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Freshwater fish conservation in the face of critical water shortages in the southern Murray–Darling Basin, Australia

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Abstract. The lower reaches of the expansive Murray–Darling Basin, Australia, are a hotspot for freshwater biodiversity. The regional ecosystem, however, has been significantly altered by river regulation, including local and catchment-wide water abstraction. Freshwater fishes have suffered from the resultant altered flow regime, together with other threats including habitat degradation and alien species. Impacts reached a critical point (imminent species extinction) during a prolonged drought (1997–2010) that lead to broad-scale habitat loss and drying of refuges during 2007–2010, and urgent conservation measures were subsequently instigated for five threatened small-bodied fish species. A critical response phase included *ad hoc* interventions that were later incorporated within a broader, coordinated multi-agency program (i.e. the Drought Action Plan and Critical Fish Habitat projects). On-ground actions included local translocation, alien species control, *in situ* habitat maintenance (e.g. earthworks, environmental water delivery), fish rescues, artificial refuge establishment and captive breeding. Improved river flows signalled an initial phase of recovery in 2011–2012 that included reintroductions. The present paper aims to document the actions undertaken in the Lower Murray, and review successes and lessons from practical examples that will help guide and inform management responses to conserve fish in modified systems subjected to severe water decline.

Additional keywords: aquatic biodiversity, conservation units, *Craterocephalus*, environmental change, ESU, *Gadopsis*, *Mogurnda*, MU, *Nannoperca*.

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Introduction

Freshwater fishes and their habitat routinely suffer because of human use of limited water resources (Ricciardi and Rasmussen 1999; Jackson *et al.* 2001; Bunn and Arthington 2002). The Murray–Darling Basin (MDB), Australia, was one of the world's more naturally variable rivers systems (Puckridge *et al.* 1998), however, it is now affected by numerous weirs, levees and barrages. Heavy regulation is pronounced in the southern-most reaches of the systems, where major reductions in flow volume (especially low flows), seasonality and duration have degraded habitats (Walker and Thoms 1993). This has jeopardised the future of a long-term freshwater refuge and biodiversity hotspot (Phillips and Muller 2006; Fluin *et al.* 2007; Kingsford *et al.* 2011). For example, 35 native fishes have been recorded in the region (Wedderburn and Hammer 2003; Ye and Hammer 2009), with many obligate freshwater species being represented by one or more genetically distinct populations (Hammer 2008; Adams *et al.* 2011). However, 19 fish species have either been lost from the region or are threatened with extinction, with threats commonly implicated in declines including hydrological alteration, habitat loss and degradation, lowered water quality, alien species and fish stocking, exploitation, and the effects of past decline, including low genetic diversity and small, restricted populations (Lintermans 2007; Hammer *et al.* 2009*b*).

The impacts of water abstraction on the southern MDB were exacerbated by a prolonged and severe drought from 1997 to 2010 (Murphy and Timbal 2008; Ummenhofer *et al.* 2009), resulting in a major environmental change. Critical water shortage between 2007 and 2010 resulted in the broad-scale loss and drying of a range of aquatic habitats, including stream pools and wetlands. Most notably, the littoral habitats of two large terminal freshwater lakes (Alexandrina and Albert, total

