The Effect of regulating the Lachlan River on the Booligal Wetlands – the Floodplain Red Gum Swamps

February 2009

Jessica L. Armstrong, Richard T. Kingsford & Kim M. Jenkins

Wetlands & Rivers,
School of Earth & Environmental Sciences,
University of New South Wales, NSW 2052

Table of Contents

List Of Tables i

List Of Figures ii

Executive Summary 1

Introduction 3

Study Area 7

2.1. The Lachlan River 7

2.2. The Booligal Wetlands 9

Methodology 11

3.1. Rainfall 11

3.2. Hydrological Analysis 12

3.2.1. Daily flow duration curves 12

3.2.2. Flow-spell analysis 13

3.2.3. Monthly flow analysis 14

3.2.4. Percentage flow analysis 14

3.3. Vegetation Analysis 15

3.3.1 Experimental Design 15

3.3.2. Aerial photography 16

3.3.3. Image processing 16

3.3.4. Image interpretation 17

3.3.4. Field assessment 18

3.4. Statistical analyses 22

Results 26

4.1 Climate 26

4.2. Volumetric Changes 27

4.2.1. Changes in daily flow duration..33

4.2.2. Changes to seasonality..38

4.2.3. Changes in flow thresholds..40

4.3. Vegetation Change..42

4.3.1. Aerial photo interpretation..42

4.3.2. Comparison of field data and API..47

4.3.3. Current red gum condition..49

Discussion..56

5.1 Changes to flow volume..56

5.2. Ecological effect on the Booligal Wetlands..59

5.3. Other hydrological changes to flow..62

5.4. Management implications..64

5.5. Summary..67

Acknowledgements..69

References..70

List Of Tables

Table 1. Two-way analysis of variance (ANOVA) design for aerial photo visual estimates of canopy cover

Table 2. Three-way ANOVA design for assessing current condition of river red gum vegetation

Table 3. Results of simple linear regression analyses for the annual proportion of flow reaching downstream gauges from upstream gauges

Table 4. Descriptive statistics for the annual proportion of flow reaching downstream gauges from upstream gauges

Table 5. Two-way ANOVA results for API visual estimates

Table 6. Comparison of accuracy for two aerial photo methods (visual and point count)

Table 7. One-way ANOVA results for field survey

Table 8. Three-way ANOVA results for assessing current condition of river red gum vegetation

List Of Figures

Figure 1. Map of study site

Figure 2. Experimental design for API visual estimates of cover

Figure 3. Experimental Design for field assessment

Figure 4. Diagram of $25m^2$ quadrat used in the field

Figure 5. Annual rainfall index cumulative deviation from the mean

Figure 6. Annual flow at Forbes and Booligal

Figure 7. Proportion of flow reaching downstream gauges from upstream gauges

Figure 8. Daily flow duration curve for Booligal

Figure 9. Daily flow duration curve for Condobolin

Figure 10. Daily flow duration curve for Boorowa

Figure 11. Seasonal monthly flow comparison at Booligal

Figure 12. Daily spells analysis at Booligal

Figure 13. Aerial photo interpretation results – visual method

Figure 14. Aerial photo interpretation results – point count method

Figure 15. Comparison of ground truth data and aerial photo estimates

Figure 16. Current condition of river red gums

Plate 1. Current images of Murrumbidgil Swamp (2008)

Plate 2. Current images of Lower Gum Swamp (2008)

Plate 3. Current Images of Top Gum Swamp (2008)

Plate 4. Current Images of Lachlan River Gums (2008)

Executive Summary

River gums *Eucalyptus camaldulensis* are increasingly signifying the significant decline in the ecological health of rivers and their floodplains. This long-lived species, sometimes living up to hundreds of years has survived long periods of drought in Australia's history but the impacts of river regulation and diversion and the current drought has caused high mortality of river red gums along the rivers of the Murray-Darling Basin. Extensive river red gum areas have died along the River Murray, Lowbidgee floodplain on the Murrumbidgee River and also in the Macquarie Marshes. Little is known of the health of river red gums on other river systems in the Murray-Darling Basin.

We focused our research on the relatively poorly studied Lachlan River in southern New South Wales and investigated the ecological health of river red gums within in a group of its more significant wetlands, the Booligal Wetlands. These wetlands are extensive covering about 15,000 ha. They are nationally important and are recognised for the large waterbird colonies they can sustain. They form a part of the extensive lower Lachlan river wetlands and rely on river flows from the upper Lachlan, with the tributaries of the Belabula and Abercrombie Rivers. These wetlands integrate long-term changes to the river system. We investigated more than one hundred years of rainfall patterns and hydrological changes to the Lachlan River and the supply of water and the impacts of the changes to the river red gum swamp communities within the Booligal Wetlands. We analysed the available sequence of aerial photographs, spanning 35 years (1973-2008) to determine trends in river red gum health backed up with ground truthing.

There are 10 large dams and 323 weirs within the Lachlan Catchment, an extensive system of canals, regulators, pumps and off-river storages that allow for the diversion of water from the river. We found no long-term decline in catchment rainfall where most flows for the Booligal Swamps are generated but there were significant declines in the Lachlan River's flow have profoundly affected the ecology of the Booligal red gum swamps and these changes have coincided with the increasing impacts of major river regulation and diversion

of water for irrigation. The proportion of annual flows reaching Booligal from Forbes has significantly decreased by 50% (from 30 to 15 %) in volume 1894-2007, coinciding with the period when extraction of water from the river was maximised. The range of flows has also halved with river regulation. Low flows have increased, while the number of periods with zero flow has decreased. With full development of extraction (1982-2007), the frequency of large floods to the Booligal Wetlands has decreased by 50%, compared to when the river was unregulated. The number and duration of key flood forming flows (800 and 2,500 ML d-1) at Booligal has decreased by 40%. Also the seasonality of flows has changed. Before regulation, monthly flows at Booligal were substantially lower during summer (December-February) and autumn (March-May) months, before increasing significantly during winter (June-July), and finally decreasing steeply during spring (September-November). After dams were built and water diverted, summer flows were significantly higher (>55%) while winter flows were lower than unregulated conditions.

Flooding of the Booligal Wetlands now occurs less frequently, for shorter durations and at different times of the year compared to before development. This has detrimentally affected the red gums in the swamp with high mortality of trees. We estimated that tree canopy cover had decreased by 85% over 12 years (1993-2008). This decline accelerated in the last three years (2005-2008). In contrast, 'control' river red gums along the river although affected by the drought with a recent loss of canopy cover, remained mostly alive. All swamp sites had more dead trees than living trees in each size class. On ground assessment showed that most red gum trees were dead, while remaining live trees showed signs of severe water stress. The river red gums are the most obvious and measureable effect of ecological decline but many other dependent organisms such as waterbirds, native fish species, frogs, reptiles, other plants and invertebrates are likely directly or indirectly affected by these changes.

The Booligal Wetlands are in severe decline and without significant improvement of river flows to these wetlands, the chances of rehabilitation will be poor. Investment by governments in the buyback of irrigation licenses offers some opportunity to rehabilitate these nationally important wetlands.

INTRODUCTION

Desert or dryland areas cover almost half of the world's land surface (Kingsford, 2006). These areas experience low rainfall (less than 500 mm per annum) which is variable in both space and time (Gordon et al., 2004a). The dryland rivers that flow wholly or partly through these regions, encompass some of the most biologically diverse ecosystems in the world (Adger & Luttrell, 2000; Zedler, 2000; Ando & Getzner, 2006). However, in comparison to mesic rivers, they remain largely unstudied (Kingsford, 1995). Dryland rivers experience highly variable flows (Puckridge et al., 1998). Low or zero flows are common, while extreme flows occur occasionally when high rainfall events produce large floods (McMahon & Finlayson, 2003; Jenkins et al., 2005). This intrinsic variability in flow regimes drive the ecology of these rivers and their associated floodplain wetlands (Puckridge et al., 1998), and make them especially vulnerable to changes associated with water resource development (Kingsford, 2006).

Human need for water has grown over the past century (Kingsford, 1995). To secure water supplies, dams have been built to divert the flows of many dryland rivers globally (Petts, 1990, 1992, 1996; Kingsford, 2006). This has significantly altered their flow regime (Kingsford, 2000a, b; Young et al., 2000a; Zedler, 2000). The effect is usually most evident downstream where floodplain wetlands, which rely on river flows, dominate the landscape (Mawhinney, 2003; McMahon & Finlayson, 2003; Lake et al., 2006). Dams usually reduce or eliminate flows to floodplains as they fill, capturing flood pulses and releasing water for diversions within the main channel (Puckridge et al., 1998). This creates a more permanent flow in channel habitats (instead of a wetting and drying cycle), and the loss of naturally high and low flows (Hollis, 1990; DWR, 1992; DLWC, 1997; Kingsford, 2000a; Young et al., 2000a; Driver et al., 2003; Petts, 2003; Driver et al., 2005). Over time the link between a river and parts of its floodplain can be severed with reductions reducing the volume, frequency and intensity of flows to them (Walker, 1985). These changes may be dramatic, usually quite sudden, and clearly discernible in the records (Kingsford & Thomas, 1995; McMahon & Finlayson, 2003).

Ecologically, floodplain wetlands are sites of high biodiversity, supporting many waterbird, native fish, invertebrate, aquatic plant and microbe communities (Crome & Carpenter, 1988; Crome, 1988; Kingsford, 2000a; Petts, 2001; Kingsford & Auld, 2005; Jenkins & Boulton, 2007). Most of these species depend on alternating wet and dry conditions to complete their life cycles, based on natural flow regimes of dryland rivers (Crome & Carpenter, 1988; Jenkins & Boulton, 2003). Regulation has reduced flood frequency and duration of floodplain wetland (Kingsford, 2000b; Jackson et al., 2001). As a result the amount of time that floodplain wetlands remain dry is increasing (Jackson et al., 2001; Jenkins & Boulton, 2007). This has impaired waterbird (Kingsford & Thomas, 1995, 2002; Kingsford & Thomas, 2004; Kingsford & Auld, 2005) and fish breeding (Puckridge et al., 1998), killed riparian vegetation (Bren & Gibbs, 1986; MDBC, 1990; Capon & Brock, 2006), and diminished invertebrate and macrophyte communities (Jenkins & Boulton, 2003; Jenkins et al., 2005; Jenkins & Boulton, 2007).

The Murray-Darling Basin (MDB), Australia's largest exorheic drainage basin (1,100,000,000 ha^2), supports a large wetland area (at least 4,000,000 ha^2), 89% of which is floodplain (Kingsford et al., 2004). Over the last 100 years major headwater dams have been constructed to support large agricultural areas, including extensive irrigation areas (Young et al., 2000a; MDBC, 2002). Prior to river regulation, floodplains along the Murray-Darling Basin filled from local run-off and riverine floods, drying as river levels fell and evapotranspiration exceeded inflows and local rainfall. Today many Murray-Darling Basin floodplains are degraded (Shields & Good, 2002; Jayasuriya, 2003; Mawhinney, 2003; Driver et al., 2005; Kingsford & Auld, 2005). Current rehabilitation efforts have turned towards providing environmental flows to restore ecological integrity to the system (McMahon & Finlayson, 1995; Papworth & Lewis, 2003; Schofield & Burt, 2003).

The Lachlan River forms part of the Murray-Darling Basin and has undergone a long history of regulation (DWR, 1992; Roberts & Sainty, 1996; DLWC, 1997; Hillman & Brierley, 2002) following construction of Lake Cargelligo weir in 1902. Currently there are 10 dams and 323 weirs within the Lachlan catchment (Kingsford et al., 2004) plus an extensive system of canals, regulators, pumps and off-river storages (DLWC, 1997; Hillman & Brierley, 2002). Intensive agriculture occupies more than 20% of the Lachlan Catchment area (Kingsford et al., 2004). Water for irrigation is extracted directly from the river or from regulated distributary streams, which provide water for 50,000–100,000 ha^2 annually (DLWC, 1997). Current average surface water availability is 1,139 GL^{-1} year and on average about 321 GL^{-1} year (or 28%) of this water is used (CSIRO, 2008). This is a moderately high level of development and includes surface water diversions (292 GL^{-1} year) and eventual streamflow leakage to groundwater induced by current groundwater use (CSIRO, 2008).

The Lachlan Catchment supports 471,011 ha of wetlands (Kingsford et al., 2004), 95% of which is floodplain, predominantly in the lower western region of the catchment (DLWC, 1997; MDBC, 2002; Kemp, 2004; Driver et al., 2005). Nine sites are listed in the Directory of Wetlands of National Significance, including the Booligal Wetlands (EA, 2001). The Booligal Wetlands provide important habitat for a wide variety of native flora and fauna, including migratory waterbirds protected under international agreements (Young et al., 2000b). They are well known for the large numbers of waterbirds that congregate to breed and forage in the area during and following floods (Magrath, 1992), and have been identified as among the most important in Australia for waterbird breeding (Blakers et al., 1984; Serventy, 1985; Maher, 1990). The regulation of the Lachlan River has decreased the amount of water reaching this system increasingly over time (Hillman & Brierley, 2002; Driver et al., 2003; Driver et al., 2005).

River red gums *Eucalyptus camaldulensis* form large monospecific forests on the floodplains within the Booligal Wetlands, and are integral to the ecology of these areas (Roberts & Sainty, 1996; Roberts, 2007). Tree hollows, fallen timber and twigs provide habitat for aquatic and terrestrial fauna (Maher, 1984; Maher & Carpenter, 1984; Crome & Carpenter, 1988; Crome, 1988; Briggs et al., 1993). The canopy moderates radiation and temperature, while the leaf and bark litter help to maintain a high carbon content in the soils (Briggs & Maher, 1983). The subsequent release of dissolved organic carbon (DOC) from these soils on re-flooding or on rising water levels helps sustain wetland productivity and support breeding of waterbirds (Maher, 1984; Maher & Carpenter, 1984; Crome & Carpenter, 1988; Crome, 1988; Briggs & Thornton, 1999). Red gums reflect the water regime gradient, and can be used as indicators of ecosystem health (Bren, 1987; Bren, 1988). As flood frequency decreases, tree height and canopy size become progressively smaller, and tree density decreases (Stewart & Harper, 2002). Major reductions in river flows have resulted in the deterioration in much of the riparian red gum forest in the Murray-Darling Basin (Briggs & Maher, 1983; Bacon et al., 1993; Briggs et al., 1997; Stewart & Harper, 2002; Driver et al., 2005; Roberts, 2007).

Identifying the relationship between the lower Lachlan wetland ecology and flow regime is a first step towards understanding the ecological responses to changes in flow, and future opportunities for rehabilitation (Kingsford, 2000a; Hillman & Brierley, 2002; DECC, 2008a, b). Knowledge of vegetation changes in response to changing flow regime is lacking, and in particular, ecological health of the Booligal Wetlands is poorly known. The NSW Government has bought water from the irrigation industry as part of its RiverBank program of $105 million with 10,800 ML potentially providing an opportunity for rehabilitation of the Booligal wetlands.

Our aim was to study the impact of an altered flow regime to the Booligal Wetlands using river red gum swamp habitats to identify changes in vegetation health over time. This study addressed two main objectives: i) identification of the impact of river regulation, including water extraction, on the Lachlan River's natural flow regime, focusing on the Merrimajeel/Muggabah Creek system; and ii) examination of the response of flood dependent riparian vegetation to river regulation. As ecological impacts of regulating rivers and diverting their water occur over long temporal scales (Kingsford & Thomas, 2002), we used two long-term data sets. Annual hydrological data were available over more than 100 years (1894-2007) to investigate changes in river flows. We also analysed a sequence of aerial photographs that span 35 years (1973-2008) to determine trends in river red gum health, coupled with ground truthing.

Study Area

2.1. The Lachlan River

The Lachlan River in central western NSW has an overall length of about 1,450 km, draining a catchment of 8,470,000 ha^2. It flows from the Great Dividing Range near Goulburn, where elevations reach 1,200 m above sea level (ASL), to the lower Lachlan wetlands including the Great Cumbung Swamp and the Booligal Wetlands (≤80 m ASL) (Figure 1). Rainfall averages 1200 mm per annum along the eastern part of the catchment, and 250 mm per annum in the region of the lower Lachlan wetlands, where evaporation greatly exceeds rainfall about 4:1 (DLWC, 1997). Rainfall variability increases from east to west, and summer rainfall is more variable than winter rainfall. The Lachlan River is influenced by northern and southern climates producing flows spread evenly throughout the year, but generally highest between June and October, and lowest in late summer (February-March) (DLWC, 1997). Major tributary rivers include the Belubula and Abercrombie Rivers, and distributary creeks include Willandra, Middle, Merrowie, Merrimajeel and Muggabah Creeks (Figure 1). The Lachlan River is a tributary to the Murrumbidgee River during large scale flood.

The major dam on the Lachlan is Wyangala Dam (1,220,000 ML, built 1931, enlarged 1971), at the junction of the Lachlan and Abercrombie Rivers (Figure 1). The Belubula River is regulated by Carcoar Dam (36,000 ML, built 1970), while Lake Brewster (153,000 ML, built 1951) and Lake Cargelligo (36,000 ML, built 1902) are en-route storages for maintaining a regulated flow in the lower Lachlan (Figure 1). Wyangala and Carcoar Dam regulate about 70% of runoff, while Lake Brewster and Cargelligo regulate about 30% of flows (Figure 1).

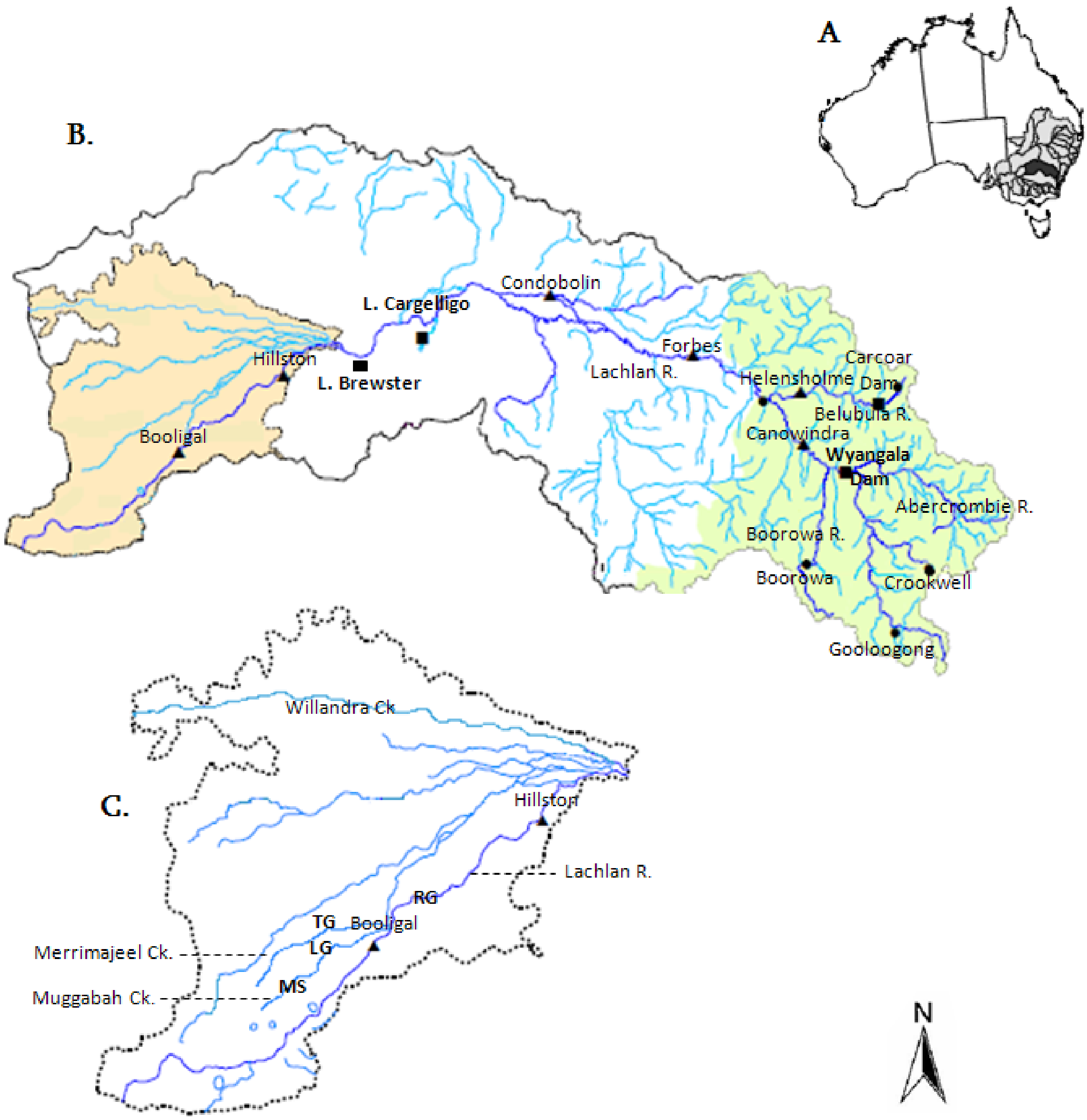

Figure 1. Map of Lachlan River catchment in the Murray-Darling Basin, Australia (A); Lachlan Catchment: major channels (dark blue), minor channels (light blue), major storages (black squares), weirs (triangles), rainfall stations (circles), lower Lachlan (orange shading), Upper Lachlan (green shading) (B); Lower Lachlan: Merrimajeel and Muggabah Creek channel, red gum sites (Murrumbidgil Swamp MS, Lower gum Swamp LG, Top Gum Swamp TG, Lachlan River Gum RG).

