Comments on the Ecological Case for a Flow Regulator on Chowilla Creek, SA

September 2006

Justin Brookes[1], Darren Baldwin[2], George Ganf[1], Keith Walker[1] and Brenton Zampatti[3]

[1] School of Earth and Environmental Sciences, The University of Adelaide, SA 5005

[2] Murray Darling Freshwater Research Centre, Wodonga, Vic 3690

[3] Inland Waters Program, SARDI Aquatic Sciences, PO Box 120, Henley Beach, SA 5022

Contents

Executive Summary

The floodplain at Chowilla, near Renmark, is one of six recognised *Icon Sites* associated with the River Murray. It is a habitat for river red gum, Murray cod and other well-known native species, and a scenic area worthy of preservation in its own right. For several decades the area has been deprived of water, and in recent years many trees have died. There has been substantial work toward restoration, including exclusion of grazing and an intensive program of pumping. The pumped water has improved tree health and germination, attracted waterfowl and enhanced wetlands, but has benefited only small areas. The outlook for local wetlands and woodlands is bleak unless there is more frequent, more extensive flooding.

The ideal, long-term solution would be to restore significant flows to the river. This is unlikely to be realised, despite the 500 GL per annum target of *The Living Murray* program proposed for 2009. Under present operating conditions, seasonal 'entitlement' flows to South Australia, determined by irrigation requirements rather than environmental needs, are 3500–7000 ML d^{-1}, and 3900 GL would be required to sustain a flow of 65,000 ML d^{-1} for 60 days. In future, there is likely to be less water available, as a consequence of global warming. A pragmatic solution therefore must be sought in using smaller flows to best effect, acknowledging that this is a palliative rather than a cure.

This paper considers three alternatives. The first, a 'do nothing' option, is unsupportable given the nature, extent and rate of degradation of the Chowilla environment. The second option is to continue deployment of mobile pumps, and the third is to construct a flow regulator on Chowilla Creek. The latter option is preferable because the benefits of flooding would be spread over a larger, more continuous area than could be achieved by pumping water into isolated wetlands and ephemeral creeks.

The proposed regulator would operate only for short periods, typically three months in three years, and should not be compared to the permanent weirs on the main channel of the Murray. It would include a series of 6-m bays supporting concrete 'stop logs' that could be added/removed to raise/lower water in Chowilla Creek by up to 3 m, forcing water onto the floodplain. Levee banks would provide supplementary options for water-level management. Operated in a flow band of 5000–20,000 ML d^{-1}, the regulator could be used to inundate 28% of the floodplain area, comparable to a river discharge of 65,0000 ML d^{-1}. The maximal pool depth would be 5.2-5.5 m. When the stop-logs were removed, the supporting piers would not significantly impede flow. Regional water levels then would be determined by flows in the Murray and operations at Locks 5-6 and existing regulators on Pipeclay and Slaneys Creeks.

The proposed regulator could provide a number of environmental benefits within the area affected by the impoundment. These include increased connectivity between riverine and floodplain habitats, improved soil condition, rejuvenation of existing vegetation, establishment of new floodplain and wetland plant communities, enhanced regional biodiversity, increased zooplankton abundance, and additional habitat for small native fish. Nevertheless, operation of the regulator would not be without some risk of negative impacts. These include an increased potential for cyanobacterial blooms, invasion by weeds, reduced lotic or flowing water habitats, interrupted fish passage, decrease in large-bodied native fish populations and increases in populations of common carp. In general, the regulator would need to be designed and operated to maximise the benefits and minimise negative impacts. To ensure that these goals are met, it is imperative that a

comprehensive, scientifically rigorous, long-term monitoring program is implemented, and that the results are subjected to continuing scrutiny by environmental scientists.

The degraded state of the Chowilla environment, and the prospect of continued low flows, demand a bold approach. The proposed regulator is such an initiative, and appears to offer more benefit than the mobile pumping option, notwithstanding certain risks. This commentary concludes that the proposal should be further investigated, with regard for measures to offset the risks incurred.

1. Introduction

The River Murray floodplain at Chowilla has a high conservation value (O'Malley and Sheldon 1990; Margules and Partners *et al.* 1990; DEH 2006). It is a *Wetland of International Importance* under the Ramsar Convention, and an *Icon Site* for *The Living Murray* program of the Murray-Darling Basin Commission (MDBC). For several decades the area has been deprived of water, and in recent years many trees have died. There has been substantial work toward restoration, including exclusion of grazing and an intensive watering program. Pumped water has improved tree health and germination, attracted waterfowl and enhanced wetlands, but has benefited only small areas of the floodplain. The outlook for local wetlands and woodlands is bleak unless there is more frequent, more extensive flooding.

The ideal, long-term solution would be to restore significant flows to the river, but even the 500 GL per annum target of *The Living Murray* program, proposed for 2009, is likely to be insufficient. Under prevailing conditions, seasonal 'entitlement' flows to South Australia are 3500–7000 ML d^{-1}, and 3900 GL would be required to sustain a flow of 65,000 ML d^{-1} for 60 days. This entitlement has no ecological basis; rather, it reflects an historical agreement determined by irrigation requirements. The scenario is complicated by projected declines in discharge associated with climate change. A pragmatic solution therefore must be sought in using smaller flows to best effect, acknowledging that this is a palliative rather than a cure.

This commentary outlines the status of Chowilla floodplain and its flora and fauna, and evaluates three options for restoration: (1) 'Do nothing', (2) Deploy mobile pumps and (3) Construct a flow regulator on Chowilla Creek. These options are considered with reference to connectivity between floodplain and channel habitats, floodplain soil condition, aquatic and riparian vegetation, fish ecology, algae and invasive species.

This paper does not consider groundwater or salinity issues, but relies upon prior investigations of regional groundwater hydrology (Overton *et al*. 2005; URS 2006).

2. Floodplain Condition

2.1 Biological surveys

A survey was conducted at Chowilla in 1988–89 by the Nature Conservation Society of South Australia, supported by MDBC (O'Malley and Sheldon 1990). It documented 307 vascular plant species, 134 bird species, 17 native and 8 introduced species of mammals, 31 species of reptiles and frogs, 29 plant species occupying wetland habitats, 96 taxa of macroinvertebrates and 11 species of fish. The survey concluded that the area warranted 'high' conservation status, due to:

- Diverse terrestrial and aquatic habitats, including habitats poorly represented elsewhere on the lower Murray,
- Presence of rare, endangered and uncommon aquatic species (e.g. Murray cod),
- Breeding areas for native fish, and
- Less human disturbance than in other areas of the Murray in South Australia.

An investigation of the riparian vegetation of the Murray by Margules and Partners *et al.* (1990) also recommended that "significant areas of the floodplain habitat such as the Chowilla area should be considered for conservation reserve status". This was echoed by DWLBC (2006): "The floodplain has a high diversity of both terrestrial and aquatic habitat, including fish breeding habitat and areas that support populations of breeding water-birds. Significantly, it contains the largest remaining area of natural river red gum (*Eucalyptus camaldulensis*) forest in the lower River Murray (Sharley and Huggan 1995) and also supports populations of rare and endangered species including four nationally threatened species (southern bell frog, regent parrot, Murray cod and Murray hardyhead) and 23 state-listed threatened species (DEH 2005)".

Despite the significance of the region, the riparian vegetation has continued to decline. O'Malley and Sheldon (1990) noted that "One of the most striking aspects of the Chowilla floodplain vegetation is the high incidence of dieback amongst red gum and back box woodland associations". They suggested that dieback was more prevalent in associations remote from the main channel and anabranch creeks, and that it increased upstream of Lock 6, perhaps due to salinity. Margules and Partners *et al.* (1990) attributed the poor health of riparian vegetation variously to saline ground water (53%), drowning or waterlogging (37%), water stress (6.2%), logging/clearing (1.9%) and grazing (1.7%). Jolly *et al.* (1996) identified salinity and decreased flooding frequency as factors, particularly for black box, and suggested that water stress could be offset by supplies of fresh water (<40 dS m^{-1}).

A review of the Chowilla Regional Reserve in 1993-2003 (MDBC 2003) identified water stress and grazing as causes of declining vegetation health, and recommended that "exclosures could be utilised to test 'drought' effects (i.e. if sites could be artificially watered, are there still sufficient seed sources available to allow recruitment of vegetation?)… a long term monitoring program is strongly recommended to document the response of the environment to de-stocking and watering point closure or relocation". This review concluded that the local decline of river red gum was consistent with prolonged water stress, and noted that all size- and age-classes of river red gums were affected. The then-current flow regime was considered inadequate for tree survival and insufficient to leach salt accumulated in floodplain soils between floods.

