequency and path distance held constant. For every unit increase in inundation frequency, there was a slightly reduced likelihood of river redgum death (OR = 0.95).

Spatial variation was ignored by the logistic regression but the local GWR identified 26 out of 165 sites with significant spatial non-stationarity ($t < -2$, $t > 2$) in one or more independent variables (Fig. 29). As the Macquarie River flows downstream from Warren in the South Section (between UTM 6520000 and 6550000), the relationship between vegetation mortality and path distance became positive (Fig. 29a); the further away, the greater the mortality. In the Northern Section near the Nature Reserves, distance between sites and the river channel (Fig. 29a) became negatively correlated with river redgum mortality with the exception of two northernmost, adjacent to irrigation. The global coefficient for inundation frequency was predominantly negative, so the probability of dead redgums was low when the flow frequency was high. The exception was several undeveloped sites in the Southern Section (Fig. 29b) (UTM 6505000 to 6516000) and in the Northern Nature Reserve. In the Northern Section, there were three sites where density of earthworks was highly positively correlated with river redgum mortality (Fig. 29c), a difference that the global regression model failed to detect. In the Southern Section, the GWR suggested that river redgum mortality decreased with increasing density of earthworks, a relationship that fluctuated in strength (-0.59 to -0.02) across the Southern Section (Fig. 30), although this relationship was not significant. The major spatial trends were clearest in the Southern Section of the floodplain where earthworks and sampling points were dense. The Gaussian distribution was better at calculating the goodness-of-fit using redgum mortality likelihoods than the logistic
Figure 26. Condition of river redgum at 55 sites in the study area based on aerial photography classification. Mortality was calculated as the percentage of dead redgums (mortality = dead / [live + dead]) and displayed within five categories: 100% dead, 75 – 100% dead, 50 – 75% dead, 25 – 50% dead, 0 - 25% dead.
Table 9. Error matrix to assess the accuracy of the river redgum mortality classification (KHAT = 0.263) based on comparison between aerial photography analysis and visual assessment recorded on digital voice recorders.

<table>
<thead>
<tr>
<th>River redgum Mortality</th>
<th>100%</th>
<th>75 – 99%</th>
<th>50 – 74%</th>
<th>25 – 49%</th>
<th>0 – 24%</th>
<th>Total</th>
<th>Commission Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>12</td>
<td>66.67%</td>
</tr>
<tr>
<td>75 – 100%</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>25.00%</td>
</tr>
<tr>
<td>50 – 74%</td>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>100.00%</td>
</tr>
<tr>
<td>25 – 49%</td>
<td>1</td>
<td>1</td>
<td>8</td>
<td>4</td>
<td>14</td>
<td>24</td>
<td>28.57%</td>
</tr>
<tr>
<td>0 – 24%</td>
<td>4</td>
<td>2</td>
<td>7</td>
<td>12</td>
<td>12</td>
<td>30</td>
<td>48.00%</td>
</tr>
<tr>
<td>Total</td>
<td>5</td>
<td>6</td>
<td>12</td>
<td>13</td>
<td>12</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Omission Error</td>
<td>40.00</td>
<td>16.67%</td>
<td>16.67%</td>
<td>30.77%</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 27. River redgum mortality (% dead) across 55 sites in the study area, based on the aerial photography classification.
Figure 28. Connectivity measured as three independent variables and used in logistic regression on effects on river redgum mortality: (a.) path distance variable (distance between a site and the nearest river channel, circumnavigating earthworks); (b.) inundation frequency (compilation of flooding frequency 1979 – 2006); and (c.) density of earthworks across the study area.
Table 10. Results of the logistic regression analysis for predicting effects of three independent variables on river redgum mortality. The null deviance was 1,236.69 on 51 degrees of freedom and the residual deviance was 511.91 on 48 degrees of freedom.

