Scientific Forum on River Condition and Flow Management of the Moonie, Warrego, Paroo, Bulloo and Nebine River Basins

Peter Cottingham for the Queensland Department of Natural Resources

November 1999

Scientific Forum on River Condition and Flow Management of the Moonie, Warrego, Paroo, Bulloo and Nebine River Basins

Report prepared for
the Queensland Department of Natural Resources

Peter Cottingham
Cooperative Research Centre for Freshwater Ecology

November 1999

The Cooperative Research Centre for Freshwater Ecology improves the health of Australia's rivers, lakes and wetlands through research, education and knowledge exchange. It was established in 1993 under the Australian Government's Cooperative Research Centre Program.

The Cooperative Research Centre for Freshwater Ecology is a collaborative venture between:

- ACTEW Corporation
- CSIRO Land and Water
- Department of Land and Water Conservation, NSW
- Department of Natural Resources, Queensland
- Department of Natural Resources and Environment, Victoria
- Environment ACT
- Environment Protection Authority, NSW
- Environment Protection Authority, Victoria
- Goulburn-Murray Rural Water Authority
- Griffith University
- La Trobe University
- Lower Murray Water
- Melbourne Water
- Monash University
- Murray-Darling Basin Commission
- Sunraysia Rural Water Authority
- Sydney Catchment Authority
- University of Canberra

Ph: 02 6201 5168
Fax: 02 6201 5038
Email: pa@lake.canberra.edu.au
http://freshwater.canberra.edu.au

ISBN 0 95770 482 8

Scientific Forum on River Condition and Flow Management of the Moonie, Warrego, Paroo, Bulloo and Nebine River Basins

For the Queensland Department of Natural Resources

Peter Cottingham

November, 1999

Scientific Forum on River Condition and Flow Management of the Moonie, Warrego, Paroo, Bulloo and Nebine River Basins

Report prepared for
the Queensland Department of Natural Resources

Peter Cottingham
CRC for Freshwater Ecology
November, 1999

ISBN No. 0 95770 482 8

Tables

Figures

ACKNOWLEDGEMENTS
The information compiled in this report represents many years of extensive investigation by a number of individuals. The inputs from the following people was greatly appreciated: Kevin Baxter (Queensland Department of Natural Resources), Margaret Brock (Department of Land & Water Conservation), Stuart Bunn (Griffith University), Peter Davies (University of Western Australia), Peter Gehrke (NSW Fisheries), John Harris (CRC for Freshwater Ecology, ex NSW Fisheries), Richard Kingsford (NSW Parks & Wildlife Service), David Moffatt (Queensland Department of Natural Resources), Jim Puckridge (Adelaide University), Stephen Skull (Queensland Environment Protection Agency) and Brian Timms (University of Newcastle).

1 INTRODUCTION

The Queensland Government has introduced the Water Management Planning (WMP) process to provide for the improved allocation and management of water resources. The WMP has statutory effects under the 'Water Resources Act 1989', and provides a set of policies, principles and criteria for decisions on applications to take water from selected areas of Queensland. The WMP process is currently being applied to the Bulloo, Paroo, Warrego, Nebine and Moonie catchments (collectively called the Western Rivers), and the local Department of Natural Resources in consultation with local communities is currently developing draft plans that will be submitted to the Queensland Government by April 2000.

A workshop was held in Charleville on the 4th and 5th November 1999, to provide a forum at which the scientific and ecological aspects of the western rivers were presented and considered by many (not all) of the stakeholders in the WMP process. The workshop was faciltated by Prof Peter Cullen (CRC for Freshwater Ecology) and attended by local community members, State natural resource management agencies and authorities, and scientists who collectively have conducted the majority of investigations of the ecology of the Western Rivers and other similar arid river systems in Australia. The objectives of the workshop were to:

- Collect and collate existing scientific information on the environmental water needs and flow management principles for the western rivers and their floodplains;
- Provide a forum for scientific debate as to our knowledge base for these systems and any critical uncertainties;
- Provide a forum for water management planning advisory committees or panels to identify areas of concern and to have dialogue with the scientific community present;
- Provide a forum for stakeholders to express their views or concerns about relevant issues.

Consideration of scientific and ecological aspects is only one component of the wider WMP process; resource management, cultural heritage and socio-economic issues are also important factors that require careful consideration in the formulation of WMP's. However, the terms of reference for the scientific forum did not allow detailed consideration of socio-economic and other related issues; these issues are to be considered in the consultation phase of the WMP process.

A number of important questions require consideration in order to provide the best available scientific advice to the Department of Natural Resources and local communities as they develop WMP's for the catchments. These include:

- What are the processes that are important for maintaining the ecological integrity of the rivers in the study area and what is the current state of these processes and are they under threat?
- What are the important habitats and associated flora/fauna communities and their current state? Are they under threat?
- Is the current state in equilibrium with respect to the existing level of water resource development? How would we know? Is there a lag response to current water resource development and should we expect a decline in ecological health over the next five years?
- What are the ecological values associated with the river systems? Are there high ecological values due to unique flora/fauna, RAMSAR wetlands, unusual processes etc.?

These questions were considered throughout the scientific forum.

2 STUDY AREA

The study area covers approximately 271,100 km^2 over the catchments of the Bulloo, Paroo, and Warrego Rivers, Nebine Creek and the Moonie River (Figure 1 to Figure 3). Rainfall in the region is variable (Table 1; Appendix 1), both across the study area (spatial variability) and annually (temporal variability). Annual evaporation exceeds rainfall by between 1,000-2,000 mm. To date, there has been little surface water resource development on the rivers. Existing development (Table 2) has been privately funded with the exception of Cunnamulla Weir on the Warrego River, Bollon Weir on Wallum Creek and Thallon and Nindigully Weirs on the Moonie River. All bores and water conservation and diversion works located within defined watercourses require licensing by the DNR (in QLD) or DLWC (in NSW). Water conservation works, such as dams, outside of watercourses generally do not require licencing. However these works are licenced from a safety point of view if they are of a significant size (e.g. banks greater than 5m depth). DNR is assessing the impact of these storages on flows in the river systems, but such impacts were an unknown in the following discussions.

Industries across the study area include beef cattle, sheep for wool, dryland and irrigated cropping, commercial fishing (Paroo), bee-keeping (particularly the Paroo), opal mining (Bulloo, Paroo), oil (near Moonie and Alton) and natural gas production (Gilmore gas field, Bulloo) and tourism.

Table 1: Catchment information for the Western Rivers (from K. Baxter, QDNR, pers. comm.)

Catchment	Catchment Area (km^2)	Typical Annual Average Rainfall Range (mm)
Bulloo	74,900	150-500
Paroo	64,800	200-400
Warrego	78,400	250-650
Nebine	38,100	350-600
Moonie	14,900	450-650

Table 2: Water development in the Western Rivers (from K. Baxter, QDNR, pers. comm.)

Catchment	Water Development (from existing licence information)					
	Publicly Funded Storages	Privately Funded Storages	Diversion Channels	Pumps	Bores	Length of Bore Drains (km)
Bulloo	-	4	2	5	730	800
Paroo	-	2	-	10	1200	1400
Warrego	Cunnamulla Weir	70	7	107	1300	5000
Nebine	Bollon Weir	13	2	10	400	4000
Moonie	Thallon Weir Nindigully Weir	50	6	76	84	900

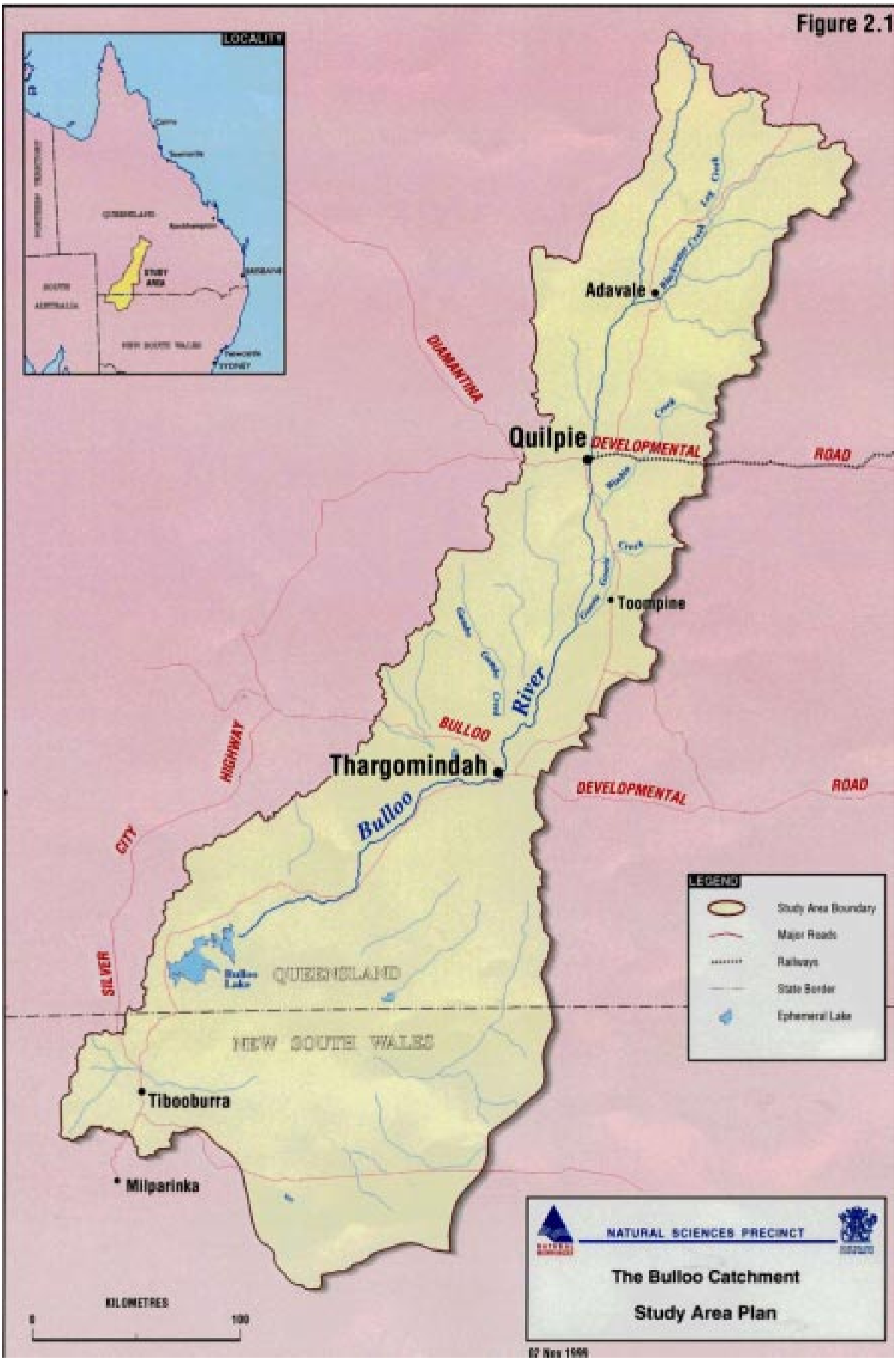

Figure 1: Bulloo River catchment area

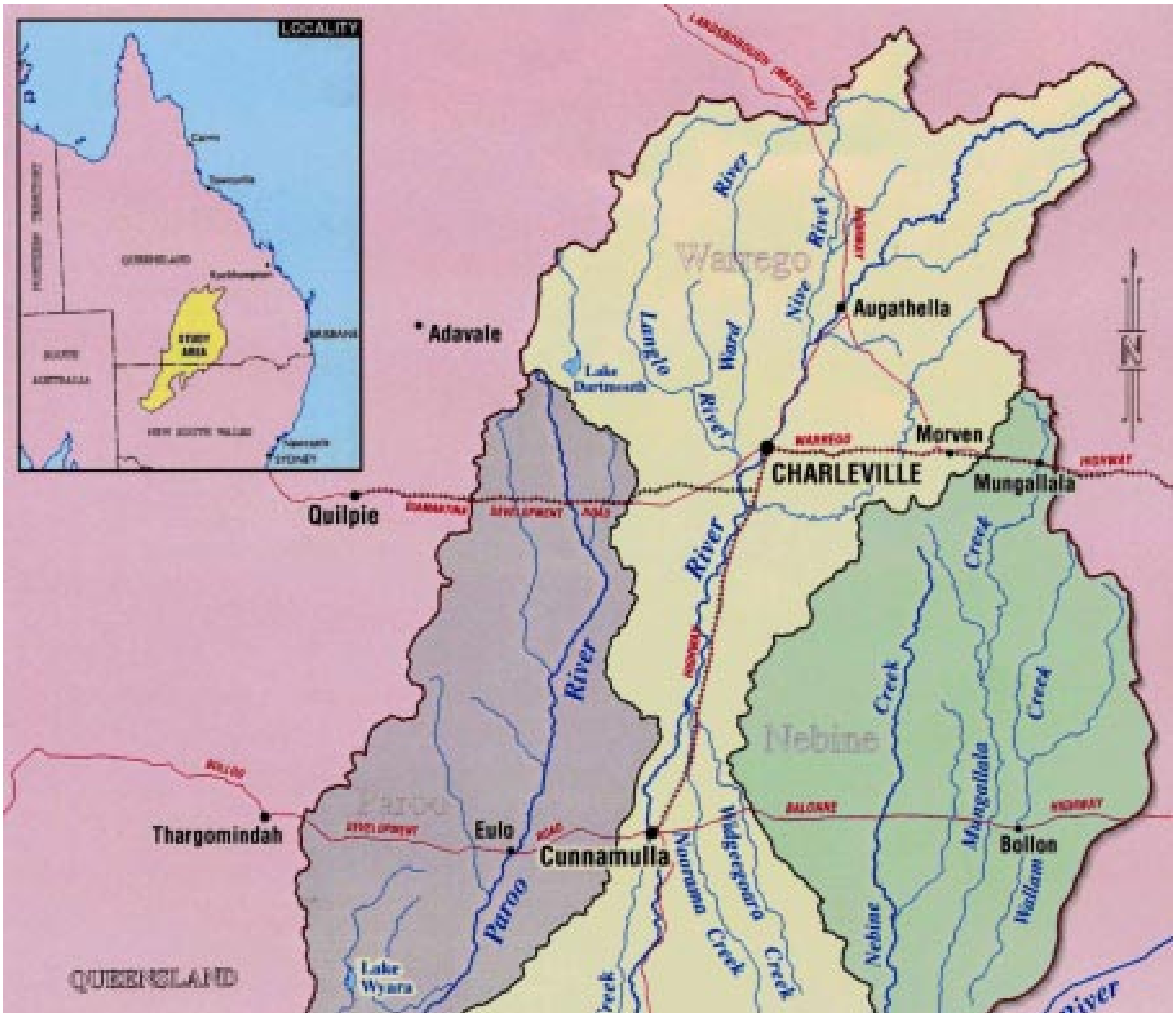

Figure 2: Paroo, Warrego and Nebine catchment area

Figure 3: Moonie River catchment area

3 KEY ENVIRONMENTAL PROCESSES

An overview of the key environmental processes that maintain the integrity of the Western Rivers (i.e. processes that maintain plant and animal communities, and functions such as production and respiration) was presented by various researchers at the scientific forum. A summary of these processes is provided in the following sections. Much of the information presented and discussed at the scientific forum focussed on the Paroo River. This was mainly due to the fact that this has been the most studied of the Western Rivers and does not imply that the ecological and conservation status of the other systems is less important. Many of the lessons learnt from the Paroo River are also likely to be imporant for the management of the other river systems.

3.1 Flow Variability

Variable rainfall and runoff is a key hydrological feature of the Western Rivers. This is highlighted with rainfall data for Charleville, Augathella, Cunnamulla and Fords Bridge and discharge data for the Warrego river at Wyandra and Fords Bridge (Appendix 1). By comparing 23 measures of hydrological variability (Appendix 1), Puckridge*. et al*.(1998) found that flows in systems such as the Paroo River and Cooper Creek in Australia are amongst the most variable in the world (Figure 4).

