A case study approach to managing ephemeral wetlands for native fish: linking fish ecology to regulatory structure design and operation

Shaun N. Meredith, Sylvia Zukowski and Anthony Conallin
Murray-Darling Freshwater Research Centre,
PO Box 3428, Mildura, Victoria, 3502
Email: Shaun.Meredith@csiro.au

Abstract

River regulation has had a landscape scale impact on the hydrology of Murray-Darling floodplain wetlands and the fish that live within them. At the scale of the individual wetland, the design of regulatory structures and the operational rules that dictate their use has only rarely considered the behavioural and reproductive ecology of native fish species beyond the provision of fish passage. This is perhaps not surprising because our knowledge of how native fish use wetland habitat and the importance of this habitat to the overall health of the native fish community is still only perfunctory.

More recently, however, there has been a move toward installing regulatory structures on wetlands to achieve wholly ecological, rather than water delivery, outcomes. The design of these structures and their operating rules requires decisions that unambiguously link native fish ecology to flow requirements, often with only circumstantial or extrapolated knowledge. This lack of explicit knowledge combined with a diversity of competing wetland-specific issues (e.g. 'non-fish' ecological objectives, risk of groundwater intrusion, disturbance of culturally significant sites, wetland bathymetry) have meant that the establishment of a broadly applicable rule base linking native fish to wetland hydrology and structure design is not possible. A case study approach to examining the management of wetlands for native fish is thus warranted.

In this paper we describe in detail three naturally ephemeral wetland systems on the Lower Murray River floodplain; Webster's Lagoon, Lake Wallawalla and Potterwalkagee Creek. Regulatory structures and operational rules are currently being designed for each of these wetlands as part of the Living Murray Initiative, and in each case native fish ecological objectives have been considered during the design process. Two structure design features likely to have a significant impact on the fish fauna within and adjacent to the case study wetlands – carp screens and fish passage – are discussed here and their variable application described. Similarly, the variable application of operating rules that define how and when to wet or dry a wetland are discussed for each case study structure, with a view to maximising the likelihood of achieving the ecological objectives for which the structure was designed. Finally, the ecological and social risks associated with structure operation are discussed in a context of adaptive management.

We conclude that in order to test our current understanding of the use of wetlands by native fish, and to influence future structure design and operation, there is a clear need for a co-ordinated monitoring and experimental approach. Such an opportunity is afforded by the Living Murray Initiative. This important landscape scale project represents a long-term political commitment driven by ecological, as well as social and economic, objectives and therefore represents an ideal opportunity for the 'grand experiment' necessary to dramatically improve our understanding and management of the use of wetlands by native fish.

Introduction

Wetland hydrology in the Murray-Darling Basin (MDB) has undergone landscape-scale change since European settlement. The frequency and duration of wet and dry spells, flood return period, lateral connectivity, seasonality, depth and extent of inundation have been altered through direct (e.g. installation of structures to regulate wetland inflows/outflows) and/or indirect (e.g. flood mitigation due to upstream capture of floodwaters) flow manipulation. This, combined with the need to dispose of water with excessive salt or nutrient loads, has lead to broad scale changes in the abundance and distribution of wetland types (*cf.* Corrick and Norman 1980) within the riverine landscape (Table 1).

Table 1. Change in wetland number and area within the Mallee catchment since European settlement (adapted from Mallee Catchment Management Authority 2005).

Wetland Category*	Number of wetlands in 1788	Number of wetlands in 1994	Area (ha) of wetlands in 1788	Area (ha) of wetlands in 1994	Change in wetland number	Change in wetland area (ha)	Change in wetland area (%)
Freshwater meadow	**214**	**201**	**26,824**	**5,273**	**-13**	**-21,551**	**-80.3**
Shallow freshwater marsh	**134**	**161**	**2,377**	**2,240**	**27**	**-137**	**-5.8**
Deep freshwater marsh	**154**	**189**	**6,520**	**3,584**	**35**	**-2,936**	**-45.0**
Permanent open freshwater	**136**	**237**	**4,837**	**5,079**	**101**	**242**	**5.0**
Semipermanent saline	**258**	**347**	**24,724**	**27,004**	**89**	**2,280**	**9.2**
Sewage pond	**0**	**8**	**0**	**93**	**8**	**93**	**N/A**
Total	**896**	**1,143**	**65,282**	**43,273**	**247**	**-22,009**	**-33.7**

* from Corrick and Norman (1980)

This imposed change to wetland hydrology and function has lead to a concomitant change in wetland fish community structure. In particular, the stabilisation of wetland hydrological regime to achieve water supply targets is commonly thought to be the major reason for the low fish species diversity recorded in more regulated systems (Walker and Thoms 1993; Gehrke *et al*. 1995; Gehrke and Harris 2001). Similarly, regulation of wetland hydrology frequently requires structural modification at inlet or outlet points, and these structures often represent either physical or physico-chemical barriers to fish attempting to enter or exit a wetland (Pollino *et al*. 2004).

Through the introduction of the Native Fish Strategy (Murray-Darling Basin Commission 2004; 2005) and more recently The Living Murray Initiative, the Murray-Darling Basin Commission (MDBC) aims to arrest the decline and, where possible, rehabilitate native fish communities in key locations throughout the Basin. To achieve this, The Living Murray program promotes the construction of regulatory structures on selected floodplain wetlands to facilitate the management of environmental water to achieve a broad suite of ecological objectives. Because many of these ecological objectives are directly related to fish, explicit decisions are required to link wetland-related aspects of native fish ecology to regulator design (e.g. addition of carp screens, provision of suitable fish passage) and operation (e.g. timing and duration of wet and dry phases).