2.2. The Booligal Wetlands

The Booligal Wetlands on the lower Lachlan floodplain have an area of about 150,000 ha^2 with braided channels and depressions on and adjacent to Merrimajeel and Muggabah Creeks (Figure 1). Sheep and cattle grazing is the predominant land use around and within the wetlands (Magrath, 1992). The wetlands are temporary, that are inundated with moderate to large floods of the Lachlan system (DWR, 1992; DLWC, 1997; Driver et al., 2003; Driver et al., 2005). These sites are not responsive to creek flows below a threshold and so effects of river management on moderate and high river flows (peak, duration, or seasonality) are critical to inundation patterns and their ecological state (e.g. vegetation, waterbird use). Flooding is usually in late winter and spring, and many of the wetlands dry by late summer (Moore, 1992).

Merrimajeel and Muggabah Creeks are distributaries of Torriganny Creek, an anabranch of the Lachlan River that carries about 60% of the total Lachlan upstream of Booligal (Magrath, 1992; Wettin, 1997). They begin to flow when the Lachlan River at Booligal Weir (Figure 1) exceeds around 300 ML d^{-1}. As the flow increases above 800 ML d^{-1}, water spreads across the floodplain and the creek systems interconnect via flood-runners to inundate an extensive area of floodplain (Dwyer & Bennett, 1988). During these uncontrolled flows more water flows down Merrimajeel Creek than Muggabah Creek, but the reverse is true during controlled flows. Torriganny Weir (3.2 m) is a dropboard weir on the Torriganny Creek which allows regulated flows into Merrimajeel and Muggabah Creeks for 5-6 weeks during winter/spring. This provides local landholders with water for stock and domestic use (50 – 100 ML d^{-1}); flows are generally confined to single channels in the creeks (Moore, 1992).

Discrete wetlands retain water after Merrimajeel and Muggabah Creeks cease to flow, and support large stands of river red gum, including Murrumbidgil Swamp (MS) (33º52'32.48"S, 144º38'53.30"E), Lower Gum Swamp (LG) (33º50'14.11"S, 144º51.40.33"E), and Top Gum Swamp (TG) (33º45'19.11"S, 144º51'40.41"E) (Magrath, 1992; Moore, 1992; DLWC, 1997). These stands occur on heavy grey clay soils subject to frequent or periodic flooding and are usually depauperate in understorey species (Moore, 1992). These sites are especially important for colonial and non-colonial waterbird feeding and nesting sites for egrets *Egrettta intermedia, E. alba, cormorants Phalacrocorax sulcirostris, P. melanoleucos*, herons *Ardea pacifica, A. novarhollandiae, Nycticorax calefonicus*, ibis *Plegadis falcinellus, Threskiornis aethiopica, T. spinicollis,* spoonbills *Platalea regia, P. flavipes*, and ducks *Anas superciliosa, A. gibberifrons, A. rhynchotis, Chenonetta jubata, Oxyura australis* (Magrath, 1992).

Murrumbidgil Swamp (about 110 ha^2) on Merrimajeel Creek (Figure 1), is a potential target for environmental flows (DECC, 2008a, b). It has a distinctive internal topography, comprising a series of channels and mounds that reach a maximum depth of about 1.9 m. Lower (47 ha^2) and Top Gum Swamp (about 170 ha^2) receive water from Muggabah Creek (Figure 1) via flood runners. Compared to Murrumbidgil Swamp these sites are more evenly leveled in topography and have a maximum depth of about 1.6 m. These swamps stand out on the floodplain as they are structurally diverse within a relatively flat environment. We focused on these three red gum swamps to investigate how they have changed over time in response to an altered flow regime.

Methodology

3.1. Rainfall

Essential to an understanding of the nature of the Lachlan Catchment's hydrological regime is a consideration of the climatic changes that have occurred over the last century (Riley, 1988; Schreider *et al.*, 2002). About 82% of the runoff enters the Lachlan River originates in the eastern 20% of the catchment, specifically four subcatchments: the Upper Lachlan, Belubula, Boorowa, and Gooloogong (Wettin *et al.*, 2000). We used long-term annual rainfall data for the period 1894-2007 as an index of run-off. We averaged annual rainfall data for two weather stations per subcatchment (Upper Lachlan subcatchments: Gunning (070043) and Crookwell (070025); Belubula subcatchments: Blayney (063294, 063010) and Canowindra (065006); Boorowa subcatchments: Boorowa (070220) and Cowra (062031, 069091); Gooloogong subcatchments: Gooloogong (065019), and Eugowra (065013)), and then weighted the contribution of each subcatchment (Upper Lachlan: 821,500 ha^2, 61.1%; Boorowa: 221,400 ha^2, 16.5%; Gooloogong: 43,200 ha^2, 3.2%; Belubula: 258,000 ha^2, 19.2%) as a percent of total catchment area (1,344,000 ha^2). Annual rainfall for all these subcatchments were then added together to give a cumulative rainfall index (RI) per year.

The corrected annual rainfall index was examined for changes over the period 1894 to 2007. Variation in rainfall was investigated using a graph showing the cumulative deviation from the mean. We standardised annual RI data to a mean annual rainfall of 1.0 by dividing each annual RI by the mean annual RI (Riley, 1988). Cumulative deviations were calculated by accumulating the annual RI for each successive year and subtracting 1.0 at each step. The resulting time series of cumulative deviation from the mean shows those periods when rainfall were less than the mean (deviations decrease in value over time) and periods when flows were greater than the mean (deviations increase in value) (Van Der Wateren-De Hoog, 1995; Loth *et al.*, 2004). We used annual rainfall data for the 12 month period January-December to coincide with the flow data.

3.2. Hydrological Analysis

We investigated changes in daily, monthly and annual flow over time to the Booligal Wetlands. We used total daily flow data (ML d^{-1}) (NSW DNR, 2005; DWE, 2007) for five river gauges on the Lachlan River: Cowra (412002); Forbes (412004); Condobolin (412006); Hillston (412039); and Booligal (412005); one gauge on the Belubula River: Helensholme (412033); and one gauge on the Boorowa River: Boorowa (412029) (Figure 1). Daily flow values were transformed to monthly and annual (January-December) total flow values (ML) to investigate long-term changes in annual river flows. Hydrological data were only available from 1940-2007 for Forbes, 1896-2007 for Condobolin, 1942-2007 for Hillston, 1909-2007 for Booligal, 1938-2007 for Helensholme, and 1936-2007 for Boorowa. We used local polynomial regression (LOESS function), (Cleveland *et al.*, 1992) to estimate unknown yearly data using known upstream gauge values. LOESS function is used to do local regressions in R language. No long term (≥100 years) flow gauge exists on either Merrimajeel or Muggabah Creeks, thus flows into the Booligal Wetlands are based on data from the Booligal gauge, located on the Lachlan River. This gauge was used to estimate the amount of water entering the wetlands.

Describing the status and any trend in streamflow requires comparing current flows to unregulated flows over all flow regimes. We identified three distinct time periods where Lachlan River flows were affected by different levels of regulation: 1894-1930, 1931-1981, and 1982-2007. From 1894-1930 there were no major storages along the Lachlan River, and flows were mostly unregulated. From 1931-1981 (dams), flows were regulated by dams and off river storages such as Wyangala Dam, Lake Cargelligo, Lake Brewster and Carcoar Dam. From 1982-2007 many of the irrigation licences were taken up and fully developed and extraction was maximised (extraction maximised) (DLWC, 1997).

3.2.1. Daily flow duration curves

We produced mean daily flow duration curves (FDC) to compare the relationship between stream flow and the percentage of time it is exceeded at Booligal, Condobolin and Boorowa for the three time periods. An FDC provides a simple, yet comprehensive, graphical view of the overall historical variability associated with streamflow in a river basin (Vogel &

Fennessey, 1994). FDC is a function which gives flow (q), as a function of probability (p), i.e. q = q(p), where p is the probability that the specified flow is exceeded. We ranked annual flow measurements, (qi), with each corresponding p giving the percentage of days for which the flow value was equaled or exceeded (Searcy, 1959).

Daily FDC show more of the details of variation in flow data than monthly or yearly curves, where extremes are smoothed out through averaging (Donald *et al.*, 1999). Condobolin (1907-2007) and Booligal (1907-2007) were used to compare the effect of river regulation at an upstream and downstream site on the Lachlan River, while Boorowa (1936-2007) was selected as an unregulated stream to determine whether any changes in flow were related to climate. FDCs were constructed using all available daily flow data (ML d^{-1}) (Vogel & Fennessey, 1994, 1995), and any missing data were omitted. We presented each FDC using log-normal probability plots. This allowed each FDC to be linearised so that the low- and high-flow ends of the curve were clearly displayed (Gordon *et al.*, 2004a).

3.2.2. Flow-spell analysis

We used long-term daily flow data for Booligal to analyse flow spell patterns over time. FDCs give no information on how flows are distributed, and streams with similar FDCs may be very different in the way flows are grouped into long or short periods of time (Gordon *et al.*, 2004a). In contrast, flow-spells analyses can identify the timing, number, duration and intensity of a flow above or below a threshold, and it accounts for the sequencing of flows. Using Aquapak™ (Gordon *et al.*, 2004b), we calculated the number of times daily flows were above a specified flow threshold for the period of record. A 'commence to flow' (CTF) value of a wetland is the flow at the nearest river gauge at which a wetland starts to fill (from observations, wetland gauges or landholders). Three thresholds were selected for spells analysis: 300, 800, 2500 ML d^{-1} based on flows at Booligal gauge (Driver *et al.*, 2003) to investigate how the frequency and duration of small flows and moderate to large flood have changed over time (1898-2007).

We counted spells above each threshold as independent spells when they were greater than seven days apart (Gordon *et al.*, 2004a). Aquapak outputs the start and end date of a spell greater than a given threshold, so it is possible to analyse the frequency of spells above a certain height and also the duration of individual spells. We categorized the flow data into five year blocks starting at 1898-1902 and ending with 2003-2007. Within each five year period and for each threshold we counted the number of spells longer than specified durations (≥1, ≥3, ≥7, ≥14, ≥21, ≥28, ≥56 and ≥112 days). We then calculated the average (mean and standard errors) number of spells for all 5 year blocks before Wyangala Dam (1898-1932), after Wyangala (1933-1982), and when extraction was maximised (1983-2007). Data from 1928-1932 and 1978-1982 were not included in the analysis to create a gap between time periods (unregulated, regulated, maximized extraction), providing some independence.

3.2.3. Monthly flow analysis

To investigate the impact of river regulation and maximised extraction on the seasonality of flows we calculated mean monthly (Jan-Dec) flows at Booligal for each time period (1908-1930, 1931-1981, and 1982-2007).

3.2.4. Percentage flow analysis

Long-term (≥50 years) historical data for diversions were not available, so we calculated the volume (ML) of flows reaching downstream gauges from upstream gauges (Forbes to Condobolin, Condobolin to Hillston, Hillston to Booligal) as a percent (annual downstream gauge/upstream gauge*100) (Kingsford & Thomas, 1995) to provide an annual index of water extraction on the Lachlan River between 1894 and 2007. This provided an indirect assessment of reductions over time at the downstream gauge as a result of diversions to the major irrigation areas. We calculated these indices using all annual flow data (ML) for the 12 month period January to December.

3.3. Vegetation Analysis

3.3.1 Experimental Design

We used aerial photography to track the effects of changing flow regimes on floodplain vegetation condition, specifically river red gum communities along the Merrimajeel and Muggabah Creek system over a 35 year period (1973-2008). Aerial photography can effectively identify changes in riparian vegetation (Bowden & Brooner, 1970; Knapp *et al.*, 1990; Sickel *et al.*, 2004; Tickle *et al.*, 2006; Yang, 2007). In particular we compared changes in red gum swamp communities at five times (1973, 1993, 1998, 2005, and 2008) that spanned the regulated periods with dams (1931-1981) and maximised extraction (1982-2008). Using repeated measures, we sampled 40 points in the same swamp areas at different times and quantified changes in canopy cover (%) (Figure 2).

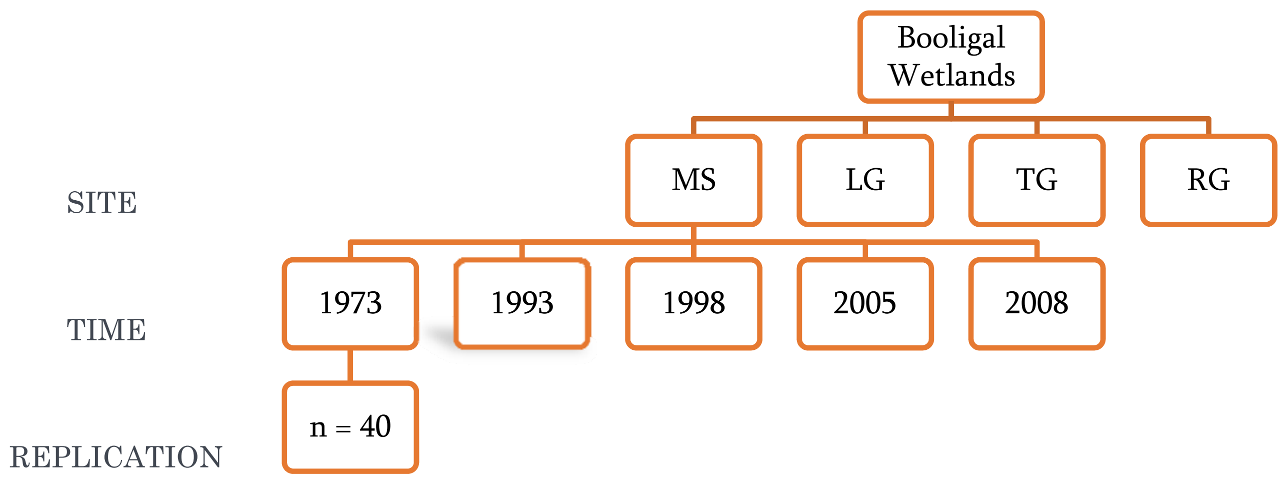

Figure 2. Hierarchical experimental design for visual aerial photo vegetation analysis showing the two levels Site and Time. There were four Site treatments: MS (Murrumbidgil Swamp), LG (Lower Gum Swamp), TG (Top Gum Swamp), RG (Lachlan River Gum); and five Time treatments (1973, 1993, 1998, 2005, and 2008). Each treatment was sampled 40 times (total n = 800).

We first mapped (pilot study – June 2008) vegetation types on the Booligal 7830 topographic map sheet (1:100,000) for aerial photo interpretation (API). Murrumbidgil Swamp (MS), Top Gum Swamp (TG) and Lower Gum Swamp (LG) were selected as red gum floodplain swamp sites expected to be impacted by regulation. Trees along the Lachlan River channel, river gums (RG), were selected as a control site as they were close to water and less likely to be affected by river regulation (Roberts & Marston, 2000; Roberts *et al.*, 2000).

3.3.2. Aerial photography

All available aerial photographs were obtained from the NSW Department of Lands and Vision Communicators™. These included five sets of 1:50,000 aerial photographs: one black and white set (18/7/1973) RC10 frame camera (87.80 mm focal length) at about 5365 m (ASL); three colour sets (22/8/1993, 17/3/1998, 20/7/2005), and flown at 7800 m ASL with an RC30 frame camera (157.8 focal length), and an additional colour set (26/8/2008) flown at 6500 m ASL with a CONTAX 645 digital camera. All photos were taken on cloud free days near noon when shadow effects were minimal. Several photos (3-5) were needed to fully cover the study area; (1973: film 2126, run 4/4, print 5200, 5174, 5204; 1993: film 4144, 4150, run 3, 4, 5, print 120, 137, 139, 143; 1998: film 4432, run 4, 5, print 190, 195, 230; 2005: film 4915, 4916, run 4, 5, print 21, 24, 29; 2008: commissioned flight, one photo per site). Other photographs of the site were available but taken at different scales making comparisons more difficult and so were not used (Fensham & Fairfax, 2007).

3.3.3. Image processing

High resolution film scans of all photographs from 1973-2005 were completed at a resolution of 2000 dots per inch (dpi) using a Leica DWS700 scanner and dodged as a 0-255 tonal file using Fast Dodge™. Film transparencies tend to have higher spatial resolutions and a greater range of grey values in comparison to paper prints (Kasser & Egels, 2002; Linder, 2003). Commissioned 2008 digital images had a 0.6 m pixel size. Each digital photograph was stored in tagged interchange file format (TIFF). Images were orthorectified using Leica Photogrammetry Suite component of ERDAS Imagine™ version 8.7 software and a 1:50,000 topographic map raster of the Booligal area (NSW Department of Lands).

This uses digital elevation model (DEM), ground control points (GCPs), and camera calibration data to remove radial, tilt, and relief distortions inherent in aerial photographs (Bowden & Brooner, 1970; Fensham & Fairfax, 2002).

We used a minimum of six GCPs per photo. The resulting images were projected in the Geometric Datum Australia 1994 (GDA94) zone 55 coordinate system. A cumulative root mean squared error (RMSE) of no more than 30 m was found for all image sets (1973, 1993, 1998, 2005 and 2008). We experimented with three different resampling algorithms (nearest neighbour, bilinear, and cubic convolution) at three resolutions (0.5, 1.0, and 2.0 m). The bilinear resampling with a 1.0 m pixel spacing best allowed identification of individual trees in the original images while optimizing file size and processing time(Danby & Hik, 2007). Differences in colour, brightness and contrast among images were corrected using Photoshop™. First we adjusted all colour images to grayscale for comparability over the full sequence, as colour was not available for early years. Then we corrected differences in brightness and contrast among individual images of the same year, and then corrected for brightness among different year images (Graham & Koh, 2002).

3.3.4. Image interpretation

Automated classification of panchromatic aerial photography for detecting vegetation change has been applied successfully to large-scale photography (≤1:20,000) (e.g. (Carmel & Kadmon, 1998; Kadmon & Harari-Kremer, 1999), but it becomes increasingly problematic at smaller scales (≥1:20,000) (Danby & Hik, 2007). Pixel-based image classification schemes based only on grey values may fail because of reduced variation in brightness among vegetation types, particularly in old photographs (Fensham & Fairfax, 2002). Shadows are also problematic for automated pixel-based classification of panchromatic images (Hudak & Wessman, 1998; Hutchinson *et al.*, 2000). Experience is growing with object-based classification (Liliberte *et al.*, 2004), but poor contrast in the 1973 photographs limited such application (Fensham & Fairfax, 2007). For these reasons we opted for user-based interpretation of digital images rather than an automated classification (Danby & Hik, 2007).

We quantified canopy cover (%) visually at random location in each of the sites. Using ARCGIS (ESRI) version 9.3 Hawth's Tool we generated 40 random points per site: MS, LG, TG, RG; for each time period: 1973, 1993, 1998, 2005, 2008. In total, 800 points were generated. We then used the grid overlay tool to establish 25m² grid layer oriented to the cardinal points (north, south, east and west). We used each random point to guide which grid was assessed. If a point fell on two grids, then we selected the grid to the west; if a point fell on more than two grids, we selected the grid to the north-west. Canopy cover (%) was estimated per quadrat visually using a standardised visual chart (SRA, 2008). Canopy cover was categorized into 11 classes: 0, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100%. The original photographic stereo pairs were used for interpretation providing a stereo view of the study sites in the third dimension (Fensham & Fairfax, 2002).

The visual (ocular) method for estimating canopy cover is relatively easy to use, but has known precision issues (Nowak *et al.*, 1996). To verify the visual estimates we also quantified canopy cover using the point count method to compare the accuracy of the visual canopy cover estimates. We generated a further 100 random points per site per time. Tree canopy cover was estimated by counting the number of points that fell on tree crowns compared with the total number of points in the area sampled. Tree canopy cover was calculated as % canopy cover = 100 x (dots falling on tree canopy/total number of dots within sampled area). These data were then compared to visual estimates and ground truth data. To minimise bias, all images were interpreted by one observer in a random order.

3.3.4. Field assessment

We compared field data that corresponded to the timing of the last image analysed to test the rigour of the methodology (29/8/08-3/9/08) (Figure 3). It was not possible to collect similar data for any of the historic images. First we generated 18 random points within each site (MS, LG, TG, RG) using ARCGIS Hawths Tool random point generator. We then located these points in the field (global positioning system (GPS), Trimble Pathfinder Basic+, ±2 m). Each point centered a 25 m² quadrat, orientated to the cardinal points using a handheld magnetic compass. At each point we laid out two 25 m tapes and 4 corner flags that included trees for measurement. we divided each 25 m² quadrat into six separate transect lines (Figure 4), as these produce precise estimates of vegetation cover (Hanley, 1978) at 0, 5, 10, 15, 20, 25 m along the northern edge of each quadrat. The transects ran in a north – south direction, making up 150 m of transect for each quadrat.

Using the point intercept method, we systematically measured tree canopy cover (%) visually at 2.5 m intervals along each transect using a crosshair vertical periscope (Dodd *et al.*, 2003), at 66 points per quadrat. The crosshair vertical periscope allowed unambiguous assessment of canopy as we could position it vertically and then where the cross hairs met, we could make an assessment. At each point percentage cover estimates were standardized using a visual chart (SRA, 2008) as a guide. We estimated canopy cover of each grid by averaging all 66 points per 150 m transect. Before sampling a series of digital photos of the canopy were taken in the field and calibrated between observers to minimise bias. This exercise was repeated at each site.