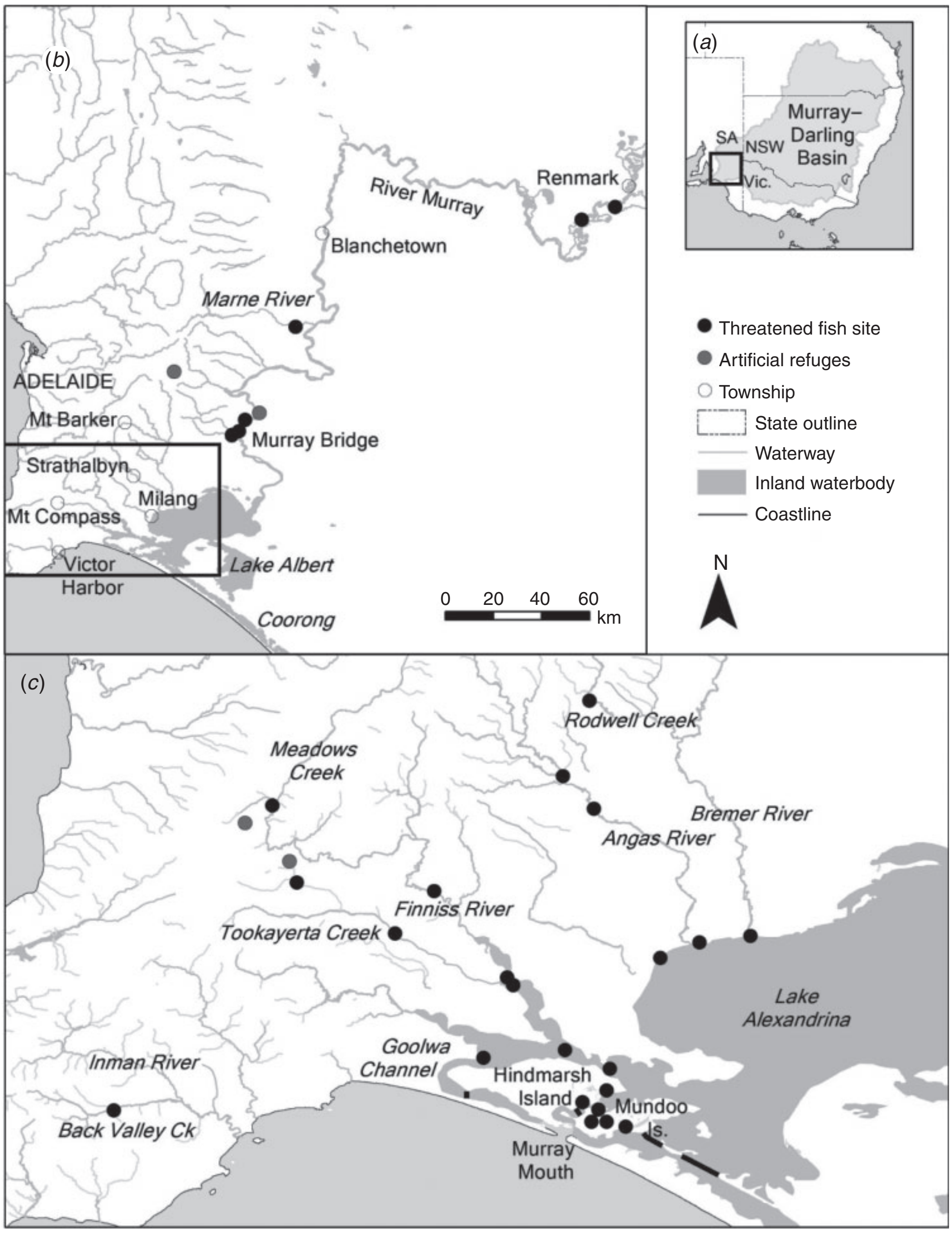

Fig. 1. Sites relevant to conservation management of freshwater fish during critical water shortages from 2007 to 2010. (*a*) the Murray–Darling Basin in south-eastern Australia, (*b*) the River Murray in South Australia and (*c*) Lake Alexandrina and stream tributaries of the Eastern Mount Lofty Ranges. Specific site details are contained in Bice *et al.* (2011).

area >750 km^2, Fig. 1) were desiccated following a rapid ~2-m water-level recession, resulting in a near complete lack of submerged aquatic vegetation and disconnection of fringing emergent vegetation from remaining water (Aldridge *et al.* 2009; Kingsford *et al.* 2011). Massive habitat loss significantly increased pressure on threatened fishes with already restricted distributions and those that had specialised habitat requirements such as dense vegetation that provides cover from predators, shelter, spawning substrate, areas for rearing juveniles, and access to food resources (Hammer *et al.* 2009*b*; Wedderburn *et al.* 2012). In response, conservation measures were instigated to prevent the loss of fish-related ecological assets. Initial urgent interventions were undertaken by individuals and later coordinated within multi-agency response and recovery phases.