Here we describe the rationale behind the design and operation of floodplain structures soon to be installed at three case study sites; Webster's Lagoon, Lake Wallawalla and Potterwalkagee Creek. In each case, operation of new structures aims to achieve a broad range of bird, fish, invertebrate, water quality, terrestrial vertebrate and aquatic and floodplain vegetation related ecological objectives. At all three wetlands, fish related objectives do not provide the primary rationale for structure installation, instead they are often complementary or in competition with ecological objectives for other flora and fauna. We explore the nature of this relationship in detail and outline the basis for decisions made in line with achieving fish related outcomes as part of this broader context.

Specifically, the aims of this paper are to:

1. Outline three case study wetlands where the installation of proposed regulatory structures requires that explicit decisions be made about native fish management.
2. Describe for each case study the decisions that link fish ecology to the *design* of regulatory structures, with a focus on the installation of carp screens and provision of appropriate fish passage.

Figure 1. Significant Ecological Assets (SEAs) established as part of The Living Murray initiative.

3. Describe for each case study the decisions that link fish ecology to the *operation* of regulatory structures, with a focus on how and when to wet and dry a wetland.
4. Describe for each case study the major non-fish related risks that need to be considered during the installation and operation of wetland regulatory structures.
5. Provide comment on key gaps in our knowledge regarding the use of wetlands by freshwater fish in Australia and how we might address these knowledge gaps.

Case studies

The Living Murray initiative has established six icon sites (or 'significant ecological assets'; SEAs) within which environmental water will be delivered to achieve a range of ecological objectives (Figure 1). Here, we describe three case studies within the Lindsay and Wallpolla Islands area of the Chowilla/Lindsay/Wallpolla SEA.

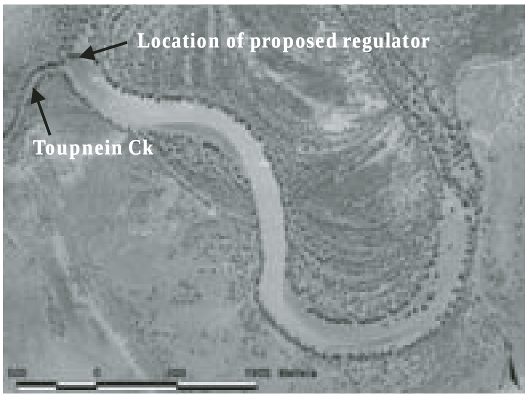

Figure 2. Webster's Lagoon.

Case study 1: Webster's Lagoon

Webster's Lagoon is a permanently inundated wetland located on Lindsay Island in northwest Victoria (Figure 2). As a result of regulation in the Murray River and the weir pool created by Lock 6, Webster's Lagoon has become an impounded wetland with a permanent connection to the Murray River through Toupnein Creek. At the Lock 6 pool level

(19.2 m AHD), approximately 25 ha of the Lagoon is inundated, however the entire Lagoon depression which would be inundated during medium to large floods covers approximately 80 ha (>21 m AHD) (Beovich 1994).

River regulation has changed the natural water regime of Webster's Lagoon from seasonal wet-dry to permanently wet. The lower Murray supports many such permanent wetlands which are commonly formed as a result of water backing up feeder creeks due to the presence of weir pools. For Webster's Lagoon, Toupnein Creek is the feeder creek, and it is under the influence of the Lock 6 weir pool and the tail water from Lock 7.

As part of The Living Murray Initiative's structures and works program, it is proposed that a regulator be built at the junction of Toupnein Creek and Webster's Lagoon such that the Lagoon can be isolated from its water supply and undergo a complete drying phase. Linked to this reinstatement of a drying phase is a full suite of ecological objectives (Scholz *et al*. 2005) describing the expected response of groundwater and surface water quality, wetland vegetation, algae, invertebrates, fish and waterbirds. For fish, the objectives describe the stranding of the extant Carp population during the initial drying period and their subsequent exclusion during refilling, the gradual reduction in the abundance and diversity of small native fish during the drying phase, and the stimulation of spawning and successful recruitment of small bodied natives during the refilling phase.

Case study 2: Lake Wallawalla

Lake Wallawalla is an 815 ha floodplain wetland lunette system situated south of Lindsay Island in the Murray-Sunset National Park (Figure 3). It is considered a 'high value' Australian wetland because it supports a range of significant flora and fauna and numerous sites of indigenous heritage (SKM 2003).