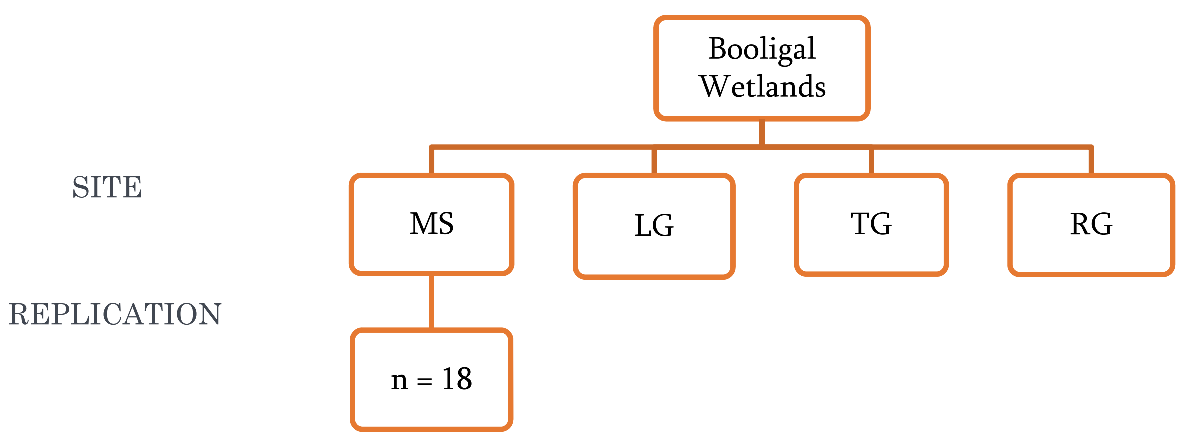

Figure 3. Experimental design of field assessment to compare red gum sites: MS (Murrumbidgil Swamp), LG (Lower Gum Swamp), TG (Top Gum Swamp), and RG (Lachlan River Gums) 2008. Each site was sampled 18 times (Total samples = 72).

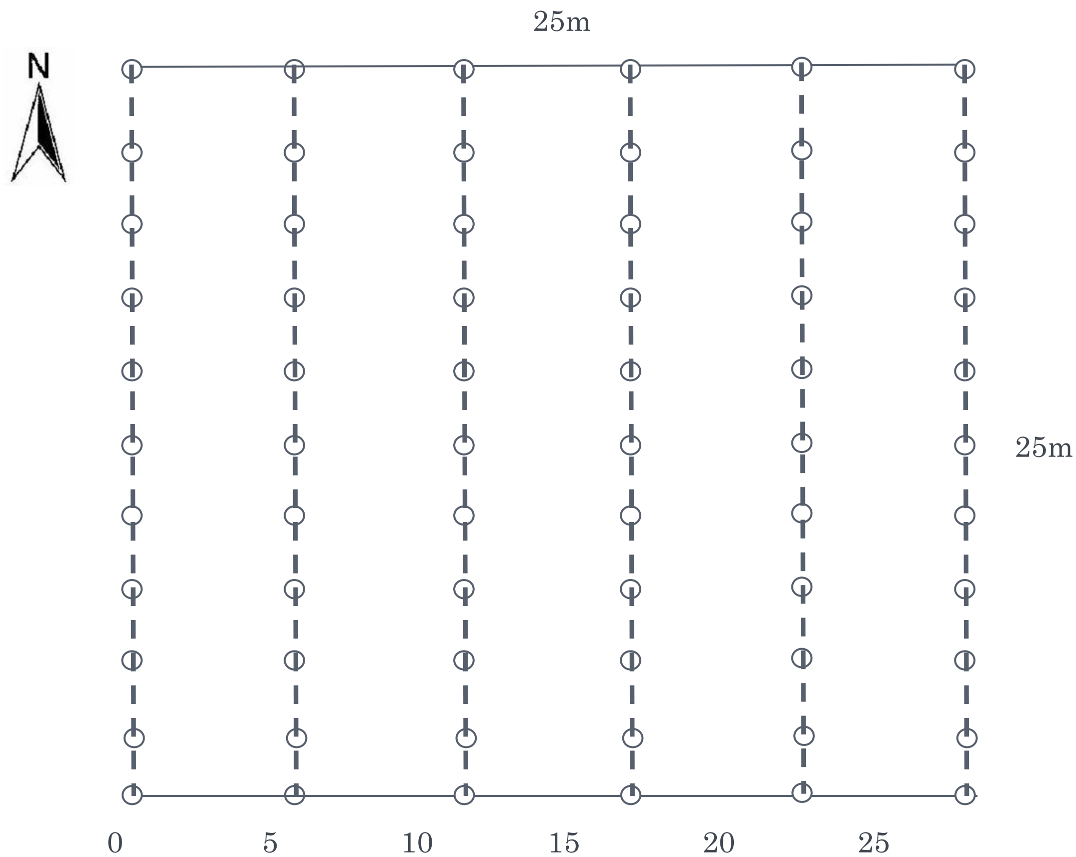

Figure 4. Diagram of 25m² quadrat used for field assessment. Dashed lines represent 6 × 25 m line transects orientated North-South direction. Open circles represent 66 × percentage cover points where tree cover was estimated at 2.5 m intervals along each 25 m transect (11 per 25 m transect).

We counted all trees within each 25m^2 quadrat, and grouped them into four diameter at breast height (DBH) size classes (10-50 cm, 50-100 cm and ≥100 cm) (Roberts, 2007) assessing if they were dead or alive. Dead trees had trunk bark peeled away and were devoid of green leaf growth; trees classed as alive exhibited green leaf growth and trunk bark condition was still intact (Cunningham *et al.*, 2007). From the assessment, we got an overall tree density count as well as a percentage live versus dead measure per quadrat. We also described understorey condition (presence/absence, species, and height), ground cover (density, composition), trunk bark condition of trees (peeling away of cork cambium), evidence of reproduction (flowers and buds) and disturbance (cattle, sheep, goats, rabbits, rubbish, and proximity to roads). Additionally we collected GCPs using a GPS for orthorectification.

3.4. Statistical analyses

We used linear regression analyses to investigate the effects of time (1894-1930, 1931-1981, 1982-2007) (independent variable) on changes in hydrology between different parts of the river (Forbes to Condobolin, Condobolin to Hillston, Hillston to Booligal) as a proportion of flow (%) (dependent variable). Residuals from regressions were examined to ensure that assumptions of analyses held. The Shapiro-Wilk normality test (Shapiro & Wilk, 1965) showed the data were not normal ($W = 0.897$, $P \leq 0.001$). Percentage flow estimates were arcsine-square-root transformed in all analyses to improve normality and to prevent dependence between the variance and the mean (Sokal & Rohlf, 1995). Assumptions of independence were not violated, but data were still not normally distributed. Linear regression is robust to assumptions of normality (Zar, 1999), and inspection of residual plots showed the data were not drastically skewed and so were used for the regression models.

Means of all API visual percentage cover data were compared using a two-way analysis of variance (ANOVA). Site (S) was a random factor while time (T) was a fixed factor, while and the dependent variable was percentage cover. Means of all API tree numbers were compared using a three-way ANOVA. This analysis used the measures of health (either dead or alive) and class (four DBH size classes) as categorical variables. Site (S) was a random factor and Health (H) and Class (C) were fixed factors. For both these ANOVAs, statistical models were produced with multipliers, mean square estimates, F-ratio denominators, and degrees of freedom (Tables 1 & 2). Equations for the variance of each term in the ANOVA model were applied for both random and fixed factors on the basis that arithmetically, the equivalent to a variance component can be calculated for fixed terms (Quinn & Keough, 2002). Means of all field cover data were compared using a one-way ANOVA. Site (S) was a random factor while percentage cover was the dependent variable with $n=18$ quadrats per site.

All statistical analyses were done using SYSTAT for Windows, Version 11.0 (SYSTAT, Evanston, Illinois, USA). Power of all tests was significant at $P = 0.05$. The relationship between the mean and variance as well as the residuals from the analysis was examined to check for heterogeneous variances and non-normality (Winer, 1991, Quinn & Keough, 2002). Tukey's tests were employed for the unplanned multiple comparisons (Day & Quinn, 1989).

Table 1. Statistical design for API visual analysis. Factor S has $i = a$ levels where a=4; factor T has $j = b$ levels where b=5. All combinations of 2 effects are replicated n times (r =40n). Factor Site (S) is random and factor Time (T) is fixed. Formulae to determine estimated mean squares (E(MS)), variance components, denominators for F-ratio tests (den.) and degrees of freedom (df) are shown.

Source of variation	Multipliers			E(MS)	Den.	df	Variance component
	i	j	r				
1. S_i	1	b	n	$\sigma^2_e + bn\sigma^2_S$	4	3	$\sigma^2_S = [MS_S - MS_e] / bn$
2. T_j	a	0	n	$\sigma^2_e + n\sigma^2_{S\times T} + an\sigma^2_{(T)}$	3	4	$\sigma^2_T = [MS_T - MS_{S\times T}] / an$
3. $S\times T_{ij}$	1	0	n	$\sigma^2_e + n\sigma^2_{S\times T}$	4	12	$\sigma^2_{S\times T} = [MS_{S\times T} - MS_e] / n$
4. $e_{r[ij]}$	1	1	1	σ^2_e		780	MS_e

Table 2. Statistical design for API visual analysis. Factor S has $i = a$ levels where a=4; factor H has $j = b$ levels where b=2; factor C has k=c levels where l=3. All combinations of 3 effects are replicated n times (r =40n). Factor Site (S) is random, while factors Health (H) and Class (C) are fixed. Formulae to determine estimated mean squares (E(MS)), variance components, denominators for F-ratio tests (den.) and degrees of freedom (df) are shown.

Source of variation	Multipliers				E(MS)	Den.	df	Variance component
	i	*j*	*k*	*r*				
1. S_i	*1*	*b*	*c*	*n*	$\sigma^2_e + bn\sigma^2_S$	7	3	$\sigma^2_S = [MS_S - MS_e] / bn$
2. H_j	*a*	*0*	*c*	*n*	$\sigma^2_e + cn\sigma^2_{S\times H} + acn\sigma^2_{(H)}$	4	1	$\sigma^2_H = [MS_H - MS_{S\times H}] / acn$
3. C_k	*a*	*b*	*0*	*n*	$\sigma^2_e + bn\sigma^2_{S\times C} + abn\sigma^2_C$	5	2	$\sigma^2_C = [MS_C - MS_{SxC}] / abn$
4. $S\times H_{ij}$	*1*	*0*	*c*	*n*	$\sigma^2_e + cn\sigma^2_{S\times H}$	7	3	$\sigma^2_{SxH} = [MS_{SxH} - MS_e] / cn$
5. $S\times C_{ik}$	*1*	*b*	*0*	*n*	$\sigma^2_e + bn\sigma^2_{S\times C}$	7	6	$\sigma^2_{SxC} = [MS_{SxC} - MS_e] / bn$
6. $H\times C_{jk}$	*a*	*0*	*0*	*n*	$\sigma^2_e + an\sigma^2_{HxC}$	7	2	$\sigma^2_{HxC} = [MS_{HxC} - MS_e] / an$
7. $e_{r[ijk]}$	*1*	*1*	*1*	*1*	σ^2_e		414	MS_e

Results

4.1 Climate

For the period that rainfall data are available (1894-2007), several wet and dry periods can be distinguished (Figure 5). The series begins with a succession of wetter-than-normal years until the late 1890s. There is a dry period from 1901-1916, an increase in rainfall to about the mid 1930s, a decrease to the mid 1940s and a very wet period to 1960. Rainfall is above average from 1958 to 2007, although within this time period there three periods of rainfall increase and decrease which peaked in 1962, 1978, and 1990. From 1990 to 2007 there is a declining trend in rainfall; however, the amount of rainfall is above the long term average.

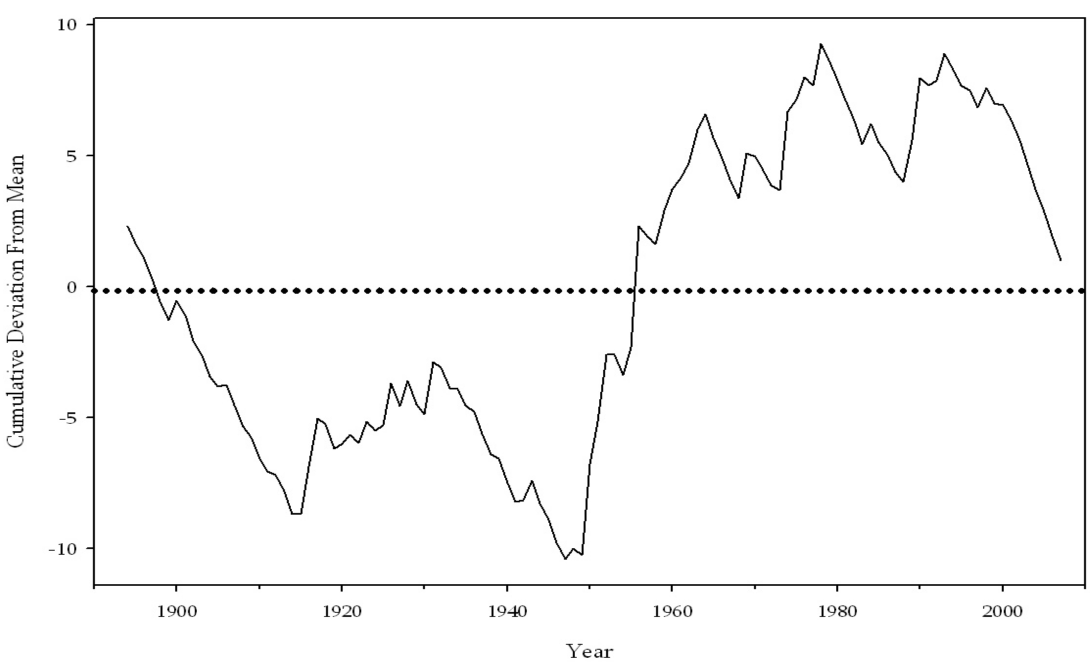

Figure 5. Cumulative deviation from mean annual rainfall index. All annual rainfall have been standardised to the mean annual flow for the total period of record (1894-007). Dotted line represents average rainfall.

4.2. Volumetric Changes

Before Wyangala Dam was built in 1931, annual flows at Booligal followed a similar pattern of variability and quantity to annual river flows measured at Forbes (Figure 6) but afterwards, the pattern of flows diverged in quantity although annual patterns of variability coincided. After 1971 when Wyangala Dam's storage capacity was increased and the construction of Carcoar Dam was complete (Figure 6), this trend intensified. The proportion of annual flows reaching Booligal from the Forbes have significantly decreased by 50% (from 30 to 15 %) in volume 1894-2007 (R^2=0.22, p=≤0.001, (percentage flow) =282.5-0.13 year) (Figure 6).

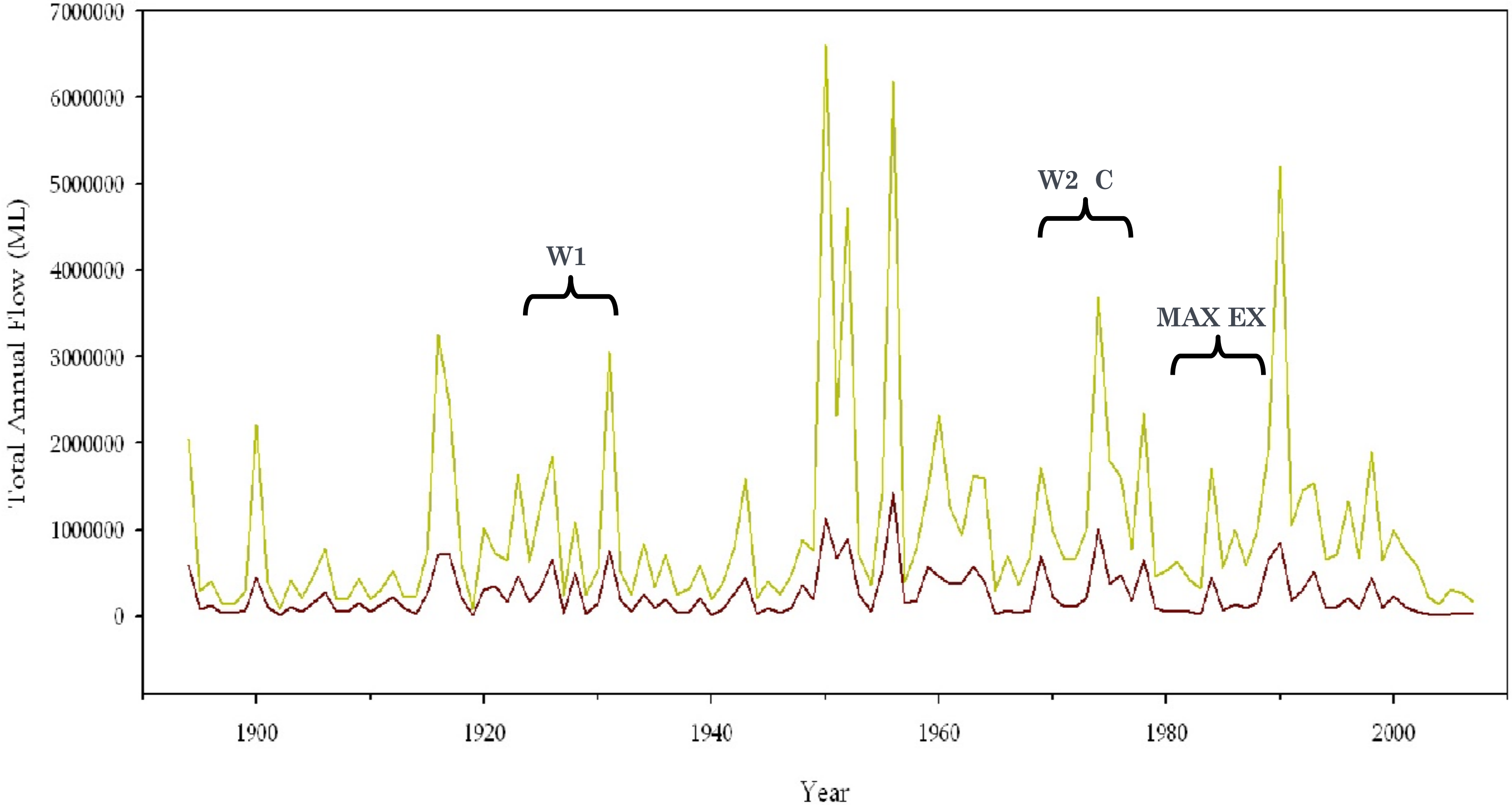

Figure 6. Annual flow (ML) at Forbes (green line) and Booligal (brown line) from 1984-2007. Brackets show the original construction of Wyangala Dam, 1931; the enlargement of Wyangala Dam (W2) and construction of Carcoar Dam (C), 1970; and maximised extraction (MAX EX), 1982.

The proportion of annual flows reaching downstream gauges from upstream gauges (Condobolin from Forbes, Hillston from Condobolin, and Booligal from Hillston) has generally decreased over time (Table 3, Figure 7). However, the percentage of the volume of annual flows reaching Condobolin from Forbes increased significantly over the 113 year period (1894-2007) (Table 3, Figure 7), resulting in about a 5% increase. There was no trend ($p \geq 0.05$) in flows between 1894-1930, 1931-1981 and 1982-2007 (Table 3). In contrast, the proportion of annual water reaching Hillston from Condobolin decreased significantly from 1894-2007 (Table 3, Figure 7,), resulting in about a 15% decline. There was no trend for flows in the period 1894-1930, 1931-1981, and 1982-2007 (Table 3).

The percentage of annual flow reaching Booligal from Hillston declined significantly over the 113 year period (1894-2007) (Table 3), reducing by about 50% (Figure 7). There was a significant decrease in flows (~20%) in the period after regulation (1931-1981). After extraction was maximised (1982-2007) this trend increased with about a 30% reduction in the proportion of flows reaching Booligal from Hillston. There was no trend for flows in the period 1894-1930, when the river was unregulated (Table 3).