The present paper details the situation under which management actions were required to conserve threatened small-bodied freshwater fishes in the Lower Murray over a 6-year period (2007–2012). Conservation plans routinely outline strategies to ameliorate threats, whereas details on subsequent actions are often lost in ‘grey literature’ or not reported; thus, we aim to document and synthesise into an available source the types of activities and programs that can be undertaken in

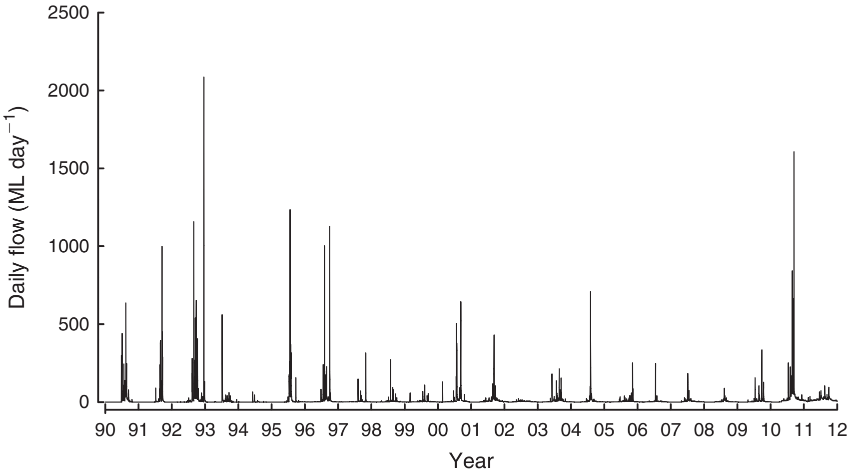

Fig. 2. Representative flow data for streams of the Eastern Mount Lofty Ranges. Daily flow (ML day^{-1}) in the Angas River (Station A4260503) from 1990 to 2012 (Department for Water, unpubl. data).

practice. We also assess the interim success of these measures considering species status and ecology, to inform future recovery planning in modified systems subjected to severe decline in water resources, including drought-prone regions.

Materials and methods

Study region

The MDB is an expansive river system, covering 1 073 000 km^2. The focus of management actions reported herein was the lower-most reaches of the system downstream of Blanchetown (i.e. Lower Murray region), including wetlands of the River Murray, channel and wetland habitats of lakes Alexandrina and Albert, and intermittent to perennial stream tributaries in the Eastern Mount Lofty Ranges (EMLR), namely the Marne, Bremer, Angas, Finniss, Tookayerta and Inman catchments (Fig. 1). The region is influenced by a local Mediterranean-type climate, with moderate austral winter–spring-dominated rainfall and streamflow in the EMLR (VanLaarhoven and van der Wielen 2009), and by broader regional climatic zones (semiarid to wet temperate) in the MDB and accompanying high seasonal and inter-annual flow variability, with natural periods of flood and drought (Walker *et al.* 1995; CSIRO 2008). Salinity values presented are based on the Practical Salinity Scale of 1978 (PSS 78).

Critical water shortage

Water abstraction and drought in the EMLR resulted in successive low annual flow volumes and short flow duration from 2001 to 2010 (Fig. 2). Limited catchment flows, and the cumulative effects on local groundwater–surface-water interactions (i.e. reduced spring discharge) had a widespread impact on summer/autumn water availability (VanLaarhoven and van der Wielen 2009), especially in 2008 when extensive pool drying was observed, including many areas previously thought to be critical summer fish refuges. Elevated salinity (>3), low dissolved oxygen concentrations ($<2\ mg\ L^{-1}$), and high water temperatures (>28°C) were also noted at sites that retained water (Hammer 2009; Bice *et al.* 2011).

Water abstraction and extended drought triggered concomitant extreme water shortages for habitats directly influenced by regulated water levels in the lower River Murray and Lake Alexandrina (Bice and Zampatti 2011; Kingsford *et al.* 2011). A rapid decrease in water levels eliminated virtually all habitat for small fishes requiring off-channel environments and specialised micro-habitat requirements (e.g. previous beds of aquatic vegetation and edge habitat became deserts of sand) within a period of 3–6 months from early 2007 (Figs 3, 4). Small amounts of estuarine vegetation became established in channels. Prolonged lowering of water levels and chronic environmental stress then continued from 2008 to 2010 (Aldridge *et al.* 2009; Wedderburn *et al.* 2012), before easing in late 2010–2011 (Figs 2, 3). Three clear phases of conservation management for freshwater fishes were associated with the initial decline (urgent response), prolonged stress (coordinated response) and return to more favourable conditions (initial recovery).