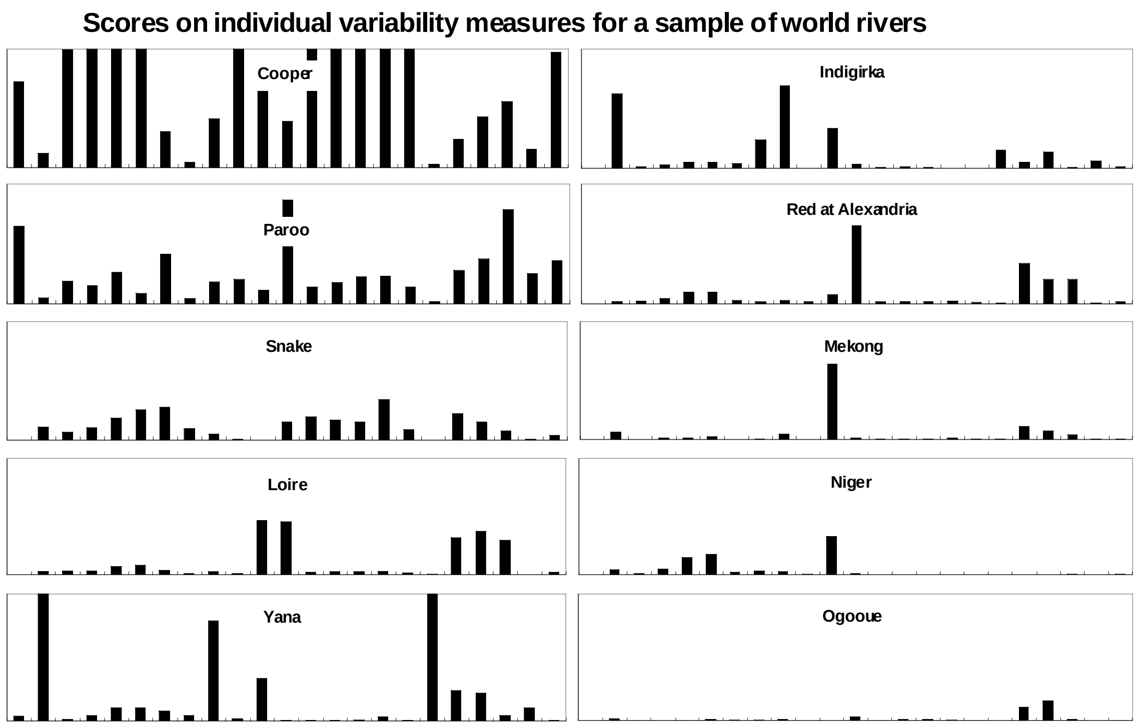

Figure 4: Values of 23 hydrological variables for selected world rivers (from Puckridge *et al.,* 1998)

Local plants (see section 3.3) and animals are adapted to this variability, often with ‘boom and bust’ responses to changes in flow conditions. Flow-related ecological processes play a key role in the life cycles of many aquatic species and are important for resetting aquatic communities and controlling alien species. For example, golden perch and western carp gudgeon populations expand their range and biomass in response to floods following drought periods; alien species such as carp or gambusia (‘mosquito fish”) prefer stable water conditions and are less well adapted to variable flow conditions. Examples of the response of native and alien fish to flow variability are presented in Figure 5 and Figure 6 respectively. Similarly, waterbird populations exhibit boom and bust periods in response to flows on dryland river systems (Kingsford *et al*. 1999). The anticipated behaviour of waterbirds in response to flow conditions is presented in Figure 7.

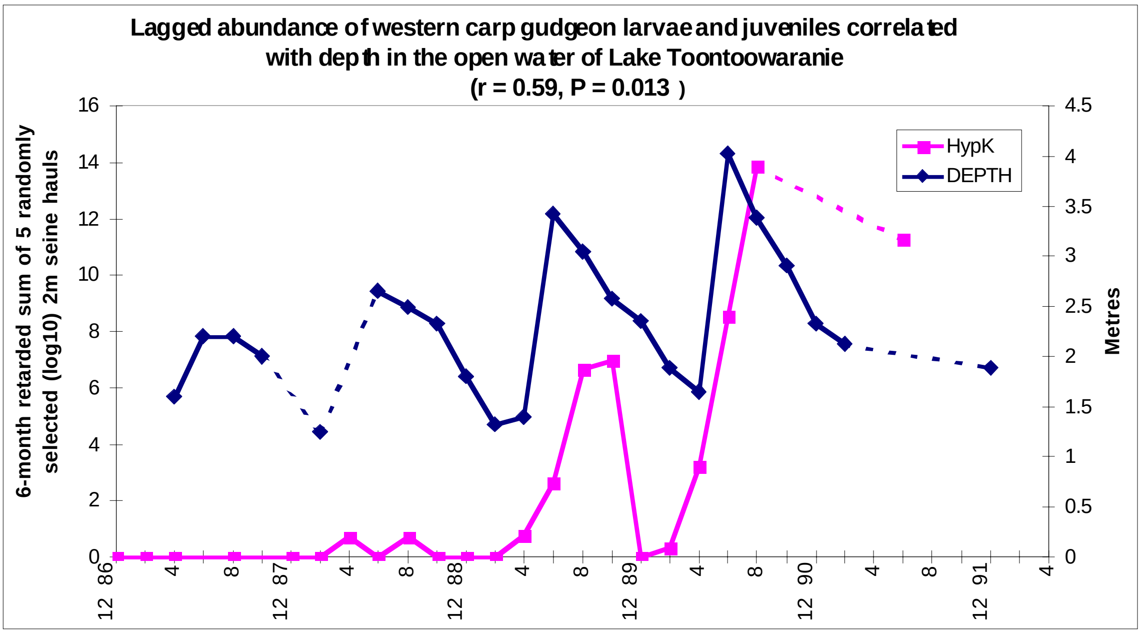

Figure 5: Response of western carp gudgeon in Lake Toontoowarinie, Cooper Creek catchment, to flow variability (from Puckridge *et al*., in press)

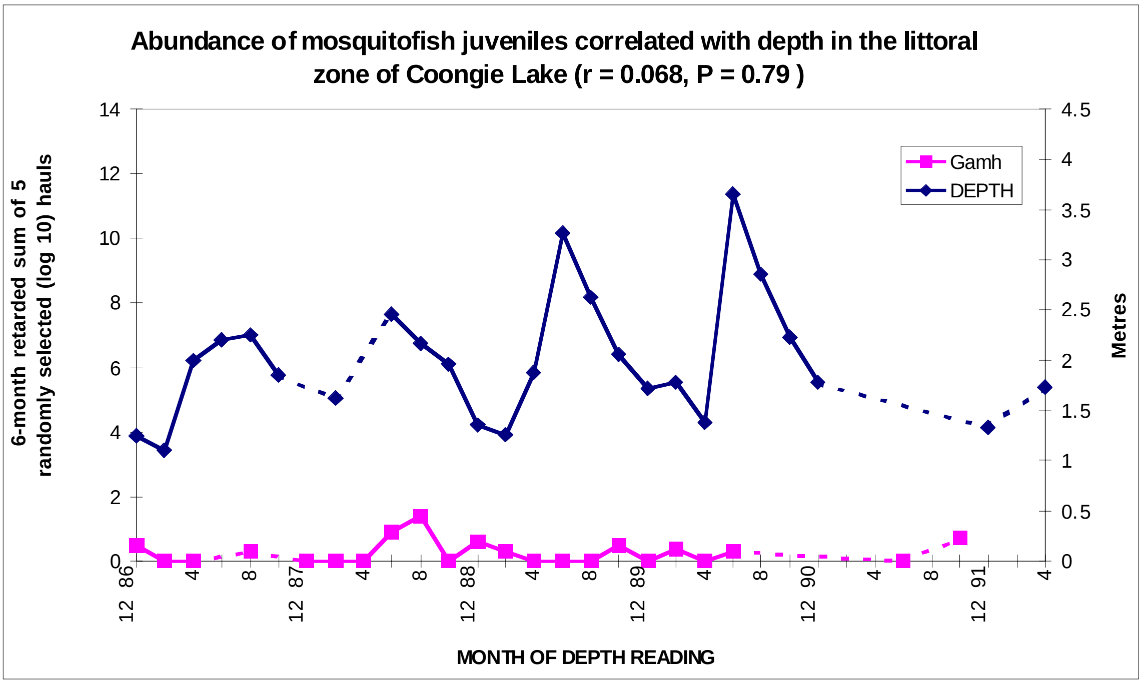

Figure 6: Response of the alien fish, gambusia in Coongie Lake, Cooper Creek catchment, to flow variability (Puckridge *et al*., in press)

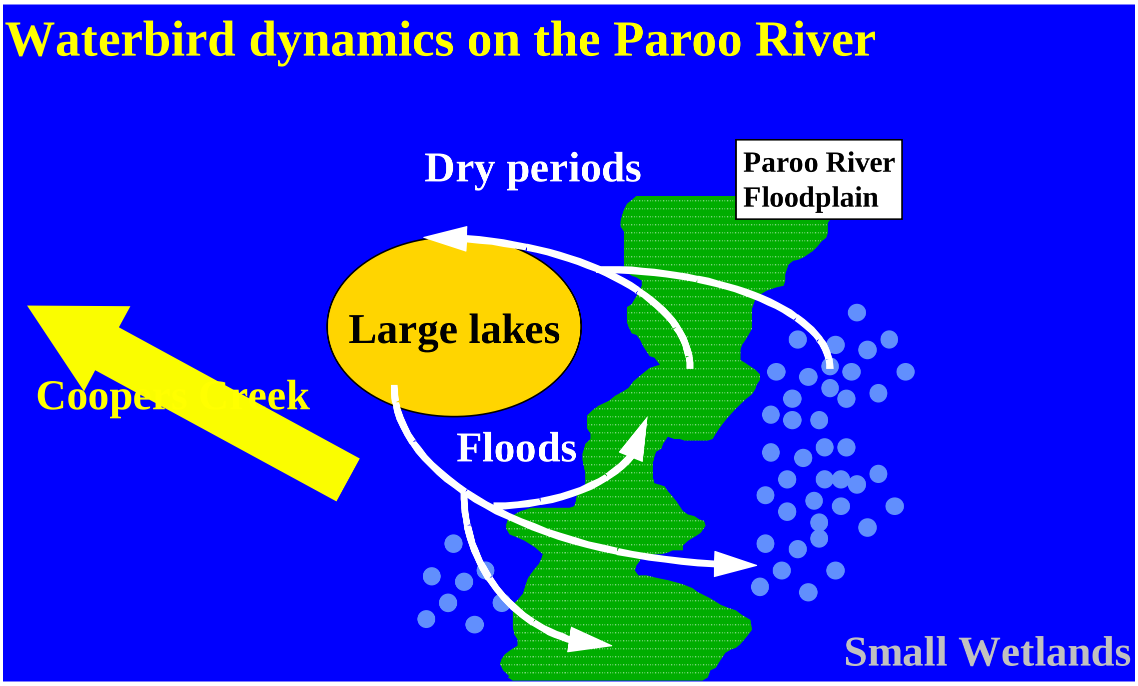

Figure 7: Response of waterbirds in the Paroo to flow conditions (from R. Kingsford, NSW P&W, pers. comm.)

3.2 Photosynthesis and Production

The Western Rivers area is characterised by a network of river and creek channels, wetlands and riparian areas and overflows. This provides a far larger area for riparian-water interaction than would be the case for a system dominated by a single large river channel. From this, it might be expected that the input of organic matter and nutrients from the floodplain and riparian zone would be the main driver of productivity in local waterways, especially as the water in river channels and wetlands is generally very turbid and likely to limit the amount of light available for photosynthesis by plants and algae. However, studies by Bunn and Davies (1999) in the Cooper Creek system have found a high level of productivity and a high ratio of photosynthesis:respiration (P:R) in the shallow margins of waterholes. Productivity and P:R in the mid-channel water column was found to be relatively low. This band of intense productivity by algae in the shallow margins is analogous to a 'scum ring around a bath' and was considered to be common throughout the Cooper Creek system. Anecdotal evidence suggests that a similar situation exists in water holes and other wetlands in the Western Rivers region also (S. Bunn, Griffith University, pers. comm.).

Table 3: Rates of primary production, respiration and P:R in shallow littoral and deeper mid-channel habitats in Cooper Creek at Windorah. Values represent means (± 1 S.E.) from three sites (from Bunn and Davies, 1999)

Habitat	Gross Primary Productivity ($mgC/m^2/d$)	Respiration ($mgC/m^2/d$)	P:R
Shallow littoral margins	3650 (289)	1960 (207)	1.9 (0.4)
Mid-channel of waterhole	53 (9)	48 (12)	0.7 (0.2)

Using stable-isotope (^{13}C) tracing techniques, Bunn and Davies (1999) also found that the algae growing in the littoral margins of waterholes were a major source of food for other organisms in the food web. For example, 95% of the biomass of snails was found to be derived from the consumption of algae, and algae accounted for 74% and 58% of the biomass of shrimps and yabbies consumption of algae, and algae accounted for 74% and 58% of the biomass of shrimps and yabbies respectively. Overall, this work suggests that the importance of algal production for river and wetland productivity in arid river systems may have been underestimated. Conversely, the inputs of carbon and nutrients from the floodplain may have been over-emphasised, although these inputs are still very important. The relative importance of riparian/floodplain and algae-derived carbon and nutrients will become clearer once investigations of productivity and respiration have been conducted throughout an entire flood cycle.

Potentially toxic blue-green algae are often a concern in regulated water systems. However, the blue-green species recorded in waterholes in the Cooper Creek catchment to date were mostly non-toxic species that were palatable to other biota and therefore an important part of the food web (S. Bunn, Griffith University, pers. comm.). This is also likely to hold true for the Western Rivers.

Trampling may disrupt the algal layer around waterholes accessible to stock. This needs to be managed in order to protect the productivity of individual wetlands. Investigation of the recovery of littoral algae following trampling suggested that productivity had recovered by 40-50% within five days following disturbance (S. Bunn, Griffith University, pers. comm.).

3.3 Vegetation Response to Flow Variability

Differences in vegetation assemblages across a landscape may be expected due to variation in water regime and flood patterns. A study of the response of groundcover vegetation to flooding in the Cooper Creek system (S. Capon, Griffith University, pers. comm.) indicated that distinct assemblages may be expected in response to floods of different return frequencies (Figure 8). This suggests that variability in flow is a key feature for maintaining the biodiversity of vegetation on the floodplain.

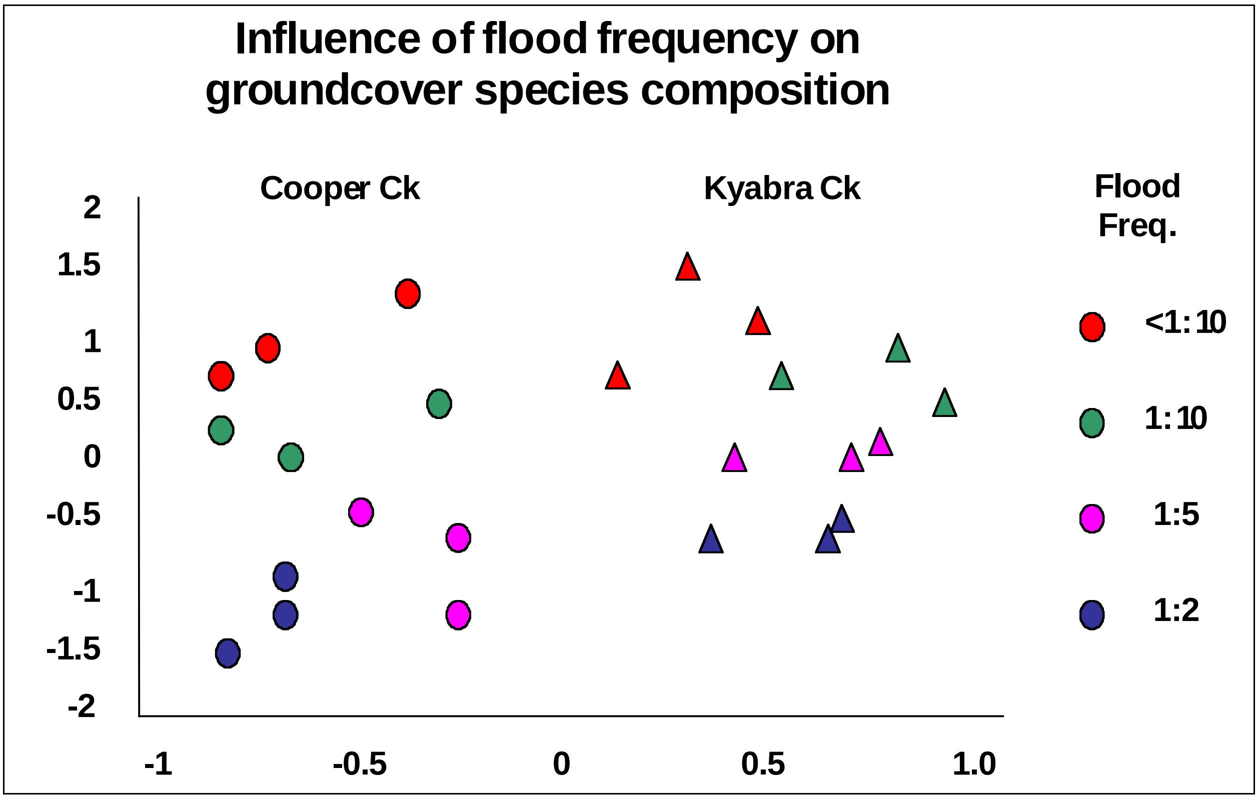

Figure 8: Ordination showing separation of sites based on vegetation in response to flood frequency (from S. Capon, Griffith University, pers. comm.)