As well, variability in terms of proportion of flows reaching downstream gauges has decreased over time for all gauge comparisons (Table 4). There is a progressive decrease in the range of flows for increasing regulation (dams and maximized extraction) for all gauges (Table 4). For all gauge comparisons, the range has more than halved. Maximum flows reaching Condobolin from Forbes have decreased and minimum flow increased (~550%) with extraction maximised. Minimum and maximum values of flows reaching Hillston from Condobolin have decreased with regulation while minimum flows to Booligal from Hillston have remained stable but maximum values have decreased over time (Table 4)

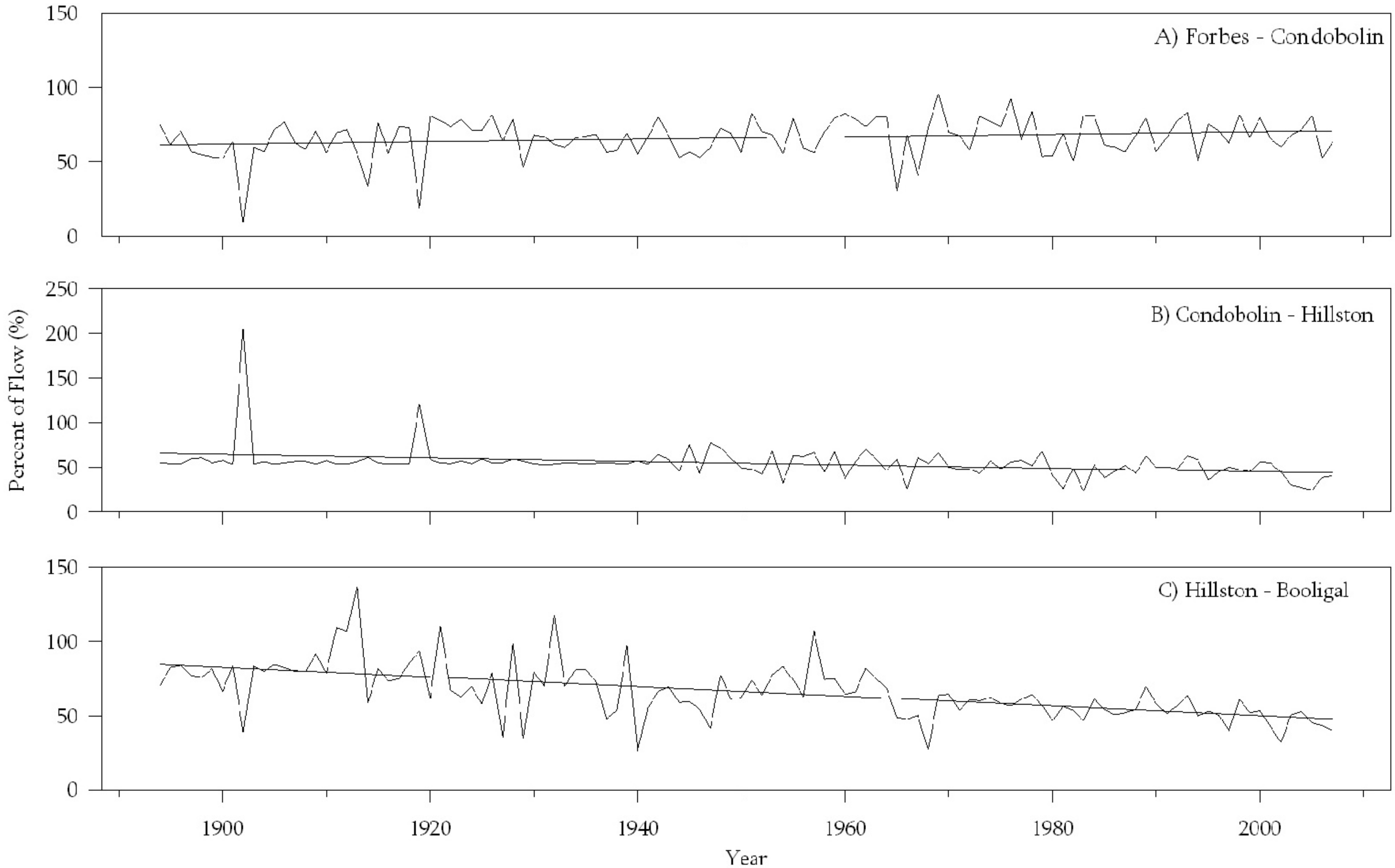

Figure 7. Percentage of annual river flows reaching downstream gauges from upstream gauges (1894-2007) :Condobolin from Forbes (a); Hillston from Condobolin (b) and; Booligal from Hillston (c).

Table 3. Results of simple linear regression analyses for the annual proportion of flow reaching downstream gauges from upstream gauges (Forbes to Condobolin, Condobolin to Hillston, and Hillston to Booligal) for four time periods (1894-2007, 1894-1930, 1931-1981, 1982-2007). Data were transformed by arcsine-square root.

	Time Period	R^2	Coefficient (Intercept)	Constant (Slope)	P Value
Forbes – Condobolin	1894-2007	0.0462	-0.361	0.000493	0.022
	1894-1930	0.0458	-3.116	0.00193	0.203
	1931-1981	0.0401	-1.107	0.000877	0.159
	1982-2007	0.00148	0.0684	0.000273	0.852
Condobolin – Hillston	1984-2007	0.113	2.870	-0.00119	≤0.001
	1894-1930	0.0128	4.077	-0.00183	0.505
	1931-1981	0.0457	2.318	-0.00910	0.132
	1982-2007	0.0654	4.861	-0.00219	0.207
Hillston - Booligal	1894-2007	0.314	3.906	-0.00169	≤0.001
	1894-1930	0.0244	3.538	-0.00150	0.356
	1931-1981	0.0821	3.892	-0.00169	0.041
	1982-2007	0.248	6.513	-0.00300	0.010

Table 4. Descriptive statistics (means, medians, min., max.) of the annual proportion of flow reaching downstream gauges from upstream gauges (Forbes to Condobolin, Condobolin to Hillston, and Hillston to Booligal) for three time period (1894-1930, 1931-1981, 1982-2007).

	Time Period	Mean ± SE (%)	Min (%)	Max (%)	Median (%)
Forbes – Condobolin	1894-1930	63 ± 3	9	82	68
	1931-1981	67 ± 2	31	96	68
	1982-2007	68 ± 2	50	83	68
Condobolin – Hillston	1894-1930	61 ± 4	53	205	55
	1931-1981	54 ± 2	26	77	54
	1982-2007	45 ± 2	23	62	46
Hillston - Booligal	1894-1930	78 ± 3	35	138	78
	1931-1981	65 ± 2	26	117	64
	1982-2007	51 ± 2	32	70	52

4.2.1. Changes in daily flow duration

Since regulation, the duration of daily flows within the Lachlan River has changed considerably. The most significant differences are at the low-flow end of the curves (Q_{70}-Q_{99}, 70th-99th percentile). Low flows have increased, while zero flows have decreased. This effect is similar at Condobolin (Figure 9) and Booligal (Figure 8) sites, but the impact is most severe at Booligal. Before regulation (1907-1930), the river ceased to flow 26% of the time at Booligal, and 9% of the time at Condobolin. After regulation (1930-1981), cease to flow decreased to 3% and 0.6% respectively. This trend continued after extraction was maximised (1982-2007) when no zero flow days were recorded at either Booligal or Condobolin (Figure 8 & 9). The 95% (Q_{95}) (95th percentile) low-flow after maximised extraction is two orders of magnitude more than the unregulated flows at Booligal (Figure 8). The number of flows exceeding Q_{50} (50th percentile) at Booligal have increased substantially since regulation, from 60% to 86% of the time under unregulated (1907-1930) and regulated conditions (1931-1981 and 1982-2007) (Figure 8).

High flows were less affected than low flows. The duration of large floods (≥25,000 ML d^{-1}) at Condobolin (Figure 9) and at Booligal (Figure 8) (≥3,000 ML d^{-1}), is similar to before regulation (1907-1930) and after regulation (1931-1981), occurring about ≤1%, and 9% of the time respectively. But after maximised extraction (1982-2007), the frequency of large floods at Booligal decreased by 50% (Figure 8). This pattern was not repeated upstream at Condobolin where the incidence of flows ≥25,000 ML was similar (≤1%) (Figure 9). Also after maximised extraction, high flows (Q_{10}) at Booligal decreased in magnitude by 50% compared to unregulated flows while upstream at Condobolin high flows (Q_{10}) remained the same (Figure 8 & 9).

Medium and low to moderate flows at Condobolin (3,000-25,000 ML d^{-1}) were not significantly affected by regulation or maximised extraction (Figure 9). In contrast, downstream at Booligal, medium size flows were reduced (Figure 8). Flows of 500 ML d^{-1} were exceeded 30% and 35% of the time under unregulated (1907-1930) and regulated (1931-1981) conditions respectively, but only 17% of the time after maximised extraction (1982-2007) commenced (Figure 8).

At Booligal, all flows important for wetland inundation (300 ML d^{-1}, 800 ML d^{-1}, and 2,500 ML d^{-1}) were reduced after maximised extraction started in 1982. The occurrence of these flows increased after regulation, but decreased after maximised extraction (Figure 8). Flows exceeding 300 ML d^{-1} increased after regulation from 36% to 44%, but then declined to 30% of the time after maximised extraction. Flows exceeding 800 ML d^{-1} occurred 25% and 28% of the time before and after regulation, but since maximised extraction only 15% of all flows have exceeded this threshold. Flows exceeding 2,500 ML d^{-1} occurred 11% and 13% of the time before and after regulation respectively, but after maximised extraction this decreased to around 8% (Figure 8).

The daily FDC for Boorowa (Figure 10) revealed that changes in streamflow were not consistent throughout the catchment. High and medium flows were very similar under regulated (1936-1981) and maximised extraction (1982-2007) periods. But in contrast to flows of the Lachlan River, where low flows replaced zero flow periods, the number of zero flow days at Boorowa has actually increased by about 4% in the Boorowa River.

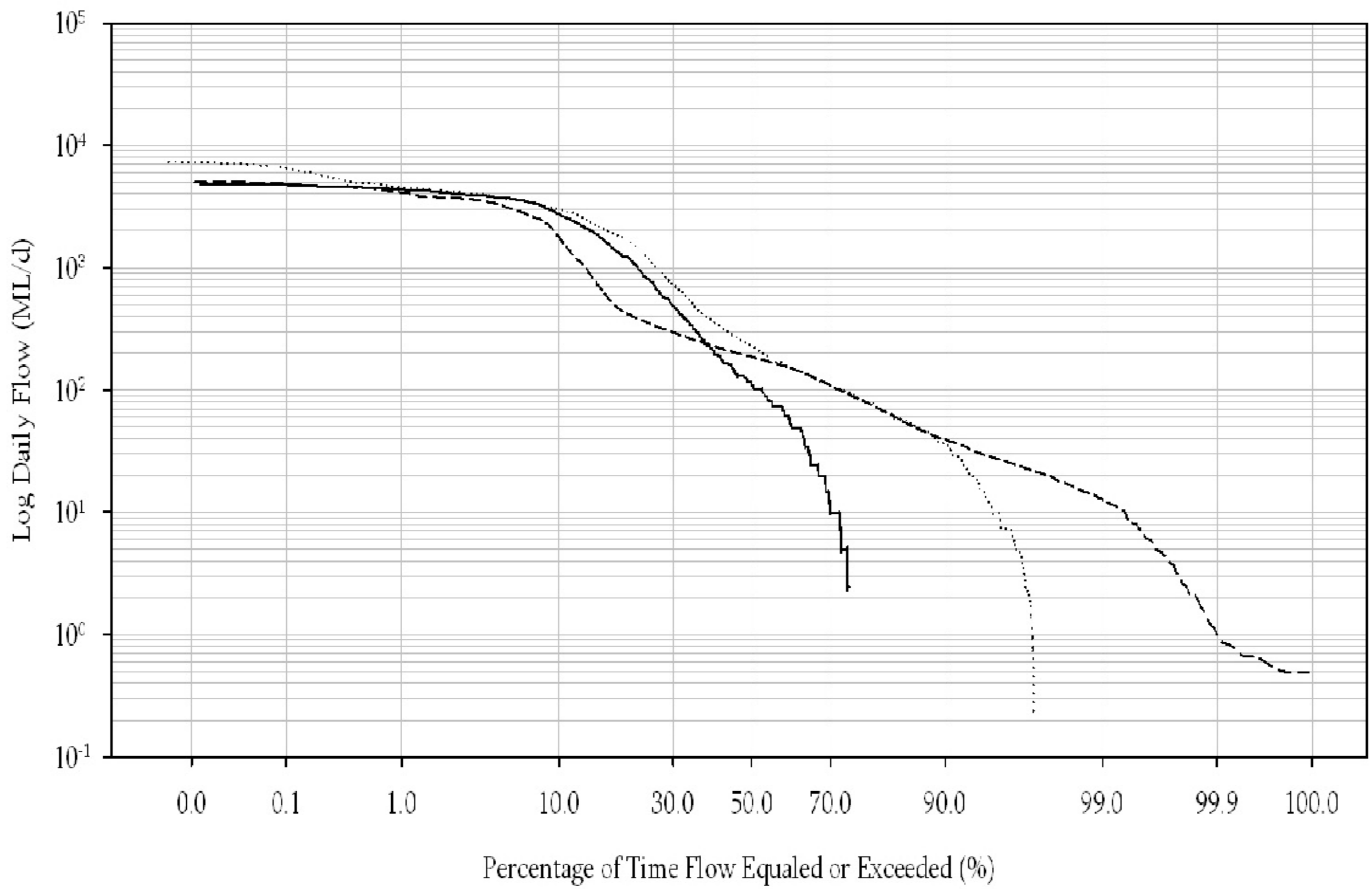

Figure 8. Daily flow duration curve (FDC) at Booligal on the Lachlan River in relation to three separate time periods: pre regulation time (1907-1930, solid line), main dam building period (1931-1981, dotted line), maximum extraction period (1982-2007, dashed line).

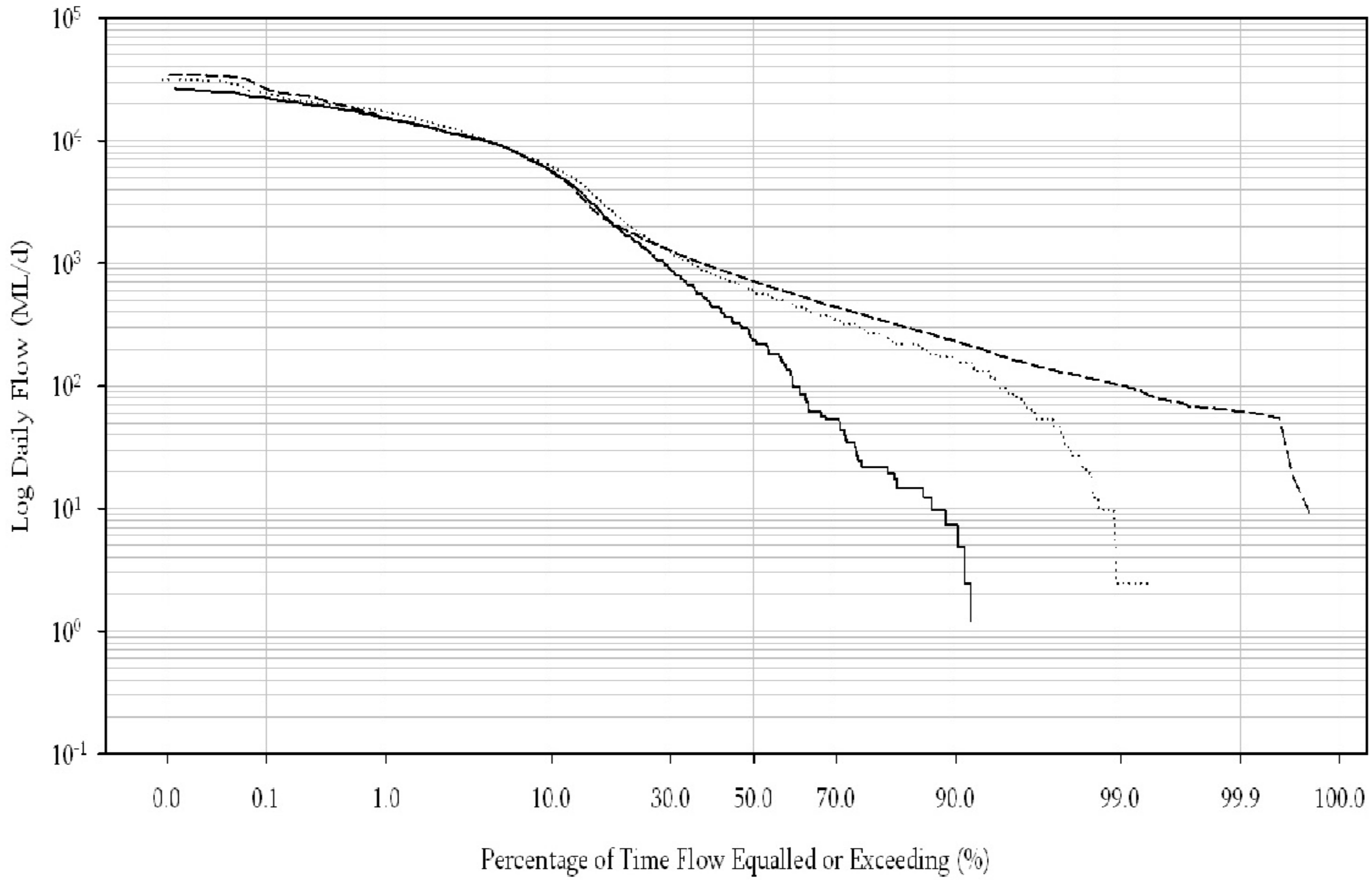

Figure 9. Daily flow duration curve (FDC) at Condobolin on the Lachlan River in relation to three separate time periods: pre regulation time (1907-1930, solid line), main dam building period (1931-1981, dotted line), maximum extraction period (1982-2007, dashed line).

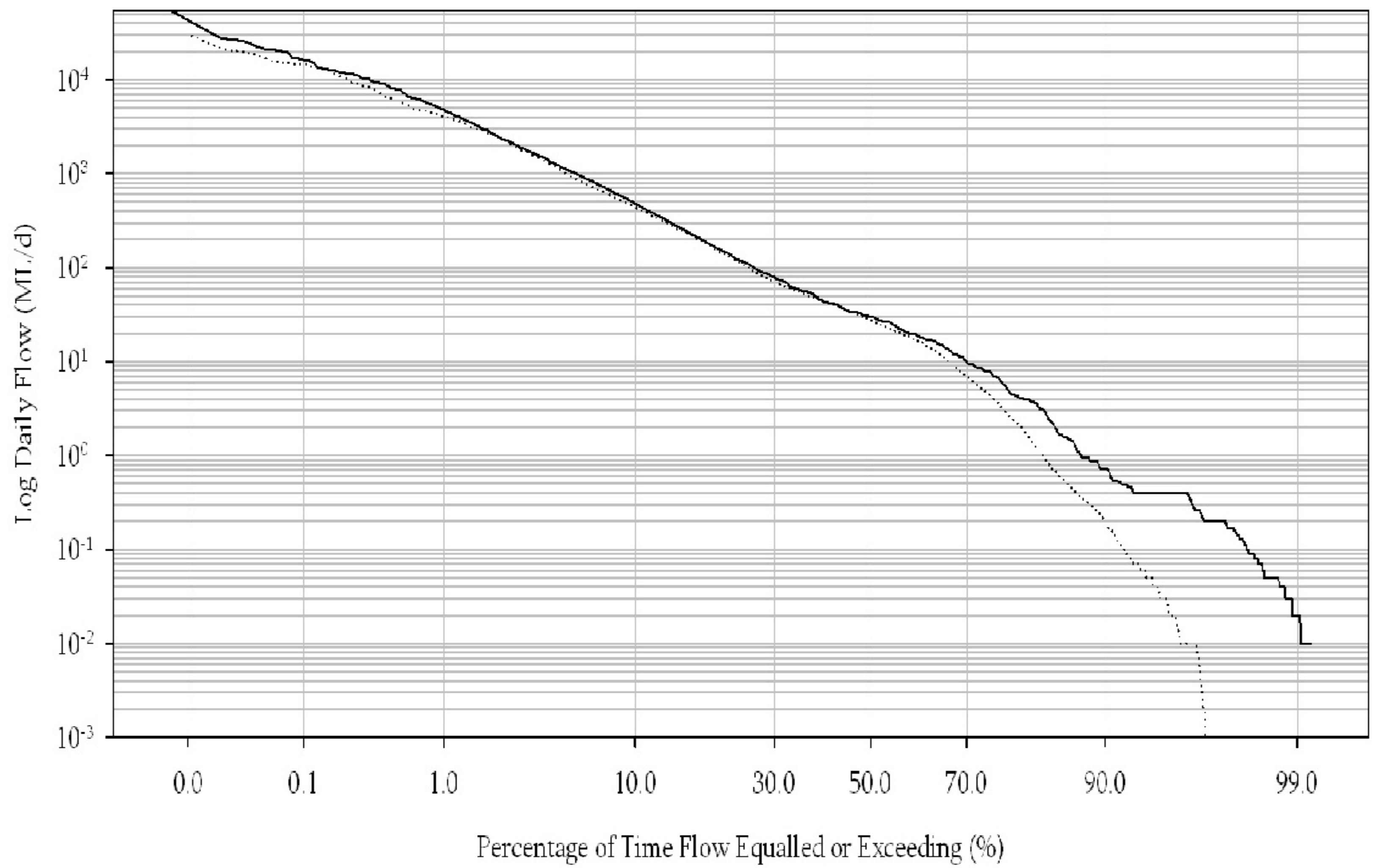

Figure 10. Daily flow duration curve (FDC) at Boorowa on the Boorowa River in relation to two separate time periods: main dam building period (1936-1981, solid line), main

4.2.2. Changes to seasonality

The seasonal regime of the Lachlan River at Booligal has also changed since regulation commenced in 1931 (Figure 11). For each time period (1907-1930, 1931-1981, 1982-2007), the curve has become progressively flatter, suggesting a loss in monthly heterogenic flows (Figure 11). Consequently, considerably less water has reached Booligal over time. Before regulation (1908-1930), monthly flows at Booligal were substantially lower during summer (December-February) and autumn (March-May) months, before increasing significantly during winter (June-July), and finally decreasing steeply during spring (September-November) (Figure 11). After river regulation began (1931-1981), summer flows in the Lachlan were significantly higher (55%) while winter flows were lower than unregulated conditions. For spring, September flows were lower but subsequent spring monthly flows were higher compared to unregulated conditions (Figure 11). After extraction peaked (1982-2007), this effect was further exacerbated (Figure 15) with a drop in volume of summer and winter flows relative to unregulated conditions.