River regulation has impacted on the Lake Wallawalla ecosystem by changing the timing and duration of the floods that support it. Under current regulated conditions, three small culverts beneath a road embankment (Mail Route Road) provide the only means for water to enter and exit the lake during small to medium sized floods. Largely as a result of this 'throttling' of

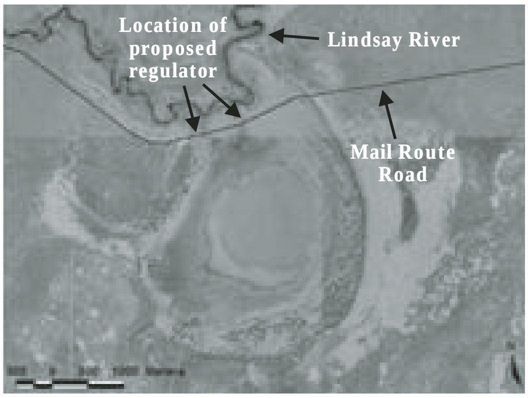

Figure 3. Lake Wallawalla.

inflows and outflows, Lake Wallwalla floods two months later in the year than would have naturally occurred, flood elevation is nearly 1m lower than natural, and floods have a much shorter duration (SKM 2004b).

The proposed structure for Lake Wallawalla aims to alleviate much of this 'throttling' effect by increasing culvert capacity. It is also proposed that the Mail Route Road embankment is increased in height from its current (low point) level of 21.96 mAHD to a uniform 22.35 mAHD to allow a greater volume of water to be retained for an appropriate period in the lake after filling.

Unlike other case studies, the ecological objectives for Lake Wallawalla follow a strong hierarchy, allowing for an 'instantaneous adaptive management' approach to monitoring and management of lake water levels (see Scholz *et al* 2005). Specifically, the ecological objectives, listed in order of priority, are to:

1. facilitate a successful waterbird breeding event;
2. maximise Red gum tree health; and
3. release young-of-the-year native fish that have successfully recruited in Lake Wallawalla back to the Lindsay River system.

Case study 3: Potterwalkagee Creek

Mulcra Island (2400 ha) is located on the Murray River approximately 80 km west of Mildura between Lindsay and Wallpolla islands. It is bounded by the Murray River to the north and by Potterwalkagee Creek to the south (Figure 4). Mulcra Island is representative of broad expanses of floodplain wetland along the lower Murray River that is inundated much less

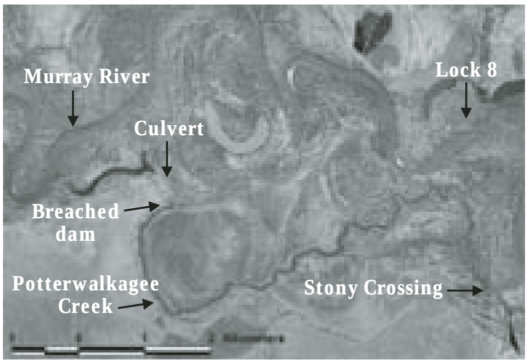

Figure 4. Potterwalkagee Creek.

frequently under current conditions because of the reduced frequency of small to medium sized floods resulting from river regulation.

The major inflow to Potterwalkagee Creek from the Murray River occurs through Stony Crossing (Figure 4), and this provides permanent flows in the downstream section of Potterwalkagee Creek at normal Lock 8 operating pool level. Under current conditions, flows through two other minor tributaries upstream of Stony Crossing occur approximately once every two to three years for an average duration of 60 days between May and November, although no flows have occurred over the past ten years. Under natural unregulated Murray River conditions, flows through these tributaries would have been twice as frequent and twice as long, and Stony Crossing would not have flowed (SKM 2004a).

To meet a broad range of ecological objectives, it is proposed that a downstream culvert (or number of culverts) be constructed at the Breached Dam site on Potterwalkagee Creek (Figure 4). Culvert(s) will be designed such that it can be sealed and have water backed up behind it, allowing more frequent inundation of a yet to be defined area of floodplain wetland habitat and simulate a small-scale ‘flood’ in this area.

The ecological objectives for Potterwalkagee Creek are still to be finalised. It is envisaged that similar to Webster’s Lagoon, the ecological objectives for the backfilling of Potterwalkagee Creek will encompass the broadest range of flora (terrestrial and aquatic), fauna (from birds to microinvertebrates) and water quality (including turbidity and nutrient flux) objectives based around the reinstatement of a pre-regulation flow regime.

Structural and operational decisions

It is important to note that determination of a final structural design and operational rules at each case study site is an ongoing process that has not yet been finalised. Outcomes presented below are therefore still interim, and further discussion and sign off by relevant authorities is necessary before designs and operational rules are finalised.

Carp Screens

‘Carp screens’ (alternatively named ‘fish screens’) are physical barriers of variable mesh size and design that are placed across inflow points with a view to excluding large fish from entering or exiting a wetland. Nichols and Gilligan (2003) found no consistent difference in carp abundance or biomass when comparing wetlands with and without carp screens attached, and attributed these results largely to the rapid growth of young-of-the-year carp that were sufficiently small to move through the carp screens during wetland filling periods. These results were not, however, interpreted in a context of historical inundation for the permanently wet study wetlands, thus the efficacy of carp screens in wetlands managed for shorter term (e.g. annual) wetting and drying periods is still not clear. Importantly, Nichols and Gilligan (2003) do indicate that carp screens inhibit the entry of breeding age Carp into wetlands, and suggest that appropriate operation of regulatory structures during filling periods might further limit the entry of smaller Carp. In particular, they suggest operation of structures to achieve an outgoing flow velocity of greater than 0.4 m.sec-1 (Dooland *et al*. 2000), filling wetlands only during the day to avoid the crepuscular and night time increase in Carp activity, and the linking of seasonal wetland filling timing to water quality (particularly temperature, salinity, conductivity and turbidity) and flow velocity at the nearest lock and weir in the main stem of the Murray river may reduce the abundance of young-of-the-year Carp in a wetland (Nichols and Gilligan 2003).