3.4 Habitats and Refugia

Timms (1999) identified a range of wetland types and habitats that support a diversity of plant and animal communities. The studies revealed that invertebrate populations supported by the lakes and wetlands across the region varied significantly, with small freshwater lakes, black box swamps, vegetated depression and claypans being species-rich, while large freshwater lakes, riverine waterholes and saline lakes were relatively depauperate in species. However, even though the permanent waterbodies supported a smaller number of species, invertebrate abundance was often high (e.g. saline lakes supported large numbers of crustaceans) and was a significant food source for fish and waterbirds, especially during long dry periods.

Researchers from the CRCFE at the Department of Environmental Biology, University of Adelaide and from the Department of Geomatics, University of Melbourne, have completed a new computer model to help assess potential changes to the ecology of inland rivers as a result of irrigation. Called DRY/WET, the computer model is aimed at providing pastoralists, irrigators, water resource managers and conservationists with detailed information about how irrigation is likely to affect the fauna of dryland rivers. The DRY/WET computer model uses a unique database gathered over five years in the Coongie Lakes region of the lower Cooper Creek. The database links river flow with responses of fish, zooplankton and macroinvertebrates and has been used to predict what effects water withdrawals would have on these communities. For example, investigations and modelling (Figure 10 to Figure 12) of the response of fish and invertebrates of the Cooper Creek system (Puckridge *et al*., 1999), suggests that as the relative permanence of waterbodies increase:

- Fish abundance, species richness, species diversity and species evenness rise, and species dominance (unevenness) falls;
- Fish disease rises and macroinvertebrate abundance falls.

The results indicated that frequently inundated or permanent waterbodies are refuges of fish diversity. However, these places also have a higher incidence of disease than more ephemeral systems, and fish may need to migrate to less-often inundated waterbodies to restore their condition. Less permanent waterbodies support the greatest populations of macroinvertebrates, which are vital for episodic fish and waterbird breeding. The maintenance of wetland diversity and health will therefore require a wide range of inundation frequencies.

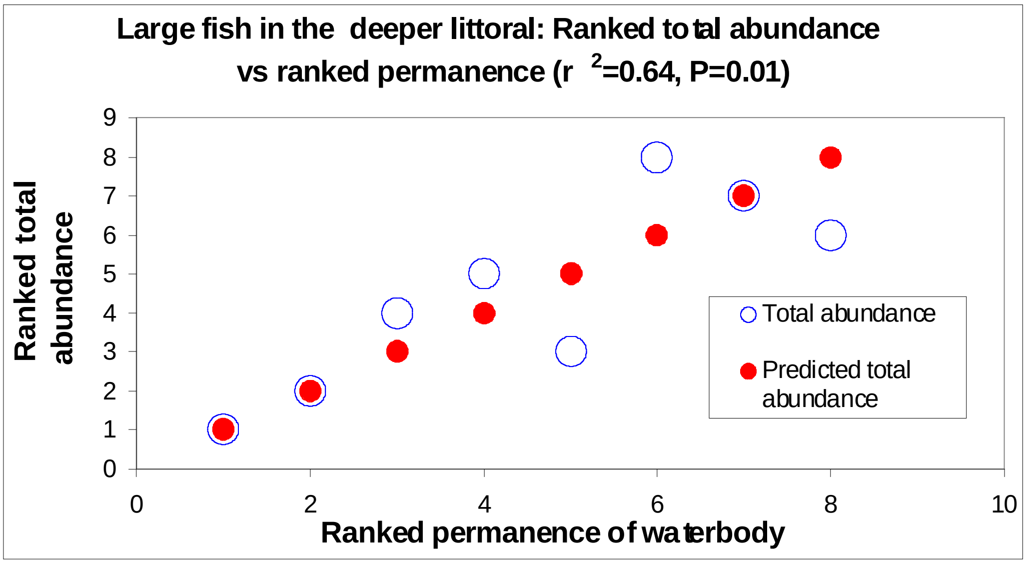

Figure 9: Output of the Wet/Dry Model– Large fish abundance versus waterbody permanence (from Puckridge *et al*., 1999).

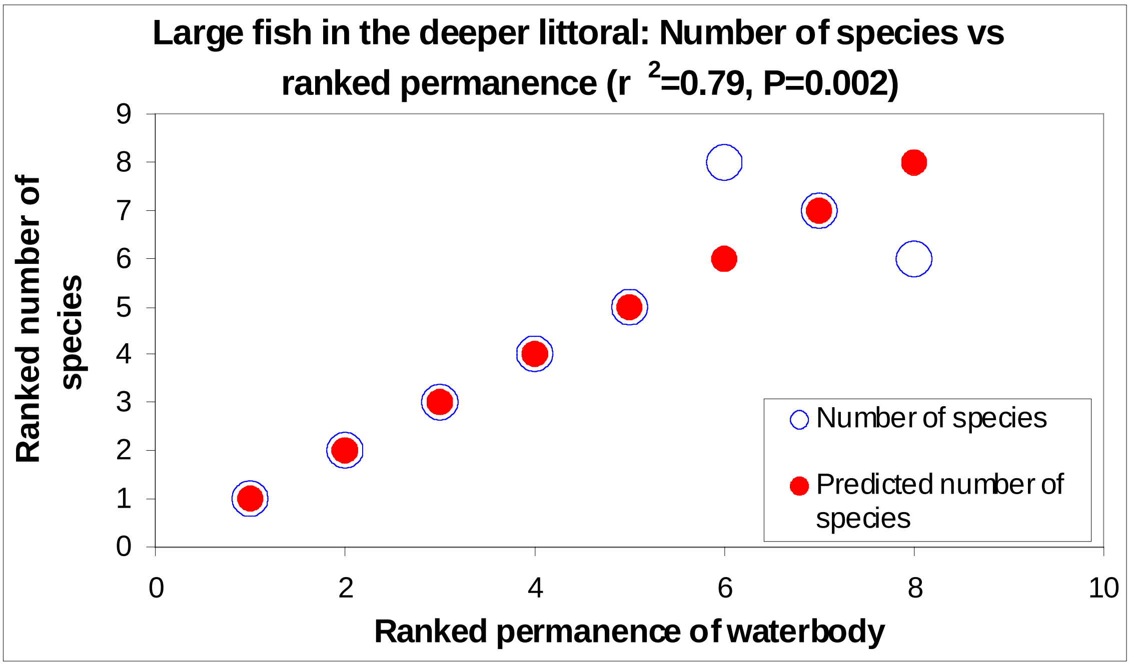

Figure 10: Output of the Wet/Dry Model – Large fish species versus waterbody permanence (from Puckridge *et al*., 1999)

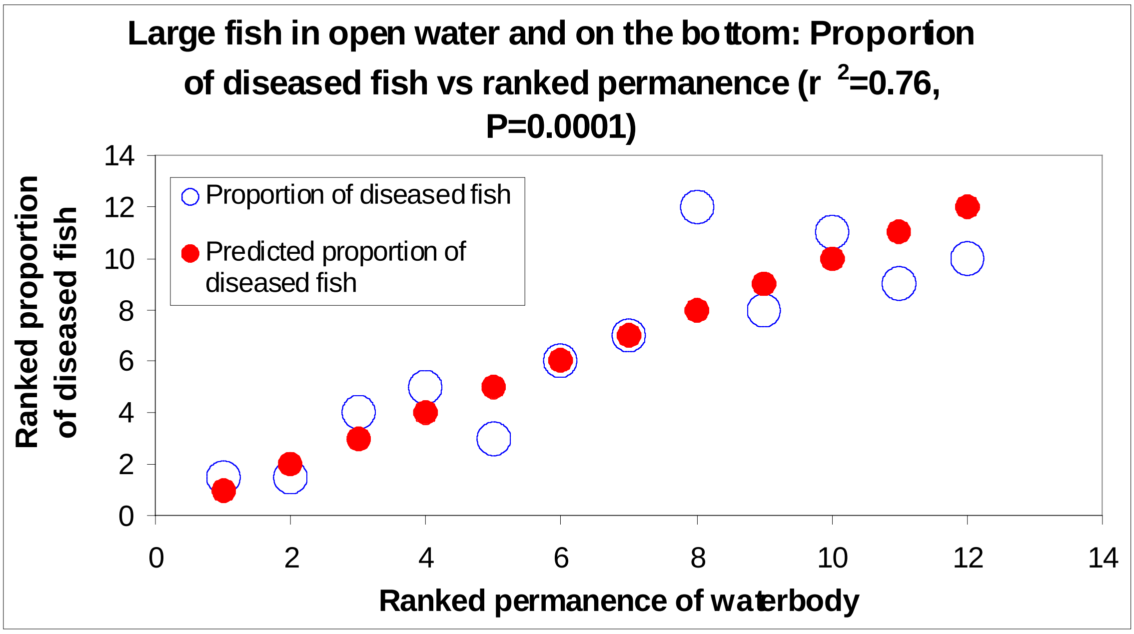

Figure 11: Output of Wet Dry Model - Fish disease versus wetland permanence (from Puckridge *et al*., 1999)

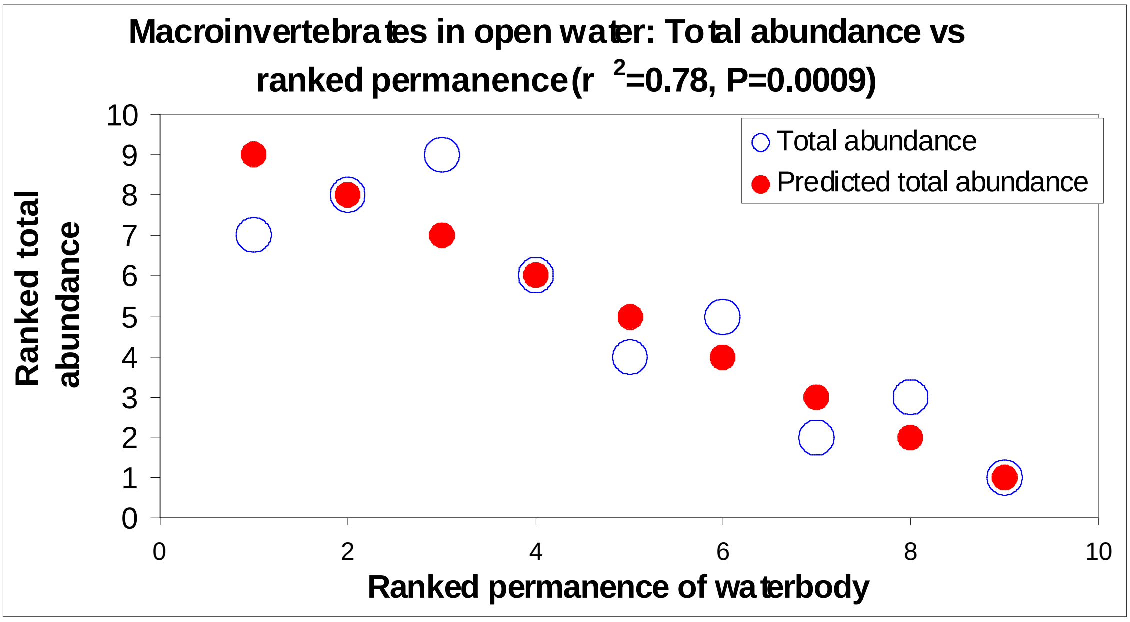

Figure 12: Output of Wet/Dry model – Macroinvertebrate abundance versus waterbody permanence (from Puckridge *et al*., 1999)

3.5 River - Floodplain Connectivity

The importance of the river and wetland habitats of the Western Rivers has already been discussed in terms of hydrological variability, productivity, biodiversity, habitat and refuge. The resilience of the Western Rivers to natural or human-induced change will depend to a large degree on maintaining the connectivity of the system during flood events. The connection of habitat during floods results in the transport or dispersal of biota and materials, such as carbon and other nutrients, between the floodplain and river channels. This interconnection is vital to ensure that refugia such as permanent and semi-permanent waterbodies are available to help maintain biodiversity across the region.

4 BIODIVERSITY IN THE WESTERN RIVERS CATCHMENTS

The Western Rivers, particularly the Paroo River, are recognised and valued for their high levels of biodiversity (Watts, 1999). This biodiversity is especially evident in the wetlands of the region, which provide a mosaic of different habitats with different flooding regimes and flood histories (Kingsford and Porter, 1999; Timms, 1999). This diversity exists at the ecosystem (e.g. wetland, river channel), species (e.g. species of birds, fish, invertebrates) and genetic level (e.g. distinct golden perch populations). The maintenance of this biodiversity will be an important consideration of the WMP process. The following sections provide a brief summary of the key features of biodiversity across the study area.

4.1 Wetland Systems

The range of geomorphology, hydrology and habitats associated with the wetlands of the Western River catchments support a great diversity of riparian and wetland biota. Wetlands range from freshwater to saline, and ephemeral to semi-permanent and permanent waterbodies. The QLD EPA (1999) identified 20 wetland types from south-western Queensland. However, many are a subset of the wetland types listed by Timms (1999) and Kingsford and Porter (1999) for the Paroo-Warrego catchments. Timms (University of Newcastle, pers. comm.) suggests that the simpler classification of wetlands is supported by statistical analysis of invertebrate populations. The seven wetland types identified by Kingsford and Porter (1999) are:

- Claypans and canegrass swamps;
- River channels and waterholes;
- Blackbox swamps;
- Eleocharis swamps;
- Lignum swamps;
- Salt lakes; and
- Freshwater lakes.

The above wetland systems are dependent on water from various sources, including local and regional rainfall and runoff, stream inflows and river floods. When floods from the Paroo and Warrego Rivers coincide and mix through the Cuttaburra Creek system, they combine to flood the most extensive wetland area in the Murray Darling Basin (Kingsford and Porter, 1999). The conservation status of many of the wetland types is ‘of concern’ (S. Skull, QLD EPA, pers. comm.; Sattler and Williams, 1999), for reasons such as:

1. Only 10-30% of their original extent remains intact;
2. Moderate degradation of the ecosystem over an extensive area;
3. They are naturally restricted ecosystem subject to a threatening process.

4.2 Riparian Vegetation

The diverse nature of wetland and riparian systems across the Western Rivers gives rise to a diverse vegetation assemblage, ranging from large trees such as river red gum and black box, to shrubs such as lignum, grasses such as canegrass and aquatic plants such as Nardoo, spike rush and stoneworts. Further information on the variety of vegetation growing in and around the various wetland systems can be obtained from Settler and Williams (1999) and resulting publications from Jaensch (1999) and the QEPA (1999), and also from Casanova (1999), Brock (1999) and Kingsford and Porter (1999).

Water supply to wetlands and the riparian zone along rivers may be from local rainfall, or streamflow originating locally or elsewhere in the catchments. The variability of water supply has meant that local vegetation has evolved a range of strategies for establishment and reproduction. For example, large trees tolerate high water levels during floods and establish themselves as floodwaters recede. Some wetland plants require flooding to initiate reproduction, while others establish during floods and reproduce as water levels fall (

Figure 13).