Recently, Overton *et al.* (2006) attributed the decline in tree health to soil salinization, driven by a lack of flooding and rising groundwater related to operations at Lock 6. They estimated that 65% (5658 ha) of floodplain trees at Chowilla were affected by salinization, compared with 40% in 1993.

2.2 Responses to watering trials

The current watering program at Chowilla has benefited the vegetation (Wallace 2006). Tree condition surveys performed 6-months post-pumping of water into wetland and creeks sites, showed that trees classified as 'near dead' prior to watering produced new growth, and that the condition of moderately-stressed trees improved, producing aerial seed banks. Wetlands developed new communities of aquatic plants (e.g. *Eleocharis* spp., *Myriophyllum* spp., *Phragmites australis*, *Potamogeton* spp., *Typha domingensis*). Other photographic evidence is recorded for Pilby Lagoon (Mike Harper, *Chowilla Integrated Natural Resource Management Project* 2006). In this case, river red gums were stressed when the lagoon remained dry for 10 months in 2002-2003, but recovered two months after the lagoon was refilled in April 2003. More evidence exists for trees at Monoman Island and Werta Wert, after trials in 2004 (Todd Wallace, DWLBC, unpubl.); these data were used to argue for a further 3600 ML for projects in 2004–05 and 2005-06.

3. Soil Health

The lack of flooding and loss of under-storey vegetation at Chowilla contribute to low levels of soil moisture, one of the main drivers of soil condition ('health') (cf. Anderson and Hodgkinson 1997). Local floodplain communities depend on floods, rather than rainfall, to maintain soil moisture. As the soil dries, the soil water potential decreases, making it difficult for plants to extract moisture from the soil matrix. This effect is compounded by the presence of salt. It leads to the early death of shallow-rooted, under-storey species, exposing the soil to further drying and erosion (Blackburn *et al.* 1992).

Soils at Chowilla are likely to be low in organic carbon. Inputs from under-storey plants may be direct, in the form of litter and root exudates, or indirect, as trapped fallen litter from over-storey plants (cf. Garcia *et al.* 2005). Where under-storey plants are few the carbon supply is reduced and, when the soil is dry, the soil biota also is affected, reducing the rate at which organic material is decomposed and incorporated into soil. Carbon depletion limits the soil's capacity to retain moisture and nutrients (Olness and Archer 2005), making conditions more unfavourable still for under-storey plants.

4. Vegetation

4.1 Responses to watering

The responses of riparian and wetland plants to wetting trials at Chowilla in 2005–06 were monitored by Dr Jason Nicol (SARDI Aquatic Sciences). In a first trial at Monoman Island Horseshoe (November 2005), a rich community of native species developed, including aquatics and semi-aquatics (*Bolboschoenus caldwellii, Juncus usitatus, Ludwigia peploides, Myriophyllum verrucosum, Schoenoplectus validus, Typha domingensis,*) and riparian herbs (*Alternanthera denticulata, Ammania multiflora, Epaltes australis, Centipeda minima, Limosella australis, Polygonum plebium*). This site has received a second watering and will be surveyed again in June 2006.

At Werta Wert wetland, a similar community developed but exotic species (*Abutilon theophrasti*, *Heliotropium europapeum, H. amplexicaule*, *Sonchus oleraceus*, *Vicia sativa*) were common, sometimes dominant. River red gum and black box developed denser canopies, and there was evidence of germination.

Although pre-watering data were not available for either of these wetlands, it is unlikely that any of the recorded aquatic species were present prior to watering. Pre-watering data were obtained, however, for Woolshed Creek, Punkah Island horseshoes and other wetlands watered in 2005-06, and these will be surveyed again in June 2006. Early indications are that many river red gum seedlings have germinated, and that there are new populations of *Centipeda minima*, *Epaltes australis* and *Vallisneria americana*.

Hancock Creek was chosen as a reference site, for sake of comparison. This site received minimal watering during a period of above-entitlement flows (15,000 ML d^{-1}), augmented by the effects of raising Locks 5-6. Local wetlands are dominated by sparse terrestrial (e.g. *Atriplex* spp., *Carpobrutus rossii*, *Craspedia* sp., *Maireana* spp., *Mesembryanthemum crystallinum, Osteocarpum acropterum*) and riparian species (e.g. *Cyperus gymnocaulos, Sporobolus mitchellii*).

These data, and evidence from oral history, photographs and quantitative surveys, show that wetland and riparian plants respond rapidly to watering, and confirm that viable seeds or vegetative propagules persist in areas prone to flooding. The increased plant biomass reflects changes in the carbon economy of the floodplain (Section 6.3.2).

4.2 Water regime requirements

Although the recent trials demonstrated that there is a viable seed bank for some species, Siebentritt *et al.* (2005) reported only minor responses to artificial flooding above Lock 5, mainly from rat's tail couch, *Sporobolus mitchelli*, and lignum, *Muehlenbeckia florulenta*. It is not clear whether the muted response was due to a depauperate seed bank, or to the way that water was delivered, but the comparison suggests that good responses are not inevitable, and that both hydrograph and responses should be monitored.

Ideally, the proposed regulator would be used to mimic a quasi-natural flooding regime. This would increase the spatial heterogeneity of habitats, ensuring that some areas of the floodplain would receive water at irregular but relatively frequent intervals, whereas others would receive less water, less often. This would promote a balance of diverse terrestrial, flood-tolerant and flood-dependent species.

The rates of rise and fall of flood waters need to be considered in management operations. If seedlings of aquatic or terrestrial species are top-flooded rapidly, they lose access to atmospheric carbon dioxide and oxygen, and soon die (cf. Denton and Ganf 1994). At Chowilla, seedlings that germinate on the main strandline are not likely to be top-flooded in successive floods, but those germinating on secondary strandlines are vulnerable. These secondary strandlines are typically below the "natural" tree line, and therefore not a major concern. Similarly, if water is drawn-down before it has had penetrated the soil, root extension will not be able to maintain contact and seedlings especially would be vulnerable. The rate of root elongation is unlikely to exceed 7 cm per week.

5. Fish

5.1 Species and habitats

The Chowilla system is a diverse complex of perennial and ephemeral creeks, backwaters, billabongs and lakes. Under low-flow conditions (<10,000 ML d^{-1}), 20-90% of flow in the Murray is diverted through the system by operations at Lock 6 (Stace and Greenwood 2004), and once-ephemeral streams are now perennial lotic (flowing) habitats. These are uncommon in a region where lentic (still water) habitats predominate as a consequence of weir operations (Walker 2006). The significance of lotic habitats at Chowilla is indicated by the presence of 'endangered' flora and fauna (O'Malley and Sheldon 1990; Pierce 1990; Sharley and Huggan 1995).

Fifteen species of fish are recorded from Chowilla, including four 'threatened' species, namely Murray cod (*Maccullochella peelii peelii*), silver perch (*Bidyanus bidyanus*), freshwater catfish (*Tandanus tandanus*) and Murray hardyhead (*Craterocephalus* *fluviatilis*) (Lloyd 1990; Nicols and Gilligan 2004; Zampatti *et al.* 2006). The system is a significant spawning and nursery area for golden perch, Murray cod and silver perch (Lloyd 1990; Pierce 1990; Zampatti *et al.* 2006).

During low-flow periods, most of the resident species are widespread, although macro-habitats contain distinctive assemblages (Zampatti *et al.* 2006). For example, Murray cod and golden perch (or callop, *Macquaria ambigua*) are most abundant in fast-flowing anabranches which, with Chowilla Creek and the Murray channel, harbour most species (11-12 species). There is less species richness (7-9 species) in backwaters and slow-flowing creeks (Zampatti *et al.* 2006).

Figure 1. Watering trials, 2005-2006: levee bank and hoses flooding wetland (photo: J. Nicol).

Figure 2. An un-watered section of the Chowilla floodplain (photo: J. Nicol).

Any loss of free-flowing reaches caused by the regulator may be significant for Murray cod and golden perch, as they prefer lotic habitats. On the other hand, the hydraulic changes may benefit small native fish like carp gudgeons (*Hypseleotris* spp.), unspecked hardyhead (*Craterocephalus stercusmuscarum fulvus*) and Murray rainbowfish (*Melanotaenia fluviatilis*). These species are most abundant in Murray weir pools, where there is cover from aquatic plants (Zampatti *et al.* 2006), and are likely to benefit if similar plants proliferate in the impounded area of Chowilla Creek.