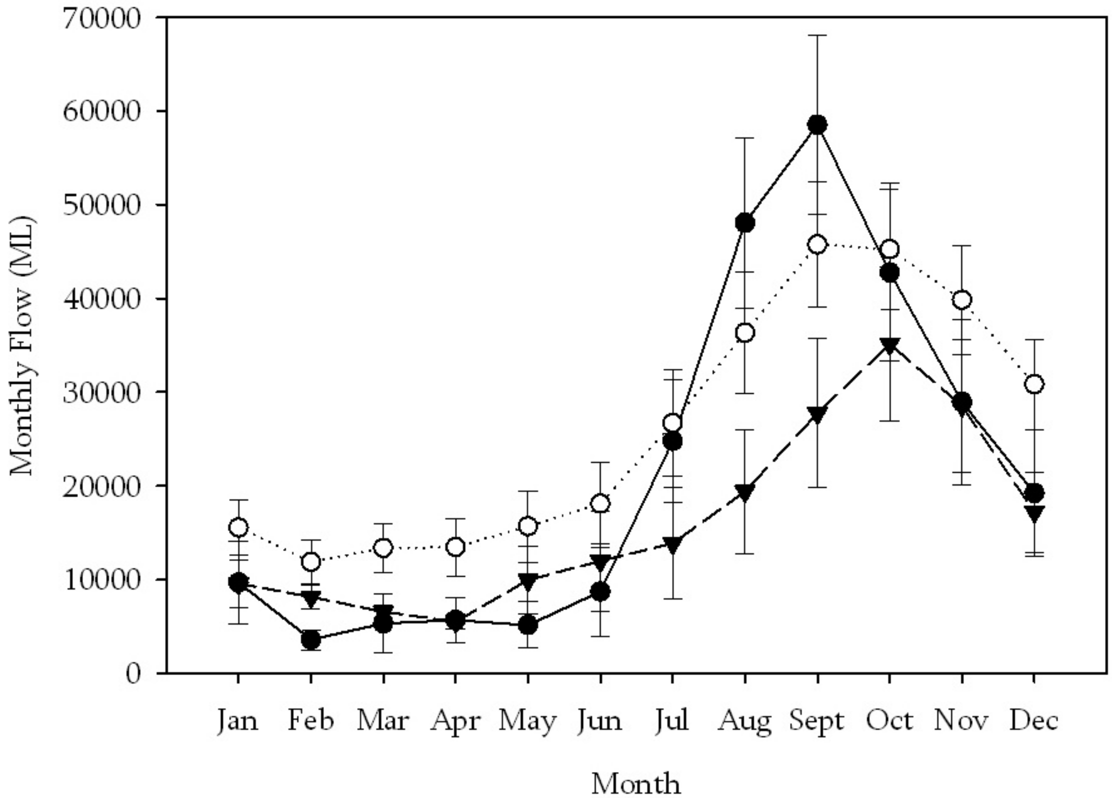

Figure 11. Mean (±SE) monthly flow st Booligal on the Lachlan River before regulation (1908-1930, solid line, filled circles)), after regulation (1931-1981, dotted line, open circles) and after maximum extraction (1982-2007, dashed line, filled triangles).

4.2.3. Changes in flow thresholds

The frequency and duration of different flows at Booligal changed with increasing regulation and extraction. At flows of 300 ML d^{-1}, spells of 7-112 days had similar frequencies before regulation (1908-1927), after regulation (1931-1981), and after maximised extraction (1982-2007) (Figure 12). But, the number of spells lasting 1-3 days substantially increased after extraction was maximised, from about 9 to 19 per 5 year period (Figure 12).

The number and duration of spells at thresholds of more than 800 ML d^{-1} and 2,500 ML d^{-1} did not differ before (1908-1930) and after regulation (1931-1981) (Figure 12). However, in comparison to unregulated flows, the number of spell lasting 1-56 and 1-28 days at 800 ML d^{-1} and 2,500 ML d^{-1} respectively decreased by around 40% since maximised extraction (Figure 12). Spells at thresholds of 800 ML d^{-1} and 2500 ML d^{-1} and exceeding 56 days were not significantly different across all time periods.

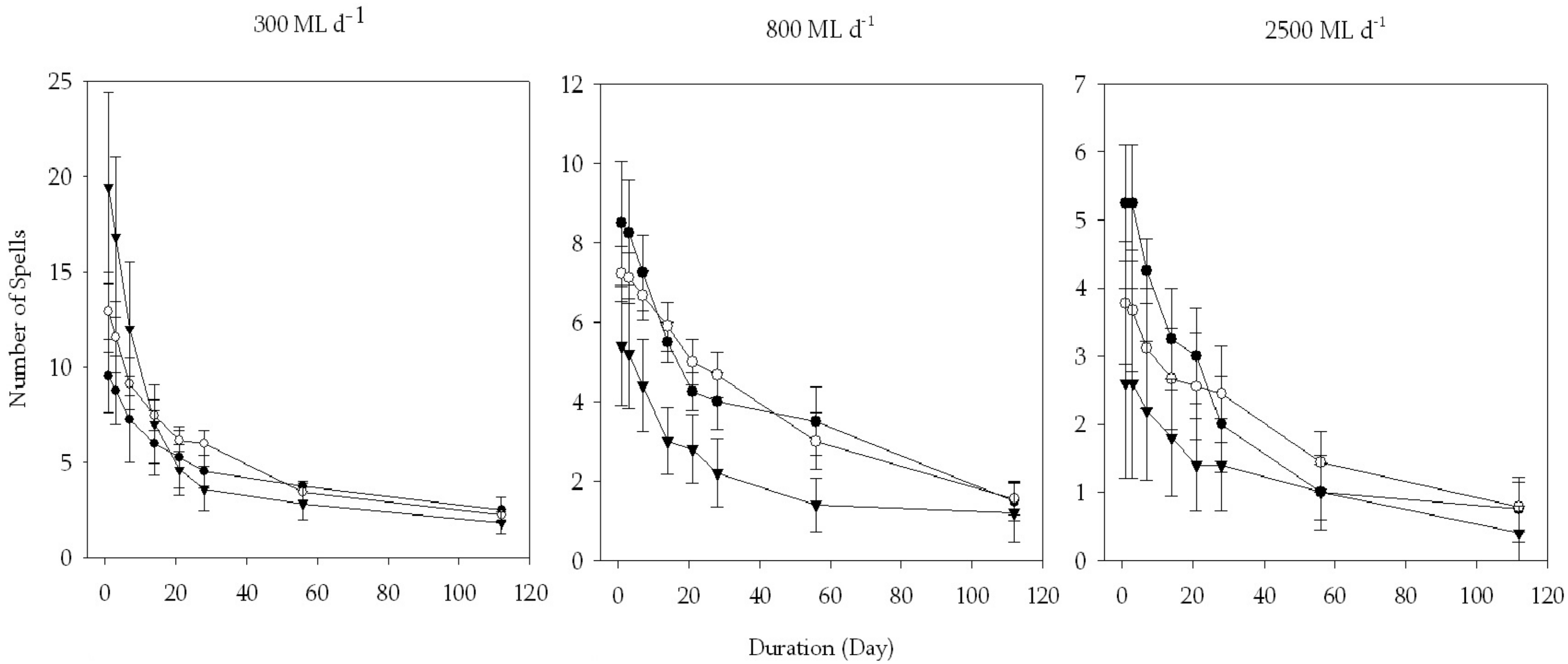

Figure 12. Mean (±SE) number of spells at Booligal where flows were above 300 ML d^{-1} 800 ML d^{-1} and 2500 ML d^{-1} for specified durations of 1, 3, 7, 14, 21, 28 56 and 112 days or longer before regulation (1908-1930, filled circles), after regulation (1931-1981, open circles) and after maximised extraction (1982-2007, filled triangles). Sample sizes were formed from different five year periods within each of the three time periods.

4.3. Vegetation Change

4.3.1. Aerial photo interpretation

All four sites (MS, LG, TG and RG) demonstrated a similar trend in vegetation condition; they increased canopy cover from 1973 to 1993, then decreased from 1993 to 2008 (Table 5, Figure 13). Time was a significant factor, accounting for 73% of variation in the model (Term 2, Table 5), due to the significantly reduced canopy cover in 2008 compared to 1973, 1993, 1998 and 2005 years (Tukey's $p \leq 0.05$). Sites were also significantly different (Table 5, $p = \leq 0.001$, 26% variation), with MS, LG and TG maintaining less cover than the control site RG (Tukey's $p = \leq 0.05$). The degree and rate of change was not consistent over time or among sites as indicated by the significant interaction in visual estimates of cover between site and time (Table 5, $P = \leq 0.01$). Cover declined more rapidly and was more widespread at swamp sites (MS, LG, and TG) compared to trees found along the Lachlan River (RG).

MS, LG and TG had higher canopy cover in 1993 than RG but were considerably lower in 2008, decreasing significantly by over 60% (Table 5 & 6, Figure 13). This reduction in canopy cover was gradual from 1993 to 2005; (~15%), but between 2005 and 2008, there was further substantial reduction (MS 56%, LG 40%, TG 35%) in canopy cover. By contrast, canopy cover of RG remained relatively stable from 1973-2005 (64.0 - 68.3% cover) but experienced a 20% reduction from 2005 to 2008 (48.5 ± 3.1%) (Table 6, Figure 13).

Remote visual and point count methods for estimating vegetation canopy cover yielded similar results between site and time (Table 6, Figure 13 & 14). All classes were observed (0, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100%), but most ranged from 30-70%, which equates to open forest under the Specht's classification (Specht *et al.*, 1974).

Table 5. API visual canopy cover two-way ANOVA results. Mean squares, degrees of freedom, f ratio, P values (≤0.05), and variance components are presented

Source of Variation	MS	df	F	P	VC (%)
1. Site	14,044.833	3	31.703	0.000	.26
2. Time	32,602.313	4	73.591	0.000	.73
3. Site×Time	1709.729	12	3.859	0.000	≤1
4. Error	443.019	780			≤1

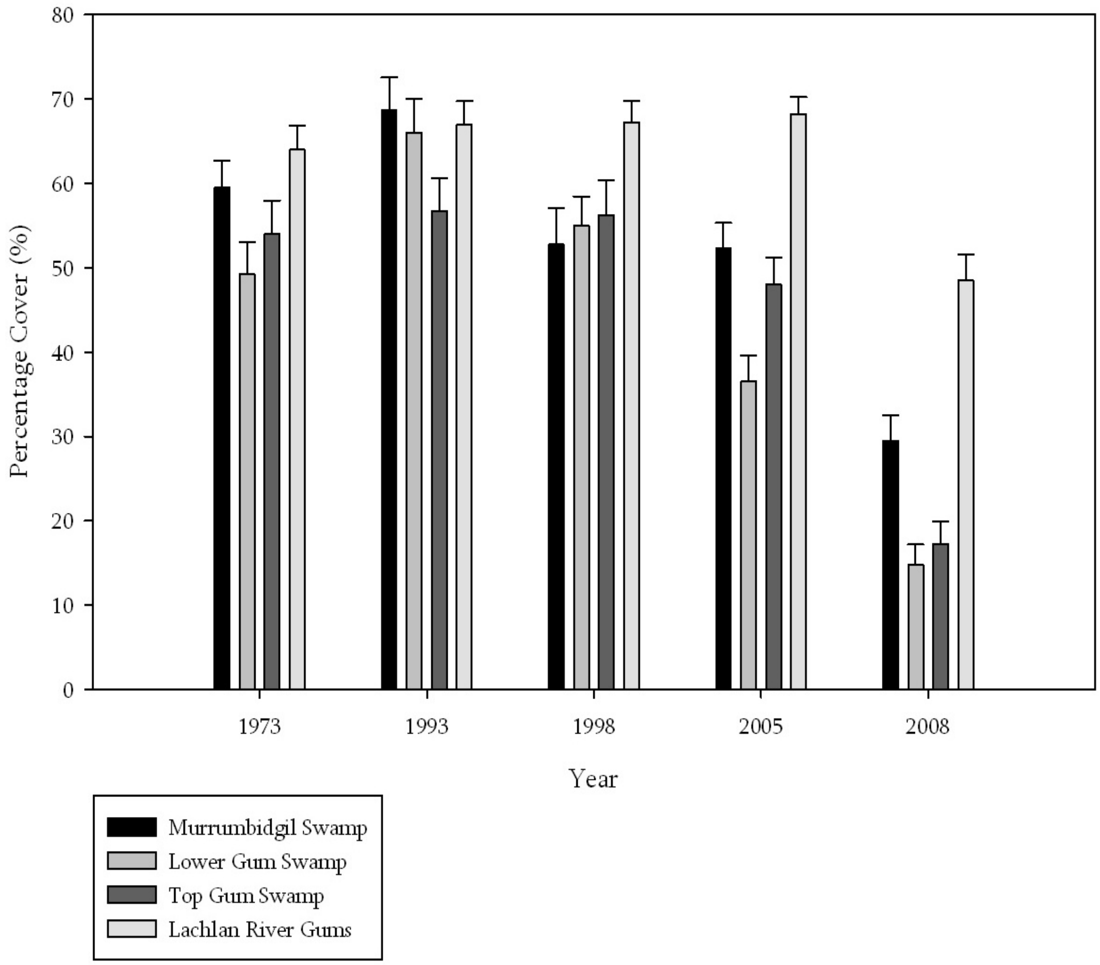

Figure 13. Mean (±SE) estimates of tree percentage cover at five dates (1973-2008) for the four sites: Murrumbidgil Swamp (MS), Lower Gum Swamp (LS), Top Gum Swamp (TS) and Lachlan River Gums (LR) estimated from aerial photo interpretation – visual classification method.

Table 6. Comparison of API remote canopy cover estimation methods (visual percentage cover method verses point count method) at each site (MS - Murrumbidgil Swamp, LG – Lower Gum Swamp, TG – Top Gum Swamp, and RG – Lachlan River Gums), for each year (1973, 1993, 1998, 2005, 2008). Means and standard error (SE) terms are presented. All terms are percentages (%).

	MS		LG		TG		RG	
YEAR	Visual Mean ± SE	Point Count Estimate	Visual Mean ± SE	Point Count Estimate	Visual Mean ± SE	Point Count Estimate	Visual Mean ± SE	Point Count Estimate
1973	59.5 ± 3.2	60	49.3 ± 3.8	46	54.0 ± 4.0	67	64.0 ± 2.9	58
1993	68.8 ± 3.8	71	66.0 ± 4.0	69	56.8 ± 3.9	51	67.0 ± 2.8	71
1998	52.8 ± 4.3	67	55.0 ± 3.5	67	56.3 ± 4.2	60	67.3 ± 2.5	62
2005	52.3 ± 3.1	51	36.5 ± 3.1	37	48.0 ± 3.2	48	68.3 ± 2.0	55
2008	29.5 ± 3.0	37	14.8 ± 2.5	18	17.3 ± 2.7	18	48.5 ± 3.1	46

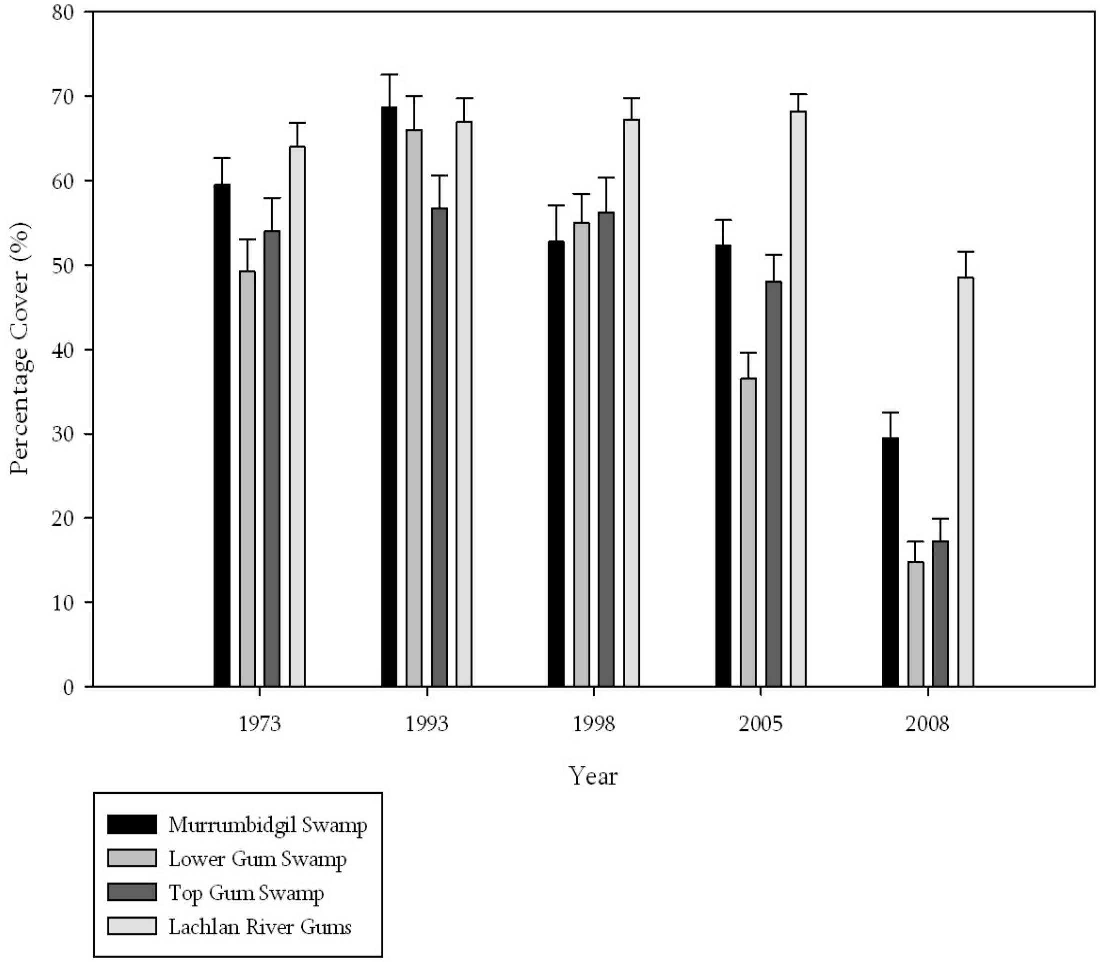

Figure 14. Mean (±SE) estimates of tree percentage cover at five dates (1973-2008) for the four sites: Murrumbidgil Swamp (MS), Lower Gum Swamp (LS), Top Gum Swamp (TS) and Lachlan River Gums (LR) estimated from aerial photo interpretation – visual classification method.

4.3.2. Comparison of field data and API

There was a significant difference among the four sites in the canopy cover estimated in the field in 2008 (Table 7, p=≤0.001, Figure 15). Post-hoc tests show that MS, LG and TG were similar, with canopy cover around 12.6%; while RG has significantly more cover (33%) (Tukey's p=<0.05). These results are similar to those from API, where swamp sites were more similar to each other than the control site RG in the comparison of river red gum canopy cover (Table 7, Figure 15).

Both remote methods (visual and point count) tended to over-estimate canopy cover compared to ground assessments (2008) at MS, TG (11 ±1.2) and RG (33 ± 2.7) sites (Table 6, Figure 15). Photographic estimates and field data were similar at LG (13 ±1.1%) (Table 6, Figure 15). Error was highest at MS, TG, and RG, where remote methods overestimated cover by around 114% (14 to 30%), 33% (11.6 to 17.2%) and 46% (33 to 48.5%) respectively; whereas LG was only about 6% (14 to 14.8%).

Table 7. One way ANOVA results comparing field data. arcsine square root transformed data. Mean squares, degrees of freedom, f ratio and p values are presented.

	MS	df	F	P
Site	0.224	3	34.224	≤0.001
Error	0.007	68		

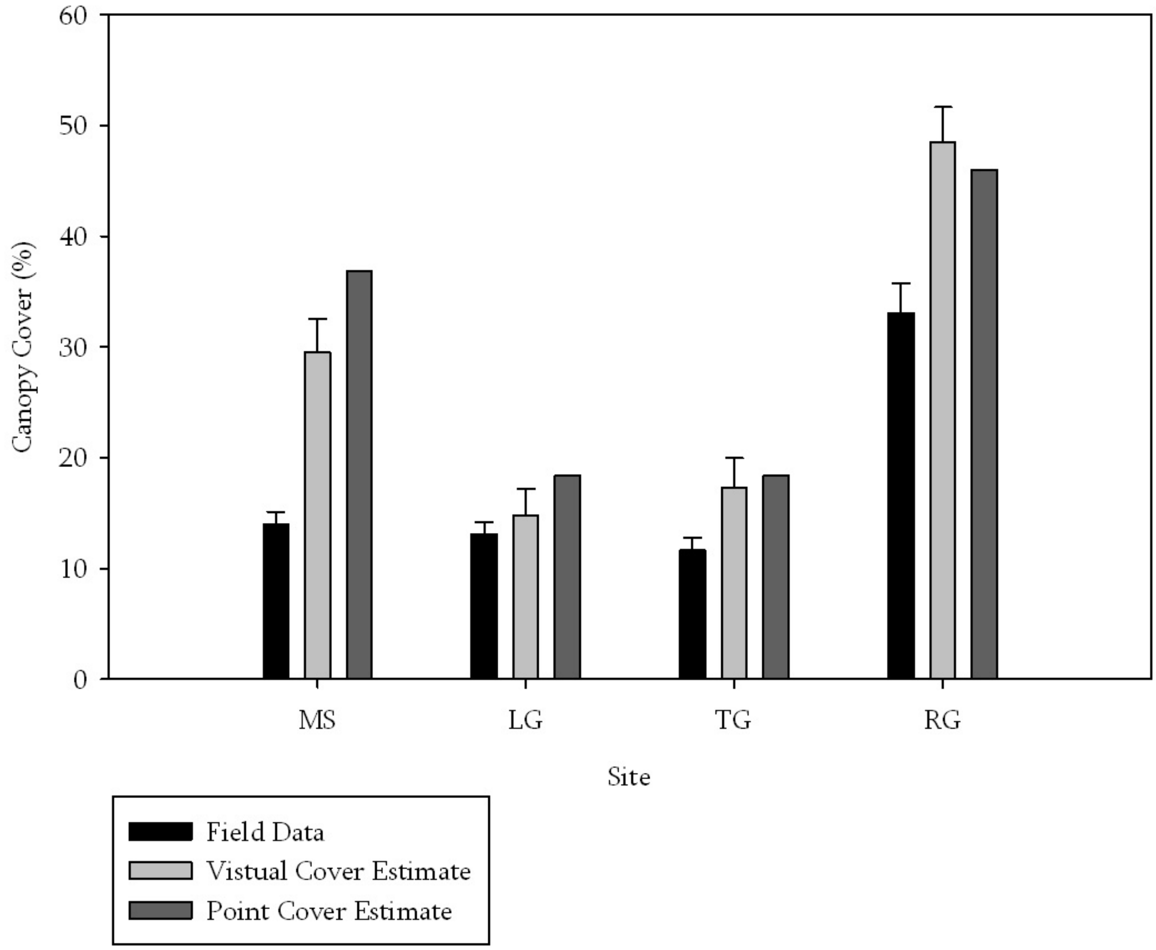

Figure 15. Comparison of aerial photo interpretation (visual and point cover estimate) and ground truth data for 2008.