<table>
<thead>
<tr>
<th>Independent variable</th>
<th>Coefficient</th>
<th>Standard Error</th>
<th>Z Value</th>
<th>p Value</th>
<th>Odds Ratios^a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path distance</td>
<td>0.000234</td>
<td>5.5e^{-3}</td>
<td>4.2</td>
<td>P&lt;0.001</td>
<td>1.00023</td>
</tr>
<tr>
<td>Inundation Frequency</td>
<td>-0.0476</td>
<td>4.1e^{-3}</td>
<td>-11.6</td>
<td>P&lt;0.001</td>
<td>0.95</td>
</tr>
<tr>
<td>Density</td>
<td>-0.6535</td>
<td>7.1e^{-2}</td>
<td>-9.2</td>
<td>P&lt;0.001</td>
<td>0.52</td>
</tr>
<tr>
<td>Constant</td>
<td>-0.1387</td>
<td>0.15</td>
<td>-0.9</td>
<td>P=0.357</td>
<td></td>
</tr>
</tbody>
</table>

^aCalculated as the exponential of the logistic regression coefficient

Table 11. Four combinations of independent variables were tested using the Akaike’s Information Criterion (AIC). The better model has a lower AIC value.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Number of Variables</th>
<th>AIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path Distance, Inundation Frequency</td>
<td>2</td>
<td>806.94</td>
</tr>
<tr>
<td>Density, Inundation Frequency</td>
<td>2</td>
<td>878.92</td>
</tr>
<tr>
<td>Path Distance, Density</td>
<td>2</td>
<td>944.52</td>
</tr>
<tr>
<td>Path Distance, Inundation Frequency, Density</td>
<td>3</td>
<td>674.78</td>
</tr>
</tbody>
</table>

Table 12. Results of the logistic regression analysis for predicting effects of three independent variables on river redgum mortality. The null deviance was 1,236.69 on 51 degrees of freedom and the residual deviance was 511.91 on 48 degrees of freedom.

<table>
<thead>
<tr>
<th>Independent variable</th>
<th>Coefficient</th>
<th>Standard Error</th>
<th>Z Value</th>
<th>p Value</th>
<th>Odds Ratios^a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path distance</td>
<td>0.000234</td>
<td>5.5e^{-3}</td>
<td>4.2</td>
<td>P&lt;0.001</td>
<td>1.00023</td>
</tr>
<tr>
<td>Inundation Frequency</td>
<td>-0.0476</td>
<td>4.1e^{-3}</td>
<td>-11.6</td>
<td>P&lt;0.001</td>
<td>0.95</td>
</tr>
<tr>
<td>Density</td>
<td>-0.6535</td>
<td>7.1e^{-2}</td>
<td>-9.2</td>
<td>P&lt;0.001</td>
<td>0.52</td>
</tr>
<tr>
<td>Constant</td>
<td>-0.1387</td>
<td>0.15</td>
<td>-0.9</td>
<td>P=0.357</td>
<td></td>
</tr>
</tbody>
</table>

^aCalculated as the exponential of the logistic regression coefficient
Figure 29. Spatial variation of three predictor variables for river redgum condition across the floodplain: (a.) path distance parameter; (b.) inundation frequency parameter; and (c.) earthworks density parameter. The larger circles represents sites with a significant $t$-value ($t < -2, t > 2$).
Figure 30. The regression coefficient relating density to river redgum mortality is primarily negative in the Southern Section and positive in the Northern Section, although not statistically significant. Increasing the density of earthworks in the Southern Section may decrease the probability of dead river redgums, but increasing the density of earthworks in the Northern Section may increase the probability of dead river redgums.
regression and the Pearson’s $R^2$ statistic of goodness-of-fit was excellent in some regions ($R^2 = 0.99$) but not others ($R^2 = 0.34$).

**Discussion**

*Extent and Distribution of Earthworks*

Using GIS landscape analyses, we identified 338km of levees, 1,648km of channels, 54 off-river storages and 664 tanks that could affect flows across a floodplain spanning 4,793km$^2$ in area (Table 4, Fig. 20). This is the first study in Australia to identify and explore the extent and distribution of earthworks on a dryland river floodplain. This assessment did not include elevated gravel roads and paved roads that cross the floodplain and may also affect flow.