The perceived ecological and water quality benefits of Carp exclusion from a wetland are numerous (see King 1995 for review), and include a reduction in turbidity and sedimentation (King *et al*. 1997) and an associated reduction in nutrient loading (Gallo and Drenner 1995; Harris 1995), increased aquatic vegetation density (Crivelli *et al*. 1983; Roberts *et al*. 1995), a range of benthic properties (Robertson *et al*. 1997), and decreased competition for resources required by native fish (Fletcher 1986) (Table 2). Despite debate regarding the causal role of Carp in each of these benefits, there is broad agreement that Carp exclusion during re-wetting of ephemeral floodplain systems would confer significant ecological benefit.

In Webster's Lagoon (Case study 1) and Lake Wallawalla (Case study 2), a full drying phase either currently exists, or is proposed, meaning that carp screens could provide an additional benefit by restricting the return of adult Carp to the river system during the drying phase, effectively trapping them on the floodplain such as occurs 'naturally' at the Menindee Lakes (Scholz and Gawne 2004). Potterwalkagee Creek (Case study 3), however, is a permanently flowing system that will never be completely dried under current operational constraints, thus the benefits of Carp stranding and ultimate mortality through desiccation cannot be achieved.

The disbenefits of installing carp screens centre on the restriction of flows due to clogging of the screens and the high maintenance costs associated with this (Nichols and Gilligan 2003). Additionally, in trying to achieve other ecological outcomes for each of the case studies, the exclusion of other large-bodied fish by carp screens is likely to cause a decrease in the abundance of fish prey for piscivorous birds following re-wetting, and both concentrate carp (thus also their impacts) and restrict turtle passage during the drying phase. The latter is particularly important for the Murray Turtle (*Emydura macquarii*) at the ephemeral Webster's Lagoon and Lake Wallawalla sites because unlike the other turtle species in the area, the Murray turtle is not well adapted for overland migration (Cann 1998).

For Webster's Lagoon, it appears likely that the benefits of installing an effective carp screen outweigh the disbenefits, and given this it has been recommended that screens be installed at the inflow and outflow point in the proposed regulator (Table 2).

Conversely, bird breeding is the primary ecological objective at Lake Wallawalla, and exclusion of breeding age Carp and other large fish during the wetting phase will likely have a significant impact on the abundance of small (young-of-year) fish available to piscivorous waterbirds. This coupled with other listed disbenefits (Table 2) means that operation of carp screens during the filling phase of the lake is not recommended. However, the release of native fish recruited in Lake Wallawalla back to the Lindsay River system (ecological objective 3) is likely to be achieved through the release of water through the culverts beneath the Mail Route Rd. To avoid the release of adult carp back to the river system, it is proposed that carp screens be installed and operated accordingly, and that other measures (such as rescuing stranded turtles and native fish) be examined and managed appropriately.

As discussed above, Potterwalkagee Creek is a permanently flowing system, and already has a resident carp population (SKM 2004a). It will not be possible to exclude carp from the backfilling event, negating the use of a carp screen during this phase. Further, operation of a carp screen during the managed backfill recession would result in the concentration of large carp in the permanent Creek system, and it is feared that this would significantly compromise the attainment of other ecological objectives for this system. It is therefore recommended that no carp screen be installed in the Potterwalkagee Creek system.

Fish Passage

In each of the three case studies presented here, the construction of a wetland regulator will result in narrowing of natural inflow and outflow points. As a result, fish attempting to enter or exit the wetland are forced to negotiate unnaturally high flow velocities during wetland filling and draining. Often these velocities exceed the physiological and/or behavioural capabilities of individual species or size classes (Dooland *et al*. 2000; Haro *et al*. 2003), excluding them from the wetland. The provision of appropriate structural and operational solutions to facilitate passage for these fish is therefore critical to the attainment of a full suite of ecological objectives.

There is considerable knowledge of appropriate fishway designs for native fish (Mallen-Cooper 1992, 1994, 1999, Harris *et al*. 1998, Stuart and

Table 2. Likely benefits, disbenefits and decisions regarding the installation and operation of carp screens at regulators proposed for each of the case study sites.