4.3.3. Current red gum condition

The number of dead red gums was higher at swamp sites (MS, LG, TG) for all diameter at breast height (DBH) classes than at the control site along the Lachlan River (Figure 16). RG (Plate 4) site had significantly more living trees and less dead trees in all (Figure 16) compared to swamp sites (MS, LG, and TG) ($p \leq 0.05$) Dead trees were more common in smaller trees, in comparison to larger trees for RG. All swamp sites had more dead trees than living trees in each size class. MS had significantly more large dead trees (class C, ≥100cm DBH) ($p \leq 0.05$), in comparison to other sites. LG and TG had significantly more small dead tress in class A in comparison to MS and RG ($p \leq 0.05$) (Figure 16).

There was a significant interaction effect between site*health and site*class ($p = \leq 0.05$) (Table 8). However inspection of the variance components reveal that the site*health effect is contributing much more to the model (Term 4, Table 8). Tukey's test show that within each site (MS, LG, TG and RG) the number of live versus dead trees significantly differed (Tukey's $p = \leq 0.05$), swamp sites had more dead trees than alive, but the opposite was true for RG. Also there were significantly more live trees found at the RG in comparison to swamp sites (Tukey's $p = \leq 0.05$).

Trees at MS (Plate 1), LG (Plate 2) and TG (Plate 3) were exhibiting signs of dieback. Dieback describes a condition where trees die or decline in condition prematurely and often rapidly. As was seen in the field, large numbers of trees were affected at once. Dieback contributed to the loss of tree cover. Trees exhibiting symptoms had poor crowns, with sparse foliage and a large proportion of dead twigs and branches. They were also susceptible wind-throw and clearing. Large dead trees (Class C: DBH >100cm) were most common (Figure 16). There were signs of partial recovery by the growth of new shoots from the trunk and major branches (epicormic shoots). But in most cases these shoots had died back as well. Fallen trees, branches and bark within the swamps had contributed substantially to the ground layer.

Table 8. Red gum condition and diameter class three-way ANOVA results. Mean squares, degrees of freedom, f ratio, P values (≤0.05), and variance components (VC) are presented.

Source of Variation	MS	df	F	P	VC (%)
1. Site	0.007	3	0.109	0.955	0.1
2. Health	0.597	1	8.949	0.003	11
3. Class	0.084	2	1.257	0.285	0.6
4. Site×Health	4.342	3	65.099	0.000	87
5. Site×Class	0.383	6	5.739	0.000	0.6
6. Health ×Class	0.055	2	0.823	0.440	0.01
4. Error	0.067	414			0.02

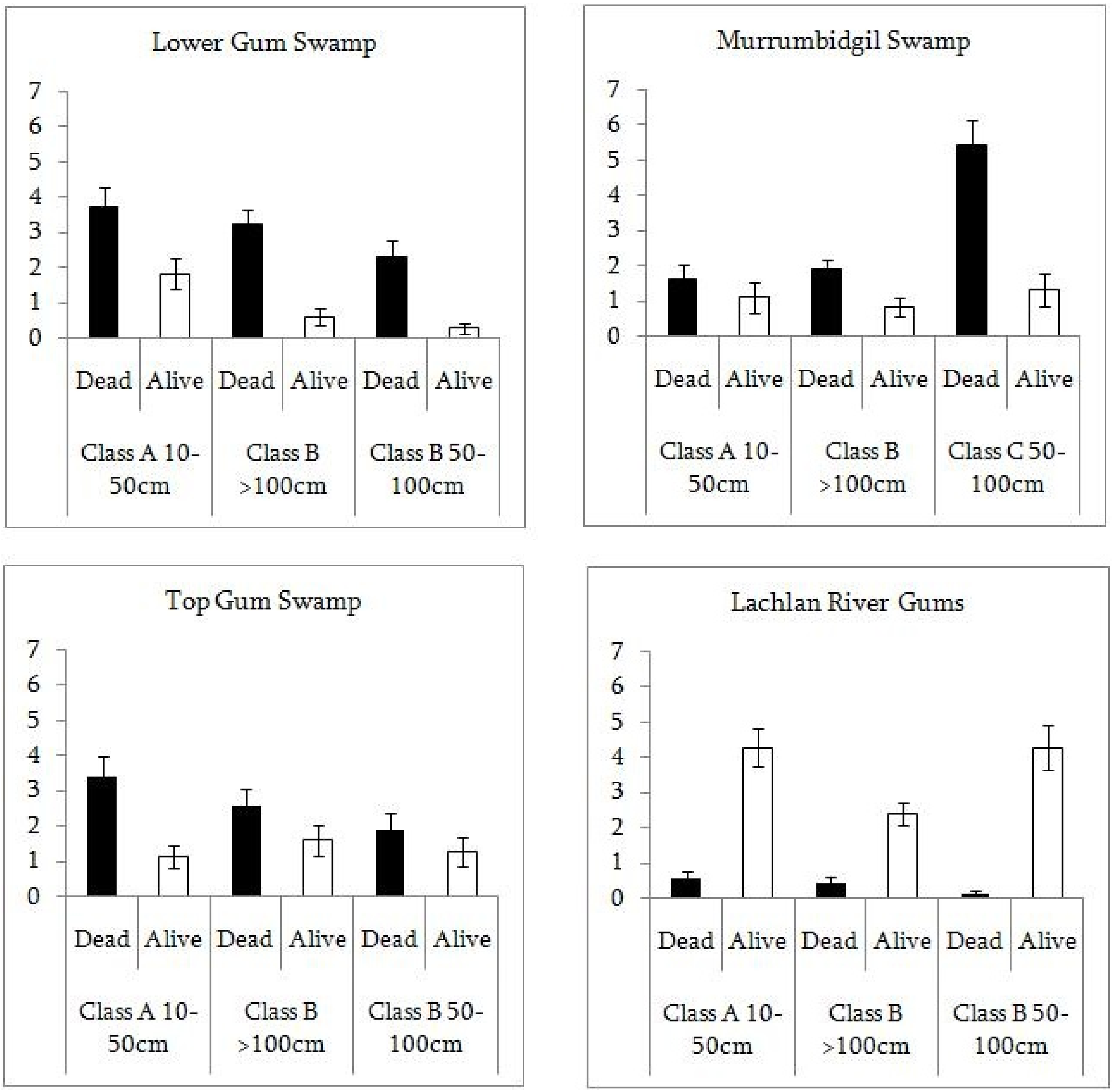

Figure 16. Mean (±SE) number of trees per 25m² quadrat in three categories of DBH (Diameter at breast height (cm)) and condition (A-alive, D-dead) of red gums at each site in September 2008 (MS, LG, TG, and RG), based on field assessment.

Plate 1. Pictures showing the current condition of Murrumbidgil Swamp, 2008.

Plate 2. Pictures showing the current condition of Lower Gum Swamp, 2008.






Plate 3. Pictures showing the current condition of Top Gum Swamp, 2008.

Plate 4. Pictures showing the current condition of Lachlan River Gums, 2008.

Discussion

The Booligal Wetlands on the Lachlan River in arid Australia (Figure 1) have joined a growing list of wetland ecosystems that exhibit symptoms of ecological collapse as a result of water resource development. The intrinsic character of the Lachlan River's hydrological regime has changed. The frequency, duration, variability and volume of flows have reduced (Figures 8-10), while the seasonality of flows has changed (Figure 11). This has meant less flooding of the Booligal Wetlands. Consequently, the condition of red gums in swamps has declined over the last 35 year period (1973-2008), with an accelerated dieback of trees over the last three years (2005-2008) (Figure 13 & 14). On ground assessment showed that most red gum trees were dead, while remaining live trees showed signs of severe water stress (Figure 15).

River regulation has affected flow regimes of other rivers within the Murray-Darling Basin (Walker, 1985; Kingsford & Thomas, 1995; Maheshwari *et al.*, 1995; Kingsford, 2000a; McMahon & Finlayson, 2003), including the Lachlan (Massey, 1997; Driver *et al.*, 2003; Driver *et al.*, 2005). Few published studies have addressed the specific impacts on terminal wetland systems (but see Kingsford & Thomas 1995; 2004) and there are no detailed studies of the ecological impacts on the Booligal Wetlands of the Lachlan River. The most ecologically important parts of the river are usually at its lowest point where it spreads onto the floodplain wetlands, such as the Booligal wetlands. Effects on these wetlands can best examined through changes to flow volume and also examination of ecological effects (e.g. river red gums). This information can then form the basis of a planned environmental flow strategy.

5.1 Changes to flow volume

River flows to the Booligal Wetlands have been reduced by at least 50% by diversions upstream (1894 to 2007) (Figure 6 & 7). Flows from Condobolin to Hillston and Hillston to Booligal have been most affected (Figure 7). Much of this occurred after irrigation licenses were fully developed in the catchments: after 1982 (Figures 6 &7). Irrigation use of water in the Lachlan Catchment has varied from about 100,000 to 450,000 ML y^{-1} since 1983

(DLWC, 1997). This water use decreased the frequency of small and medium flood events in the Lachlan River. Such flows are especially important for maintaining flood dependent riparian vegetation such as river red gums (Meeson *et al.*, 2002). This has decreased the frequency of small and medium flood events in the Lachlan River. These flows are especially important for maintaining flood dependent riparian vegetation such as river red gums (Jansen & Healey, 2003). Irrigation usage in the Lachlan Catchment has varied from about 100,000 to 450,000 ML y-1 since 1983 (DLWC, 1997).

The number and duration of key flood forming flows (800 and 2,500 ML d^{-1}) at Booligal has decreased by 40% (Figure 12). Flows lasting four to eight weeks have declined which has affected duration of flooding. Similarly, the size and duration of large spring floods (>3,777 ML d^{-1}) and smaller (>315 ML d^{-1}) floods have decreased at Booligal (Sims, 1996). Floods of long duration are essential to allow flood dependent aquatic organisms sufficient time to breed and recruit (Wood *et al.*, 2000; Sheldon *et al.*, 2002; Jenkins & Boulton, 2003). As a result the Booligal Wetlands floodplain has been almost severed from its river, resulting in a loss of connectivity. This impact may increase over time with increasing extraction of groundwater. Projected groundwater access is set to increase in the Lachlan (CSIRO, 2008), which may mean further reductions to flows to Booligal wetlands even though the surface extractions are capped because of connectivity between ground and surface waters in the Lachlan. Although the contribution of groundwater to streamflow within the Lachlan Catchment was not assessed, groundwater over-extraction has occurred in the lower Lachlan alluvial aquifers (CSIRO, 2008), further contributing to decreased streamflow. Extractions have increased substantially during the drought to offset the lack of surface water.

Connectivity between a river channel and a wetland is dictated by the position of the wetland (both elevation and distance from channel) with respect to the main channel and the flow regime of the river (Kondolf *et al.*, 2006). Floodplain–river ecosystems are dynamic mosaics of patches (Thoms *et al.*, 2005). Hydrological connectivity between the river channel and various floodplain patches stimulates floodplain–river ecosystems (Tockner & Standford, 2002). Flooding facilitates not only exchanges of water, but sediments, nutrients and biota between the river channel and the floodplain (Jenkins & Boulton, 2003). These transfers are considered to be essential for the functioning and integrity of these systems (Lake & Marchant, 1990; Lake *et al.*, 2006).

Connectivity between the Booligal wetlands and the river channel has also been reduced (both incidentally and intentionally) by channel incision and levee construction resulting in less frequent inundation of the floodplain and flow through side channels (DLWC, 1997). Channel incision and consequent increased channel capacity has further reduced the frequency and depth of floodplain inundation for the same flows delivered from upstream. Merrimajeel and Muggabah Creeks are used as conduits to deliver stock and domestic water to landholders downstream (DLWC, 1997). Past clearing of lignum from the creek channels has probably also resulted in more efficient fast flowing water as the lignum would have promoted increased flooding (Driver *et al.*, 2003). Restricted lateral connectivity also decreases floodplain productivity, nutrient exchange, and dispersal of biota between the river and floodplain wetlands (Jenkins & Boulton, 2003).

The manipulation of flows over time to meet irrigation, stock, industrial, domestic and town water supply requirements has been well documented in other regulated dryland rivers in the Murray-Darling Basin. In the Barwon–Darling River, flows are highly modified through the presence of nine headwater dams, 15 main channel weirs and 267 licensed water extractors, reducing median annual runoff by 42% over a 60-year period (Thoms & Sheldon, 2000). Small flood events suffered the greatest impact with reductions in magnitude of between 35 and 70%. Overall, flows show a marked increase in predictability and consistency (Thoms & Sheldon, 2000). In the Gwydir River valley, a combination of water extraction, drainage and levee construction has resulted in a 75% reduction in total wetland area (Mawhinney, 2003; Powell *et al.*, 2008).

Australia is not alone in diverting a large proportion of the flow from its dryland rivers. Some of the world's largest rivers now run dry for part of the year or are likely to do so as a result of large-scale water abstraction (Petts, 1996; Kingsford, 2000a; Gunderson *et al.*, 2006a; Omer, 2008). The most striking example of the consequence of diverting water from a dryland river system, however, must be that of the Aral Sea in Uzbekistan and

Kazakhstan where water from the incoming Amu- and Syr-Darya Rivers has been diverted for irrigation (Micklen, 1988). There has been a change in lake volume from 1,090 km^3 in 1960 to 310 km^3 in the 1990s (Aladin & Williams, 1993). As a result, 83% of the fish fauna and 96% of the macroinvertebrate fauna of the Aral Sea are extinct, with only 3.6% of the vast reedbeds remaining (Micklen, 1988). Approximately 50% of all the flows in South Africa are held within storage dams, with an unknown percentage diverted. Such hydrological changes have had drastic impacts on the aquatic ecology of the southern African rivers (Allanson *et al.*, 1990).

This halving of the water volume to the Booligal Wetlands and changes to commence to flow thresholds which have reduced the frequency of flooding has had major impacts on the Booligal wetlands. Consequently, water for flood dependent vegetation such as river red gum has become insufficient to maintain viable populations.

5.2. Ecological effect on the Booligal Wetlands

The Booligal Wetland red gum swamp ecosystems have been dramatically affected by river regulation and water extraction. These floodplain wetlands have been disproportionately affected by river regulation and water extraction (Kingsford, 2000a), in comparison to red gums located on the main river channel. The recent dieback in red gum vegetation (2005-2008) signals a critical change in state of the Booligal Wetlands swamp ecosystems; and follows a 12 year erosion of the natural resilience of the system. Ecological resilience in aquatic and wetland systems is defined as the amount of disturbance that a system can absorb without a change in structure and composition (Capon & Brock, 2006; Gunderson *et al.*, 2006b; Walker *et al.*, 2006). The significant percentage of trees exhibiting signs of stress indicate that the phenomenon is related to floodplain and river processes, and likely the result of a combination of drought and a lack of extensive or frequent flooding.

Similar declines in red gum health have been observed on several other rivers within the Murray-Darling Basin (Bren & Gibbs, 1986; Bren, 1987; Bren, 1988; Francis & Sheldon, 2002; Stewart & Harper, 2002). In southeastern Australia, regulation of the Murray River, Australia's longest river (2,520 km), has significantly decreased the frequency and duration of flooding (Maheshwari *et al.*, 1995). Qualitative assessments of red gum crown condition from aerial photographs and field observations have shown a substantial decline in tree condition in the lower Murray River during the past 20 years (MDBC, 2005). Surveys between December 2002 and May 2004 along the River Murray revealed that there has been a dramatic decline in tree health over a relatively short period of time. The number of unhealthy trees assessed rose from 51.5% to 75.5% (MDBC, 2005).

There is a close association between the health of mature red gum trees, the establishment of seedlings, and the duration, frequency and timing of flooding. As flooding is the primary source of water for river red gums. They require flood events one in three years for optimal growth (Roberts & Marston, 2000). Reflecting this, we found canopy cover was highest in 1993 (Figure 13), following the 1990 and 1993 flood events within the Booligal Wetlands.

As well, floods are needed for germination and successful recruitment. Seedling survival limits recruitment (Bren & Gibbs, 1986; Bren, 1988). While seeds are held in the aerial seed bank for a minimum of two years, studies of red gum populations along the River Murray have found that the volumes of seeds in stressed trees are significantly reduced (Meeson *et al.*, 2002). As a result of declining health and dry conditions, recruitment rates of trees within the Booligal Wetlands are expected to be insufficient to maintain populations as a result of the lack of flooding.

There will be direct consequences on the entire ecosystem. Foliage loss has impacts beyond that of individual or tree populations (MDBC, 2005). Large-scale foliage loss will reduce organic detritus inputs into the river. This will likely lead to reductions in detritus-dependant flora and fauna that would cause commensurate losses of ecologically linked plant and animal populations, such as fish and waterbirds (Briggs *et al.*, 1997; Briggs & Thornton, 1999). The decline of the Booligal wetlands red gum swamps and its associated impact on waterbird breeding is unknown but many waterbirds require live trees for nesting. River red gum swamps of the Lachlan, Murray, and Murrumbidgee Rivers are important breeding areas for waterfowl (Frith, 1967).

Decreases in flood events have been linked to declines of waterbirds in the Macquarie Marshes and Lower Murrumbidgee floodplains (Kingsford & Thomas, 1995; Kingsford & Thomas, 2004). Inland wetlands are also important for shorebirds (Charadriiformes) (Nebel *et al.*, 2008). A large-scale aerial shorebird survey which sampled about a third of the Australian continent found that migratory shorebirds have declined by 73% over a period of 24 years (1983–2006) (Nebel *et al.*, 2008). This has been linked to river regulation and water extraction.

The current drought is not the major cause of the death of red gums in the Booligal wetlands. Severe droughts can cause trees and other woody plants to die off suddenly if the soil-profile dries out completely (Brock *et al.*, 2003; Bond *et al.*, 2008). The foliage wilts and browns-off, and usually the trunk splits, making tress more susceptible to insects. South-eastern Australia is presently experiencing one of the worst droughts observed in the region in the last 200 years (BOM, 2008). However despite the years between 2005 and 2008 recording the lowest Lachlan River inflows since the 1890's, this is not considered uncommon historically (DLWC, 1997). This is the first major drought since the construction and operation of Wyangala Dam. Anecdotal evidence suggests that drought-related tree decline events have occurred in the past, with tree condition improving once rainfall or flooding resumed (Roberts & Sainty, 1996). Many of the trees are likely to be hundreds of years old (CSIRO, 2008), and so would have experienced other droughts as severe as the present one.

Grazing may have exacerbated the impact of reduced flooding on river red gum regeneration. Grazing and trampling by livestock are important post-recruitment mortality agents for river red gums (Robertson & Rowling, 2000). Wetlands in the Murray-Darling Basin are prone to greater impacts by introduced grazers, as stock concentrate around water sources (Meeson *et al.*, 2002). Domestic cattle and sheep cause soil compaction and erosion while reducing plant biomass and species richness and water quality (Bacon *et al.*, 1993). All lower Lachlan River sites (MS, LG, TG, RG) had similar grazing pressure from domestic cattle and sheep, as well as feral animals (goats, rabbits, pigs), however the red gum trees surveyed along the Lachlan River (RG) were healthier than those found within the swamp sites (MS, LG, TG). The number of stock (cattle and sheep) kept on farms has decreased with the drought. The condition of mature trees is less affected by grazing effects and so it does not explain the recent collapse of red gums.

This powerful evidence for the state of the red gums swamps of the Booligal wetlands comes primarily from the ability to assess their state over a long period of time. Few studies have applied digital image processing as a tool for extracting vegetation data from aerial photographs (Apan *et al.*, 2002). This reflects uncertainty about the effectiveness of digital processing for extracting reliable vegetation data from aerial photographs (Kadmon & Harari-Kremer, 1999; Fensham & Fairfax, 2003; Danby & Hik, 2007). This is true for black and white photos in which the spectral information is limited to grey levels and resulted in my overestimation of tree canopy cover (1:50,000). However, black and white photos are both the most common type of aerial photograph and the only type for which long-time sequences are available which is essential to demonstrate change in long lived species and landscapes (Fensham & Fairfax, 2002; Fensham *et al.*, 2002). This makes black and white aerial photographs an invaluable source of information on long-term patterns and rates of vegetation change. Other hydrological changes to the flow regime of the Lachlan River may also have affected the viability of not just the river red gums in the Booligal Wetlands but other organisms that utilize these wetlands (e.g. waterbirds, frogs, native fish species, and invertebrates).

5.3. Other hydrological changes to flow

Seasonality, frequency of low flows and reduced variability has fundamentally changed in the Lachlan River (Figures 8-12). The intensity and timing of high winter flows has been dampened (Figure 11) with regulation and water extraction. Naturally occurring high winter flows are now captured and stored in the main reservoirs (Wyangala Dam, Carcoar Dam, Lake Cargelligo and Lake Brewster) for release in the dry summer season to support irrigation and agriculture. As a result, summer flows have become unnaturally high when stored water is being released for downstream uses. This finding is supported by other studies (Driver *et al.*, 2000; Driver *et al.*, 2003; McMahon & Finlayson, 2003; Driver *et al.*, 2005). As a result, peak winter floods have reduced in intensity. Sims (1996) also found a large reduction in spring flows in the lower Lachlan. Changes to seasonal flooding regime may have impacted on the survival and recruitment of river red gums. Optimal conditions for recruitment of river red gums are winter-spring flooding (when seed fall is at a peak) followed by spring-summer rainfall (Dexter, 1970). Recruitment of river red gums is also dependent on seed supply, with trees producing between 100 and 150 million seeds before they are replaced by a single individual (Meeson *et al.*, 2002). Trees produce large seed crops every 2-3 years but this cycle can be highly variable (Boland *et al.*, 1980; Meeson *et al.*, 2002).