5.2 Movements

Freshwater fish move between areas to optimise feeding, spawning success and dispersal, and to avoid unfavourable conditions (Northcote 1978). All 33 species in the Murray-Darling Basin (MDB) undergo movements on some scale (Mallen-Cooper 1996, Koehn and Nicol 1998, Harris 2001), from lateral movements between river and floodplain habitats to longitudinal migrations over hundreds of kilometres (Reynolds 1983; Koehn and O'Connor 1990; Nichols and Gilligan 2004). Maintaining mobility is a goal for the MDBC *Native Fish Management Strategy* (MDBC 2004).

5.3 Effects of barriers

Diversions and flow regulation through dams and weirs have substantially changed patterns of flow in the MDB (e.g. Walker and Thoms 1993; Maheshwari *et al.* 1995). These changes obstruct fish movements, reduce habitat areas and affect water quality (e.g. Arthington and Pusey 2003). They discourage most native fish and encourage exotic species (Cadwallader 1978; Gehrke *et al.* 1995; Pollino *et al.* 2004).

Instream barriers cause downstream accumulations of fish, delay migrations, increase predation, competition and disease, and reduce the range of migratory species (Harris 1984; Mallen-Cooper 1996; Stuart and Mallen Cooper 1999; Gehrke *et al.* 2002; Baumgartner 2005). They also restrict access to spawning grounds and habitats, prevent dispersal and recolonization and disrupt the lateral and longitudinal connectivity of floodplain-river systems (Cadwallader 1978; Gehrke *et al.* 1995; Mallen-Cooper 1996). Weirs on Slaneys and Pipeclay Creeks at Chowilla cause significant downstream accumulations of fish throughout spring and summer (Zampatti *et al.* 2006).

Murray cod, silver perch, golden perch and other native species have drifting larval stages (Humphries and Lake 2000; Humphries *et al.* 2002; Gilligan and Schiller 2003). Given the biology of these species, drifting larvae would naturally be most abundant from September to January, the period over which the regulator would be operated. Little is known of the effects of barriers on larval dispersal, but a regulator on Chowilla Creek probably would accumulate larvae rather than allow free passage (Gilligan and Schiller 2003; Humphries and King 2003).

Downstream fish passage is another issue (e.g. Kynard 2003), but is little understood for Australian species. Adult Murray cod and golden perch, for example, are reluctant to pass downstream at a low-head (2.0 m) over-shot weir and medium-head (6.5 m) under-shot weir (O'Connor *et al.* 2003).

Small rises in flow may be significant. From September to December 2005, larval Murray cod, silver perch and golden perch were recorded during a small but prolonged in-channel rise from 4000 to 14,000 ML d^{-1}, but no larvae were apparent during the same period in 2004, when flows were relatively stable (Zampatti *et al.* 2006). Larvae spawned during minor flow increases may be food-limited, and increased zooplankton biomass associated with floodplain inundation may enhance survival/recruitment (Meredith 2006). The proposed regulator should be managed in such a way as to preserve small rises in "un-regulated" flows to provide for spawning events similar to that observed in 2005.

5.4 Floodplain utilisation

Flooding and inundated floodplains generally benefit fish, although the mechanisms are unclear for MDB species (Graham and Harris 2005). Some species, including Murray cod, spawn independently of flow, whereas golden perch and silver perch spawn with or without small in-channel rises (Humphries *et al.* 1999; Mallen-Cooper and Stuart 2003; King *et al.* 2005). Nevertheless, Murray cod and golden perch have shown strong recruitment during high river flows in South Australia (Ye *et al.* 2000). In these species the benefits of flooding may be through increased juvenile survival, hence recruitment.

Radio-telemetry studies at Chowilla have shown that golden perch move to backwaters and small creeks during relatively small rises in river level (<0.4 m) (Zampatti, unpubl.). Pierce (1997) suggested that golden perch numbers during floods at Chowilla were sevenfold greater 'on the floodplain' than in the main channel, but did not indicate whether this referred to the inundated floodplain or to wetlands.

Other work on the Ovens River (Victoria) suggests that only one large species, the introduced common carp *Cyprinus carpio*, uses the floodplain environment directly (King *et al.* 2003). Indeed, carp is the only species to show an increase in larval abundance during or shortly after floods. It is likely that reductions in flow velocity and expansion of lentic habitats associated with a regulator on Chowilla Creek would benefit spawning and recruitment in this species (cf. Koehn *et al.* 2000).

5.5 Operation of a regulator

The regulator on Chowilla Creek would be operated for three months (September–December), once every 3–5 years. This is the peak migratory and spawning season for most resident fish species.

Given the width of the creek channel (>70 m), fish passage will be required on each side of the regulator (Clay 1995). The design should allow for the swimming abilities of different species, and different-sized fish, and downstream passage also will need to be considered. The MDBC *Fish Passage Task Force* is currently considering dual fishways at weirs on the River Murray, one fishway to cater for fish greater than 150 mm (a 1:18 vertical slot fishway) and another to cater for fish less than 150 mm (a small lock). Both fishways will share a common entrance.

Flow over the regulator could facilitate downstream dispersal of larvae, but there is also some risk of mortality. Murray cod and golden perch larvae are vulnerable at undershot weirs (Baumgartner *et al.* 2006), and an overshot design is recommended for Chowilla.

Despite the adverse impacts, slow-flowing pools may promote larval survival. Gilligan and Schiller (2003) suggested that weir pools enhance the survival of larval Murray cod and common carp. Lentic waters tend to be more productive than lotic ones (Pace *et al.* 1992), and weir pools are dominated by micro-crustacean zooplankters (Shiel *et al.* 1982) that are food for larval fish (Rowland 1992, 1996; King 2005). The Chowilla regulator might therefore be used to offset the adverse effects of regulation, provided that the presence of fish larvae coincides with peak invertebrate abundance. It would also be necessary to maintain spatial habitat heterogeneity and temporal fluctuations similar to those associated with an 'un-regulated' flood, as static water-level rises do not adequately match the functionality of flood pulses (cf. Toth *et al.* 1998).

6. Management Options

6.1 Present situation

The Living Murray program of MDBC, supported by the SA Department of Water, Land Biodiversity and Conservation (DWLBC), includes measures to rehabilitate Chowilla. In 2005, the SA Department of Environment and Heritage (DEH) obtained an agreement from pastoralist Mr Jock Robertson to end sheep grazing at Chowilla, and has made efforts to conserve remnant vegetation, using mobile pumps to transfer water between areas. The pumping program requires long-term logistic and financial commitments, none of which are secure. From an ecological viewpoint, the pumping strategy does not permit a flow-through of water and so does not achieve a key objective in restoration, namely to re-connect the floodplain and river *via* creeks and flood runners. The area of floodplain watered by pumping is limited to low-lying areas, and there is little or no return flow to the river.

6.2 Future options

(a) Do nothing

The condition of floodplain trees at Chowilla is clear evidence of continuing decline. In 1993, 40% of river red gum and black box were affected by salinization (Taylor *et al.* 1996), and 10 years later the proportion had increased to 65% (DEH 2005) or more, in the case of the red gums (MDBC 2003). Similar declines are apparent for other faunal and floral communities. The 'do-nothing option' therefore is unsupportable. It would lead to unrecoverable losses of flora and fauna, including local extinctions, and would deprive South Australia, and the Murray-Darling Basin, of a major conservation asset. It would mean also that Australia defaulted on its obligations under the Ramsar Convention.

(b) Mobile pumps

A second option is to maintain the current watering program to rejuvenate stressed areas. For logistic and financial reasons, however, this program can benefit only a relatively small area. In the absence of flooding from the river, most of the floodplain (65%) would continue to experience water stress, compounded by the effects of salinization, leading to further declines of flora and fauna. Whilst mobile pumping does have short-term value, a more secure, more sustainable approach is required.

(c) A new regulator

A third option is to install a flow regulator at the lower end of Chowilla Creek, as proposed in the *Chowilla Asset Environmental Management Plan* (DWLBC 2006). The proposed design includes a series of 6-m bays supporting removable concrete 'stop-logs' that could be added/removed to raise water levels by up to 3 m above river pool level, forcing water onto the floodplain. At capacity, the maximum pool depth in Chowilla Creek would be 5.2–5.5 m. Levee banks would provide supplementary controls for water-level management. When the stop-logs were removed, the supporting piers would not significantly impede flow. Water levels then would be determined by flows in the Murray and operations at Locks 5-6 and existing regulators on Pipeclay and Slaneys Creeks.