	Case study 1: Webster's Lagoon	**Case study 2: Lake Wallawalla**	**Case study 3: Potterwalkagee Ck**
Likely benefits	• decreased abundance of large Carp • decreased turbidity/ sedimentation • decreased nutrient cycling and likelihood of algal blooms • increased aquatic vegetation (and subsequent follow on effects: macroinvertebrates etc) • decreased competition for native fish for prey and habitat • retain large Carp in the Lagoon during drying phase	• decreased abundance of large Carp • decreased turbidity/ sedimentation • decreased nutrient cycling and likelihood of algal blooms • increased aquatic vegetation (and subsequent follow on effects: macroinvertebrates etc) • decreased competition for native fish for prey and habitat • retain large Carp in the lake during drying phase	• retention of large Carp in the Creek following inundation of floodplain (ie. not release YOY Carp to river)
Likely disbenefits	• decreased prey available to piscivorous birds • restriction of inflows • higher maintenance costs • concentration of Carp in the Lagoon will likely have a short term disbenefit on water quality, aquatic vegetation and native fish ecological objectives during drying phase • restrict turtle passage • stranding of large native fish	• decreased prey available to piscivorous birds • restriction of inflows • higher maintenance costs • medium sized floods will overtop road, thus Carp screens may be ineffective at excluding Carp from lake. • concentration of Carp in the Lagoon will likely have a short term disbenefit on water quality, aquatic vegetation and native fish ecological objectives during drying phase • restrict turtle passage • stranding of large native fish	• restriction of outflows • higher maintenance costs • concentrate large Carp abundance in the Creek. Because this is a permanently inundated system (ie., no dry phase) this will likely have a long term disbenefit on water quality, aquatic vegetation and native fish ecological objectives. • restrict turtle passage
Install carp screen? Operational rules?	Yes. Install carp screens and operate during both filling and drying events. Positive outcomes are likely to outweigh negative outcomes.	Yes. Install carp screens, but do not operate during inflows, only during outflows (once water has receded below road embankment level) to minimise return of captive carp to Lindsay River.	No. Installation of Carp screens will likely only result in concentrating Carp in the permanent flow within the Creek. The risk that this may have a significant negative impact on other ecological objectives is too great.

Mallen-Cooper 1999, Stuart and Berghuis 2002) and these can potentially be applied at case study sites to address fish exclusion resulting from high water velocities. In Australia, a diversity of fishway designs have previously been implemented, including vertical slot, pool-and-weirs, Denil, rock ramp and lock type fishways (Stuart and Berghuis 2002). Structural solutions can also be designed to accommodate river operational rules acting at the catchment scale, such as for the multiple intake fishways currently being constructed on the locks and weirs of the Lower Murray River (MDBC 2005).

The key knowledge gap in applying these fishways designs centres on the ecology of lateral fish migrations into and out of wetlands in the MDB. At present we have inadequate knowledge of the species and size range of fish moving between the river and off-channel habitats and the flows and times over which these fish are moving. Key specific questions are the minimum and maximum size of fish that are moving, and the maximum head difference at a regulator when fish passage is needed. For our case study sites, where no regulatory structure currently exists, this information can only be estimated.

At Webster's Lagoon (Case study 1), provision needs to be made for small fish only, as all managed filling and emptying will occur through a carp screen. At Lake Wallawalla (Case study 2), passage for all size classes of fish must be considered during a filling event (where water does not overtop the Mail Route Road, in which case fish passage would occur 'naturally'). To achieve ecological objective 3 at Lake Wallawalla (release of young-of-the-year fish recruits during a draining phase), however, the passage of large Carp should be blocked through carp screens, thus, passage for small fish through these culverts needs to be accounted for in structure design. For Potterwalkagee Creek (Case study 3), carp screens are not being used, thus passage for all size classes of fish needs to be considered during release of backfilled water.

In addition to regulator design considerations, there are several key questions that need to be resolved to ensure appropriate fish passage (Table 3). All case studies will require fish to move into or out of wetlands in the absence of broader scale flow cues and at different filling/emptying rates such as would occur naturally during a flood. This may result in a bias in community species composition and overall abundance entering the system, which could possibly be corrected for by the provision of attractant flows (see Nichols and Gilligan 2003) or other structural/operational solutions. Additionally, for large flood events in Lake Wallawalla, it is not yet clear if the bulk of adult Carp will exit the lake during flood recession while flows are still overtopping the Mail Route road (thus negating the need for carp screens and the necessity for small fish passage only during lake emptying), or if a significant proportion of the adult Carp population will remain in the lake. These questions (and others) appear only answerable through the 'learning by doing' approach that forms the basis of the adaptive management framework (see Scholz *et al*. 2005).

How and when to dry a wetland

Drying periods are critical for maintaining ecosystem integrity in ephemeral wetlands (Boulton and Lloyd 1992, Bunn *et al*. 1997, Boulton and Jenkins 1998). For managed wetlands, decisions regarding how and when to instigate a dry phase can characterise ecological response at both the individual wetland and landscape scale (Scholz and Gawne 2004; Scholz *et al*. 2005).

Ephemeral wetland drying occurs primarily through two mechanisms;

1. a relatively rapid draining through inlet/outlet points during flood recession; and
2. a more gradual reduction in water levels as a result of evaporation and seepage.

Under natural conditions, both drying mechanisms occur in combination with a full suite of sometimes poorly understood ecological cues and indicators to which many water dependent native flora and fauna have adapted. Some functional groups of waterbirds, for example, have been shown to respond to both the spatial distribution of wetlands and the area flooded, while other groups respond to temporal sequences of wetting and drying (Roshier *et al*. 2002). Similarly, duration and season of the wet and dry periods in ephemeral wetlands influence not only the germination and establishment of wetland plants, but also completion of the life cycle through to sexual or asexual reproduction (Warwick and Brock 2003).

Table 3. Size class and other structural and operational issues to be resolved regarding the allowance for appropriate fish passage at regulators proposed for each of the case study sites.