Low flows have also increased, replacing zero flows. Dams typically affect the hydrology of regulated systems by imposing an artificial lake environment on the stream (Finlayson *et al.*, 1994). Increases in low flows extend beyond the main river channel and affects some of the lower distributary creeks. Low flows in Willandra Creek, which extends west between Lake Cargelligo and Hillston (Figure 1), have substantially increased since regulation. The model by Sims (1996) compared regulation flow data against flow data when flow regulation was much less intense. Modelling of the lower Lachlan flows indicated that the frequency of smaller flows (about 200 ML day^{-1}) at Booligal weir has increased. There are primarily two contributors to increased low flows: supply of stock and domestic flows to lower end users and the current operation of environmental flows in the Lachlan as translucent flow releases.

Water for stock and domestic use is permitted to persons with land that has water on or adjacent to a water body (Driver *et al.*, 2003). Land use along Willandra Creek is predominantly grazing and wool production but also includes the use of irrigated water for pastures, fodder, and cash crops. Irrigation flows have been delivered since 1982. Willandra Creek have entitlements comparable to irrigation entitlements on the Lachlan River. Naturally the creek would have been largely or completely dry for much of the year, and occasionally for successive year, and flows were most likely dominated by winter/spring freshes, and low flow periods during summer to autumn. Before regulation the creek could have required about 8,280 ML d^{-1} to flow from the Lachlan River off-take. After regulation the flow regime of the creek changed to supply water for irrigation and stock and domestic needs (Driver *et al.*, 2003). A regulator at Willandra Creek Weir (Figure 1) now controls flows into the system. Lesser flows into the creek have increased substantially. Typically

50-100 ML d^{-1} are diverted into the creek most days of the year since the enlargement of Wyangala Dam in 1971. As well, the environmental flow management strategy is to utilise translucent dam releases. These require part of the reservoir inflow at Wyangala to be passed immediately downstream, essentially increasing low flows. While an increase in low flow duration is less likely to impact on the Booligal Wetlands the implications for the Lachlan River's aquatic biodiversity may be profound.

Variability has also decreased in the flows of the Lachlan (Figure 11 & 12). Arid dryland rivers have aquatic (Sheldon *et al.*, 2002; Brock *et al.*, 2003) and riparian (Bren, 1988) species with special behavioural or physiological adaptations for variability. The timing, or predictability, of flow events is critical ecologically because the life cycles of many aquatic and riparian species are timed to either avoid or exploit flows of variable magnitudes (Poff *et al.*, 1997).

Decreases in flow variability change the biota from lotic to lentic and can increase water losses to evaporation and groundwater recharge (Gordon *et al.*, 2004a). Generally, maximum biotic diversity is maintained in streams by a level of disturbance that creates environmental heterogeneity, yet still allows the establishment of communities (Ward & Standford, 1983; Resh *et al.*, 1988). A 'patchy' substrate maintained by periodic flooding will support more diverse biota than one which is inundated constantly, or conversely, not at all. For fish, flow variability parameters influence length of breeding season, spawning periodicity, length of life cycles, age at maturity, colonisation ability, species richness and major variations in assemblage structure (Puckridge *et al.*, 1998).

5.4. Management implications

A compromised river is one that preserves a simplified form but has lost function because the hydrologic processes no longer create and maintain habitat and natural disturbance regimes necessary for ecosystem integrity (McAllister et al., 2006). The Lachlan River is an ecologically compromised river. The use of water to meet the economic and social needs has affected the whole flow regime of the Lachlan River system, so much so that many ecosystem processes no longer or seldom occur, particular for its terminal wetlands.

Environmental flow management will be challenged by the current state of the Booligal Wetlands.

The ecological integrity of riverine ecosystems depends on their natural dynamic character (Poff *et al.*, 1997). While a return to natural flows is not feasible for the Lachlan River and its Booligal Wetlands, it is important for sustainable water management to recognise that water use and river regulation affect the health of rivers and other flood-dependent ecosystems, and to attempt to address these impacts where possible. Regulated rivers, such as the Lachlan, have the capacity to manipulate flow patterns to provide ecological benefits. The delivery of additional water for the red gum swamps of the Booligal Wetlands is essential to improve wetland health and prevent further degradation.

Current river restoration projects, such as RiverBank, the NSW Government's $105-million initiative, are returning water to parched floodplain wetlands via environmental water allocations through the purchase of water licenses (DECC, 2008a, b). With insufficient water to recover natural flood patterns, the challenge is to predict thresholds for flood frequency, duration and timing that will restore structure, function and resilience (Lake & Marchant, 1990; Lake & Bond, 2007) to arid-zone floodplain wetlands. Targets and indicators for arid-zone river restoration must incorporate this variability and ability to recover after flooding that typifies the 'boom–bust' ecology of arid-zone rivers and avoid interpreting 'bust' populations as 'unhealthy' (Sheldon *et al.*, 2000; Sheldon *et al.*, 2002).

However, despite best effort, it may take some time before the Booligal Wetlands red gum swamps show signs of improved health. There may be opportunities for increased flows to the Booligal wetlands by ensuring that bought environmental flows are delivered there, perhaps utilizing current stock and domestic flows. As well, it may be possible to reconsider the current translucent flow rules and acknowledge that this water may also be needed to produce effective ecological benefits.

Increased irrigation activities, and the associated diversion of flows may limit the recovery potential of floodplain trees compared with past drought events. This would have widespread implications for both the appearance and the ecological functions of the Booligal Wetlands and floodplain. While recovery from dieback is possible (Haines *et al.*, 1994; George *et al.*, 2005), the regeneration capacity of the Booligal Wetlands red gum swamps is severely diminished. Red gums do not depend on soil seed banks for persistence (Meeson *et al.*, 2002; MDBC, 2005); instead they exhibit serotiny, retaining most of their seeds in the canopy and release them as light, continuous seed rain (Jensen *et al.*, 2007). Due to limiting surface and sub-surface soil moisture, successful regeneration via seedling establishment follows major flood events (Bacon *et al.*, 1993). For the river red gum community, environmental flows would be needed at least one year in three years to ensure the survival of established tress, while successful germination and seed bank recruitment require winter-spring flooding, usually following autumn rains (Bren & Gibbs, 1986; Bren, 1987).

In many respects the far reaching effects of river regulation and water extraction are yet to be realised for the Lachlan River. El Niño droughts may increase. The El Niño Southern Oscillation (ENSO) is a major climatic event that globally influences soil dynamics and the abundance, community structure, and species and genetic diversity of dryland flora and fauna (Niemeyer *et al.*, 2005). The ENSO globally induces either severe floods or intense droughts in drylands for a period of ≥ 12–18 months and has a return interval of 2–10 years (McMahon & Finlayson, 2003; Bond *et al.*, 2008). Human induced climate change is predicted to increase the frequency and intensity drought events in south eastern Australia (CSIRO, 2008). Rainfall-runoff modelling with climate change projections from global climate models indicates that runoff in the Lachlan region is more likely to decrease than increase. Increase drought would further affect end of system flows in the Lachlan River (CSIRO 2008).

Floodplains are a vital component of lowland rivers but our knowledge of the effects that droughts have on their aquatic biota and processes during extended dry periods and drought remains poor and fragmentary (Kingsford, 2006). With drought the movement of water, nutrients and trophic subsidies from the catchment and the riparian zone into streams becomes progressively weaker, if not ceased altogether. Drought combined with river regulation may severely damage the "flood pulse" boom of floodplain river systems (McMahon & Finlayson, 2003; Gordon *et al.*, 2004a). Whilst we have some understanding of how the biota of running waters contend with drought at both the population and community levels, we have a poor understanding of how ecosystem processes, such as nutrient cycling, and the nature of trophic interactions, change with drought, and whether permanent or lasting changes occur (Kinzig *et al.*, 2006). Research should pursue the question of what long-term proactive measures need to be progressively implemented to contend sustainably with drought and drying due to climate change

5.5. Summary

The impact of dams and water extraction are a global ecological challenge. During the latter half of the 20th century, two large dams were built each day, on average (WCD 2000). By 2000, the number of large dams had climbed to more than 47,000, and an additional 800,000 smaller dams now block the flow of the world's rivers (Petts, 1992; Cowell & Stoudt, 2002; Petts & Gurnell, 2005). That existing dams retain approximately 10,000 km^3 of water, the equivalent of five times the volume of all the world's rivers illustrates the global extent of human alteration of river flow.

Major water resource development in the Lachlan catchment has altered the hydrological regime of the Lachlan River, affecting its terminal wetlands, including the Booligal Wetlands. The median annual discharge has been reduced, flows have become more predictable and the summer flow peaks have been dampened. These hydrological changes have affected physical and biological processes within the river and its dependent wetlands.

River regulation and water extraction for irrigation have effectively cut the river off from its floodplain and the results are catastrophic. The red gum swamps of the Booligal Wetlands have experienced a 15 year decline in health, accelerated over the past three year period most likely due to the current drought. If current tree health decline continues, the Booligal wetlands red gum swamps may be lost. With only 15% of all the trees surveyed in 2008 considered healthy, there are serious implications for the long term survival of a range of terrestrial and aquatic ecosystems, as well as the dependent flora and fauna. Environmental flows are the key to restoration but they must be sufficient to provide for life history requirements of the river red gums.

Increased irrigation activities, and the associated diversion of flows may limit the recovery potential of floodplain trees compared with past drought events. This would have widespread implications for both the appearance and the ecological functions of the Booligal Wetlands and floodplain.

Acknowledgements

The following landholders provided help and support in the field and gave permission for access to their properties: Jim, Alison and Rob Crossley of “Tom’s Lake”, Cole and Ron of “Lilydale”; Gordon Turner of “Brassbutt”; Keith Turner of “Woorondarra”; Fay of “Booligal Station”; of property owners of “Euragabah”; and Greg and Anne-Marie of “The Booligal Pub”. Many thanks for their kindly patience and attention.

We would like to thank Daniela Binder, Rowena Hamer, Ben Wolfenden, Simone Stimpson for providing enthusiastic entertainment in the field. And in particular Dr Lucy Nairn for advice on red gums, experimental design, API, writing and helping in the field. Shiquan Ren for statistical advice and assistance with the LOESS regression to fill gaps in the hydrological record, David Edwards for hydrological advice, Evan Webster, Shawn Laffan, Melissa Head and Kate Brandis for their help with API and GIS.

We would like to thank Dr Mike Maher and the RiverBank Program for funding the project and providing expertise. And Patrick Driver for providing recent flow data, sampling advice and support.

References

ADGER, W. N. LUTTRELL, C. (2000) Property Rights and the Utilisation of Wetlands. *Ecological Economics*. 35**,** 75-89.

ALADIN, N. V. WILLIAMS, W. D. (1993) Recent Changes in the Biota of the Aral Sea, Central Asia. *International Society of Liminology*. 25**,** 790-792.

ALLANSON, B. R., HART, R. C., O'KEEFE, J. H. ROBARTS, R. D. (1990) Inland Waters of Southern Africa: An Ecological Perspective. IN DUMONT, H. J. & WERGER, M. J. A. (Eds.) *Monograph Biologicae*. Kluwer Academic, Dordrecht.

ANDO, A. W. GETZNER, M. (2006) The Roles of Ownership, Ecology, and Economics in Public Wetland-Conservation Decisions. *Ecological Economics*. 58**,** 287-303.

APAN, A. A., RAINE, S. R. PATERSON, M. S. (2002) Mapping and Analysis of Changes in the Riparian Landscape Structure of the Lockyer Valley Catchment, Queensland, Australia. *Landscape and Urban Planning*. 59**,** 43-57.

BACON, P. E., STONE, C., BINNS, D. L., LESLIE, D. J. EDWARDS, D. W. (1993) Relationships between Water Availability and Eucalyptus Camaldulensis Growth in a Riparian Forest *Journal of Hydrology*. 150**,** 541-561.

BLAKERS, M., DAVIES, S. J. J. F. REILLY, P. N. (1984) *The Atlas of Australian Birds,* Carlton South, Melbourne University Press.

BOLAND, D. J., BROOKER, M. we. H. TURNBULL, J. W. (1980) *Eucalyptus Seed*. CSIRO. Canberra, Australia.

BOND, N. R., LAKE, P. S. ARTHINGTON, A. H. (2008) The Impacts of Drought on Freshwater Ecosystems: An Australian Perspective. *Hydrobiologia*. 600**,** 3-16.

BOWDEN, L. W. BROONER, W. G. (1970) Aerial Photography: A Diversified Tool. *Geoforum*. 2**,** 19-32.

BREN, L. (1987) The Duration of Inundation in a Flooding River Red Gum Forest. *Australian Forest Research*. 17**,** 191-202.

BREN, L. (1988) Effects of River Regulation on Flooding of a Riparian Red Gum Forest on the River Murray, Australia. *Regulated Rivers: Research & Management*. 2**,** 65-77.

BREN, L. J. GIBBS, N. L. (1986) Relationships between Flood Frequency, Vegetation and Topography in a River Red Gum Forest. *Australian Forest Research.* 16**,** 357-370.

BRIGGS, S. K. MAHER, M. T. (1983) Litter Fall and Leaf Decomposition in a River Red Gum (Eucalyptus Camaldulensis) Swamp. *Australian Journal of Botany.* 31**,** 307-316.

BRIGGS, S. V., MAHER, M. T. TONGWAY, D. J. (1993) Dissolved and Particulate Organic-Carbon in 2 Wetlands in Southwestern New-South-Wales, Australia. *Hydrobiologia.* 264**,** 13-19.

BRIGGS, S. V. THORNTON, S. A. (1999) Management of Water Regimes in River Red Gum Eucalyptus Camaldulensis Wetlands for Waterbird Breeding. *Australian Zoologist.* 31**,** 187-197.

BRIGGS, S. V., THORNTON, S. A. LAWLER, W. G. (1997) Relationships between Hydrological Control of River Red Gum Wetlands and Waterbird Breeding. *Emu.* 97**,** 31-42.

BROCK, M. A., NIELSEN, D. L., SHIEL, R. J., GREEN, J. D. LANGLEY, J. D. (2003) Drought and Aquatic Community Resilience: The Role of Eggs and Seeds in Sediments of Temporary Wetlands. *Freshwater Biology.* 48**,** 1207-1218.

CAPON, S. J. BROCK, M. A. (2006) Flooding, Soil Seed Bank Dynamics and Vegetation Resilience of a Hydrologically Variable Desert Floodplain. *Freshwater Biology.* 51**,** 206-223.

CARMEL, Y. KADMON, R. (1998) Computerised Classification of Mediterranean Vegetation Using Panchomatic Aerial Photographs. *Journal of Vegetation Science.* 9**,** 445-454.

CLEVELAND, W. S., GROSSE, E. SHYU, W. M. (1992) "Local Regression Models" In Statistical Models in S. IN CHAMBERS, J. M. & HASTIE, T. J. (Eds.). Pacific Grove, Wadsworth & Brooks/Cole.

COWELL, C. M. STOUDT, R. T. (2002) Dam-Induced Modifications to Upper Allegheny River Streamflow Patterns and Their Biodiversity Implications. *Journal of the American Water Resources Association.* 38**,** 187-196.

CROME, F. H. J. CARPENTER, S. M. (1988) Plankton Community Cycling and Recovery after Drought - Dynamics in Basin on a Flood Plain. *Hydrobiologia.* 164**,** 193-211.

CROME, F. J. H. (1988) To Drain or Not to Drain? - Intermittent Swamp Drainage and Waterbird Breeding. *Emu.* 88**,** 243-248.

CSIRO (2008) *Water Availability in the Lachlan.* A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO. 133pp. Canberra, Australia.

CUNNINGHAM, S. C., READ, R., BAKER, P. J. MACNALLY, R. (2007) Quantitative Assessment of Stand Condition and Its Relationship to Physiological Stress in Stands of Eucalyptus Camaldulensis (Myrtaceae). *Australian Journal of Botany.* 55 692-699.

DANBY, R. HIK, D. (2007) Evidence of Recent Treeline Dynamics in Southwest Yukon from Aerial Photographs. *arctic.* 80**,** 411-420.

DECC (2008a) *New South Wales Riverbank Business Plan A: Buying and Managing Water for the Environment.* Part A: Program plan 2006-2011. The New South Wales Department of Environment and Climate Change. 43. Sydney.

DECC (2008b) *New South Wales Riverbank Business Plan B: Buying and Managing Water for the Environment.* Part B: Annual plan 2007-2008. The New South Wales Department of Environment and Climate Change. 44. Sydney.

DEXTER, B. (1970) Regeneration of River Red Gum Eucalyptus Camaldulensis Dehn. *MSc Thesis University of Melbourne.* Melbourne, Australia.

DLWC (1997) *Lachlan Catchment State of Rivers Report - 1997.* New South Wales Department of Land and Water Conservation.

DODD, N. L., STATES, J. S. ROSENSTOCK, S. S. (2003) Tassel-Eared Squirrel Population, Habitat Condition, and Dietary Relationships in North-Central Arizona. *Journal of Wildlife Management.* 67**,** 622-633.

DONALD, A., NATHAN, R. REED, J. (1999) Use of Spells Analysis as a Practical Tool to Link Ecological Need with Hydrological Characteristics. IN RUTHERFURD, we. D. & BARTLEY, R. (Eds.) *Proceedings of the second Australian stream management conference.* Adelaide, Cooperative research centre for catchment hydrology, Monash University, Clayton.

DRIVER, P. D., CHOWDHURY, S., HAMEED, T., LLOYD-JONES, P., RAISIN, G., RIBBONS, C. SINGH, G. (2003) *Reference and Modified Flows of the Lachlan Valley Wetlands.* Lachlan Floodplain Wetlands Adaptive Water Management Framework. New South Wales Department of Infrastructure, Planning and Natural Resources.

DRIVER, P. D., HAMEED, T., SMITH, T., WETTIN, P. RASIN, G. (2005) Rehabilitation of Wetland Inundation Regimes in the Lachlan River, Nsw, Australia: Achievements and Ongoing Challenges. *Proceedings of the 2005 River Symposium.*

DRIVER, P. D., WETTIN, P., RAISIN, G. SRITHARAN, S. (2000) *Lachlan River 1999/2000 Environmental Flow Rules.* Operation and performance report. New South Wales Department of Land and Water Conservation. Central West Region.

DWR (1992) *Water Management Strategy for the Wetlands of the Lachlan Valley Floodplain.* New South Wales Department of Natural Resources. Lachlan Region.

DWYER, K. BENNETT, M. (1988) *Hydrology and Water Management Capability of the Booligal Wetlands - 1986 Flow.* Department of Water Resources.

EA (2001) *A Directory of Important Wetlands in Australia,* Canberra, Environment Australia.

FENSHAM, R. J. FAIRFAX, R. J. (2002) Aerial Photography for Assessing Vegetation Change: A Review of Applications and the Relevance of Findings for Australian Vegetation History. *Australian Journal of Botany.* 50**,** 415-429.

FENSHAM, R. J. FAIRFAX, R. J. (2003) A Land Management History for Central Queensland, Australia as Determined from Land-Holder Questionnaire and Aerial Photography. *Journal of Environmental Management.* 68**,** 409-420.

FENSHAM, R. J. FAIRFAX, R. J. (2007) Effect of Photoscale, Interpreter Bias and Land Type on Woody Crown-Cover Estimates from Aerial Photography. *Australian Journal of Botany.* 55**,** 457-463.

FENSHAM, R. J., FAIRFAX, R. J., HOLMAN, J. E. WHITEHEAD, P. J. (2002) Quantitative Assessment of Vegetation Structural Attributes from Aerial Photography. *International Journal of Remote Sensing.* 23**,** 2293-2317.

FINLAYSON, B. L., GIPPEL, C. BRIZGA, S. O. (1994) Effects of Reservoirs on Downstream Aquatic Habitat. *Journal of australia water works association.* 21**,** 15-20.

FRITH, H. J. (1967) *Waterfowl in Australia,* Sydney, Angus & Robertson.

GEORGE, A. K., WALKER, K. F. LEWIS, M. M. (2005) Population Status of Eucalypt Trees on the River Murray Floodplain, South Australia. *River Research and Applications.* 21**,** 271-282.

GORDON, N., FINLAYSON, B. L., MCMAHON, T., GIPPEL, C. RORY, N. (2004a) *Stream Hydrology: An Introduction for Ecologists,* West Sussex, England, John Wiley & Sons, Ltd.

GORDON, N., MCMAHON, T., FINLAYSON, B., GIPPEL, C. RORY, N. (2004b) Aquapak Download. *Stream Hydrology: an introduction for Ecologists.* John Wiley and Sons

GRAHAM, R. KOH, A. (2002) *Digital Aerial Survey: Theory and Practice,* Scotland, UK, Whittles Publishing.

GUNDERSON, L. H., CARPENTER, S. R., FOLKE, C., OLSSON, P. PETERSON, G. (2006a) Water Rats (Resilience, Adaptability, and Transformability) in Lake and Wetland Social-Ecological Systems. *Ecology and Society*. 11.

GUNDERSON, L. H., CARPENTER, S. R., FOLKE, C., OLSSON, P. PETERSON, G. D. (2006b) Water Rats (Resilience, Adaptability, and Transformability) in Lake and Wetland Social-Ecological Systems. *Ecology and Society*. 11**,** 16.