Operated in a flow band of 5000–20,000 ML d^{-1}, the regulator could be used to inundate 28% of the floodplain area, incorporating 83% of the ephemeral creeks and wetlands and 37% of the red gum woodlands. Its effects would be comparable to those of a river discharge of 65,000 ML d^{-1} (Overton *et al*. 2005). Operated during a flow of 40,000 ML d^{-1}, the pool would inundate 48% of the floodplain and simulate a natural flood of 82,000 ML d^{-1}.

It is important to recognize that the proposed regulator would operate only for short periods, typically three months in three years. Further, it would be operated expressly to meet environmental objectives. For these reasons, it should not be likened to the fixed weirs on the main channel of the Murray.

The regulator could be operated to mimic the natural hydrograph, as in the following 100-day scenario:

- Periods of above-entitlement flow would be targeted, so that the effects of naturally-high flows could be augmented. Alternatively, water could be released from upstream storages to increase flows above entitlement. For example, at 10,000 ML d^{-1} flow to SA, 4000 ML d^{-1} would be diverted into the system.
- As river flows increased, stop-logs would be added progressively to the bays, over at least two weeks, to raise the water in Chowilla Creek.
- With 4000 ML d^{-1} flowing through the system, at least 2000 ML d^{-1} would be allowed to flow over the regulator and return to the Murray, maintaining flow through the system.
- With a retention rate of 2000 ML d^{-1}, the impoundment would attain capacity (30 GL) in 15 days. This probably is too fast, from operational and ecological viewpoints, as a 3-m rise over 15 days would require daily rises of 200 mm.
- Raised water levels would be maintained for about 50 days, with some short-term variations if necessary.
- Levels then would be lowered gradually to river pool level. A head of 3 m, drawn down over 30 days, would lower the water at about 10 cm per day.

6.3 Comparison of options

6.3.1 Continued pumping

Observations at 20 wetlands, ephemeral creeks and floodplain depressions that have been watered to date at Chowilla indicate that delivery of additional water would be beneficial whether it is delivered *via* pumps or a regulator. The salient ecological difference is that a smaller area can be influenced by pumping.

Other possible disadvantages are that:

- Pumping does not promote inter-site or river-floodplain connectivity, which is a prerequisite for a viable river-floodplain system (e.g. Pringle 2003). Rather, the pumped water is allowed to evaporate or seep into the soil.
- There is no return flow of water or resources (e.g. nutrients) to the river.
- Fish movements to and from watered areas are limited.
    - Water pooled in localized depressions could become unsuitable habitats for some aquatic species. For example, pools could become hypoxic (depleted in

oxygen), even anoxic, owing to algal growth or decomposition of organic matter (cf. Sheldon and Lloyd 1990; Wallace 2006). Many fish and invertebrates are sensitive to hypoxia, and sensitive also to the toxins produced by algal blooms. Anoxia may stimulate production of methanogenic bacteria (e.g. Muller *et al*. 1994) and nutrient release from the sediments.

6.3.2 Proposed regulator

As noted, a regulator on Chowilla Creek would increase the area that could be flooded. Within its area of influence, it would enhance surface-water connectivity between wetlands and the river channel, increase the productivity of the wetlands and woodlands, promote leaching of salt from the plant root zone and encourage penetration of fresh water into the soil profile. It would also promote re-establishment of a healthy plant community, including under-storey and over-storey species, and combat accumulation of salt in the plant root zone (cf. Garde *et al.* 2004). The ecological benefits of the regulator relative to pumping would be much reduced, however, if there were not substantial continual flow over the regulator.

The following sections outline risks associated with the proposed regulator. These need to be considered in plans for design and operation, and until appropriate counter-measures or strategies are in place it would be premature to proceed.

(a) Soil condition

Where soils are compacted and deficient in organic material, surface water may not penetrate far down the soil profile. A field experiment could be undertaken to assess the time required for water to penetrate to different depths (cf. Bramley *et al.* 2003) and so determine the flood duration needed to replenish soil water. A single flood is unlikely to improve soil condition, but serial floods should lead to measurable increases in organic carbon content and slower decreases of soil moisture and matric potential between floods.

(b) Salinity and vegetation response

Managed inundation could increase leaching of salt from the floodplain soil, and reduced soil salinity and increased soil-water availability would reduce the area available to halophytic (salt-tolerant) plants like samphires. Pooling water in a floodplain depression may cause surface-water salinity to increase (e.g. from 0.15 to 0.35 dS m^{-1} after 10 weeks' inundation: Wallace 2006), although this may not be ecologically significant. The effects of managed flooding on groundwater salinities are likely to be site-specific, due to local soil characteristics and recharge rates (cf. Jolly *et al*. 1996). Watering trials at some sites suggest that it may be possible to maintain a fresh-water lens over saline groundwater, and this is a matter for joint investigations between CSIRO and DWLBC (Wallace, pers. comm.).

Vegetation will not respond to lower soil salinities, however, unless fresh water is available. It could be necessary to pump down the saline groundwater to create "space" for the freshwater to penetrate, although it may take decades to achieve major benefits (Jolly *et al*. 1996). These issues are critical, but beyond the scope of the present paper (see Overton *et al*. 2005, 2006; URS 2006).

(c) Material fluxes

As flood waters spill onto the floodplain, flow velocity decreases and inorganic materials settle out. Coarse Particulate Organic Matter (CPOM) is deposited, depending on flow velocity, the density of the CPOM and the hydraulic 'roughness' of the floodplain and its vegetation. This is likely to enhance soil condition.

Water returning to the channel from the floodplain will carry carbon and other nutrients leached from litter (Baldwin 1999; Baldwin and Mitchell 2000). These will promote primary and secondary productivity in floodplain and riverine environments. Increased organic carbon and increased productivity, hence production of carbon dioxide, and exchanges with acidic soils and sediments, could lower pH in the return water, although this is not supported by observations over a recent 12-week inundation of a floodplain depression at Chowilla (Wallace 2006). The net effect would depend upon the buffering capacity of the river water.

Rapid deoxygenation of water pooled in floodplain depressions is likely, at least in warmer seasons (e.g. Appendix; Howitt and Baldwin 2006; Wallace 2006), but this probably is of no more consequence than it would be for water from naturally-flooded areas. It could be limited by maintaining flows through the system.

In the absence of flooding, there is little exchange of material between floodplain and river. Conceptual models of river-floodplain interactions (Junk *et al.* 1989; Thorp and Delong 2002) suggest that water returning to the Murray from flooded areas would have a lower pH, less suspended solids (hence lower turbidity), lower oxygen and total (organic plus inorganic) phosphorus and higher dissolved phosphorus, nitrogen (nitrate, ammonia) and dissolved organic carbon (hence more coloured). The projected decreases in turbidity and increases in nutrients may stimulate downstream riverine productivity, as nutrient levels in the lower Murray often are in short supply (Baker *et al.* 2000).

(d) Weed invasion

Weed invasion is a significant risk after watering degraded habitats, particularly where the area has been used for grazing stock. Exotic plants like *Abutilon theophrasti, Heliotropium europaeum, H. amplexicaule, Phyla canescens, Sonchus oleraceus, Vicia sativa, Xanthium* sp. and many grasses are prone to invade new habitats. Native plants like cumbungi, *Typha domingensis*, and common reed, *Phragmites australis*, have similar invasive characteristics, and quickly attain dominance along the margins of impoundments and other slow-flowing habitats. There is a significant risk that these two latter species could expand their distribution, and promote sedimentation, in the impounded area of Chowilla Creek.

(e) Algal blooms

Weir pools are notorious for cyanobacterial (blue-green algal) blooms and other water-quality problems associated with thermal stratification. Consequently, it is necessary to avoid the onset of persistent stratification by maintaining sufficient flow. Blooms could be limited by manipulating the size and timing of river flows in such a way that stratification is destroyed and Cyanobacteria are flushed from the pool. For this to succeed, through-flow must be sufficient to de-stratify on days of high insolation and low wind speed.

Bormans and Webster (1997) used meteorological data (Bormans *et al.* 1997) to infer critical flow velocities required to avoid persistent diel stratification in weir pools of the lower Murray. In their model, stratification is determined by the relative effects of stratifying thermal energy and de-stratifying Turbulent Kinetic Energy (TKE) and their potential to mix the water column.