Most levees (68%), channels (73%) and off-river storages (67%) were in the Southern Section (representing 42% of the entire study area) mainly for flood protection and the provision of water for irrigation. The average density of earthworks in the Southern Section (799m km$^{-2}$) was higher than the Northern Section (254.7m km$^{-2}$) (Table 4). Levees and channels in the Northern Section were more singular and elongated in shape, except in two irrigated areas (Fig. 20). They were primarily for stock and domestic supply, erosion control and diverting flows around wetlands. Tanks (664) were distributed across the entire floodplain for stock and domestic supply. Earthworks showed significant potential to affect flow distribution and allow development of the floodplain. Further, the upstream floodplain (Narromine to Warren) was not assessed so the amount of development on the original floodplain of the Macquarie would be considerably greater.
Temporal Trends

There was a clear trend in the development of earthworks with the most significant overall increase occurring after 1981 (Fig. 23). Before the construction of Burrendong Dam in 1967, the number and rate of development was slow. Flows were largely unregulated and small tanks for stock and domestic water supply were the main structures potentially affecting flow on the floodplain. The rate of irrigation development escalated after 1982 when the length of levees and channels was double 1949 levels (577m km⁻²), a period of growth in the irrigation industry with guaranteed supply from Burrendong Dam (Fig 11) that stimulated the development of earthworks for irrigation. Development in the Southern Section was greater than the Northern Section (Table 4). This corresponds with the prohibition of irrigation earthworks in the north in the 1980s (Fig. 20) (DLWC and NPWS, 1986; Millington, 1985) but not in the south. The non-irrigated areas, predominantly in the Northern Section, experienced a slower, incremental rise in development (Fig. 23). The rate of development continued at a slower rate during the mid-1990’s, coinciding with the introduction of the 1995 Murray-Darling Basin Commission Cap (MDBC Cap) designed to limit surface water extractions from the river basin at the 1993/94 levels (MDBC, 2004). Further development after the Cap (at least 240km of levees and channels and two off-river storages) could increase surface water extractions beyond the levels identified for the MDBC Cap.

Connectivity

Half of the world’s larger rivers are regulated by dams, weirs and floodplain earthworks (Nilsson et al., 2005) that remove hydrological connectivity in two main ways. Firstly, upstream regulation and floodplain earthworks reduce flooding extent
and frequency, dampen the temporal variability of flows by reducing peak flows
(Kingsford, 2000) and shift the timing of flood from winter-spring to spring-summer
(Maheshwari et al. 1995). Secondly, earthworks recontour the landscape and
physically block surface flooding and alienate sections of the floodplain from fluvial
processes. They also allow the floodplain to be developed for agriculture. Between
1979 and 2006, 61.5% of the original Macquarie floodplain was disconnected from
flooding during Spring - Summer (Table 8; Fig. 24): 73.04% in the South Section
was alienated by earthworks and upstream river regulation; and 53.2% in the
Northern Section was alienated by upstream river regulation, increasing dry periods
and a small number of earthworks.

Unlike dams that impose catchment-scale changes, earthworks on the floodplain are
site-specific flow controllers that modify flow pathways on the floodplain,
controlling natural flow and its lateral connectivity. Earthworks prevent overbank
flows from spreading across the floodplain (Schumm, 2005), reducing the stream
power to zero outside the earthworks (Gergel et al., 2002) and disconnecting active
pockets of the original floodplain from fluvial processes. For the Macquarie, we
found levees enhanced drying and alienated parts of the original floodplain,
particularly in the Southern Section. Our results were probably conservative of
impacts, as water pooled behind levees (two instances), presumably after rain. The
pooled water could not flow back to the main channel because lateral connectivity
between the floodplain and the river was blocked by levees. Also, lack of
information on levee age biased results towards less impact. Levees constructed after
1979 when the inundation frequency was available had less time to affect inundation
patterns.
While earthworks have severed floodplain vegetation communities in the intensively developed Southern Section, river redgum mortality in the Northern Section is caused by reduced flows, a different form of hydrological connectivity loss. One third of river redgums sites in the Northern Section were dead due to upstream water extractions and drought, even though they were well-connected to the river.