	Case study 1: Webster's Lagoon	**Case study 2: Lake Wallawalla**	**Case study 3: Potterwalkagee Ck**
Fish size class	Small fish only (approx < 10 cm TL) due to operation of carp screen during both drying and re-wetting phases.	All size classes of fish during lake filling (swimming with inflows), but only small fish (approx < 10 cm TL) during drying phase due to operation of carp screen.	All size classes of fish during release of back filled water.
Issues to be resolved	• Do we need to provide flow cues to attract fish to the inlet during filling events? • Will there be a species bias (independent of the size bias imposed by the carp screen) for fish entering the Lagoon?	• Do we need to provide flow cues to attract fish to the exit point from the lake? • Will there be a species bias (independent of the size bias imposed by the carp screen) for fish exiting the lake? • If flood flows overtop the lake, will large Carp leave the system on the falling hydrograph when there is still connectivity with Lindsay River and thus negate the need for operating carp screens?	• Do we need to provide flow cues to attract fish to the exit point from the Creek? • Will there be a species bias for fish exiting the lake?

Under regulated conditions, however, wetland drying events (if they occur at all) are often decoupled from these landscape scale cues and indicators. This, combined with our only perfunctory knowledge of the drying cues and indicators important to most biota, means that prediction of ecological response as a result of a managed wetland drying is an imprecise science.

For fish, the 'how' and 'when' of managed dry phase instigation has implications primarily for fish mortality. Although it is broadly accepted that fish respond to a reduction of water depth on the floodplain during flood recession by seeking more permanent, deeper waters, there is little empirical evidence to support this or to isolate the specific cues that trigger fish to seek refuge. Indeed, Jones and Stuart (2002) demonstrated that a rapid drawdown resulted in the stranding of 417 individuals of both native and exotic fish species behind a regulatory structure. Balancing the provision of an escape route for native fish with the need to retain exotic species (primarily Carp) in a drying wetland is thus a key management focus.

Decisions as to how a wetland should be dried will greatly affect the potential for escape of all fish (Table 4). For Webster's Lagoon (Case study 1), inducing a drying event by rapid wetland draining is unlikely to occur because manipulation of Lock 7 (and possibly Lock 6) would be required to create a sufficient head difference across the proposed regulator to allow even partial drainage. As such, evaporation and seepage will be required to achieve full drying of Webster's Lagoon. Although this likely reflects a natural process, a managed drying of Webster's Lagoon will be of longer duration (as evaporation of the water above natural wetland sill height is required) and will be dissociated from natural cues that would normally prompt fish to leave the 'doomed' wetland (e.g. more rapid reduction in water level due to draining). Depending on the composition of the resident fish population (native to exotic species ratio, presence of endangered species etc) and significance of/threats to other flora/fauna, evaporative drying events may need to be accompanied by salvage operations or complex operational rules such that unnecessary mortality of important fauna and flora in Webster's Lagoon is minimised.

At both Lake Wallawalla (Case study 2) and Potterwalkagee Creek (Case study 3), conditions at the end of a managed wetting event are likely to be such that a considerable head difference would exist across the proposed regulators, thus facilitating a partial rapid -draining of the wetlands. Similar to Webster's Lagoon, this represents a natural method of drying, separated from the natural cues and patterns associated with the draining event (e.g. increasing water level immediately prior to onset or draining, spatial segregation of water inlet and exit points etc). As above, it may therefore be necessary to manage for this by providing measures such as attractant flows to ensure appropriate fish can exit the 'doomed' wetland system, or by defining operational rules such that opportunities for fish to exit the system are maximised. This is particularly the case for Lake Wallawalla, where evaporation and seepage will drive the final drying phase, and so, operation of the structure may be conditional on the same limitations as for the Webster's Lagoon structure (see above).

For each of the managed ephemeral wetland case studies, decisions regarding when to dry the wetland (Table 4) are among the most important for achieving ecological objectives, and also the most complex. Although the average 'natural' drying regime is often used to define when drying should occur, equally as 'natural' is the inter-annual variability around this average. Such hydrological variability is likely to confer a similarly inter-annual variability in individual fish species year class strength due to temporal preferences in spawning times (Meredith *et al*. 2002). Similarly, the landscape scale condition and state of wetlands should be considered, again with a view to maintaining a diversity of wetland types and states to maximise habitat

Table 4. How and when to dry a wetland: likely drying options and key decision points to be considered during the drying phase at each of the case study sites.

	Case study 1: Webster's Lagoon	**Case study 2: Lake Wallawalla**	**Case study 3: Potterwalkagee Ck**
How to dry: likely drying options	• evaporation • pumping	• draining (partial) • evaporation	• draining (partial) • evaporation
When to dry: key decision points	• Do we follow natural seasonality? • When did we dry last season – maintain temporal diversity of drying cycle? • What is happening elsewhere in the MDB – landscape scale effects (e.g. waterbirds)? • Carp size class vs carp screen mesh size: do we release newly spawned Carp into the system? • Have other ecological objectives been met? • Have risks been mitigated (e.g. salt) • Do protected species (e.g. Murray hardyhead) exist in the system?	• Do we follow natural seasonality? • When did we dry last season – maintain temporal diversity of drying cycle? • What is happening elsewhere in the MDB – landscape scale effects (e.g. waterbirds)? • Carp size class vs carp screen mesh size: do we release newly spawned Carp into the system? • Have other ecological objectives been met? • Have risks been mitigated (e.g. salt) • Do protected species (e.g. Murray hardyhead) exist in the system?	• Do we follow natural seasonality? • When did we dry last season – maintain temporal diversity of drying cycle? • What is happening elsewhere in the MDB – landscape scale effects (e.g. waterbirds)? • Do we release Carp into the system? • Have other ecological objectives been met? • Have risks been mitigated (e.g. salt)

diversity for native fish. Also important are issues around exotic fish and other non-fish related risks and ecological objectives at the individual wetland scale. For example, at Lake Wallawalla and Potterwalkagee Creek, there is the potential for significant numbers of sufficiently small young-of-the-year carp to exit the wetland through carp screens. Holding back the decision to release water for several months such that Carp are sufficiently large to be excluded by the carp screen could, if not significantly compromising other ecological objectives or increasing risk of unacceptable salt release, mean that these Carp could be excluded from returning to the permanent waterways.