Urgent response

Many fish species in the MDB were threatened with extinction before the critical water shortages in 2007 (Lintermans 2007). There was no formal conservation program for freshwater fishes in South Australia, because small-bodied species fell outside of fisheries management (no commercial value) and threatened species programs were largely terrestrial-based (Hammer *et al.* 2009*b*). Severe drought conditions in 2007 put extreme added pressure on fish populations; however, there was limited capacity and resources for managers to respond.

Several major actions were undertaken in 2007, during the period of greatest environmental change. The load of conservation action fell to private individuals and singular managers with appropriate expertise. Moreover, actions encountered inertia through complacency and a general lack of awareness and accountability. Available resources were limited to discretionary funds and makeshift facilities, with significant in-kind contributions.

Coordinated response

In 2008, a consortium of South Australian Government agencies and non-government organisations collaborated on developing a

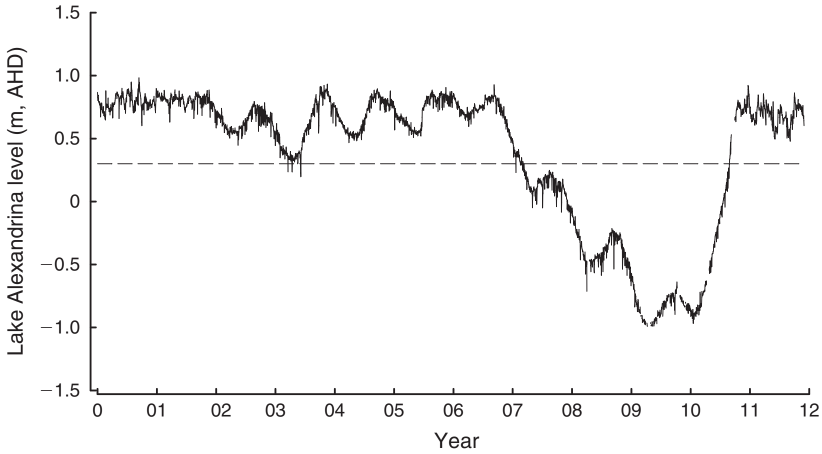

Fig. 3. Mean daily water level (Australian height datum, AHD) in Lake Alexandrina at Milang Jetty (Station A4260524) from 2000 to 2012 (Department for Water, unpubl. data). The water level where major habitat loss occurred (~0.3 m AHD) is represented by the dashed horizontal line.

Fig. 4. Pictorial examples of rapid and extreme habitat loss witnessed after 2007 on the Lower Murray. (*a*) Jury Swamp, the last known habitat for southern purple-spotted gudgeon in the southern Murray–Darling Basin, in January 2009 (left image) and March 2008 (right image). (*b*) Goolwa Channel, Lake Alexandrina, habitat for a distinct evolutionarily significant unit of Yarra pygmy perch, in April 2007 (left image) and February 2009 (right image).

multi-stakeholder response to fish declines. Funding was sought and granted from a variety of state and federal government sources. The Drought Action Plan for South Australian Murray–Darling Basin Threatened Freshwater Fish Populations (DAP), provided a coordinated framework for continuing and enhancing initial responses, identifying and addressing ongoing issues and logistics including securing and delivering environmental water, and instigating medium-term approaches to conservation management. There was a complex number of fish populations, sites, actions, funding bodies and stakeholders requiring considerable co-ordination.

The DAP was literal in the production of an internal technical report coordinated by the then South Australian Department of Environment and Heritage (DEH) (A. Hall, J. Higham, M. Hammer, C. Bice, and B. Zampatti, unpubl. data) and figurative as a project title for collective conservation action. Overall, it informed decision-making, pooled resources, and united the efforts of stakeholders and broader programs such as The Living Murray program (MDBC 2002), Native Fish Strategy (MDBC 2004) and Commonwealth Environmental Water Holder (DFW 2010). The key elements of the DAP *document* included (1) identifying ecological assets, their distribution and status, (2) background to species and sites, (3) establishing a monitoring plan, (4) determining critical environmental and population thresholds for intervention, (5) determining feasible management actions and (6) prioritising sites and actions within available resources. The DAP *project activity* was underpinned by monitoring (see below) to refine focus and direct funding to sites and populations in greatest need.