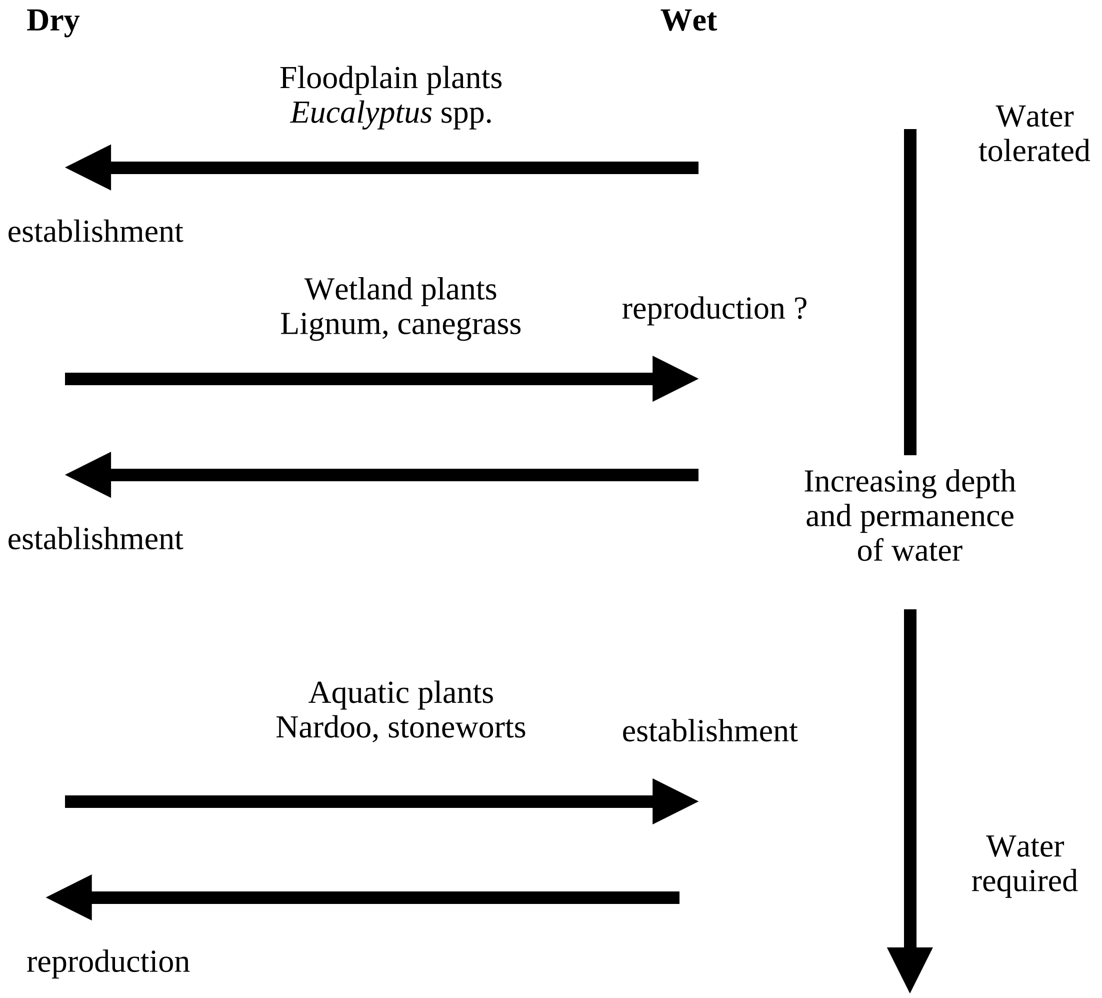

Figure 13: Life history response of wetland and floodplain vegetation (from Casanova, 1999)

Investigations of wetlands in the New England Tableland suggest that flooding periods of 8-16 weeks favoured the germination of native species while discouraging the germination of introduced species. Exotic species were favoured by damp conditions (waterlogging) or flooding for short periods (Brock, 1999). Brock (1999) has summarised the response of riparian and wetland vegetation to changes to water regime (Table 4). The main effect of reduced water availability is thought to be an increase in the prevalence of terrestrial species and a decrease in the species richness of aquatic and semi-aquatic plants. The survival of species in wetlands or the riparian zone following changes to water regime may depend heavily on the longevity of seedbanks.

Riparian and wetland vegetation has economic value in addition to its biodiversity value. The local pastoral industry makes extensive use of the vegetation (especially grasses such as water couch, channel millet and neverfail) that is present in the riparian zone and on the floodplain following floods.

Table 4: Predicted responses of wetland and riparian vegetation to changes in water regime (adapted from Brock (1999) and Brock and Casanova (1997))

Aspects of Water Regime	Increase	Decrease
Frequency of flooding	• Shallow wetlands and low lying riparian vegetation will experience wetting and drying more often • May encourage amphibious plants • The longevity of the seedbank of amphibious plants will be important to survival	• Shallow wetlands or low lying riparian vegetation more permanently dry • May favour submerged and terrestrial plants
Depth or extent of flooding	• More permanent water habitat • Favours competitive submerged and amphibious species	• More dry habitat • May favour weedy terrestrial invasion
Duration of flooding	• Longer flooding • Favours perennials and competitive submerged and amphibious species	• Shorter floods • Favours opportunistic short life cycle species
Variability of flooding	• More variable pattern • A range of amphibious plants may cope but depends on longevity of seed bank	• Less variable pattern • More permanently wet or dry habitat may favour competitive submerged, amphibious and terrestrial
Total effect	• May encourage competitive submerged and amphibious species • Species richness may decrease • Survival depends on the seed bank • Variety of amphibious and submerged species decreases	• May encourage weedy terrestrial species • Species richness may decrease • Survival depends on longevity of the seed bank

4.3 Invertebrates

To date, 215 aquatic macroinvertebrate species have been recorded in the Western Rivers region (Table 5). This number is expected to rise as only a small proportion of wetlands have been investigated (B. Timms, University of Newcastle, pers. comm.). Factors that affect biodiversity are salinity and differences between ephemeral and permanent waterbodies. Species richness is greatest in small freshwater lakes and claypans, and lowest in saline lakes and large freshwater lakes.

However, invertebrate abundance in saline lakes is very high and supports a diversity of fish and waterbird species (Timms, 1999).

Small freshwater lakes and claypans support a rich fauna of crustaceans, ostracods and beetle fauna. Saline lakes are dominated by crustaceans, especially ostracods. Large freshwater lakes support only a limited fauna of cladocerans, ostracods, beetles, dipterans and molluscs (B. Timms, University of Newcastle, pers. comm.).

A comparison of invertebrate populations recorded during dry and wet years indicated a decline in species richness in dry years as salinity levels rise due to evaporation. This suggests that a loss of water due to extraction is likely to result in reduced species richness (B. Timms, University of Newcastle, pers. comm.).

Table 5: Macroinvertebrate taxa recorded from the Western Rivers wetlands (from B. Timms, University of Newcastle, pers. comm)

Taxon	Species	Taxon	Species
Platyhelminthes (flatworms)	1	Insecta	
Annelida (segmented worms)	3	Ephemeroptera (mayflies)	2
Crustacea		Odonata (dragonflies)	9
Anostraca (fairy shrimps)	19	Hemiptera (true bugs)	17
Notostraca (shield shrimps)	1	Trichoptera (caddisflies)	5
Conchostraca (clam shrimps)	10	Diptera (true flies)	29+
Cladocera (water fleas)	28+	Coleoptera (beetles)	40
Copepoda (copepods)	14	Lepidoptera (moths)	1
Ostracoda (seed shrimps)	16+	Arachnida (watermites)	7
Decapoda (shrimps, yabbies)	3	Mollusca (shells)	10
		TOTAL	**215**

4.4 Fish

Gerhke *et al.* (1999) studied fish in the Paroo catchment as part of a three-year investigation of fish populations across the Murray Darling Basin. Sites in the Paroo catchment included Mullawoolka Basin (lake), Paroo River (river), Tongo Creek (creek) and Mustang Flat (floodplain). Sampling was conducted on six occasions to coincide with floods and to look at populations before and after peak flows. A total of 10 fish species (seven native and three alien species) were recorded in the Paroo catchment during the study (Gerhke *et al*., 1999). The greatest abundance was recorded at the lake and river sites, with lowest fish abundance recorded at the floodplain site (Table 6). The highest proportion of young fish (indicating population recruitment) was recorded after flood events. Statistical analysis of fish communities indicated that the populations recorded at sites in the Paroo were different to those recorded from sites on the Darling, Murrumbidgee and Murray Rivers. The ecology of fish in relation to water-resource development in the Barwon-Darling river system was also discussed by Harris (1997).

Fish populations in the Western Rivers region have also been investigated as part of a study conducted by QDNR. Sampling over two years, at two sites on the Paroo River and three sites on the Warrego River, has recorded a similar list of species to that recorded by Gerhke *et al.* (1999). The QDNR study recorded Murray cod (although in low numbers), Australian catfish and gudgeons in addition to the species recorded by Gerhke *et al*. (1999), but did not record the alien species gambusia (Table 7). The study also found that the genetic diversity of golden perch populations in the Paroo were the highest recorded for the species in the Murray Darling Basin (D. Moffatt, QDNR, pers. comm.). Overall, the fish populations in the Western Rivers region were considered to be in good health, especially when compared with other areas of the Murray Darling Basin.

Table 6: Total catches of fish species recorded at four sites in the Paroo catchment, 1992-1995 (adapted from Gerhke *et al.*, 1999)

Species	Creek	Floodplain	Lake	River
Spangled perch	158	128	150	298
Golden perch	136	76	130	235
Silver perch	0	0	1	0
Crimson spotted rainbow fish	0	0	1	0
Bony herring	1148	558	1906	480
Hyrtl’s tandan	37	0	21	43
Australian smelt	3	0	18	1
Goldfish*	16	3	17	90
Carp*	387	283	179	1661
Gambusia*	9	5	29	8
Total abundance	1894	1053	2452	2816

* alien species

Table 7: Total catches of fish species recorded at two sites in the Paroo and three sites in the Warrego catchment, 1996-1998 (D. Moffatt, QDNR, pers. comm.)

Common name	Number Caught	% Caught	Rank
Silver perch	20	1%	10
Gudgeons	101	3%	4
Spangled perch	80	2%	6
Golden perch	493	14%	2
Murray cod	2	0%	12
Crimson spotted rainbow fish	18	1%	11
Bony herring	2128	62%	1
Hyrtl's tandan	97	3%	5
Australian smelt	47	1%	9
Freshwater catfish	48	1%	7
Goldfish*	47	1%	8
Carp*	381	11%	3

* alien species

4.5 Birds

The diversity of wetland and river habitats across the Western Rivers supports a great abundance and diversity of bird species (Figure 15), and wetlands in the region are of national and international importance. For example, Kingsford and Porter (1999) list 63 species of waterbirds recorded from the Nocoleche Nature Reserve, similar to the number recorded in the Macquarie Marshes of NSW (recognised for its waterbird populations). An important area for waterbirds in the Western Rivers region is the Currawinya Lakes, with counts on Lakes Wyara and Numalla being particularly high. Both Wyara and Numulla support some of the largest populations of the endangered freckled duck in Australia.

Thirty-eight waterbird species have been recorded breeding on the lakes and wetlands of the Paroo and Warrego Rivers (Kingsford and Porter, 1999), mostly during spring and summer. Yantabulla Swamp is a particularly important breeding site, with a conservative estimate of 12 species thought to breed there. These include great egret, straw-necked ibis, glossy ibis and Australian white ibis. Peery Lake and Waitchie Lake were also important sites for breeding (10 and 12 breeding species respectively).

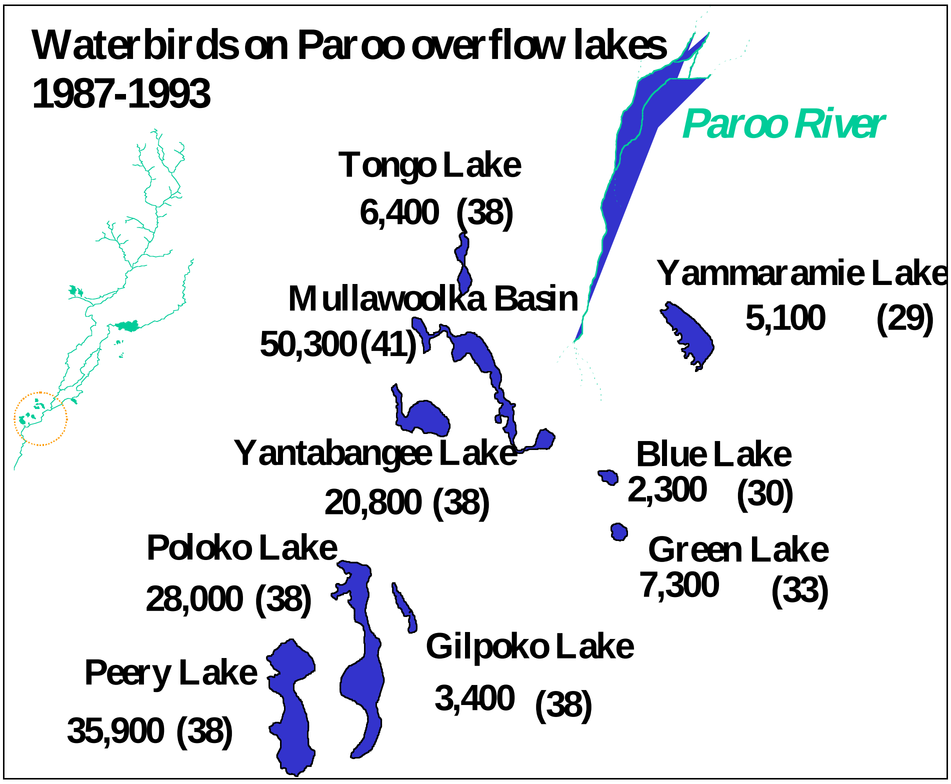

Figure 15: Waterbird numbers and species (in parenthesis) across lakes and wetlands on the Paroo overflow (R. Kingsford, NSW P&W, pers. comm.)

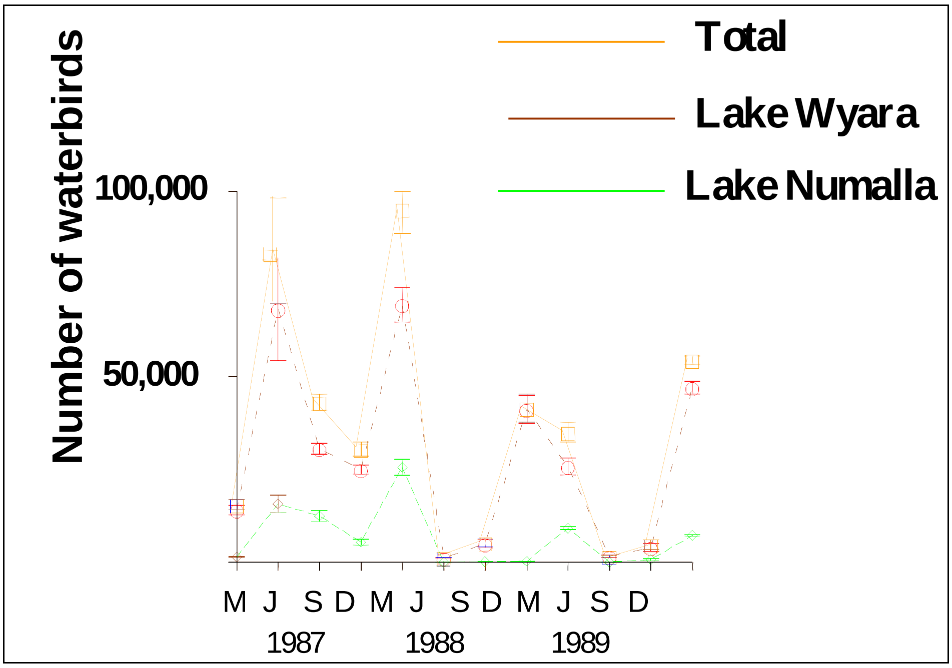

Figure 16: Waterbirds on Lakes Wyara and Numulla from aerial counts, 1987-1989 (from Kingsford and Porter, 1994)

4.6 Amphibians

Only very limited information exists on the amphibians to be found across the study area. Kingsford and Porter (1999) identified 15 species of frog at Nocoleche Nature Reserve. These and at least an additional three frog species (QLD EPA, 1999) are expected to inhabit the diverse range of wetlands across the Western Rivers and are adapted to surviving long dry periods.

4.7 Mammals

Little is known of the mammal populations dependant on the wetlands and floodplains of the region. Limited information indicates the presence of koalas, sugar gliders and bats along on wooded watercourses as habitat corridors (QLD EPA, 1999). Water rats and long-haired rats have also been recorded inhabiting local wetlands (QLD EPA, 1999; Kingsford and Porter, 1999), as have small marsupials such as *Planigale* and *Sminthopsis* (QLD EPA, 1999). Other common mammals such as eastern and western grey kangaroos, red kangaroos, euros, wallabies, wombats and echidnas may also be expected.