HAINES, P. J., BELL, A. B. THATCHER, L. P. (1994) Evaluation of Some Factors Involved in Reducing Browsing Damage to Eucalypt Trees by Sheep. *Australian Journal of Experimental Agriculture*. 34**,** 601-607.

HANLEY, T. A. (1978) A Comparison of the Line-Interception and Quadrat Estimation Methods of Determining Shrub Canopy Coverage. *Journal of Range Management*. 31**,** 60-2.

HILLMAN, M. BRIERLEY, G. (2002) Information Needs for Environmental-Flow Allocations: A Case Study from the Lachlan River, New South Wales, Australia. *Annals of the Association of American Geographers*. 92**,** 617-630.

HOLLIS, G. E. (1990) Environmental Impacts of Development on Wetlands in Arid and Semi-Arid Lands. *Hydrological Sciences Journal*. 35**,** 441-428.

HUDAK, A. T. WESSMAN, C. A. (1998) Textural Analysis of Historical Aerial Photography to Characterise Woody Plant Encroachment in South African Savanna. *Remote sensing environment*. 66**,** 317-330.

HUTCHINSON, C. F., UNRUH, J. D. BAHRE, C. J. (2000) Land Use Vs. Climate Change as Causes of Vegetation Change: A Study in Se Arizona. *Global environmental change-human policy dimensions*. 10**,** 47-55.

JACKSON, R. B., CARPENTER, S. R., DAHM, C. N., MCKNIGHT, D. M., NAIMAN, R. J., POSTEL, S. L. RUNNING, S. W. (2001) Water in a Changing World. *Ecological Applications*. 11**,** 1027-1045.

JANSEN, A. HEALEY, M. (2003) Frog Communities and Wetland Condition: Relationships with Grazing by Domestic Livestock Along an Australian Floodplain River. *Biological Conservation*. 109**,** 207-219.

JAYASURIYA, R. T. (2003) Modelling the Economic Impact of Environmental Flows for Regulated Rivers in New South Wales, Australia. *Water Science and Technology*. 48**,** 157-164.

JENKINS, K. BOULTON, A. J. (2003) Connectivity in a Dryland River: Short-Term Aquatic Microinvertebrate Recruitment Following Floodplain Inundation *Ecology*. 84**,** 2708-2723.

JENKINS, K. BOULTON, A. J. (2007) Detecting Impacts and Setting Restoration Targets in Arid-Zone Rivers: Aquatic Micro-Invertebrate Responses to Reduced Floodplain Inundation. *Journal of Applied Ecology*. 44**,** 823-832.

JENKINS, K., BOULTON, A. J. RYDER, D. B. (2005) A Common Parched Future? Research and Management of Australian Arid-Zone Floodplain Wetlands. *Hydrobiologia*. 552.

JENSEN, A. E., WALKER, K. F. PATON, D. C. (2007) Using Phenology of Eucalypts to Determine Environmental Watering Regimes for the River Murray Floodplain, South Australia. IN WILSON, A. L., DEHAAN, R. L., WATTS, R. J., PAGE, K. J., BOWMER, K. H. & CURTIS, A. (Eds.) *Proceedings of the 5th Australian Stream Management Conference. Australian rivers: making a difference.* Charles Sturt University, Thurgoona, New South Wales.

KADMON, R. HARARI-KREMER, R. (1999) Studying Long-Term Vegetation Dynamics Using Digital Processing of Historical Aerial Photographs. *Remote sensing environments*. 68**,** 164-176.

KASSER, M. EGELS, Y. (2002) *Digital Photogrammetry,* London, Taylor & Francis Inc.

KEMP, J. (2004) Flood Channel Morphology of a Quiet River, the Lachlan Downstream from Cowra, Southeastern Australia. *Geomorphology*. 60**,** 171-190.

KINGSFORD, R. (2006) *Ecology of Desert Rivers,* New York, United States of America, Cambridge University Press.

KINGSFORD, R. T. (1995) *Ecological Effect of River Management in New South Wales,* Hurstville, Surrey Beatty & Sons.

KINGSFORD, R. T. (2000a) Ecological Impacts of Dams, Water Diversions and River Management on Floodplain Wetlands in Australia. *Austral Ecology*. 25**,** 109-127.

KINGSFORD, R. T. (2000b) Protecting Rivers in Arid Regions or Pumping Them Dry? *Hydrobiologia*. 427**,** 1-11.

KINGSFORD, R. T. AULD, K. M. (2005) Waterbird Breeding and Environmental Flow Management in the Macquarie Marshes, Arid Australia. *River Research and Applications*. 21**,** 187-200.

KINGSFORD, R. T., BRANDIS, K., THOMAS, R. F., CRIGHTON, P., KNOWLES, E. GALE, E. (2004) Classifying Landform at Broad Spatial Scales: The Distribution and Conservation of Wetlands in New South Wales, Australia. *Marine and Freshwater Research*. 55**,** 17-31.

KINGSFORD, R. T. THOMAS, R. (1995) The Macquarie Marshes in Arid Australia and Their Waterbirds: A 50-Year History of Decline. *Environmental Management*. 19**,** 867-878.

KINGSFORD, R. T. THOMAS, R. (2002) Use of Satellite Image Analysis to Track Wetland Loss on the Murrumbidgee River Floodplain in Arid Australia, 1975–1998. *Water Science and Technology*. 45**,** 45-53.

KINGSFORD, R. T. THOMAS, R. F. (2004) Destruction of Wetlands and Waterbird Populations by Dams and Irrigation on the Murrumbidgee River in Arid Australia. *Environmental Management*. 34**,** 383-396.

KINZIG, A. P., RYAN, P., ETIENNE, M., ALLISON, H., ELMQVIST, T. WALKER, B. H. (2006) Resilience and Regime Shifts: Assessing Cascading Effects. *Ecology and Society*. 11**,** 20.

KNAPP, P. A., WARREN, P. L. HUTCHINSON, C. F. (1990) The Use of Large-Scale Aerial Photography to Inventory and Monitor Arid Rangeland Vegetation. *Journal of Environmental Management*. 31**,** 29-38.

KONDOLF, G. M., BOULTON, A. J., O'DANIEL, S., POOLE, G. C., RAHEL, F. J., STANLEY, E. H., WOHL, E., BÅNG, A., CARLSTROM, J., CRISTONI, C., HUBER, H., KOLJONEN, S., LOUHI, P. NAKAMURA, K. (2006) Process-Based Ecological River Restoration: Visualizing Three-Dimensional Connectivity and Dynamic Vectors to Recover Lost Linkages. *Ecology and Society*. 11**,** 5.

LAKE, P. S. BOND, N. R. (2007) Australian Futures: Freshwater Ecosystems and Human Water Usage. *Futures*. 39**,** 288-305.

LAKE, P. S. MARCHANT, R. (1990) Australian Upland Streams: Ecological Degradation and Possible Restoration. *Proceedings of the Ecological Society of Australia*. 16**,** 79-91.

LAKE, S., BOND, N. REICH, P. (2006) Floods Down Rivers: From Damaging to Replenishing Forces. *Advances in Ecological Research, Vol 39*. 39**,** 41-62.

LILIBERTE, A. S., RANGO, A., HAVSTAD, K. M., PARIS, F. J., BECK, R. F., MCNEELY, R. GONZALEZ, A. L. (2004) Object-Orientated Analysis for Mapping Sub Encroachment from 1937 to 2003 in Southern New Mexico. *Remote sensing environment*. 93**,** 198-210.

LINDER, W. (2003) *Digital Phtogrammetry: Theory and Applications,* New York, Springer.

LOTH, P., ACREMAN, M., BAUER, M., BRAUND, R., EVANS, S., EMERTON, S., DE LONGH, H., KARL, S., KOUOKARN, R., MORITZ, M., NYANTOU, D., NJOMAHA, C., PITOR, J.-Y. SCHOLTE, P. (2004) The Return of the Water : Restoring the Waza Logone Floodplain in Cameroon. IN LOTH, P. (Ed.) *Iucn Wetlands and Water Resources Programme Blue Series*. Gland, IUCN.

MAGRATH, M. J. L. (1992) *Waterbird Study of the Lower Lachlan and Murrumbidgee Valley Wetlands in 1990/91*. The New South Wales Department of Water Resources.

MAHER, M. T. (1984) Benthic Studies of Waterfowl Breeding Habitat in South-Western New South Wales we: The Fauna. *Australian Journal of Marine and Freshwater Research*. 35**,** 85-96.

MAHER, M. T. CARPENTER, S. M. (1984) Benthic Studies of Waterfowl Breeding Habitat in South-Western New South Wales Ii: Chironomid Populations. *Australian Journal of Marine and Freshwater Research*. 35**,** 97-110.

MAHER, P. N. (1990) *Bird Surveys of the Lachlan/Murrumbidgee Confluence Wetlands*. New South Wales National Parks and Wildlife Service.

MAHESHWARI, B. L., WALKER, K. F. MCMAHON, T. A. (1995) Effects of Regulation on the Flow Regime of the River Murray, Australia. *Regulated Rivers: Research & Management*. 10**,** 15-38.

MASSEY, C. (1997) *An Assessment of Riverine Environmental Health in the Lachlan Catchment Draft Report*. Department of Land and Water Conservation. Forbes, NSW.

MAWHINNEY, W. A. (2003) Restoring Biodiversity in the Gwydir Wetlands through Environmental Flows. *Water Science and Technology*. 48**,** 73-81.

MCALLISTER, R. R., ABEL, J. N., STOKES, C. J. GORDON, we. J. (2006) Australian Pastoralists in Time and Space: The Evolution of a Complex Adaptive System. *Ecology and Society*. 11**,** 41.

MCMAHON, T. A. FINLAYSON, B. L. (1995) Reservoir System Management and Environmental Flows *Lakes Reservoirs: Research Management* 1**,** 65-76.

MCMAHON, T. A. FINLAYSON, B. L. (2003) Droughts and Anti-Droughts: The Low Flow Hydrology of Australian Rivers. *Freshwater Biology*. 48**,** 1147-1160.

MDBC (1990) Riparian Vegetation of the River Murray. IN COMMISSION, E. C. A. D. O. C. F. A. L. M.-D. B. (Ed. Canberra, ACT, Margules and Partners Pty Ltd P & J Smith.

MDBC (2002) *The Living Murray: A Discussion Paper on Restoring the Health of the River Murray*. Murray-Darling Basin Commission. Canberra.

MDBC (2005) *Survey of River Red Gum and Black Box Health Along the River Murray in New South Wales, Victoria and South Australia – 2004.* Murray-Darling Basin Commission. Canberra.

MEESON, N., ROBERTSON, A. we. JANSEN, A. (2002) The Effects of Flooding and Livestock on Post-Dispersal Seed Predation in River Red Gum Habitats. *Journal of Applied Ecology*. 39**,** 247-258.

MICKLEN, P. P. (1988) Desiccation of the Aral Sea: A Water Management Disaster in the Soviet Union. *Science* 241**,** 1170-1176.

MOORE, C. (1992) *Water Management Plan for the Booligal Wetlands Ibis Rookery Preservation Strategy*. Department of Water Resources. NRMS Project N167. Forbes.

NEBEL, S., PORTER, J. L. KINGSFORD, R. T. (2008) Long-Term Trends of Shorebird Populations in Eastern Australia and Impacts of Freshwater Extraction. *Biological Conservation.* In Press, Corrected Proof.

NIEMEYER, S., PETTS, J. HOBSON, K. (2005) Rapid Climate Change and Society: Assessing Responses and Thresholds. *Risk Analysis.* 25**,** 1443-1456.

NOWAK, D. J., ROWNTREE, R. A., MCPHERSON, E. G., SISINNI, S. M., KERKMANN, E. R. STEVENS, J. C. (1996) Measuring and Analyzing Urban Tree Cover. *Landscape and Urban Planning*. 36**,** 49-57.

OMER, A. M. (2008) Water Resources and Freshwater Ecosystems in Sudan. *Renewable and Sustainable Energy Reviews.* 12**,** 2066-2091.

PAPWORTH, M. P. LEWIS, B. (2003) The Development of an Historical Baseline of Water Balance and Environmental Flows. *Water Science and Technology*. 48**,** 139-147.

PETTS, G. (1990) Regulation of Large Rivers - Problems and Possibilities for Environmentally-Sound River Development in South-America. *Interciencia.* 15**,** 388-395.

PETTS, G. (1992) Dam the Rivers, Damn the People - Development and Resistance in Amazonian Brazil. *Applied Geography*. 12**,** 82-82.

PETTS, G. (1996) Water Allocation to Protect River Ecosystems. *Regulated Rivers-Research & Management*. 12**,** 353-365.

PETTS, G. (2001) Sustaining Our Rivers in Crisis: Setting the International Agenda for Action. *Water Science and Technology*. 43**,** 3-16.

PETTS, G. (2003) Special Issue: Environmental Flows for River Systems Selected Papers from the Joint Meeting on Environmental Flows for River Systems and 4th International Ecohydraulics Symposium Cape Town March 2002. *River Research and Applications*. 19**,** 375-376.

PETTS, G. E. GURNELL, A. M. (2005) Dams and Geomorphology: Research Progress and Future Directions. *Geomorphology*. 71**,** 27-47.

POFF, N. L., ALLAN, J. D., BAIN, M. B., KARR, J. R., PRESTEGAARD, K. L., RICHTER, B. D., SPARKS, R. E. STROMBERG, J. C. (1997) The Natural Flow Regime: A Paradigm for River Conservation and Restoration. *Bioscience*. 47**,** 769-784.

POWELL, S. J., LETCHER, R. A. CROKE, B. F. W. (2008) Modelling Floodplain Inundation for Environmental Flows: Gwydir Wetlands, Australia. *Ecological Modelling*. 211**,** 350-362.

PUCKRIDGE, J. T., SHELDON, F., BOULTON, A. J. WALKER, K. F. (1998) Flow Variability and the Ecology of Large Rivers. *Marine Freshwater Res*. 49**,** 55-72.

QUINN, G. P. KEOUGH, M. J. (2002) *Experimental Design and Data Analysis for Biologists,* Cambridge, UK, Cambridge University Press.

RESH, V. M., BROWN, A. V., COVICH, A. P., GURTZ, M. E., LI, H. W., MINSHALL, G. W., REICE, G. W., SHELDON, A., WALLACE, J. B. WISSMAR, R. C. (1988) The Role of Disturbance in Stream Hydrolohy. *Journal of north american benthological society*. 7**,** 433-455.

RILEY, S. J. (1988) Secular Change in the Annual Flows of Streams in the N.S.W. Section of the Murray-Darling Basin. IN WARNER, R. F. (Ed.) *Fluvial Geomorphology of Australia*. Sydney, Academic Press.

ROBERTS, J. (2007) Conditions of Murrumbidgil Swamp: Benchmarking and Recommending a Method for Long-Term Monitoring. IN PROGRAM, A. R. T. T. N. R. (Ed.

ROBERTS, J. MARSTON, F. (2000) *Water Regime of Wetland and Floodplain Plants in the Murray-Darling Basin: A Source Book of Ecological Knowledge.* CSIRO Land & Water. Technical Report 30/00. Canberra.

ROBERTS, J. SAINTY, G. (1996) *Listening to the Lachlan.* Sainty and Associates/Murray-Darling Basin Commission.

ROBERTS, J., YOUNG, B. MARSTON, F. (2000) *Estimating the Water Requirements for Plants of Floodplain Wetlands: A Guide.* CSIRO Land & Water. Occasional Paper 04/00. Canberra.

ROBERTSON, A. we. ROWLING, R. W. (2000) Effects of Livestock on Riparian Zone Vegetation in an Australian Dryland River. *Regulated Rivers Research and Management.* 16**,** 527-541.

SCHOFIELD, N. BURT, A. (2003) Issues in Environmental Water Allocation – an Australian Perspective. *Water Science and Technology.* 48**,** 83-88.

SCHREIDER, S. Y., JAKEMAN, A. J., LETCHER, R. A., NATHAN, R. J., NEAL, B. P. BEAVIS, S. G. (2002) Detecting Changes in Streamflow Response to Changes in Nonclimatic Catchment Conditions: Farm Dam Development in the Murray-Darling Basin, Australia. *Journal of Hydrology.* 262**,** 84-98.

SEARCY, J. K. (1959) *Flow Duration Curves.* Manual of hydrology: Part 2 low flow techniques. US geological survey 1542-A. Washington, DC.

SERVENTY, V. N. (1985) *The Waterbirds of Australia,* Sydney, Angus and Robertson.

SHAPIRO, S. S. WILK, M. B. (1965) An Analysis of Variance Test for Normality (Complete Samples). *Biometrika.* 52**,** 591-611.

SHELDON, F., BOULTON, A. J. PUCKRIDGE, J. T. (2002) Conservation Value of Variable Connectivity: Aquatic Invertebrate Assemblages of Channel and Floodplain Habitats of a Central Australian Arid-Zone River, Cooper Creek. *Biological Conservation.* 103**,** 13-31.

SHELDON, F., THOMS, M. C., BERRY, O. PUCKRIDGE, J. (2000) Using Disaster to Prevent Catastrophe: Referencing the Impacts of Flow Changes in Large Dryland Rivers. *Regulated Rivers: Research & Management.* 16**,** 403-420.

SHIELDS, J. GOOD, R. (2002) Environmental Water in a Regulated River System: The Murrumbidgee River Planning Approach to the Determination of Environmental Needs. *Water Science and Technology.* 45**,** 241-249.

SICKEL, H., IHSE, M., NORDERHAUG, A. SICKEL, M. A. K. (2004) How to Monitor Seni-Natural Key Habitats in Relation to Grazing Preference of Cattle in Mountain Summer Farming Areas: An Aerial Photo and Gps Method Study. *Landscape and Urban Planning*. 67, 67-77.

SOKAL, R. R. ROHLF, F. J. (1995) *Biometry: The Principles and Practice of Statistics in Biological Research,* New York, W. H. Freeman and Co.

SPECHT, R. L., ROE, E. M. BOUGHTON, V. H. (1974) Conservation of Major Plan Communities in Australia and Papua New Guinea. *Australian Journal of Botany Supplement*. 7.

STEWART, G. HARPER, B. (2002) Barmah-Millewa Forest Environmental Water Allocation. *Water Science and Technology*. 45, 217-223.

THOMS, M. C. SHELDON, F. (2000) Water Resource Development and Hydrological Change in a Large Dryland River: The Barwon-Darling River, Australia. *Journal of Hydrology*. 228, 10-21.

THOMS, M. C., SOUTHWELL, M. MCGINNESS, H. M. (2005) Floodplain-River Ecosystems: Fragmentation and Water Resources Development. *Geomorphology*. 71, 126-138.

TICKLE, P. K., LEE, A., LUCAS, R. M., AUSTIN, J. WITTE, C. (2006) Quantifying Australian Forest Floristics and Structure Using Small Footprint Lidar and Large Scale Aerial Photography. *Forest Ecology and Management*. 223, 379-394.

TOCKNER, K. STANDFORD, J. A. (2002) Riverine Flood Plains: Present State and Future Trends. *Environmental Conservation*. 29, 308-330.

VAN DER WATEREN-DE HOOG, B. (1995) The Effects of Climate Variability on Discharge as Dependent on Catchment Characteristics in the Upper Loire Basin, France. *Hydrological Sciences Journal*. 40, 633-646.

VOGEL, R. M. FENNESSEY, N. M. (1994) Flow-Duration Curves we: New Interpretation and Confidence-Intervals. *Journal of Water Resources Planning and Management-Asce*. 120, 485-504.

VOGEL, R. M. FENNESSEY, N. M. (1995) Flow Duration Curves Ii: A Review of Applications in Water-Resources Planning. *Water Resources Bulletin*. 31, 1029-1039.

WALKER, B. H., GUNDERSON, L. H., KINZIG, A. P., FOLKE, C., CARPENTER, S. R. SCHULTZ, L. (2006) A Handful of Heuristics and Some Propositions for Understanding Resilience in Social-Ecological Systems. *Ecology and Society*. 11, 13.

WALKER, K. F. (1985) A Review of the Ecological Effects of River Regulation in Australia. *Hydrobiologia.* 125**,** 111-129.

WARD, J. V. STANDFORD, J. A. (1983) The Intermediate-Disturbance Hypothesis: And Explanation for Biotic Diversity in Lotic Ecosystems. . IN FONTAINE, T. D. & BARTELL, S. M. (Eds.) *Dynamics of Lotic Ecosystems.* Ann Arbor, Ann Arbor Science.

WETTIN, P. (1997) *Floodplain Wetlands of the Lachlan Valley.* Department of Land and water conservation.

WETTIN, P., RAISIN, G., DRIVER, P. SRITHARAN, S. (2000) *Lachlan River 1999/2000 Environmental Flow Rules.* Operation and preformance report. Department of LAnd and Water Conservation.

WOOD, P. J., AGNEW, M. D. PETTS, G. E. (2000) Flow Variations and Macroinvertebrate Community Responses in a Small Groundwater-Dominated Stream in South-East England. *Hydrological Processes.* 14**,** 3133-3147.

YANG, X. (2007) Integrated Use of Remote Sensing and Geographic Information Systems in Riparian Vegetation Delineation and Mapping. *International Journal of Remote Sensing.* 28**,** 353-370.

YOUNG, W. J., LAM, D. C. L., RESSEL, V. WONG, we. W. (2000a) Development of an Environmental Flow Decision Support System. *Environmental Modelling & Software.* 15**,** 257-265.

YOUNG, W. J., LAM, D. C. L., RESSEL, V. WONG, we. W. (2000b) Development of an Environmental Flows Decision Support System. *Environmental Modelling and Software.* 15**,** 257-265.

ZAR, J. H. (1999) *Biostatidtical Analysis,* Upper Saddle River, NJ, Prentice Hall Inc.

ZEDLER, J. B. (2000) Progress in Wetland Restoration Ecology. *TREE.* 15**,** 402-407.