Initial recovery phase

Rainfall in the EMLR was slightly above average in 2010, leading to improved streamflow (at least temporarily; Fig. 2) and considerable rainfall and streamflow occurred across the MDB in 2010 and 2011, including a return to long-term regulated water levels in Lake Alexandrina (Fig. 3). Subsequently, the DAP converted from an emergency-response intervention program towards a recovery program that aimed to re-establish fish populations in the wild, and included measures such as captive breeding, habitat restoration and reintroduction. The regional focus was narrowed to the Coorong and Lakes Alexandrina and Albert Ramsar Wetland to be known as the Critical Fish Habitat Project (CFHP). The CFHP retained and expanded stakeholders involved in coordinated response. Activity for some other populations in the original broader region was continued (Hammer *et al.* 2012; Ellis *et al.* 2013).

Species targeted for management

The focus for the three phases of conservation management was on five threatened small-bodied obligate freshwater fishes, which were those with the least chance of recolonising from broader areas following local extirpation. Detailed knowledge of the species status and distribution was available in Hammer *et al.* (2009*b*). Different conservation units were assigned from genetic investigations (Hammer 2008; Adams *et al.* 2011), namely major lineages as evolutionarily significant units (ESUs) or different subpopulations (genetic and environmental divergence) as management units (MUs) (*sensu* Moritz 1994; Moritz *et al.* 1995).

The status of populations before critical water shortages, genetic structure and ecology of the five species varied. The southern purple-spotted gudgeon, *Mogurnda adspersa* (Eleotridae), is a benthic and sedentary wetland species (total length of <120 mm), with preference for dense physical and biological cover. Having once been widespread in the southern MDB, by 2007, it remained as a single small wetland representative of a discrete MU (Hammer 2008). The Lake Alexandrina population of Yarra pygmy perch, *Nannoperca obscura* (Percichthyidae), represents the western-most limit of the species distribution and a divergent genetic lineage (ESU) (Hammer *et al.* 2010). It is sedentary (total length <80 mm), with high habitat specificity for sheltered river and lentic areas with dense submerged and emergent aquatic vegetation, and, before critical water shortages, it was reasonably widespread and abundant within its narrow area of occupancy in western Lake Alexandrina (Wedderburn *et al.* 2012). The southern pygmy perch, *Nannoperca australis* (Percichthyidae), is a sedentary species that displays high genetic structure partitioned within discrete environments of the Lower Murray, including four MUs in restricted areas of stream tributaries (Angas, Finniss, Tookayerta and Inman catchments) and a more widespread MU in Lake Alexandrina (Hammer 2008). Habitat for the species (total length of <100 mm) varies accordingly from stream to lentic environments, and is, typically, dense vegetation or structure in smaller pools or shallows. The river blackfish, *Gadopsis marmoratus* (Percichthyidae), grows slightly larger (total length of <350 mm in the MDB), and is a nocturnal predatory fish with apparent requirements for cool well oxygenated water of low salinity (Lintermans 2007; Hammer 2009). Having, historically, been common in tributary streams of the Lower Murray, by 2007, it remained in restricted areas of four stream catchments, each being a separate MU (Marne, Bremer, Angas and Tookayerta). The Murray hardyhead, *Craterocephalus fluviatilis* (Atherinidae), is a short-lived (largely annual), more mobile, schooling species (total length of <70 mm) associated with shallow wetland habitats with aquatic vegetation, and exhibits a higher salinity tolerance than do most native freshwater fishes of the MDB (Wedderburn *et al.* 2007). It became highly fragmented and restricted following the advent of river regulation, occurring patchily in restricted areas in the Lower Murray as a separate MU (Adams *et al.* 2011). A second MU for Murray hardyhead in the Riverland region of South Australia (Fig. 1) was also included in the DAP; however, only coarse details are included here (see Ellis *et al.* 2013).