A model summary and calculations are provided in an Appendix to this paper. The flow required to de-stratify the proposed Chowilla pool was calculated using daily average data for January. For a 6.5 m deep pool and a low mean daily wind-speed of 1.2 $m\ s^{-1}$, a flow of 0.15 $m\ s^{-1}$ would be required for complete mixing. As wind speed increased, a lower mean flow would be required to produce a mixed water column. The mean flow velocity in Chowilla Creek, given a daily flow of 1.2 GL and a cross-sectional area of 520 m^2 (100 m x 5.2 m deep), would be 0.26 m s^{-1}. This could effectively be halved without risk of stratification, although it would be wise to reduce flow slowly and monitor the thermal dynamics of the pool.

Water returning to the river after inundation of the floodplain may contain elevated nutrient concentrations. These are resources for phytoplankton, but problematic only when they become available to bloom-forming Cyanobacteria (Brookes *et al.* 2005). This could be avoided by operating the regulator only when flows in the main channel do not favour Cyanobacteria.

A model of physical conditions for cyanobacterial growth is shown in Figure 3 (Baker *et al.* 2000). It suggests that, with river flows above 10,000 ML d^{-1}, thermal stratification should be avoided regardless of prevailing wind speed.

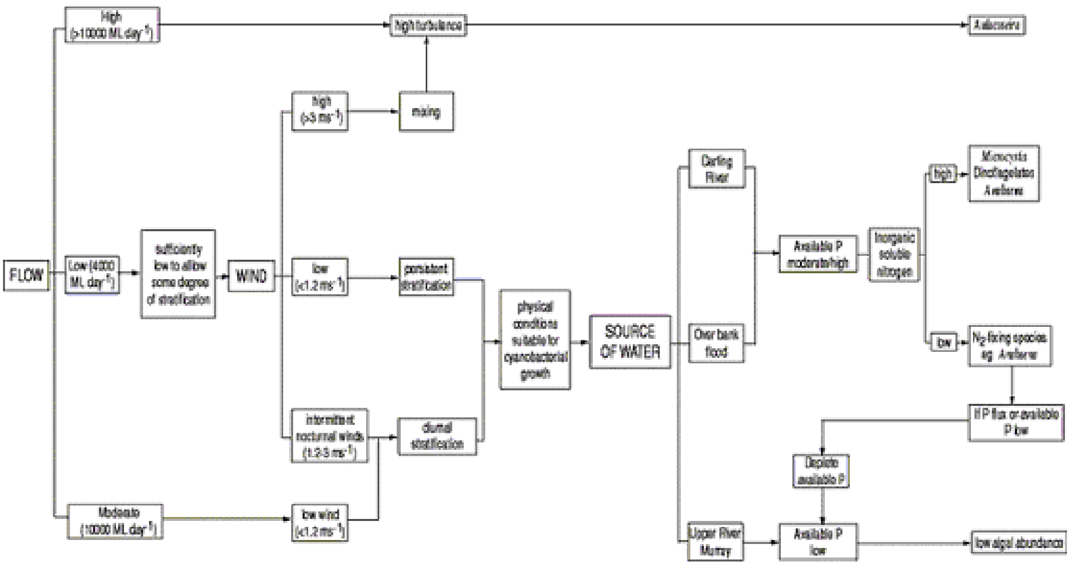

Figure 3.

A conceptual model of flow velocity, stratification and phytoplankton species dominance in the lower River Murray. After Baker *et al.* (2005).

(f) Fish

The macro-habitats of the Chowilla system contain distinctive assemblages of native fish (Zampatti *et al.* 2006), and the area is a significant spawning area and nursery for golden perch, Murray cod and silver perch (Lloyd 1990; Pierce 1990; Zampatti *et al.* 2006). Reduced flow velocity associated with the regulator could adversely affect Murray cod and golden perch, as they prefer lotic habitats. These changes may also create additional habitat for small-bodied native fish like carp gudgeons (*Hypseleotris* spp.), unspecked hardyhead (*Craterocephalus stercusmuscarum fulvus*) and Murray rainbowfish (*Melanotaenia fluviatilis*). On the other hand, lower flows and expansion of lentic habitats would also benefit spawning and recruitment of introduced common carp (*Cyprinus carpio*).

Operation of the structure would interfere with fish movements, and fishways to cater for small and large-bodied fish would be essential. Downstream fish passage also will need to be addressed. It is likely that the regulator will accumulate fish larvae rather than allow free passage. Flow over the regulator could facilitate some downstream dispersal of larvae, but there is some risk of mortality associated with passage over the structure (Baumgartner *et al.* 2006). For larvae in the pool behind the regulator, the slow-flowing water (Gilligan and Schiller 2003) and increased zooplankton abundance (Meredith 2006) could improve conditions for survival.

7. Conclusions

7.1 Review

The long-term solution for management of floodplain environments at Chowilla is to restore significant flows to the river. However, this is unlikely to be realized in the foreseeable future, despite the 500 GL per annum allocation proposed for 2009. The supply of water is limited by management for irrigation, by prevailing drought conditions and, in the long-term, the likelihood of reductions of discharge associated with global warming.

The 'do nothing' option is unsupportable given the nature, extent and rate of degradation of the environment at Chowilla. Consequently, a pragmatic solution must be sought in using low flows to best effect, acknowledging that this is a palliative rather than a cure.

The proposed regulator would affect a larger, more continuous area than could be serviced by mobile pumps, and would restore some connectivity between river and floodplain environments rather than merely delivering water to isolated wetlands and ephemeral creeks. On the basis of the available information, the proposed regulator appears to be the best option to limit further degradation at Chowilla, and it is recommended that this option should be investigated further. This is not, however, a complete endorsement of the regulator option. It recognizes that there are significant risks, and that these need further evaluation before a decision is made to proceed with construction.

The problems at Chowilla demand a bold approach and urgent action, and the proposed regulator is one such initiative. Above all, it is likely to succeed only if resource managers, stakeholders, scientists, engineers and others work collaboratively at all stages of planning, implementation, monitoring and review.

7.2 Potential benefits

The proposed Chowilla Creek regulator could provide a number of environmental benefits within the area affected by the impoundment. They include increased connectivity between riverine and floodplain habitats, enhanced supplies of carbon and other nutrients for soil microbial activity, less change in soil moisture content and matric potential between floods, a possible reduction in soil salinity, rejuvenation of existing vegetation, and new floodplain and wetland plant communities, increased zooplankton abundance, increased habitat for small native fish, and enhanced regional biodiversity.

7.3 Risk management

This proposal has no precedent in Australia, and the outcomes cannot be predicted with certainty. As it is necessary to ‘learn by doing’, it is imperative that a comprehensive, scientifically rigorous monitoring program is maintained, and that the data and conclusions are subject to critical review.

One means to ascertain the levels of risk would be to proceed with flooding trials by raising water levels in a stepwise manner, and monitoring and reviewing the responses before initiating larger floods. Some risks, including cyanobacterial blooms, may be controlled by maintaining minimal flow thresholds for operation of the regulator (the newly-developed *Murray Hydrodynamic Model* may be useful in this respect). In these ways, the technology to support management could be developed jointly by resource managers, stakeholders, scientists, engineers and other interested parties.

The risks identified in Section 6.3.2 deserve closer evaluation before final decisions are made. These risks relate to soil condition, salinity and vegetation response, material fluxes, weed invasion and effects on fish movements and recruitment.

8. References

Anderson, V.J and Hodgkinson, K.C. (1997) Grass-mediated capture of resource flows and the maintenance of banded mulga in a semi-arid woodland. *Australian Journal of Botany* 45: 331-342.

Arthington, A.H. and Pusey, B.J. (2003) Flow restoration and protection in Australian rivers. *River Research and Applications* 19: 377-395.

Asset Environmental Management Plan Overview (2005). www.thelivingmurray.mdbc.gov.au/implementing/asset_enironmental_management_plans

Baker, P.D., Brookes, J.D., Burch, M.D., Maier, H.R. and Ganf, G.G. (2000). Advection, growth and nutrient status of phytoplankton in the lower River Murray, South Australia. *Regulated Rivers: Research and Management* 16: 327-344.

Baldwin, D.S. (1999) DOM and dissolved P leached from fresh and 'terrestrially' aged river red gum leaves—Implications for assessing river-floodplain interactions. *Freshwater Biology* 41: 675-685.