Alienation of the floodplain by dams and earthworks has caused flood-dependent communities relying on frequent overland flows to become water-stressed (Brereton et al., 2000; Kingsford, 2000; Bacon et al., 1993). Some vegetation requiring flooding most years has not been flooded since 2000 (Johnson, 2005). River redgums at 9% of sampled sites on the floodplain were all dead (Fig. 27) because the underlying fluvial processes supporting the plants dependent on inundation (Bond and Lake, 2003; Pressey and Middleton, 1982) have been fragmented or removed. Consequences of habitat patchiness from clearing and urbanisation are reasonably well known (Saunders et al., 1991) but fragmentation of the underlying floodplain processes is less well studied. The poor kappa statistic ($K_{HAT}=0.263$) for the river redgum classification (Byrt, 1996) was probably related to observer inconsistency in classifying the median categories, making the reference data unreliable. Further sources of error were potential duplicate sampling of the same tree, lens distortion causing trees in the centre of the photograph to be enlarged or observer estimates not in the same place as the photographs.

With the severance of hydrological connectivity, the floodplain loses its intrinsic transport system for energy, nutrients and organic matter, and consequently its
functionality (Lemly et al., 2000, Ward, 1989). Reduced flooding limits dispersal of biota on the floodplain (Jenkins and Boulton, 2003). Species richness was higher on riverbanks of a free-flowing river (9–28%) compared to a regulated river (4–12%) in Sweden (Andersson, 2000). Acute hydrological disconnection has led to terrestrialisation in desiccated regions of the Macquarie floodplain (Kingsford and Thomas, 1995) as flood-dependent species are displaced by dryland chenopods (Brander, 1987). On the River Murray, river redgums invaded hydrophytic grass communities in floodplains after flow regulation reduced flooding frequency (Bren, 1992). Vegetation communities migrate towards the channel as the frequency pattern of flooding reduces.

Connectivity effects of earthworks are also vertical. They decrease groundwater recharge by restricting the available surface area for infiltration and reducing localised and diffuse recharge (Eamus et al., 2006) stressing groundwater-dependent vegetation and wetlands (Amezaga et al., 2002). Upstream regulation and water extractions further attenuate groundwater recharge via the Macquarie Channel bed, a primary recharge area on the floodplain (DNR, 2006).

The severe extent of vegetation habitat decline (Fig. 26) has been associated with biotic effects (Lemly et al., 2000). The numbers of waterbirds and species of birds has declined between 1983 and 1995, and there are now an estimated 100,000 fewer nests over a period of 11 years (Kingsford and Johnson, 1998), linked to reduced water flows (Kingsford and Auld, 2005) and degraded river redgum habitat. Populations of native fish such as silver perch Bidyanus bidyanus and freshwater
catfish *Tandanus tandanus* have diminished due to reduced water levels (DLWC and NPWS, 1996).

Artificial channels or wetlands do not repair alienated floodplains. They do not allow overbank flow and they are narrower and straighter than natural channels (Fig. 31). The Bypass Channel in the northern Nature Reserve shortened the Macquarie River (Kingsford, 1999) and redirected flows around the wetland to supply regulated flow primarily for stock domestic supply (Fig. 32) (Johnson, 2005; DLWC and NPWS, 1996; WRC and NPWS, 1983). Such functionally simple artificial channels may conform more to European riverine productivity models than those flow models for dryland systems, underpinned by complexity, hydrological variability and floodplain connectivity. Current non-equilibrium models for dryland river systems need to explicitly incorporate four-dimensional hydrological connectivity and a broad, system-based approach to the interconnections of hydrology, geomorphology and ecology to adequately assess future change in Australia (Kingsford, 2000).