How and when to wet a wetland

Floodplain wetland inundation has been linked to the provision of spawning cues (e.g Lake 1967a,b) and to enhanced recruitment success (e.g. Stuart and Jones 2002) of both native and exotic freshwater fish species in the MDB. In particular, the timing (season) of inundation is thought to be an important determinant of spawning and/or recruitment response (Humphries *et al*. 1999, 2002; Meredith *et al*. 2002; King 2003;; Meredith and McCasker, unpubl. data). Associated with the timing of inundation are important covariates such as day length, water temperature and food abundance, which have been causally linked to spawning and recruitment success in overseas research (Cushing 1990). In Australia, however, empirical evidence for this is scant, thus despite its importance, the relationship between timing of inundation and fish spawning and recruitment response remains poorly understood.

The *how* to inundate managed wetlands, too, is likely to affect the ecological response. Under natural conditions, flood inundation is the only means whereby significant flows could enter the three case study sites. Overland inflows would bring a diversity of fish, invertebrates, nutrients and phytoplankton resulting from upstream processes and behaviours. For managed wetlands, it is unclear if the same assemblage of flora, fauna and associated water quality is likely to enter a wetland through regulatory structures, constricted channels and culverts, and even less likely through pumps. For fish, in particular, the location of the pump intake and the likely high mortality rate of fish passing through the pump means that any wetlands filled using pumps are likely to have a grossly depauperate fish fauna.

At Webster's Lagoon (Case study 1), inflows for managed inundation (i.e. independent of flooding) will occur through carp screens (Table 5). As discussed above, it is not yet clear the effect that this method of filling will have on the initial fish (or other) fauna, nor is there a clear understanding of the level of carp screen maintenance required. It is, however, expected that the smaller native species (Australian smelt, gudgeons etc) will enter the system and prosper in the productivity boom associated with the early stages of a wetting cycle.

For Lake Wallawalla (Case study 2), inundation will not be 'managed' because the volume of water required and the ability to deliver it are currently beyond the scope of wetland management. Instead, a medium to large flood (> 48,400 ML.d^{-1} at Lock 8; SKM 2003) is required to move water into Lake Wallawalla. Initial filling will be through culverts beneath the Mail Route Road, followed by flows over the road embankment if flooding is sufficiently large (> 59,300 ML.$^{d-1}$ at lock 8; SKM 2003). Neither means of inundation is expected to exclude large or small fish from the system, thus it is expected that a broad range of fish species (including exotics) will spawn and recruit in response to wetland inundation.

This is also likely to be the case for Potterwalkagee Creek (Case study 3). Here, the Creek and its resident fish population will be backfilled, thus no size classes or species will be actively excluded from taking advantage of the expected productivity pulse resulting from floodplain inundation.

The interaction of management issues regarding a decision as to *when* inundation should occur at each case study site is complex; often site and circumstance specific, and therefore still only poorly understood. Although Lake Wallawalla is wholly at the mercy of flooding processes out of local control, both Webster's Lagoon and Potterwalkagee Creek will require management decisions to instigate filling. As for drying (see above), decisions to inundate should consider the natural wetting/drying regime and the temporal variability around this, landscape effects, Carp size classes in feeder creeks, attainment of other non-fish related ecological objectives, and risk mitigation. Again, for our case studies at least, these issues currently represent unanswerable

Table 5. How and when to wet a wetland: likely managed wetting options and key decision points to be considered during the drying phase at each of the case study sites.

	Case study 1: Webster's Lagoon	Case study 2: Lake Wallawalla	Case study 3: Potterwalkagee Ck
How to wet: likely managed wetting options	• Open the culvert – inflows through carp screen	• Nil: natural flooding is the only method currently available for filling Lake Wallawalla	• Restrict flow through downstream end structure and back fill Creek/floodplain
When to wet: key decision points	• Do we follow natural seasonality? • When did we wet last season – maintain temporal diversity of wetting cycle? • What is happening elsewhere in the MDB – landscape scale effects (e.g. waterbirds)? • Carp size class in Toupnein Ck vs carp screen mesh size: do we release newly spawned carp into the Lagoon? • Have other ecological objectives been met? • Have risks been mitigated (e.g. salt)	• Nil. wholly dependent on natural flooding.	• Do we follow natural seasonality? • When did we wet last season – maintain temporal diversity of wetting cycle? • What is happening elsewhere in the MDB – landscape scale effects (e.g. waterbirds)? • Have other ecological objectives been met? • Have risks been mitigated (e.g. salt)

questions. Thus, despite the exhaustive process that has informed the structural design and operation rules to date, an appropriately managed 'learning by doing' approach appears most likely to provide a sound site-specific basis for decisions regarding the timing of wetland inundation (see Scholz *et al*. 2005).