Baldwin, D.S. and Mitchell, A. M. (2000) Effects of drying and re-flooding on the sediment/soil nutrient-dynamics of lowland river floodplain systems — a synthesis. *Regulated Rivers: Research and Management* 16**:** 457-467.

Baumgartner, L.J. (2004) *The effects of Balranald Weir on spatial and temporal distributions of lower Murrumbidgee River fish assemblages*. Report to the Department of Agriculture, Fisheries and Forestry. NSW Fisheries Final Report 65, 30p.

Baumgartner, L.J. (2005) *Effects of weirs on fish movements in the Murray-Darling Basin*. PhD Thesis, University of Canberra, Canberra.

Baumgartner, L.J., Reynoldson, N. and Gilligan, D.M. (2006) Mortality of larval Murray cod (*Maccullochella peelii peelii*) and golden perch (*Macquaria ambigua*) associated with passage through two types of low-head weirs. *Marine and Freshwater Research* 57: 187-191.

Blackburn, W.H., Pierson, F.B., Hanson, C.L., Thurow, T.L. and Hanson, A.L. (1992) The spatial and temporal influence of vegetation on surface soil factors in semi-arid rangelands. *Transactions of the American Society of Agricultural Engineers* 35: 479- 486.

Bormans, M. and Webster, I.T. (1997). A mixing criterion for turbid rivers. *Environmental Modelling and Software* 12: 329-333.

Bormans, M., Maier, H., Burch, M. and Baker, P. (1997). Temperature stratification in the lower River Murray, Australia: implication for cyanobacterial bloom development. *Marine and Freshwater Research* 48: 647-654.

Brookes, J.D., Aldridge, K., Wallace, T., Linden, L.G. and Ganf, G.G. (2005). Multiple pathways for resource utilisation and ecosystem resilience. *Hydrobiologia* 552: 135-146.

Bramley, H., Hutson, J and Tyerman S.D. (2003) Floodwater infiltration through root channels on a sodic clay floodplain and the influence on a local tree species *E. largiflorens*. *Plant and Soil* 253: 275-286

Cadwallader, P.L. (1978). Some causes of the decline in range and abundance of native fish in the Murray-Darling River system. *Proceedings of the Royal Society of Victoria* 90: 211-224.

Chowilla Integrated Natural Resource Management Project (2006). www.dwlbc.sa.gov.au/murray/flows/chowilla.

Chowilla Integrated Natural Resource Management Project, Fact Sheet 24. www.dwlbc.sa.gov.au/files/fs24_chowilla.

Clay, C.H. (1995) *Design of Fishways and Other Fish Facilities*, 2n Ed. Lewis, Boca Raton.

Craig, A.E., Walker, K.F. and Boulton, A.J. (1991) Effects of edaphic factors and flood frequency on the abundance of lignum (*Muehlenbeckia florulenta* Meissner) (Polygonaceae) on the River Murray floodplain, South Australia. *Australian Journal of Botany* 39: 431-443.

Denton M and Ganf, G.G. (1994). The response of juvenile *Melaleuca halmaturorum* to flooding: Management implications for a seasonal wetland, Bool Lagoon, South Australia. *Australian Journal of Marine and Freshwater Research* 45: 1395-408.

Department for Environment and Heritage (2003) *A Review of Chowilla Regional Reserve 1993–2003*. Adelaide.

Department of Water, Land and Biodiversity, 2006. *Asset Environmental Management Plan: Chowilla Floodplain (excluding Lindsay–Wallpolla) Significant Environmental Asset*. South Australia. Adelaide.

Fischer, H.B., List, E.J., Koh, R.C.Y., Imberger, J. and Brooks, N.H. (1979). *Mixing in Inland and Coastal Waters*. Academic.

Garcia, C. Roladan, A. and Hernandez, T. (2005) Ability of different plant species to promote microbiological processes in semi-arid soils. *Geoderma* 124: 193-202.

Garde, L.M., Nicol, J.M. and Conran, J.G. (2004) Changes in vegetation on the margins of a constructed wetland after 10 years. *Ecological Management and Restoration* 5: 111-11

Gehrke, P.C., Brown, P., Schiller, C.B., Moffatt, D.B. and Bruce, A.M. (1995). River regulation and fish communities in the Murray-Darling river system. *Regulated Rivers: Research and Management* 11: 363-375.

Gehrke, P.C., Gilligan, D.M. and Barwick, M. (2002) Changes in fish communities of the Shoalhaven River 20 years after construction of Tallowa Dam, Australia. *River Research and Applications* 18: 265-286.

Gilligan, D. and Schiller, C. (2003) *Downstream transport of larval and juvenile fish in the Murray River*. NRMS Project R7019. NSW Fisheries Final Report 50, 66 p.

Graham, R. and Harris, J.H. (2004) *Floodplain inundation and fish dynamics in the Murray-Darling Basin. Current concepts and future research: a scoping study*. CRC for Freshwater Ecology, Canberra.

Harris, J.H. (1984) Impoundment of coastal drainages of south-eastern Australia and a review of its relevance to fish migrations. *Australian Zoologist* 21: 235-248.

Harris, J.H. (2001) Fish passage in Australia: experience, challenges and projections. In: *Third Australian Technical Workshop on Fishways* (Eds R.J. Keller and C. Peterken), pp. 1-17. Monash University, Victoria.

Henderson-Sellers, B. (1986). Calculating the surface energy budget for lake and reservoir modelling: A review. *Reviews of Geophysics* 24: 625-649.

Herbert, T. (2006) The Chowilla Floodplain Asset Environmental Management Plan 2006 www.dwlbc.sa.gov.au/murray/flows/chowilla.

Howitt, J., Baldwin, D.S. Rees G.N. and Williams, J. (2005) Blackwater Model – A revised computer model to predict dissolved oxygen and dissolved carbon downstream of Barmah-Millewa Forest following a flood. Report to the Murray-Darling Basin Commission, 139 p.

Humphries, P. (2005) Spawning time and early life history of Murray cod, *Maccullochella peelii peelii* (Mitchell) in an Australian river. *Environmental Biology of Fishes* 72: 393-407.

Humphries, P. and King, A.J. (2003) Drifting fish larvae in Murray-Darling Basin rivers: composition, spatial and temporal patterns and distance drifted. In: *Downstream Movement of fish in the Murray-Darling Basin—Workshop held in Canberra, 23-4 June 2003: Statement, Recommendations and Supporting Papers* (Eds M. Lintermans and B. Phillips) pp. 51-58. Murray-Darling Basin Commission, Canberra.

Humphries, P. and Lake P.S. (2000) Fish larvae and the management of regulated rivers. *Regulated Rivers: Research and Management* 16: 421-432.

Humphries, P., King, A.J. and Koehn, J.D. (1999) Fish, flows and floodplains: links between freshwater fishes and their environment in the Murray-Darling River system, Australia. *Environmental Biology of Fishes* 56: 129-151.

Humphries, P., Luciano, G. and King, A. J. (2002). River regulation and fish larvae: variation through space and time. *Freshwater Biology* 47: 1307-1331.

Jolly, I.D., Walker, G.R., Hollingsworth, I.D., Eldridge, S.R., Thorburn, K.L. and Hatton, T.J. (1996) The causes of decline and *Eucalyptus* communities and possible ameliorative approaches. In: *Salt and Water Movement in the Chowilla Floodplain* (Eds G.R. Walker, I.D. Jolly and M. Jawal). CSIRO Water Resources Series 15.

Junk, W.J., Bayley, P. B. and Sparks, R.E. (1989) The flood pulse concept in river-floodplain systems. *Canadian Special Publication of Fisheries and Aquatic Sciences* 106: 110-127.

King, A.J. (2005) Ontogenetic dietary shifts of fishes in an Australian floodplain river. *Marine and Freshwater Research* 56: 215-225.

King, A.J. (2005) Ontogenetic patterns of habitat use by fishes within the main channel of an Australian floodplain river. *Journal of Fish Biology* 65: 1582-1603.

King, A.J., Crook, D.A., Koster, W.M., Mahoney, J. and Tonkin, Z. (2005) Comparison of larval fish drift in the Lower Goulburn and mid-Murray Rivers. *Ecological Management and Restoration* 6:136-138.

King, A.J., Humphries, P. and Lake, P.S. (2003) Fish recruitment on floodplains: the roles of patterns of flooding and life history characteristics. *Canadian Journal of Fisheries and Aquatic Sciences* 60: 773-786.