A summary of information on the five threatened fishes targeted and their conservation units is presented in Table 1, and the levels of threat facing the various conservation units ($n = 13$) before onset of critical water shortages in 2007, are indicated in Table 2.

Monitoring

Monitoring programs consisting of annual or half-yearly surveys were already established before 2007 at many sites considered in the DAP, namely numerous stream and terminal-wetland sites in the EMLR (Hammer 2009), wetland and channel habitat on Hindmarsh Island, Lake Alexandrina (Bice *et al.* 2008) and the Lower Murray wetland habitat of southern purple-spotted gudgeon (Hammer *et al.* 2012). Other concurrent

Table 1. Threatened species and conservation units targeted for management action following critical water shortages in the lower River Murray region

Conservation status: CR = Critically Endangered, E = Endangered, VU = vulnerable, P = protected; *National* under the *EPBC Act 1999*, *State* (South Australia) from Hammer *et al.* (2009*b*) and Protected under the *Fisheries Management Act 2007*. Conservation units: ESU = evolutionarily significant unit, MU = management unit; assigned on genetic and environmental divergence (Hammer 2008; Hammer *et al.* 2010; Adams *et al.* 2011) *sensu* Moritz (1994) and Moritz *et al.* (1995). MDB = Murray–Darling Basin

Family	Species	Code	National	State	Conservation units
Eleotridae	Southern purple-spotted gudgeon, *Mogurnda adspersa*	SPSG		CR, P	Only known southern MDB population, genetically distinct (MU)
Percichthyidae	Yarra pygmy perch, *Nannoperca obscura*	YPP	VU	CR, P	MDB population only in Lake Alexandrina, a distinct major lineage (ESU)
	Southern pygmy perch, *Nannoperca australis*	SPP		E, P	MDB fish are genetically distinct and diverse; five local subpopulations (MUs)
	River blackfish, *Gadopsis marmoratus*	RBF		E, P	Four relictual lower Murray subpopulations; genetic and environment divergance (MUs)
Atherinidae	Murray hardyhead, *Craterocephalus fluviatilis*	MHH	VU	CR	MDB endemic, two SA subpopulations (MUs)

monitoring in lakes Alexandrina and Albert was aligned to complement and input information into the DAP (Wedderburn *et al.* 2012).

The DAP established an intensive monitoring program to assess fish and habitat condition and thus inform triggers for action. Twenty-eight sites were subject to seasonal monitoring during 2008–2011. Water depth (against established reference height), available habitat cover and water quality were measured quarterly, and during spring and autumn fish monitoring was conducted using a variety of techniques (i.e. electrofishing, fyke nets, bait traps, seine nets). The focus of monitoring shifted in 2011–2012 to suit the assessment of potential reintroduction sites in and around Lake Alexandrina. For full site details, methodology and raw data across projects see Bice *et al.* (2009, 2010, 2011, 2012).

Results

General conservation

The Lower Murray region experienced devastating habitat loss as a result of critical water shortages during 2007–2010. The net impact to threatened fish populations viewed immediately after this period (i.e. 2011) varied from minimal for two conservation units (e.g. more secure spring-fed sites in the Tookayerta Creek catchment) through to wild extirpation of species from some sites and the region (Table 2). The species most affected were those represented by single conservation units, namely southern purple-spotted gudgeon, extirpated from the southern MDB with the drying of its single isolated wetland (Bice *et al.* 2011; Hammer *et al.* 2012), and Yarra pygmy perch, which was also extirpated from its only known area of occupancy (35 km^2) in the MDB (Wedderburn *et al.* 2012). All three remaining species had at least one conservation unit that was extirpated or would have met this fate but for conservation action (Table 2).

In total, 52 conservation actions occurred both *in situ* and *ex situ* (Table 2). Murray hardyhead populations were subject to the most actions ($n = 24$) because of prioritisation based on its national conservation listing (*Environment Protection and Biodiversity Conservation Act 1999*) and continued presence in the wild over several years of project activity. Wild options were limited for southern purple-spotted gudgeon and Yarra pygmy perch because of rapid and complete habitat loss at the start of the project. Prioritisation within the DAP limited significant on-ground actions for southern pygmy perch and river blackfish to one site each (Table 2). The types of intervention undertaken, and the specific application and outcomes, are discussed below.