Risks for managers

Any large-scale water manipulation such as those proposed in our case studies carries with it considerable social, economic and ecological risk. Three such risks are most pertinent to native fish:

1. black water induced mass mortality of fish following wetland inundation;
2. spawning, recruitment and subsequent release of exotics (and particularly carp) into the broader floodplain system; and,
3. stranding of rare and/or threatened species during the wetland drying phase.

Blackwater events are often a natural outcome of wetland inundation. Approximately one third of the total carbon leached from leaf litter following inundation is immediately available to microbes (Baldwin 1999). In utilising this carbon source, microbes consume oxygen, often at a greater rate than can be replenished via diffusion or photosynthesis (Howitt *et al*. in prep). As a result, dissolved oxygen levels in the water column often drop below the minimum 2 $mg.L^{-1}$ level commonly acceptable to fish (Gehrke 1988). Blackwater can also result in increased water temperatures and due to greater water column light absorbance, an increased concentration of chemicals toxic to native fish (including hydrogen sulfide), and changes to water pH (often becoming more acidic in redgum forests) (Baldwin *et al*. 2001). Each of these has the potential to result in a significant fish kill which may seriously jeopardise our ability to meet the ecological objectives due to a lack of wetland-to-feeder creek connectivity (i.e. no re-seeding of fish stocks) created by wetland regulators.

Mitigation of blackwater effects on native fish in terminal wetlands is difficult and may be unachievable in many cases. By reducing leaf litter load during any single wetting event (e.g. by increased frequency of wetting and drying events), or by timing inundation such that water temperatures are low (and therefore microbial activity retarded) the impacts may be reduced, but neither can be achieved independently of other ecological objectives or natural wetting and drying cycles. The most appropriate means of risk management may therefore require management of (social) expectation or public perception of wetland inundation events.

Management of public perception would also be advantageous when considering recruitment of pest fish species. Exotics, and particularly Carp, have been shown to spawn and recruit in great abundance during previous managed floodplain inundations (e.g. Crook 2004; Stuart and Jones 2002). In such cases, the overall benefit to native fish of managed floodplain inundation is called into question, and this may threaten future inundations despite their unambiguously positive effects on a broader range of flora and fauna.

In addition to Carp, Gambusia (*Gambusia affinis*) and Redfin perch (*Perca fluviatilis*) have all been recorded in the Lindsay/Wallpolla area. Clearly, it is a priority of any managed inundation to reduce their breeding capacity and/or release of exotic recruits to the broader system during wetting and drying events. This may be achieved by simply trapping noxious fish in ‘doomed’ wetlands such as Webster’s Lagoon and Lake Wallawalla during drying events, or as described above, waiting until young-of-year recruits grow to such a size as they cannot pass through carp screens. More complex measures such as desiccation of Carp egg masses through water level fluctuation have been explored (Glenn Wilson unpubl. data), and may offer a partial solution in (at least) Potterwalkagee Creek. These and other structural and operational measures aimed at reducing the likelihood of exotic fish proliferation (discussed above) are thus pivotal to the successful management of wetlands for native fish outcomes.

In contrast, several rare and/or threatened fish species have also been recorded in and/or near the wetlands and anabranches of Lindsay and Wallpolla Islands. These include Murray hardyhead (*Craterocephalus fluviatilis*), Silver perch (*Bidyanus bidyanus*) and Murray cod (*Maccullochella peelii peelii*) (Meredith *et al*. 2002; Ho *et al*. 2004). Further, Eel-tailed catfish (*Tandanus tandanus*) appear to be rapidly disappearing from the area, despite there being considerable catches recorded from Lindsay River and Mullaroo Creek in the past (Cadwallader 1977). If any of these species were found to have spawned and recruited in one of the case study sites, this might greatly affect the decision to dry the wetland and strand young of the year fish, not least because there would be a legal requirement to do so (EPBC Act 1999). Real-time monitoring and reporting of captive fish community populations is therefore an important requirement for the success of the managed wetting and drying events at each case study site.

Conclusions

There is currently a significant lack of empirical data describing the use of wetlands by native and exotic fish in Australian river systems. This is reflected in this paper, which asks many more questions than it answers. As a result, it is expected that far greater knowledge of the link between wetlands and freshwater fish ecology will come from the operation of regulators at each of the case study sites than has gone into their design.

Current initiatives such as The Living Murray (which encompasses the three case studies described above) and the Native Fish Strategy (Murray-Darling Basin Commission 2004, 2005) offer a rare and important opportunity to redressing this gap between required and available knowledge of fish ecology in the MDB. The Living Murray Initiative, in particular, offers an unprecedented opportunity to examine fish responses to a diversity of water manipulations across the broadest possible spatial scale, and all under the banner of ‘learning by doing’, or adaptive management.

The potential knowledge gain of such a programme draws parallels with the whole-lake biomanipulation research conducted in the United States during the 1980s (see Carpenter and Kitchell 1992, Carpenter *et al*. 1987, 1992; Shapiro 1990). Such work revealed a variety of previously unforeseen ecosystem complexities that could only have been uncovered by working at such a large scale, and introduced key concepts such as 'top-down' and 'bottom-up' control of organisms that are still widely in use today. To miss an equivalent opportunity in Australia would be ignominious.

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