4.8 People

Socio-economic conditions will also affect the ecology of the region. Prevailing economic conditions will greatly influence the community's ability to adopt new ecological insights and adapt them to the management of land and water resources. While much of the discussions on ecological issues have focussed on flow related issues, it was widely acknowledged at the scientific forum that a broad range of actions are required to maintain the health of the river and floodplain systems. For example, in addition to maintaining appropriate environmental flows, good land management and addressing salinity issues will also be required in the future. Some of the factors likely to affect the way land is managed in the future will be commodity market forces and the resulting changes to current crops, land-use and management practices.

Socio-economic factors are an important part of the development of WMP's. However, there was only scope to give these factors minor attention at the scientific forum. Socio-economic and management constraints are to be considered in greater depth as part of the wider WMP process.

4.9 Potential Ecological Impacts of Water Extraction

Floodplain wetlands are sites of extraordinary biodiversity. The history of water regulation, especially in the Murray Darling Basin, suggests that wetlands and their biodiversity will continue to be lost until our understanding of the long-term ecological effects of dams and diversions is widely accepted. We need to recognise that flows to floodplain wetlands serve an ecological function and are not lost or wasted.

The building of dams and the cumulative impact of diversions upstream and river management have reduced flooding to large areas of floodplain wetlands. This has been highlighted by a review of the impacts of water regulation on the ecology of floodplain wetlands four major wetland systems (Macquarie marshes, Barmah-Millewa forest, Chowilla floodplain and Gwydir wetlands) across the Murray Darling Basin (Kingsford, in press). This review identifies changes that have caused the systems to suffer major declines in their plant and animal communities. These include the conversion of floodplains into terrestrial ecosystems and alteration of the natural flow regime of remaining wetland areas. The effects of these changes are not well studied and even for four large floodplain wetlands, data exist only for a fraction of potentially affected biota. Nevertheless, the range of biota affected by reduced flooding testifies to the generality of this problem. The ubiquity of large dams, diversions and hydrological principles mean that ecological impacts will be widespread in Australia, although few river systems have been investigated. Hydrological models need to incorporate connectivity of the floodplain so ecological costs can be adequately estimated for future water resource developments.

Table 8: Examples of ecological impacts from selected wetland systems across the Murray Darling Basin (adapted from Kingsford, in press)

	Impact
Hydrological Changes	• Barmah-Millewa Forest (65,000 ha)- 50% reduction in annual flows 100 km upstream; pattern of flow shifted from spring to summer • Chowilla floodplain (17,700 ha) – 73% of natural flows diverted upstream; median flows 50% reduction • Gwydir wetlands (Lower 24,000 ha)- 70% reduction in flows to major wetland areas • Macquarie Marshes (130,000 ha)- 50% reduction in flows
Macquarie Marshes	• Decline in the area of river redgum and water couch in the core wetland areas (Brereton, 1994; Brander, 1987) • Decline in the abundance and species richness of waterbird populations (Kingsford and Thomas, 1995)
Barmah-Millewa Forest and Moira Marshes	• Changes to distribution of floodplain vegetation (red gums and moira grass)- (Bren 1992) • Major commercial native fishing industry for 45 years, 1855-1900 but now few native fish caught (Leslie 1995) • Brolgas locally extinct (Leslie 1995) • Glossy ibis, little egrets, whiskered terns no longer breed (Leslie 1995) • Cormorants, great egrets, intermediate egrets, rufous night herons breed in declining numbers (Leslie 1995) • Snakes killed in numbers of 50 per day in 1860s – now rarely seen (Leslie 1995) • Leeches gathered 25,000-60,000 yr^{-1} in 1930s, seldom seen after the 1970s (Leslie 1995)
Chowilla Plain	• Black box dead in areas not flooded for 35 years • Floods used to leach salt from soils now saline groundwater is discharged onto floodplain • Likely reduced biodiversity of invertebrates • Reduced abundance and biomass of invertebrates • Low flows establishment of dense littoral plants
Gwydir Wetlands	• Marsh club-rush in the Lower Gwydir contracted by 66% • Terrestrial vegetation established where aquatic vegetation once lived • Degraded lignum communities • Livestock production losses

5 BEST PRACTICE WATER EXTRACTION

One of the key questions to be addressed in the WMP process is whether additional water extraction from the river system is ecologically and economically viable. Given the variability of flow in the region and a general lack of information on flow-related ecological processes (e.g. area of wetland inundation and ecological response due to various river flows), determining if or when water should be extracted will be a difficult task.

5.1 Developing A Best-Practice Water Extraction Approach

A key to the development of a best practice water extraction approach will be quantifying the relationship between the level of extraction and ecological responses (Figure 17). Community opinion at the scientific forum ranged from a view that no further water should be extracted from the rivers because of the ecological consequences, to the view that opportunities existed for the extraction of water for agricultural purposes with little effect on river and floodplain ecology.

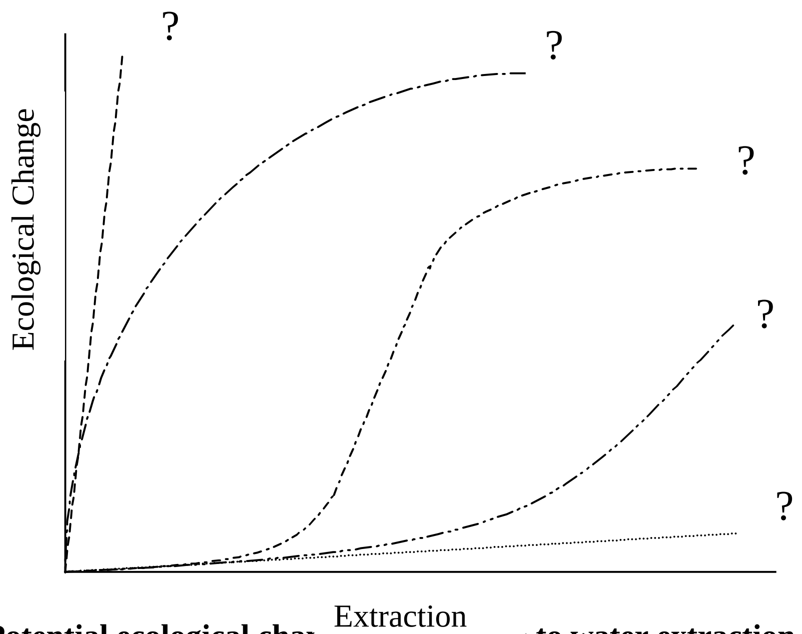

Figure 17: Potential ecological char[illegible] to water extraction

Unfortunately limitation in our understanding of the complex interactions between flows and ecological response makes it difficult to quantify ecological changes in response to extraction. One approach to ensuring that sufficient flows are maintained for ecological purposes was proposed at the forum (J. Puckridge, University of Adelaide, pers. comm.). This environmental flows methodology is outlined below.

Principles

- Develop the methodology out of current concepts in river ecology;
- Treat the river as an ecosystem, emphasising patterns and processes;
- Use as a reference the natural flow regime of the river;
- Identify and respect the river's uniqueness;
- Observe the Precautionary Principle.

Process for developing environmental flows
- State clear, measurable goals;
- Have a transparent, structured process;
- Test to see whether disturbance thresholds exist for flow-ecology relations (i.e. we cant assume they exist);
- Consider the river (particularly its variability) in four dimensions;
- Deal systematically with temporal and spatial scales, patchiness, connectivity and refugia.

Content of flow-management plans
- Consider the social and economic constraints;
- Consider all the spatial elements of the river system;
- Combine top-down and bottom-up information;
- Encompass the variety of ecologically significant facets of the flow regime;
- Be based primarily on hydrology – ecology relations tested in the field.

Follow-up
- Predict and test the outcomes of implementation;
- Incorporate monitoring for future adaptive management;
- Design strategic research to support future management.

5.2 Decision Support

Hydrologic models are being prepared for each of the study catchments to support decision making during the WMP process. At present, only the model for the Moonie River catchment has been completed. Models for the Bulloo, Warrego-Paroo and Nebine systems are likely to be completed by February 2000, at the earliest. In order to meet the pressing need for information, those at the scientific forum felt that model-building efforts should first focus on the Warrego-Paroo system, as it will require less resources and time. As there is little flow gauging in the Bulloo and Nebine systems, the level of modelling complexity and time required to develop useful models is expected to be greater than for the Warrego-Paroo.

The existing model for the Moonie River was used to explore the effects of water extraction on river flows at Westmar and Gundabloui. For brevity, only the effects at Gundabloui are considered in this report.

The model was used to compare the natural annual discharge in the Moonie River at Gundabloui between 1890 and 1998 with that expected had the current level of water extraction have been in place over the whole modelling period. It should be remembered that the modelled licence conditions do not account for floodplain harvesting into unlicensed storages, and so will under-represent the true impact of extractions. It should also be remembered that the model was constructed using data from limited stream-flow gauging and rainfall-runoff models. The robustness of the model for predicting flows to wetlands is not clear, as there is no flow gauging in wetlands.

Water extraction at the current level of development has a measurable effect on river flows, with the greatest impact recorded during low rainfall years (Appendix 2; K. Baxter, QDNR, pers. comm.). For example, flow duration curves suggest that the flow periods in the Moonie River at Gundabloui have been reduced from approximately 28% to approximately 19% of the time. The modelled results suggest that current levels of water extraction would generally have a small impact on peak flows during large events, but could have large impacts on the duration of flood events. Floodplain harvesting, which is not measured, is an added hydrological impact that can impact on peak flows, depending on the amount of water extracted. Extraction had the potential to affect both the flood peak and duration for small events.

Two approaches to extraction were presented to the forum for discussion (Figure 18 and Figure 19). Both involved pumping once flow in the rivers had passed some predetermined threshold required to support ecological processes (yet to be determined). This begs the question of whether the threshold applies at the same level throughout the year, or whether different thresholds apply at different times of the year? Modelling of flow-biology relations in the Cooper Creek system (Appendix 2; Puckridge, 1999) found no sign of thresholds. Should thresholds exist in the Western Rivers region, then water extraction would most likely occur as a 'veneer'of the hydrograph (Figure 18) so that key ecological signals may be protected. Thresholds, if present, might also be expected to vary at different points in the catchment.

There are ecological implications no matter which water-extraction practice is adopted (i.e. veneer taken off the whole hydrograph or extraction only on the falling limb of the hydrograph). In the veneer approach, the shape of the hydrograph is largely maintained (a key requirement for success in the breeding cycle of many biota) and flow is reduced evenly across the whole hydrograph. However, water available for downstream areas will be reduced. This increases the proportion of wetlands and floodplain areas in the lower catchment areas that may miss out on the benefits of flooding. This option also reduces the flow variability that is such a key feature of the hydrology of the Western Rivers.

Alternatively, extraction on the falling limb of the hydrograph maintains the peak channel-forming flows and ensures that water reaches wetlands and the floodplain in lower catchment areas, but reduces the flood duration that plays a critical role in the life cycle of biota. A difficulty with this approach given the current level of flow monitoring across the study area, will be determining when the flood pulse has peaked and at what stage pumping may commence, although this could be determined at the diversion site.

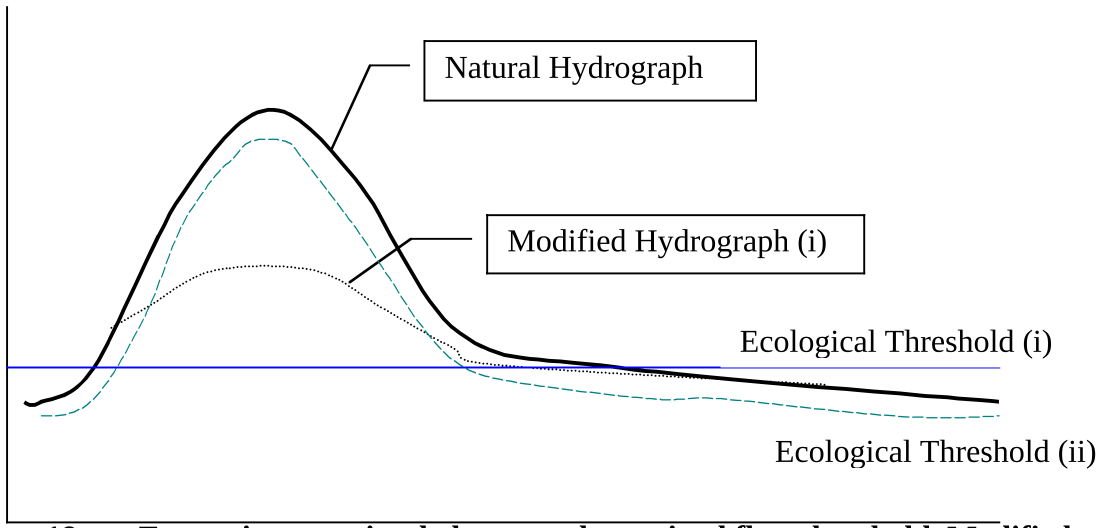

Figure 18: Extraction permitted above predetermined flow threshold. Modified hydrograph (i) is in response to a flat ecological threshold (i). Ecological threshold (ii) assumes variable thresholds with water extracted as a 'veneer' from the hydrograph.

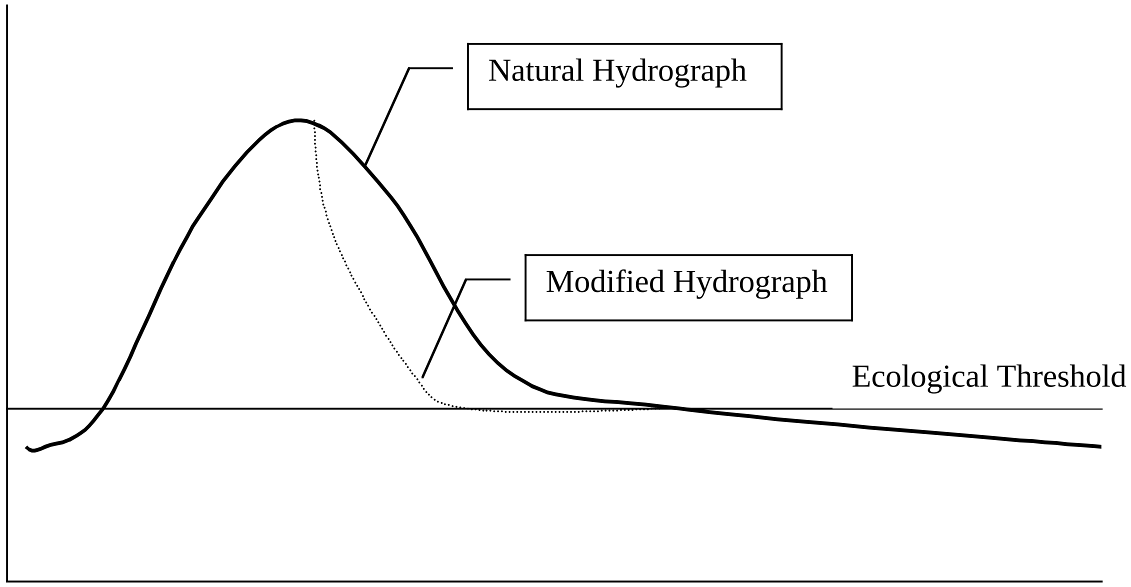

Figure 19: **Extraction permitted after flood peak has passed, down to predetermined threshold**

6 FUTURE RESEARCH AND MONITORING

One of the major requirements of future assessment and evaluation will be to quantify and confirm the relationship between the potential level of water extraction and changes in ecological values. This will involve both research and monitoring initiatives. Research, including both experiments and observations, is required to improve our understanding of how the various components of the ecosystem work, while monitoring is required to measure how the systems change over time and in response to management interventions. While this forum has focussed on ecological aspects, research will also be required on management and socio-economic aspects to support the development of the WMP's and community decision making.

6.1 Future Research

6.1.1 Hydrological Research

Little is known of what is a complex hydrology across the study area. Areas for future research include:

- Characterising the system's hydrology
  - Distribution of water in space and time
  - Identifying the sources and fate of flows in all western-river systems
  - Identifying and quantifying groundwater-surface water interactions
  - Assessing wetland filling patterns and commence to flow levels
  - Locating and quantifying transmission losses
- Effects of water resource development
  - Evaluating the effects of extraction on hydrographs
  - Evaluating the effects of off-stream storage on flows
  - Evaluating the hydrological effects of bore-water development, especially drains and tanks
  - Assessing water-table impacts of floodplain and catchment storage
- Other interactions with hydrology
  - Effects of vegetation clearing on groundwater, runoff and salinisation
  - Catchment erosion
  - Factors affecting stream geomorphology, including instream sediment transport, especially sand slugs
- Modelling to test water resource development strategies
- Modelling to test access strategies

Of particular importance for the WMP process will be the linkage of river flow with area of wetland or floodplain inundated. Timms (1999) compiled information on the commence to flow levels and frequency of flooding for wetlands in the Currawinya National Park. This work showed that extraction of water is likely to have a differential effect on the flooding frequency on wetlands in the region. For example, Lake Wyara rarely receives water from the Paroo River, while riverine waterholes may receive water from the Paroo many times per year; it is wetlands such as waterholes that are most likely to be affected by water extraction. Timms (1999) also identified that a 10cm drop in water level would result in floodplain edge lakes in the Currawinya wetlands being inundated once every four years instead of every three years. A 20cm drop in water levels would reduce flooding frequency to once every five years. As the ecology of arid-zone wetlands depends heavily on frequency of flooding, changes to community structure and functioning may be expected with increased extraction. The collection of similar information on flood levels and frequency of inundation for other wetland systems across the region will be critical for the development of WMP's.