Off-river storages and flow diversions artificially enhanced the floodplain connectivity by trapping water in areas not previously subject to such high flow frequency or duration (Fig. 16). In the lower River Murray, excess recharge from upland irrigation has formed a groundwater mound, increasing waterlogging and salinisation (Doble et al., 2006). Off-river storages do not function ecologically like natural wetlands because prolonged flooding kills floodplain eucalypts and produces low waterbird densities and reduced complexity in the food web (Kingsford et al., 2006a). Also, artificially connected habitats are ideal for invasive organisms, such as exotic plants, pathogens, algal blooms and fish (eg. European carp *Cyprinus carpio*)
Figure 31. The constructed Northern Bypass Channel is more hydraulically efficient at delivering flows downstream for irrigation and providing stock and domestic supply, compared to the natural, meandering channels that feed into the Northern Nature Reserve of the Macquarie Marshes.

Figure 32. The 18km Northern Bypass Channel diverts flow away from the inner wetlands (green in the false-colour Landsat 1994 composite) of the Macquarie Marshes Northern Nature Reserve. The Bypass Channel rejoins the Macquarie River downstream (north) of the Nature Reserve.
to exploit new pathways (Freeman et al. 2007; Pringle, 2001) and colonise with little competition from natives.

The high density of earthworks in the Southern Section decreased significant lateral and vertical connectivity but also increased connectivity to a small part of the floodplain (Fig. 24). Levees and channels confined flood pulses (Fig. 20), where the density of earthworks was high (Fig. 28c) and riparian corridors of the Macquarie River were constrained to a minimum width of 0.13km by earthworks (Fig. 33). Earthworks reduce the cross-sectional area, so peak flood levels, flow velocities and drainage times increase for a given flow magnitude. For the South Section, the flood peak probably arrives sooner and passes quicker, as outflows match inflows; a 10% reduction in the corridor area is predicted to raise the flood stage by 100mm (DNR, 2006). The restricted flow corridor can increase total flow volume in the confined area and peak flow because water no longer reaches the floodplain, increasing the potential for flows to damage infrastructure, including roads and houses.

Increased flow velocities also scour loose-boundary channels (Schumm, 2005). For example, Marthaguy and Monkeygar Creeks have become incised (Brander, 1987), further reducing floodplain flows for a given water volume. Some earthworks are constructed to restore the ecosystem. A small levee built along Monkeygar Creek near the southern Nature Reserve prevents water from running back into the creek and exacerbating erosion. Monkeygar Creek was so deeply eroded and incised (Fig. 34) that it threatened to drain an adjacent waterbird breeding site with reed beds Phragmites australis and water couch Paspalum distichum. Tailwater surge and irrigation recycling water could maintain tree health in some isolated patches of the
floodplain (Fig. 35) and contributed to unexplained spatial variances.

In some areas of increased connectivity and dense earthworks (Southern Section), river redgums were in good condition compared to open, less-developed stretches of the floodplain (Fig. 35). Increased vegetation growth within artificially narrowed, well-nourished designated floodways can increase hydraulic roughness and reduce floodway ‘efficiency’ (DNR, 2006), posing a risk to adjacent property during flood. This problem was recognised in the 2006 Draft Macquarie Floodplain Management Plan (FMP) which recommended thinning if vegetation density exceeded the 2000 flood benchmark, to maintain a density of about 10% over a 50m reach of the floodway (DNR, 2006). No quantitative data were provided for this assessment or from where costs would be met. Elsewhere, higher flow velocities than natural levels reduce species richness and diversity by flushing seeds and scouring plants (Merritt and Wohl, 2002; Nilsson et al., 1999), an effect exacerbated with high embankments (Bombino et al., 2007). For the Macquarie floodplain, flow velocity and frequency for river redgums was probably not sufficiently high to produce such an effect. Accuracy errors of the river redgum mortality assessment and vagaries at the microscale of the watercourse layer (accuracy unknown) contributed to the unexplained variance.