Koehn J., Brumley, A. and Gehrke, P. (2000) *Managing the Impacts of Carp*. Bureau of Rural Sciences (Department of Agriculture, Fisheries and Forestry), Canberra

Koehn, J. and Nicol, S. (1998). Habitat and movement requirements of fish. In: *Proceedings of the 1996 Riverine Environment Research Forum, Brisbane, Queensland* (Eds R.J. Banens and R. Lehane), pp. 1-6. Murray-Darling Basin Commission, Canberra.

Koehn, J.D. and O'Connor, W.G. (1990) *Biological Information for the Management of Native Freshwater Fish in Victoria*. Department of Conservation and Environment, Victoria.

Kynard, B. (2003) Review of Migration, Research Methods, and passage for Downstream Migrant Fishes in the Northeast USA. In: *Downstream Movement of fish in the Murray-Darling Basin – workshop held in Canberra, 23-4 June 2003: Statement, recommendations and supporting papers* (Eds M. Lintermans and B. Phillips) pp 15-23. Murray-Darling Basin Commission, Canberra.

Lloyd, L. (1990). Fish communities. In: *Chowilla Floodplain Biological Study* (Eds C. O'Malley and F. Sheldon), pp. 183-193. Nature Conservation Society of South Australia, Adelaide.

Maheshwari, B.L., Walker, K.F. and McMahon, T.A. (1995) Effects of regulation on the flow regime of the River Murray, Australia. *Regulated Rivers: Research and Management* 10: 15-38.

Mallen-Cooper, M. (1996) *Fishways and freshwater fish migration in south-eastern Australia*. PhD Thesis, University of Technology, Sydney.

Mallen-Cooper, M. and Brand, D. (1992) *Assessment of two fishways on the River Murray and historical changes in fish movement*. Report to the Murray Darling Basin Commission

Mallen-Cooper, M. and Stuart, I.G. (2003) Age, growth and non-flood recruitment of two potamodromous fishes in a large semi-arid/temperate river system. *River Research and Applications* 19: 697-719.

Margules and Partners, P and J Smith Ecological Consultants, Victorian Department of Conservation, Forests and Lands (1990) *Riparian Vegetation of the River Murray*. Murray-Darling Basin Commission, Canberra.

McKinnon, L. (1995) The effects of flooding on fish in the Barmah Forest. In: *1995 Riverine Environment Research Forum* (Eds R.J. Banens and R. Lehane), pp 1-7. Murray-Darling Basin Commission, Canberra

McKinnon, L. and Shepheard, N. (1995) Factors contributing to a fish kill in Broken Creek. *The Victorian Naturalist* 112: 93-99.

Meredith, S. (2006) Fish and flows on Lindsay Island. *Chowilla Floodplain (including Lindsay-Walpolla) Technical Information Forum, 7 June 2006.* SARDI, South Australia.

Muller, K.L., Ganf, G.G. and Boon, .PI. (1994). Methane flux from *Baumea arthrophylla* (Nees) Boeckler and *Triglochin procerum* R.Br. beds at Bool Lagoon, South Australia. *Australian Journal of Marine and Freshwater Research*. 45: 1543-53.

Murray-Darling Basin Commission (2003) Preliminary investigations into observed river red gum decline along the River Murray below Euston. Technical Report 03/03, Murray-Darling Basin Commission, Canberra.

Murray-Darling Basin Commission (2004) Business Plan to Address Water Over allocation and to Achieve Environmental Objectives in the Murray-Darling Basin. Murray-Darling Basin Commission, Canberra.

Nichols, S. and Gilligan, D. (2004) *What about the fish? Improving fish passage through wetland flow control structures in the lower River Murray*. Australian Landscape Trust and New South Wales Fisheries.

Northcote, T.G. (1978) Migratory strategies and production in freshwater fishes. In: *Ecology of Freshwater Production* (Ed. S.D. Gerking), pp. 326-359. Blackwell, Oxford.

O'Connor, J., O'Mahony, D. and O'Mahony, J. (2003) *Downstream movement of adult Murray-Darling fish species*. Report to Agriculture, Fisheries and Forestry Australia. Arthur Rylah Institute, Victoria.

O'Malley, C. and Sheldon, F. (eds) (1990) *Chowilla Floodplain Biological Study*. Nature Conservation Society of South Australia, Adelaide.

Olness A. and Archer D. (2005). Effects of organic carbon on available water in soil. *Soil Science* 170: 90-101.

Overton, I.C., Rutherford, J.C., and Jolly, I.D. (2005) Flood extent, groundwater recharge and vegetation response from the operation of a potential weir in Chowilla Creek, South Australia. Report to Department of Water, Land and Biodiversity Conservation, Adelaide. September 2005.

Overton, I.C., Jolly, I.D., Slavich, P.G., Lewis, M.M. and Walker, G.R. (2006) Modelling vegetation health from the interaction of saline groundwater and flooding on the Chowilla floodplain, South Australia. *Australian Journal of Botany* 54: 207-220.

Pace, M.L., Findlay, S.E.G. and Lindts, D. (1992) Zooplankton in advective environments: the Hudson River community and a comparative analysis. *Canadian Journal of Fisheries and Aquatic Sciences* 49: 1060–1069.

Pierce, B.E. (1990) *Chowilla Fisheries Investigations*. Department of Fisheries, Adelaide.

Pierce, B.E. (1997) The fish factory. *Southern Fisheries* 5: 7-11.

Pollino, C.A., Feehan, P., Grace, M.R. and Hart, B.T. (2004) Fish communities and habitat changes in the highly modified Goulburn Catchment, Victoria, Australia. *Marine and Freshwater Research* 55: 769-780.

Pringle, C.M. 2003. What is hydrologic connectivity and why is it ecologically important? *Hydrologic Processes* 17: 2685-2689.

Reynolds, L.F. (1983) Migration patterns of five fish species in the Murray-Darling River system. *Australian Journal of Marine and Freshwater Research* 34: 857-871.

Rowland, S.J. (1992) Diet and feeding of Murray cod (*Maccullochella peelii*) larvae. *Proceedings of the Linnean Society of New South Wales* 113: 193-201.

Rowland, S.J. (1996) Development of techniques for the large-scale rearing of the larvae of the Australian freshwater fish golden perch, *Macquaria ambigua* (Richardson, 1845). *Marine and Freshwater Research* 47: 233-242.

Schiller, C.B. and Harris, J.H. (2001) Native and alien fish. In: *Rivers as Ecological Systems: The Murray-Darling Basin* (Ed W.J. Young), pp. 229-258. Murray-Darling Basin Commission, Canberra.

Sharley, T. and Huggan, C. (1995) *Chowilla Resource Management Plan: Final Report*. Murray Darling Basin Commission, Canberra.

Shiel, R.J., Walker, K.F. and Williams, W.D. (1982) Plankton of the lower River Murray, South Australia. *Australian Journal of Marine and Freshwater Research* 33: 301-327.

Sheldon, F and Lloyd L (1990) Physical limnology and aquatic habitats. Chapter 6, O'Malley, C. and Sheldon, F. (eds) *Chowilla Floodplain Biological Study*. Nature Conservation Society of South Australia, Adelaide.

Siebentritt, M.A., Ganf, G.G. and Walker, K.F. (2004) Effect of an artificially-enhanced flood on riparian vegetation. *River Research and Applications* 20: 765-774.

Stace, P. and Greenwood, A. (2004) *Chowilla Anabranch System Surface Water Information Summary*. Department of Water, Land and Biodiversity Conservation. Report DWLBC 2004/06.

Stuart, I., Baumgartner, L., Zampatti, B. and Barrett, J. (2004) Fishways in Australia – an adaptive approach to improving fish passage along a large river system. In: D.G. Lastra and P.V. Martinez (Eds), *Proceedings of the Fifth International Symposium on Ecohydraulics, Aquatic Habitats: Analysis and Restoration*, Madrid.

Stuart, I.G. and Mallen-Cooper, M. (1999) An assessment of the effectiveness of a vertical slot fishway for non-salmonid fishes at a tidal barrier on a large tropical/subtropical river. *Regulated Rivers: Research and Management* 15: 575-590.

Taylor, P.J., Walker. G.R., Hodgson, G., Hatton, T.J. and Correll, R.L. (1996) Testing of a GIS model of *Eucalyptus largiflorens* health on a semi-arid, saline floodplain. *Environmental Management* 20: 553-564.