Very little is known of the geomorphology of the rivers and streams in the region. The factors that affect the physical character of rivers and streams also requires further investigation.

6.1.2 Ecological Research

The study of arid river ecosystems has received relatively little attention in Australia. The ecology of the Western Rivers has largely been pieced together from a limited number of local investigations and studies of systems such as Coopers Creek. While studies of systems like Cooper Creek provide valuable insights about the nature and functioning of arid rivers and their floodplains, the transfer of these insights must be undertaken with care given the highly variable and unique nature of the Western Rivers. Large rivers tend to have a distinctive hydrology and therefore distinctive ecology, as illustrated in (Figure 4).

Future research should have a 'management-experiment' approach, in which the results of best-practice management of water resources are scientifically assessed and the results are then used to refine the management. A previously agreed framework and timetable for this form of adaptive management is essential to success. The various confounding factors, especially the other ecological effects of land-use including catchment erosion, salination or pesticide contamination, must be accounted for before water-use impacts can be interpreted. These confounding factors create difficulties in determining cause and effect in aquatic ecology. The river systems are highly variable and their wet and dry cycles are on long time scales (Thoms *et al.* 1996). Furthermore, it is no longer possible to locate undisturbed systems for use as a research reference. This means that, wherever possible, an experimental approach to research is preferable for understanding the rivers' ecology.

Further ecological research should examine topics including:

- Characterisation of the system
  - ¬ Biodiversity - plants, animals, microbes
- ecological processes in the fuzzy land/water boundary
  - ¬ Biological patterns in space and time (the 'boom-bust' cycle, identification of refugia and the role of refugia)
  - ¬ What drives production primary and secondary production (among other things, what is the ecological significance of bony herring?)
  - ¬ Temporal and spatial hydrological variation at a range of scales
  - ¬ Ecological-hydrological-geomorphological relations (distinctive for each system)
- What are the key processes?
  - ¬ Primary and secondary production
  - ¬ Inundation, edge processes and connection of floodplains
  - ¬ Dispersal of organisms along rivers and onto floodplains
  - ¬ Recruitment to aquatic populations
  - ¬ Entrainment of aquatic animals into irrigation offtakes
  - ¬ Cycles of colonisation and mortality
- The time factor
  - ¬ Is timing of key processes, such as fish migration and nursery growth, affected by water resource development?
  - ¬ Are key processes steady trends, exponential curves or step functions? More generally, what are the shapes of key biology-hydrology and hydrology-geomorphology relations? (i.e. are there thresholds below which water withdrawals will have no biological or

geomorphological impact, or do impacts occur continuously in response to flow regime change? This is crucial, and must be tested.
  - ¬ Cycles, including the persistence of hydrological events such as floods and droughts, ENSO influences, production, recruitment, growth and dispersal.
- Key influences
  - ¬ Sensitivity to water supply – with respect to flood magnitude, timing, duration, rate of rise and fall, temporal and spatial variability (Puckridge *et al.*, 1999)
  - ¬ Seasonality and long-term cycles
  - ¬ Water quality impacts, including turbidity, black water flows, salt levels
  - ¬ Carp biological disturbance, turbidity, loss of water-plants, competition with native species, nutrient releases.

Research into aquatic ecology is an emerging area for QDNR and the resources available to research are limited. Many of the topics for research identified above are being considered as part of a 10 year program currently being developed by QDNR. A number of these topics will be investigated as part of the new research program being develop by the CRC for Freshwater Ecology.

Another aspect of research on the effects of land clearing identified at the forum was the effect on runoff from groundcover versus canopy cover. Anecdotal evidence suggests runoff and erosion have increased in areas where groundcover has been cleared but canopy cover, especially mulga, has been maintained or regenerated. This change should be detectable water-table monitoring.

6.1.3 Socio-economic Research

Socio-economic constraints will play a large role in determining how the Western Rivers are managed in the future. While detailed consideration of socio-economic factors was beyond the scope of this forum, some important points emerged that warrant further investigation in order to support informed decision making as part of the future WMP process. These include:

- Characterising indigenous and non-indigenous communities
  - ¬ Characterising land-use patterns and production
  - ¬ Dependence of land-use on water resource development
  - ¬ Sensitivity to water supply
- Innovation and technology development
  - ¬ More efficient irrigation technology
  - ¬ Most appropriate crops for the region
  - ¬ Changing livestock patterns to suit requirements of the region
  - ¬ Alternative town water supplies to reduce dependence on environmentally damaging weirs
- Community trade-offs over water resource development
  - ¬ Grazing versus irrigation versus town water supplies
  - ¬ Economic basis and trends in water resource development

6.2 Future Monitoring

6.2.1 Hydrological Monitoring

Future hydrological monitoring should aim to provide adequate information to ensure that management actions are meeting their objectives, and to provide sufficient information to allow modelling of systems to support future decision making. Maintaining comprehensive hydrological records will play an important part in this process. Records should include volumes abstracted by individual licence-holders, river flow, rainfall, water levels in wetlands and groundwater, and spatial patterns of inundation (from remote sensing and aerial photography). The adequacy of the existing gauging system to service current needs should be reviewed.

6.2.2 Ecological Monitoring

Ecological monitoring should be undertaken to confirm the state of the environment and to assess any ecological changes in response to management interventions (Thoms *et al.* 1996), including implementation of the WMP. The information provided will help to support an adaptive management approach to sustainable development in the Western Rivers region. Monitoring should focus on:

- River and wetland health
  - ¬ Vegetation patterns
  - ¬ AusRivas monitoring using invertebrates
  - ¬ Conditions in refugia
  - ¬ Index of Biotic Integrity using fish community measures
- Biological productivity
  - ¬ Waterbird surveys
  - ¬ Fisheries production (e.g. the NSW Angling Catch Database approach to recreational fisheries monitoring)
- Biodiversity monitoring
  - ¬ Biodiversity hot spots?
  - ¬ Routine biodiversity surveys
  - ¬ Developing a fish-kill database to monitor fish mortality events.

6.2.3 Socio-economic Monitoring

Socio-economic monitoring will also assist an adaptive management approach for the Western Rivers, and should aim to supply information on:

- Changes in land-use patterns, production and economies
- The efficiency of water usage in agriculture
- Human communities and social issues.

7 OTHER ISSUES

A number of issues were raised, that while being beyond the scope of the scientific forum, should be considered during the WMP process. These include:

- Heritage listing is proposed for the Paroo. What are the implications the WMP process?
- A number of wetlands in the region are listed as significant sites under the Ramsar agrreement, Japan-Australia migratory birds agreement (JAMBA), China-Australia migratory birds agreement (CAMBA) or protected under the Environmental Protection and Biodiversity Conservation Act 1999 (Commonwealth) that comes into force 16 July 2000. Any activity that potentially impacts on a site is will therefore become Commonwealth business.
    - Cultural heritage listing offers a number of potential benefits in ecological and socio-economic contexts and should not be ignored. For example, the protection of plant species with medicinal properties can have ecological values (e.g. locally adapted species have low water requirements and can help maintain biodiversity) and socio-economic benefits. These and other socio-economic considerations will be required for informed decision making.
    - The timelines for the development of WMP’s is very tight. Many in the community feel they are being forced to make decisions without sufficient information. Options for addressing this issue include lobbying the Minister to extend the timelines to allow informed decision making, or to go ahead with WMP development with the caveat that arrangements are interim only (e.g. place a cap on future extractions) and will be reviewed in 12-18 months time. Issues relating to the resources needed to speed the provision of information to support WMP development are being assessed by QDNR.
    - The process for implementing WMP’s is not clear, and further direction from the QDNR is sought.

8 CONCLUSIONS

Key ecological features of the Western Rivers include:

- The Paroo wetlands are of significant importance (national and international). The wetlands of the Bulloo and Warrego rivers are likely to have similar importance;
- Ramsar sites on the Paroo (Currawinya and probably Peery Lake);
- High biodiversity and unique systems;
- The most extensive wetland area in Murray-Darling Basin (Paroo, Warrego);
- The Paroo wetlands are dependent on Warrego flows;
- Most wetlands are dependent on river flows rather than local rainfall;
- River regulation with dams and diversions changes the ecology of most wetlands forever.

Water resource development has:

- Biodiversity implications;
- Wetland impacts;
- Hydrological impacts (quantity, variability, seasonality);
- Water quality impacts (e.g. salinity, erosion, pesticides, temperature);
- Cultural impacts;
- Catchment and basin context (interstate issues);
- Implications for biological productivity – fisheries and water-birds
- Implications for tourism;
- Impacts on rural communities.

Water extraction will have environmental impacts, whether water is taken as a ‘veneer’ over the hydrograph (reduced peak flows, therefore less wetland and floodplain inundated) or on the falling limb of the hydrograph (reduced flow duration – less time for completion of important breeding cycles for native species). Increased extraction, should it occur, will require local communities to make trade-offs of potential socio-economic benefits against ecological change.

9 REFERENCES

Brander, D., 1987. Environmental changes in the southern Macquarie Marshes: 1934 to 1987. Unpublished Honours Thesis, University of New South Wales.

Bren, L. J., 1992. Tree invasion of an intermittent wetland in relation to changes in the flooding frequency of the River Murray, Australia. *Aust. J. Ecol*. 17, 395-408.

Brereton, G. J., 1994. Summary Report. Macquarie Marshes Management Strategy-Stage 1, biophysical investigations, Natural Resources Management Strategy, New South Wales Department of Water Resources, Dubbo.

Brock, M. and Casonova, M., 1997. Plant life at the edges of wetlands; ecological responses to wetting and drying patterns. In: Klomp, N. and Lunt, I. (eds.) Frontiers in Ecology: Building the Links, Elsevier Science, Oxford, pp. 181-192.

Brock, M., 1999. Are aquatic plant seed banks resilient to water regime alteration? Implications for the Paroo river system. In: Kingsford R., 1999. A free flowing river – The ecology of the Paroo River. NSW Parks and Wildlife Service.

Bunn, S. and Davies, P., 1999. Aquatic food webs in turbid, arid-zone rivers: Preliminary data from Cooper Creek. In: Kingsford R., 1999. A free flowing river – The ecology of the Paroo River. NSW Parks and Wildlife Service.

Casanova, M., 1999. Plant establishment in Paroo wetlands: The importance of water regime. In: Kingsford R., 1999. A free flowing river – The ecology of the Paroo River. NSW Parks and Wildlife Service.

Harris, J., 1997. Fish in the Barwon-Darling River. In: Researching the Barwon-Darling. (M. Thoms, A. Gordon and W. Tatnell, eds.) pp. 91-96. Proceedings of the Bourke Conference, NSW 8 & 9 November, 1995. Cooperative Research Centre for Freshwater Ecology, Canberra.

Jaensch, R., 1999. The status and importance of wetlands of Queenslands south-western wetlands. Report by Wetlands International-Oceania to the Queensland Environment Protection Agency.

Kingsford, R. and Porter, J., 1999. Wetlands and water birds of the Paroo and Warrego Rivers. In: Kingsford R., 1999. A free flowing river – The ecology of the Paroo River. NSW Parks and Wildlife Service.

Kingsford, R. T., Curtin, A. L., and Porter, J. 1999. Water flows on Cooper Creek in arid Australia determine 'boom' and 'bust' periods for waterbirds. *Biological Conservation* 88:231-248.

Kingsford, R., in press. Review: Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Australian Journal of Ecology*.

Leslie, D. J. (1995) Moira Lake - a case study of the deterioration of a River Murray natural resource. Unpublished Thesis, Master of Forest Science, University of Melbourne, Melbourne.

Puckridge, J., Sheldon, F., Walker, K. and Boulton, A., 1998. Flow variability and the ecology of large rivers. *Marine and Freshwater Research* 49, pp. 55-72.

Puckridge, J., 1999. Th role of hydrology in the biology of dryland rivers. In: Kingsford R., 1999. A free flowing river – The ecology of the Paroo River. NSW Parks and Wildlife Service.

Puckridge J.T., Costelloe J.F. and Walker K.F., 1999. DRY/WET: Effects of changed water regime on the fauna of arid zone wetlands (CD-ROM model and documentation). Report to National Wetlands Research & Development Program: Environment Australia and Land and Water Resources Research & Development Corporation, Canberra.

Puckridge J.T., 1999. The role of hydrology in the ecology of Cooper Creek, Central Australia: Implications for the Flood Pulse Concept. Unpub. PhD Thesis, University of Adelaide.

Puckridge J.T., Costelloe J.F. & Walker K.F., in press. Hydrological persistence and the ecology of dryland rivers. *Regulated Rivers: Research and Management.*

QLD EPA, 1999. Wetlands of south-western Queensland. Brochures reprinted from Jaensch, R., 1999. The status and importance of wetlands of Queenslands south-western wetlands. Brochures developed from: Jaensch, R., 1999. The status and importance of wetlands of Queenslands south-western wetlands. Report by Wetlands International-Oceania to the Queensland Environment Protection Agency.

Sattler P. and Williams, R., 1999. The conservation status of Queensland's bioregional ecosystems. Environment Protection Agency, Queensland.

Timms, B., 1999. Local runoff, Paroo floods and water extraction impacts on wetlands in Currawinya National Park. In: Kingsford R., 1999. A free flowing river – The ecology of the Paroo River. NSW Parks and Wildlife Service.

Thoms M.C., Sheldon F., Roberts J., Harris J. and Hillman T.J., 1996. Scientific Panel Assessment of Environmental Flows For the Barwon-Darling River. A Report to the Technical Services Division of the New South Wales Department of Land and Water Conservation. May 1996, 161 pp. (Cooperative Research Centre for Freshwater Ecology, Canberra.)

Watts, R., 1999. Biodiversity in the Paroo River and its wetlands. In: Kingsford R., 1999. A free flowing river – The ecology of the Paroo River. NSW Parks and Wildlife Service.