**Policy and management implications**

Scientific models of hydrological connectivity differ from administrative and legal definitions (Freeman et al., 2007). A policy decision to designate only the north as a floodplain (Fig. 20) eventually protected it from development (Millington, 1985; DLWC and NPWS, 1986) but that did not protect the Southern Section from
Figure 33. Earthworks in the Southern Section have constricted the riparian corridor of the Macquarie River to a width of 0.13km.
Figure 34. Channel deepening and incision in the Monkeygar Creek leads to reduced flooding and draining of adjacent wetlands (May, 2006).

Figure 35. Black box enclosed by irrigation works are alienated from fluvial processes. This vegetation patch relies on tailwater surge, irrigation recycling water, rainfall and groundwater to maintain health.
development, even though the hydrology and the flood-dependent ecological communities were similar (Fig. 12a; Fig. 12c). Integrated, specialist policies for managing dryland rivers are required, not different legislative and policy documents that separately governed the development and protection of the Macquarie River and its tributaries and distributaries (Johnson, 2005).

The Guidelines for Floodplain Development (Narromine to Oxley) (WRC, 1978, WRC, 1982) retained riparian corridors to convey flood pulses but were primarily aimed at assisting with agricultural development in the Southern Section of the floodplain (Johnson, 2005). Subsequent irrigation development advocated by the policy direction constrained flows and fragmented the adjacent floodplain from the river (Johnson, 2005). Our analysis of satellite imagery showed that 101km of levees, 368km of channels, 16 off-river storages and 69 tanks are presently within the designated floodway of 1982, breaching the guidelines’ recommendations. The 2006 draft floodway network includes 88km of levees, 338km of channels, 8 off-river storages and 84 tanks which may be removed or modified using public funding assistance (DNR, 2006). The vision for the 2006 FMP was to coordinate floodplain development to minimise flood risk to occupiers and users of the floodplain while addressing environmental, social and economic interests of the Macquarie River Valley (DNR, 2006). The FMP failed to adequately recognise the need for connectivity beyond the floodway network boundaries, or the potential loss of connectivity and its ecological impacts. Policies and regulations that govern water resource development need to address hydrological connectivity to protect valuable wetlands.
Some earthworks continue to divert flows from the river, harvest water from the floodplain or trap surface flow unintentionally. The MDBC Cap was implemented in 1994 to limit increasing water diversion redirecting of water supplies from the main channel and impacting on river ecology (MDBC, 2004), however there were 240km of earthworks and two off-river storages built between 1994 and 2005 (Fig. 23) detected across a 1210km² area of the floodplain. The MDBC Cap is poorly measured or assessed in relation to the Macquarie River floodplain or its distributaries. Such development potentially increases water diversions, breaching the MDBC Cap and eroding environmental flows for the Macquarie Marshes.

Environmental flows, purchased from irrigation industry by the NSW Government (DECC, 2007), need to be protected to reach their target ecosystems. Some current earthworks may intercept such flows. Removal of earthworks or setting them back from the river (Florsheim et al., 2006, Galat et al., 1998) would reduce artificial water diversions, reduce channel scour and may permit floodwaters to reconnect the fragmented floodplain and promote revegetation of the original floodplain. Not all earthworks are detrimental. Some earthworks, including levees and weirs, control erosion and direct localised flows to stressed vegetation.

Worldwide, development on large floodplains has altered hydrological connectivity and threatened valuable ecological communities. The regulated Missouri River in the United States is largely disconnected from its floodplain by levees to allow for river navigation and mitigate floods (Galat et al., 1998) with significant ecological impact, as on the Wisconsin floodplain (Gergel et al., 2002; Kang and Stanley, 2005), the Mkuze River of South Africa (Ellery et al., 2002) and the Meuse floodplain in
Belgium (van Looy et al., 2003). Recognition and restoration of hydrological connectivity is essential for sustaining ecologically rich ecosystems of the Murray-Darling Basin and other dryland floodplains of the world.

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