Thorncraft, G.T. and Harris, J.H. (1996) *Assessment of rock ramp fishways*. NSW Fisheries Research Institute and CRC for Freshwater Ecology, Canberra.

Thorp, J.H., Delong, M.D. (2002) Dominance of autochthonous autotrophic carbon in food webs of heterotrophic rivers. *Oikos* 96: 543-550.

Toth, L.A., Melvin, S.L., Arrington, D.A. and Chamberlain, J. (1998) Hydrologic manipulations of the channelized Kissimmee River: Implications for restoration. *Bioscience* 48: 757-764.

URS (2006) Chowilla Management Options. Report to Department of Water, Land and Biodiversity Conservation, Adelaide. URS, CSIRO and Aquaterra. 23 June 2006.

Walker, K.F., and Thoms, M. C. (1993). Environmental effects of flow regulation the on River Murray, Australia. *Regulated Rivers: Research and Management*. 8:103-109.

Walker, K.F. (2006). Serial weirs, cumulative effects: the Lower River Murray, Australia. In R Kingsford (ed.), *The Ecology of Desert Rivers*. CUP: 248-279.

Wallace, T. (2006) Key responses of river red gum. Groundwater and surface water quality to watering. *Chowilla Floodplain (including Lindsay-Walpolla) Technical Information Forum 7 June 2006*. SARDI Aquatic Sciences, Adelaide.

Ye, Q. (2004) Golden perch (*Macquaria ambigua*): Fishery Assessment Report to PIRSA Fisheries. SARDI Aquatic Sciences, Publication RD04/0167.

Ye, Q., Jones, G.K. and Pierce, B.E. (2000) Murray cod (*Maccullochella peelii peelii*) Fishery Assessment Report to PIRSA Fisheries. SARDI Aquatic Sciences, Adelaide.

Zampatti, B., Nicol, J., Leigh, S. and Bice, C. (2006) *2005 Progress Report for the Chowilla Fish and Aquatic Macrophyte Project*. Report to DWLBC and MDBC. SARDI Aquatic Sciences, Adelaide.

9. Appendix: Critical flow velocities

In the model developed by Bormans and Webster (1997), the degree of stratification is determined by the relative supply rates of stratifying thermal energy and de-stratifying Turbulent Kinetic Energy (TKE). The rate of change of Potential Energy (PE) required to mix the heat and maintain a mixed water column of depth H, heated by a net surface heat flux Qnet, is

$$D(PE)/dt = \alpha gH/2Cp(Qnet-2Q_I/KdH)$$

where α is the thermal expansion coefficient, g is the gravity due to acceleration, Cp is the specific heat capacity of water, Q_I is the short wave radiation and Kd is the attenuation coefficient. Wind mixing and flow over the bottom are sources of turbulent kinetic energy.

The rate of working against the bottom is

$$d(TKE)/dt = c_D\rho_w U^3$$

where c_D is the bottom friction coefficient which applies to the depth-average velocity U, and ρ_w is the density of water. A fraction $\in$ of this TKE is available for increasing the PE of the water column. The column will de-stratify if the rate of increase of PE due to mixing exceeds the rate of decrease of PE due to surface heating. When the two competing processes are equal, the transition between mixed and stratified conditions is

$$R = U^3/(H(Q_{net}-2Q_I/k_dH)\ \alpha gH/2Cp) = 1/2\in c_D$$

This criterion is not valid when $Q_{net}-2Q_I/k_dH$ is negative, when the water-column is cooling and well-mixed regardless of discharge.

Well-mixed conditions in pools, such as the Chowilla Creek pool, correspond to R >55,000, and stratified conditions correspond to R <35,000. The transition between mixed and stratified conditions occurs at about R = 45,000.

To avoid stratification, flow must be sufficient to de-stratify on days of most insolation and low wind speed. The net surface heat flux into the water is

$$Q_{net} = Q_I - Q_B - Q_S - Q_E$$ (Henderson-Sellers 1986; Bormans and Webster 1997)

where QI is the net downward short-wave radiation, QB is the net upward long-wave radiation, QS is the upward sensible heat flux and QE is the heat flux of evaporation. Average QI was measured for January (354 W m^{-2}, QB 80 W $m^{-2)}$. QI and QB can be calculated if meteorological data are not available but QB is fairly constant for Murray and Murrumbidgee weir pools.

The upward sensible heat flux is

$$Q_S = C_p\rho_a C_H W(T_S-T_a)$$

where C_p is the specific heat capacity of air (1.01 x 10^3 J kg^{-1}.C), C_H is a coefficient for sensible heat exchange (1.5 x 10^{-3}; Fischer *et al.* 1979), ρ_a is the density of air (1.2 kg m^{-3}), Ts and Ta are the temperature of the water surface and air (18 and 22 °C; January averages, respectively), W is wind speed 10 m above the water surface, calculated from the wind speed at 2 m using

$$W10 = (W2 \times \ln (10/Zo))/\ln(Zm/Zo)$$

where W2 is the measured wind speed 2m above the surface (m s^{-1}), Zm is the height of the anemometer (2 m) and Zo = 0.000115 (CWR 1998).

Heat flux due to evaporation is

$$QE = Lv\rho_a C_E W(q_s-q_a)$$

where Lv is the latent heat flux of evaporation (2.5 x 10^6 J kg^{-1}), CE is the coefficient for evaporative heat flux (1.5 x 10^{-3}; Fischer *et al.* 1979), q_s and q_a are specific humidities estimated from temperature, relative humidity (0.15) after Kimball *et al.* (1982).

Table 1. A summary of anticipated benefits, challenges and possible remedies.

	Benefit	Cost	Possible remedy
Soil moisture	Increased; critical for vegetation		
Connectivity	Flux of nutrients (C, N, P) to river		
Nutrient transport	Stimulate productivity		
Aquatic-terrestrial connectivity	Resource input Support aquatic-terrestrial invertebrates		
Phytoplankton	Phytoplankton growth increased		
Cyanobacteria		Favoured by calm water in pools	Maintain flow to avoid stratification
Changed hydrology	More extensive watering	Restricted flow and fish passage. Lotic reaches need to be maintained.	Maintain flow
Vegetation	Floodplain vegetation watered	Invasive species, including weeds	
Biodiversity	Increased in all watered areas		
Groundwater salinity	Increased soil moisture		
Fish migration		Passage impaired	Installation of fish-ways
Fish habitat	Increase lentic habitat	Loss of habitat diversity	Ensure sufficient base flow by operating Pipeclay and Slaneys weirs
Fish food	Increased abundance of zooplankton and macroinvertebrates		
Fish spawning	Benefit small species	May favour carp	Monitor fish spawning and recruitment; rapid water-level reduction to expose eggs?
Carp abundance		Favours carp	

Table 2. Parameter values for the critical flow velocity model.

a	thermal expansion coefficient	2.10E-04	
g	gravitational acceleration	9.81	$m\ s^{-2}$
Cp	specific heat of water	4.18E+03	J/kg.C
Qi	short wave radiation	354	$W\ m^{-2}$
Kd	attenuation coefficient	2.5	m^{-1}
H	depth	6.5	m
Cd	bottom friction coefficient	2.50E-03	
U	depth average velocity		$m\ s^{-1}$
Pw	density of water	998	$kg\ m^{-3}$
e	mixing efficiency	0.0044	
Qio	irradiance (max)	354	$W\ m^{-2}$
as	surface albedo	0.1	Not used
sinb	solar altitude	0.802456789	
f	latitude	-34.013	
d	solar declination	-0.80723418	
h	angle hour	0	
tj	Julian day in the year	15	
t	local apparent solar time	12	
e	emissivity of water	0.972	
s	Stefan–Boltzman constant	5.70E-08	$W\ m^{-2}\ {}^{o}K^{-4}$
ea		783.0650572	measured
es		5534.434684	
rhair	relative humidity of air	0.52	
Cp	specific heat capacity of air	1.01E+03	J/kg.C
CH	coefficient	1.50E-03	Fischer *et al.*1979, p163
W	wind speed	1.258025583	$m\ s^{-1}$
Ta	air temperature	22	
Ts	water surface temperature	18	
Lv	latent heat of evaporation	2.50E+06	$J\ kg^{-1}$
pa	density of air	1.2	$kg\ m^{-3}$
qs		0.034424184	
qa		0.004870665	
CE	coefficient	1.50E-03	Fischer *et al.* 1979, p163