APPENDIX 1 RAINFALL, DISCHARGE AND HYDROLOGICAL VARIABILITY MEASURES

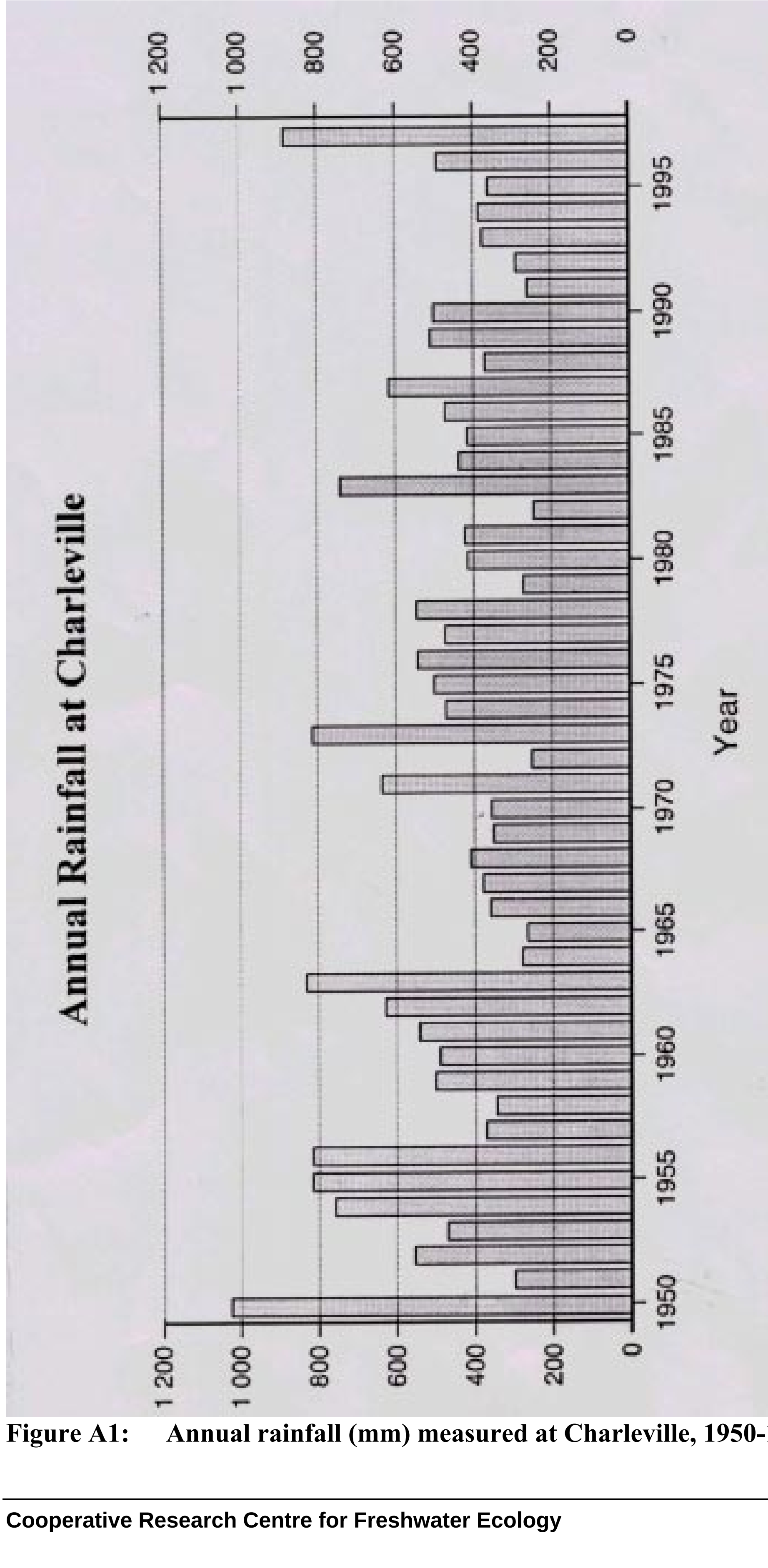

Figure A1: Annual rainfall (mm) measured at Charleville, 1950-1997

Warrego Catchment Rainfall Statistics

STATION	Augathella			Cunnamulla P.O.			Fords Bridge		
NUMBER	044002			044026			048042		
PERIOD	1889 - 1997			1879 - 1997			1896 - 1997		
	rainfall mm			rainfall mm			rainfall mm		
month	max	mean	min	max	mean	min	max	mean	min
Jan	314	77	0	272	46	0	269	40	0
Feb	292	72	0	265	49	0	290	35	0
Mar	388	64	0	278	40	0	206	32	0
Apr	307	37	0	458	25	0	188	24	0
May	276	32	0	150	27	0	160	30	0
Jun	238	31	0	117	26	0	162	24	0
Jul	204	30	0	133	22	0	120	22	0
Aug	120	21	0	114	17	0	82	19	0
Sep	154	24	0	154	18	0	90	17	0
Oct	243	38	0	158	25	0	157	23	0
Nov	242	47	0	140	28	0	132	25	0
Dec	237	61	0	361	37	0	132	29	0
Annual	1 275	531	199	924	363	134	856	324	86

Figure A2: Monthly statistics for rainfall measured across the Warrego catchment

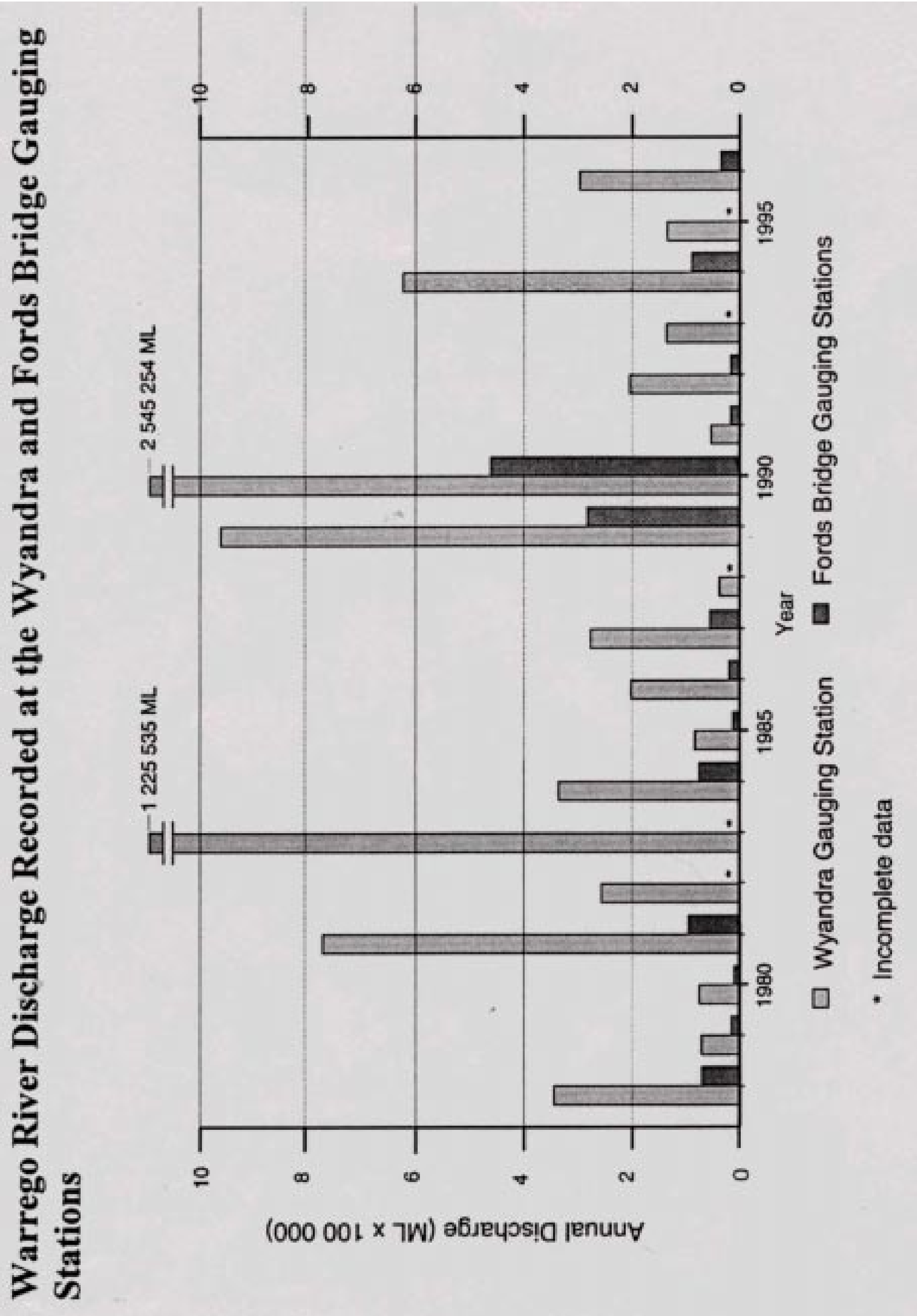

Figure A3: Annual disharge in the Warrego River

Stream Discharge Statistics for the Warrego Catchment

STATION	Warrego River at Wyandra	Warrego River at Fords Bridge
NUMBER	423203	Combined Flows of 423001 and 423002
PERIOD	1967 - 1998	1922 - 1998

	stream discharge ML				**stream discharge** ML			
month	max	mean	median	min	max	mean	median	min
Jan	504 098	57 874	8 217	0	55 031	7 994	1 381	0
Feb	2 216 451	171 432	24 139	0	81 008	9 035	3 622	0
Mar	457 243	52 186	17 216	0	131 247	13 216	5 569	0
Apr	2 404 976	87 350	1 492	0	182 207	14 613	3 255	0
May	868 088	54 325	55	0	283 157	12 912	869	0
Jun	631 381	34 389	137	0	154 771	8 188	93	0
Jul	198 783	9 024	124	0	69 903	3 738	121	0
Aug	18 462	1 641	0	0	125 891	4 154	2	0
Sep	104 387	5 919	33	0	28 401	1 452	0	0
Oct	50 743	3 864	0	0	12 131	1 104	0	0
Nov	91 971	9 511	13	0	59 084	2 457	0	0
Dec	665 797	49 863	11 629	0	55 967	3 554	37	0
Annual	2 545 254	533 407	292 852	31 370	692 426	81 098	43 394	0

Figure A4: Monthly discharge statistics for the Warrego River

Table A1: Facets and measures of flow variability (from Puckridge, 1999)

Facets	Measures
Predictability	Skew of annual flows
	Skew of monthly flows
Magnitude at various scales	% of all months with zero flow
	Variability of all minimum flows
	Variability of peak discharges
	Variability of all monthly flows
	Variability of all annual flows
	Median between years of each year's variability between months
	Median between months of each month's variability between years
	Variability between years of each years variability between months
	Variability between months of each months variability between years
	Multi-annual variability (3 year intervals)
	Multi-annual variability (5 year intervals)
	Multi-annual variability (7 year interval)
Frequency duration	Variability of number of flow pulses per year
	Variability of duration of the falling phase of the flow pulse
	Variability of duration of the rising phase of the flow pulse
Rate of Change	Variability of the rate of fall of discharge
	Variability of the rate of rise of discharge
Pulse Shape	Variability of amplitude of the falling phase of the flow pulse
	Variability of the amplitude of the rising phase of the flow pulse
Timing	Variability of the timing of low flows
	Variability of the timing of peak flows

APPENDIX 2 OUTPUTS OF THE WET/DRY MODEL

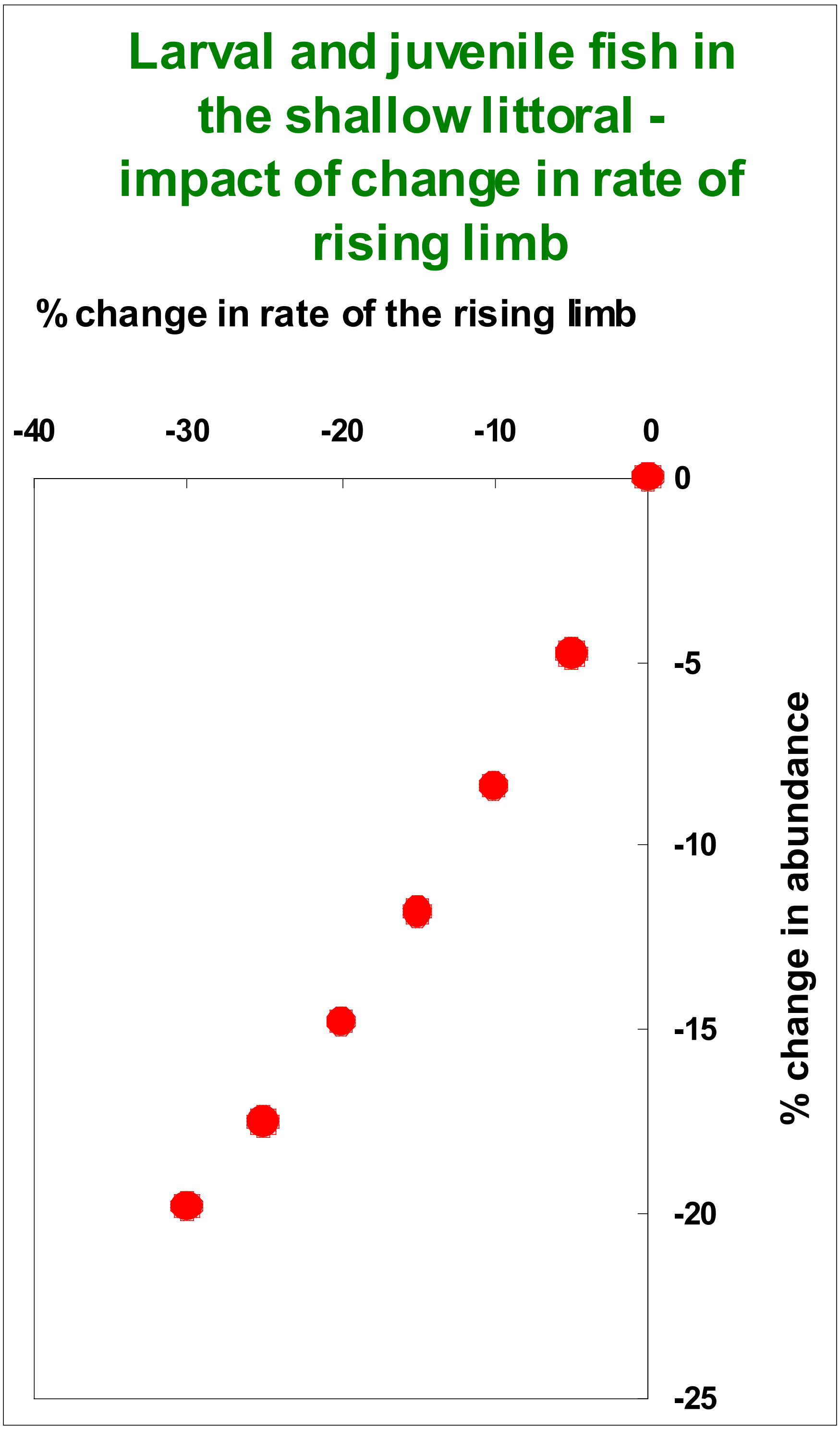

Figure A5: DRY/WET model output of changes to fish abundance in response to changed hydrological conditions (from J. Puckridge, University of Adelaide, pes. comm.)

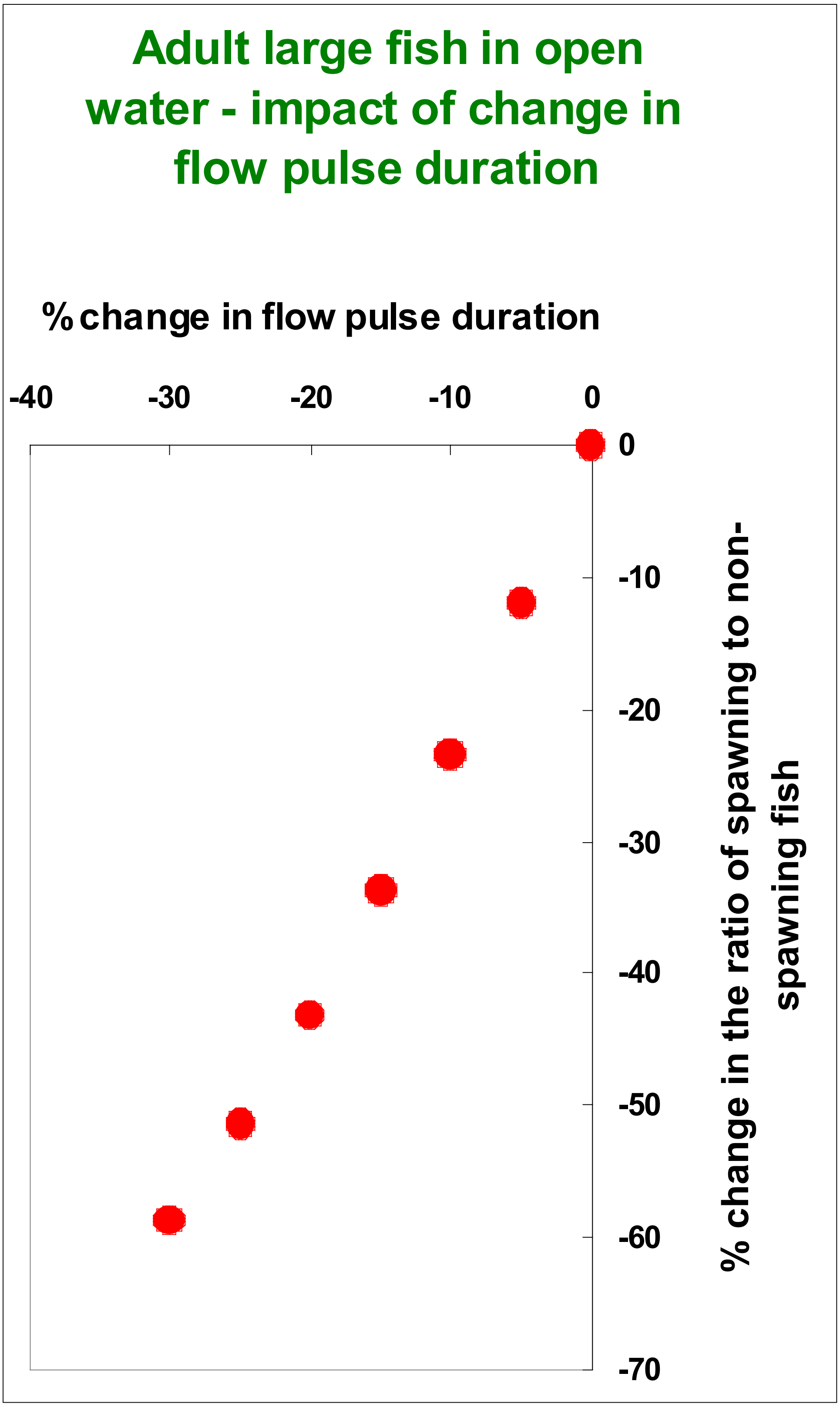

Figure A6: **DRY/WET model output of changes to fish spawning in response to changed hydrological conditions (from J. Puckridge, University of Adelaide, pes. comm.)**

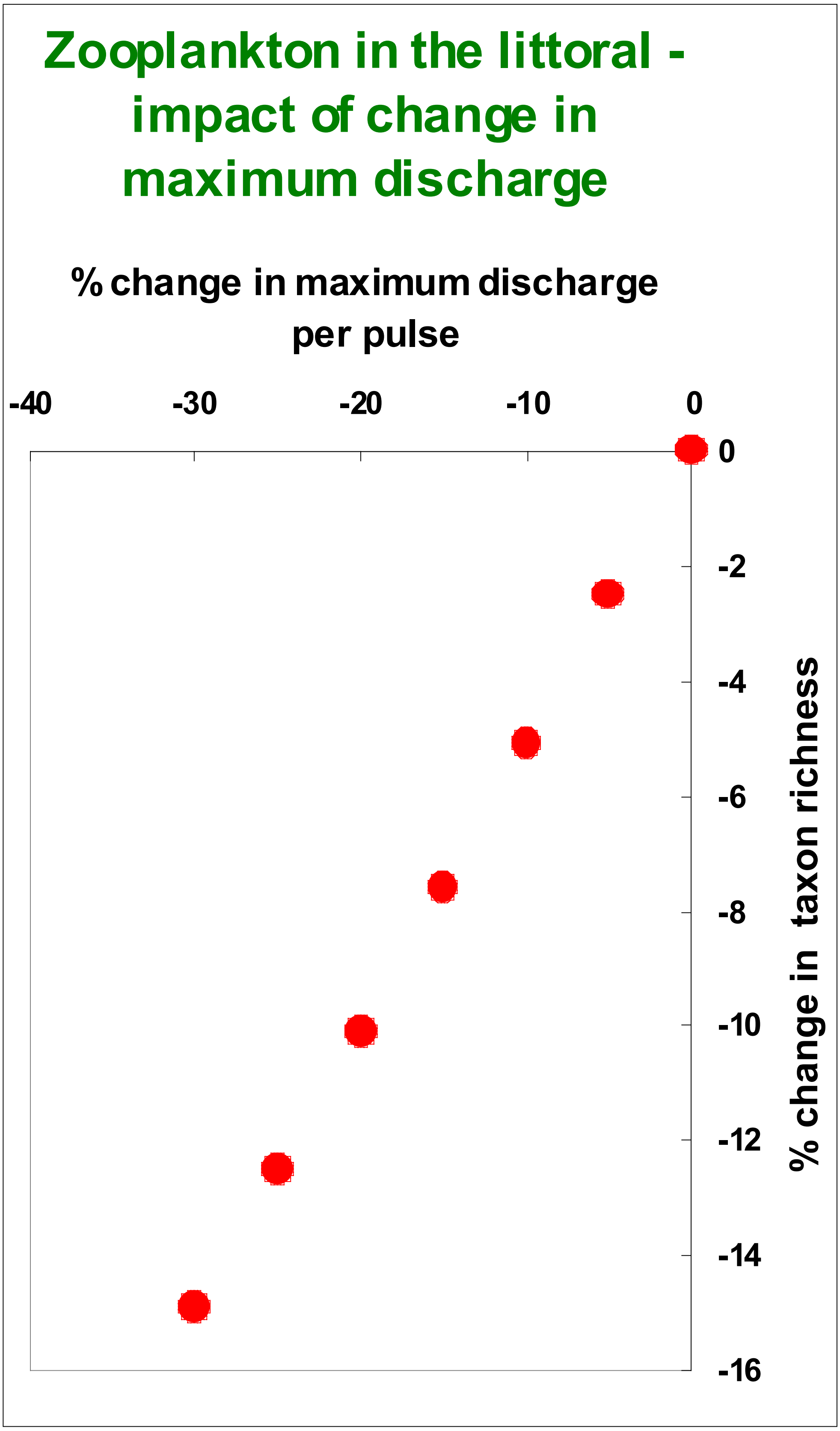

Figure A7: DRY/WET model output of changes to invertebrate taxon richness in response to changed hydrological conditions (from J. Puckridge, University of Adelaide, pes. comm.)

APPENDIX 3 IMPACTS OF WATER EXTRACTION ON FLOOD HYDROLOGY

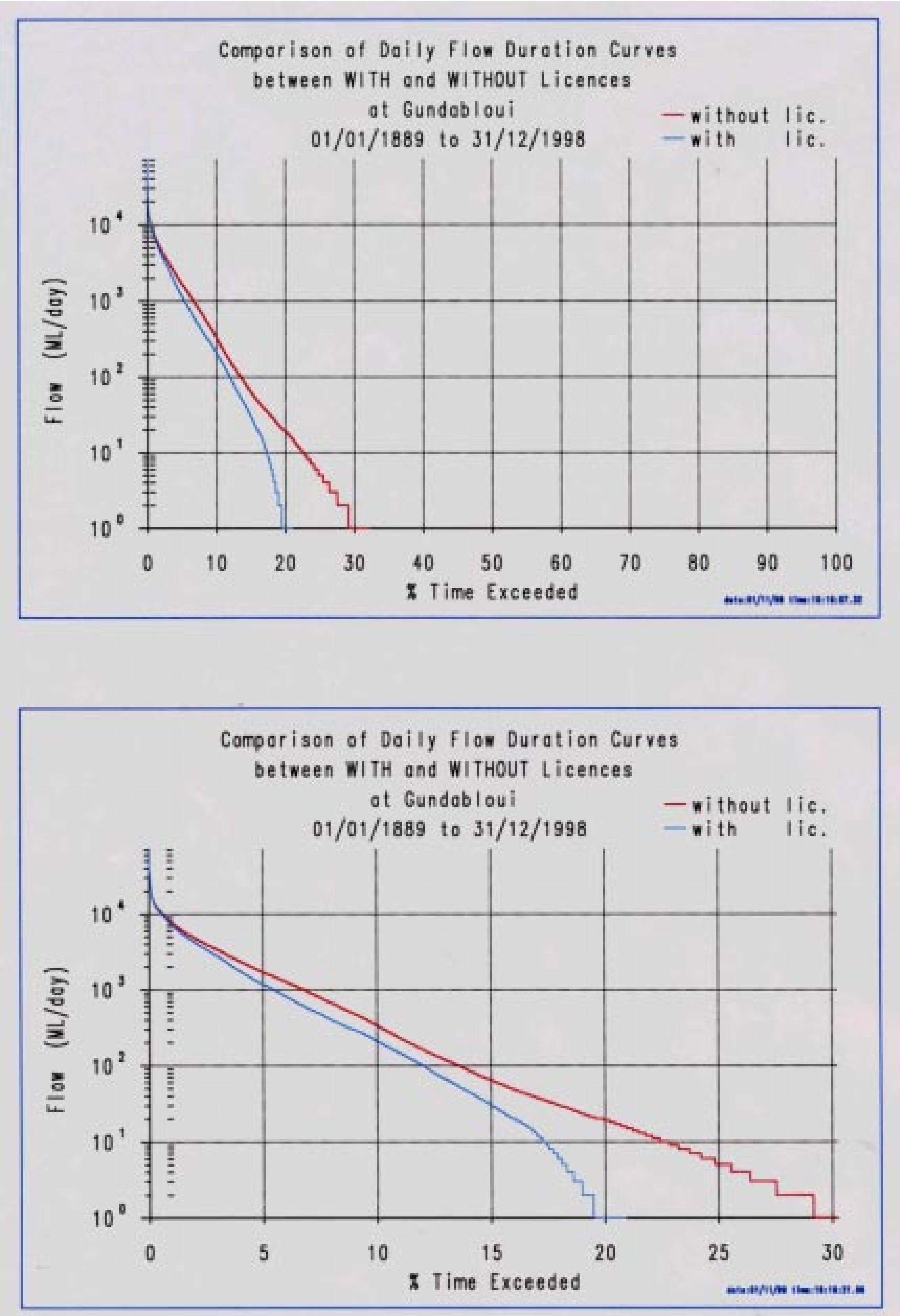

Figure A8: Flow duration curves for Gundabloui, with and without licenced extraction

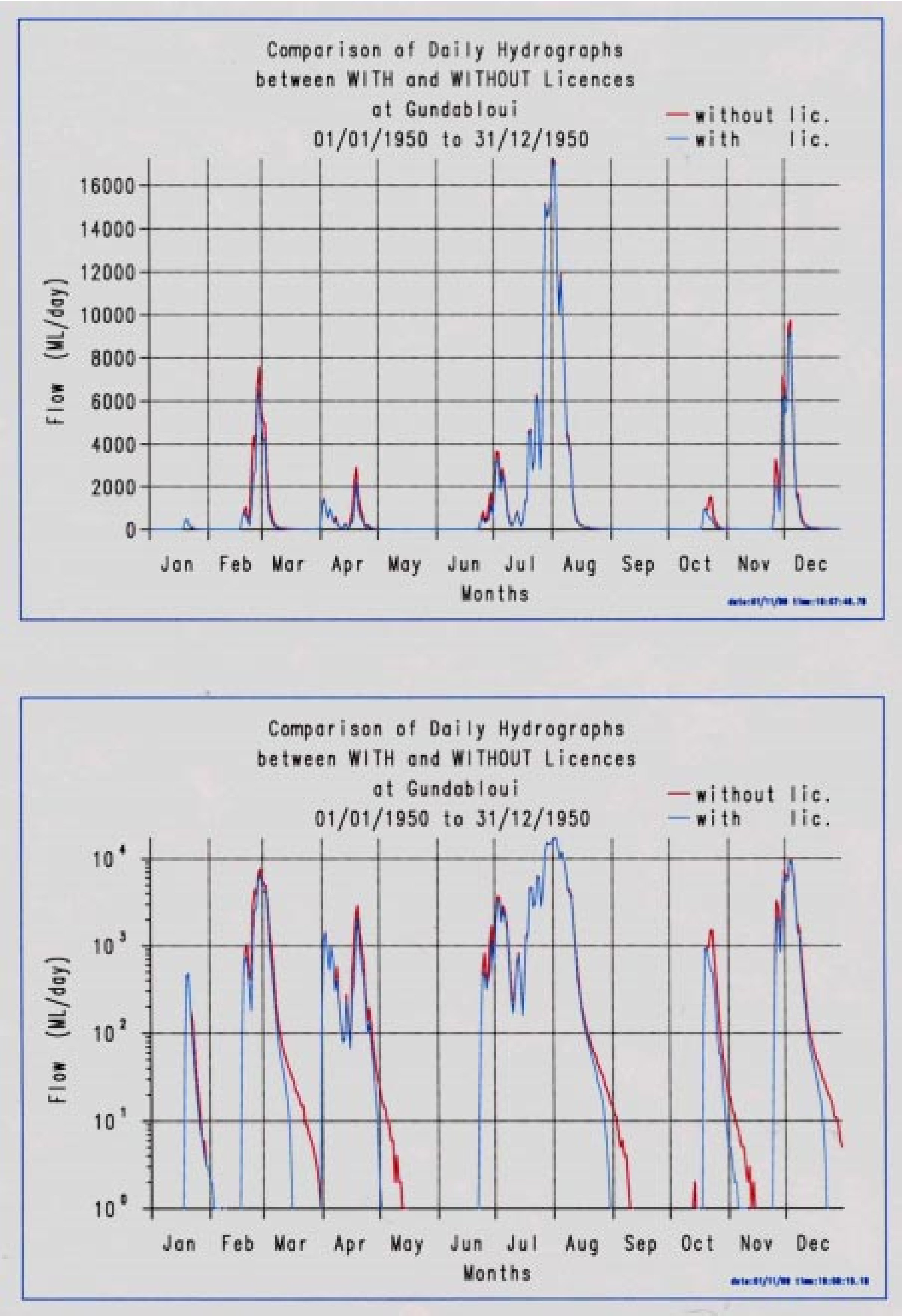

Figure A9: Flow hydrographs for Gundabloui 1950, with and without licenced extraction

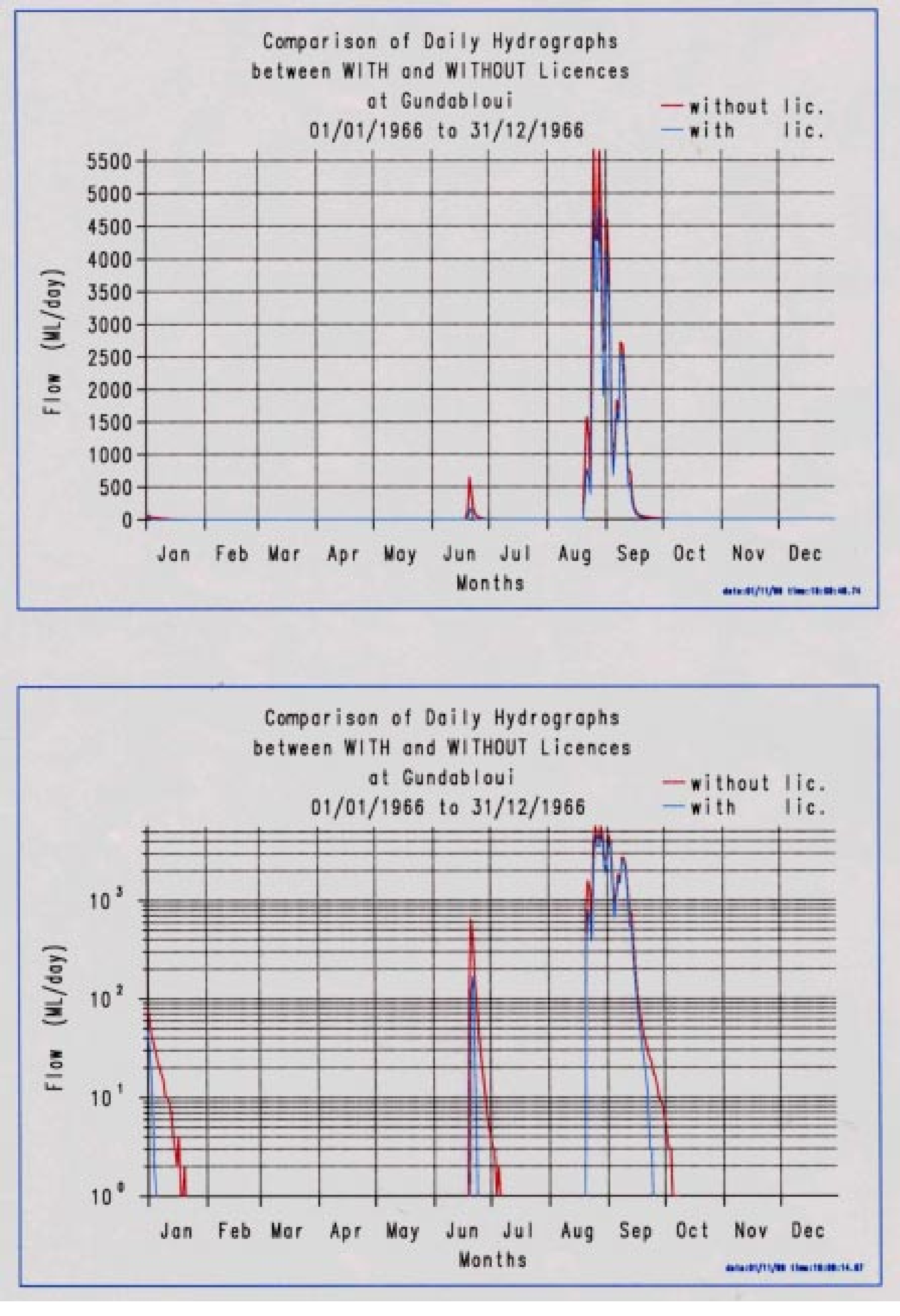

Figure A10: Flow hydrographs for Gundabloui 1966, with and without licenced extraction