Translocation

Translocations are defined here as the movement of fish between wild habitats within the natural range of a conservation unit. Three different translocations were attempted. The first involved local transfer of 57 southern pygmy perch individuals on the Finniss River (waterfalls site) from a rapidly drying pool (<0.2-m depth) with ostensibly no dissolved oxygen, to the only remaining pool (~30-m upstream). Subsequent monitoring indicated that this attempt failed because the species appears to have been lost from the site (Bice *et al.* 2011). The second translocation involved Murray hardyhead from two sites in the Riverland MU to a managed wetland. Initial survival and recruitment was noted; however, the success of this action is unknown because of flooding which inundated the site in 2010–2011 (Ellis *et al.* 2013). Third, following successful maintenance of a refuge habitat and subsequent temporary population expansion (see *In situ* habitat maintenance below), a proactive rescue and translocation was undertaken for river blackfish at Rodwell Creek. An instream farm dam above an artificial barrier 5-km upstream from the refuge pool was chosen with 66 fish translocated in January 2012. The donor sites for these fish subsequently dried whereas the translocation site retained water.

Alien species removal

Pre-existing threats at sites in some cases became more apparent as environmental conditions changed. Habitat contraction to small and often structurally simple refuges in EMLR streams exposed native species to alien predatory species including redfin perch, *Perca fluviatilis*, and brown trout, *Salmo trutta* (e.g. Hammer 2009), and shallow warm waters in concentrated wetlands favoured proliferation of the aggressive eastern Gambusia, *Gambusia holbrooki* (e.g. Wedderburn *et al.* 2012).

Table 2. Summary of population status for each of the five species of Lower Murray fishes before and after critical water shortages, including conservation actions undertaken as part of the Drought Action Plan

Refer to Table 1 for species codes. Status in 2011: A = population shows strong ongoing recruitment and survivorship, or recovery of such, B = persisting with low recruitment or survivorship, C = persisting in the wild (just), no recovery, D = persisting in the wild only as a result of intervention, E = extinction in the wild, captive stocks only, F = population extinct. Information from Hammer *et al.* (2009*b*) and Bice *et al.* (2011)

Species	Conservation unit	Location	Pre-2007 distribution	Impacts 2007–2010	Status 2011	Translocation	Alien species control	*In situ* habitat works	Environmental watering	Rescue and/or captive breeding	Artificial refuges	Reintroduction (>2011)
SPSG	(1) Southern MDB	Jury Swamp	Single small wetland (~0.05 km^2)	All habitat dried by mid-2007	E			X	X	X	X	X
YPP	(1) L. Alexandrina	Hindmarsh Island	Widespread in channels (~20 km^2)	All habitat dried by February 2008	E					X	X	X
		Goolwa Channel	Widespread patchy (~10 km section)	All habitat dried by June 2007	E					X	X	X
		Black Swamp	Localised in wetland (~4 km^2)	All habitat dried by February 2008	F							X
SPP	(1) Angas River	Middle Creek junction	Two small pools (200 m stream)	Pools became concentrated (especially 2009)	B		X			X	X	
	(2) L. Alexandrina	Hindmarsh Island	Widespread channels (~20 km^2)	All habitat dried by 2008	E					X		X
		Black Swamp	Localised in wetland (~2 km^2)	All habitat dried 2008, acid-sulfate soils	C							
		Turvey's Drain	In 500-m artificial drain	Became disconnected, persisted by levees and water pumping; high salinity, decline in vegetation	D		X	X	X	X		X
	(3) Finniss River	Meadows Creek	200-m spring-fed stream	Base flow ceased annually, 2008 concentrated to single pool	B		X					
		Mid-Finniss	200-m stream (small pools)	Small pools, predatory alien species in refuges, major population decline	C							
		Waterfalls	200-m spring-fed stream	Baseflow stopped 2009	F	X						
	(4) Tookayerta Ck	Tookayerta	Well distributed (~20 km^2)	One swamp habitat dried. Catchment baseflow slowed in summer 2008	A							
	(5) Inman River	Back Valley Creek	4-km intermittent stream	Major habitat contraction, very low dissolved oxygen during summer/autumn	B							

(*Continued*)

Table 2. (Continued)

Species	Conservation unit	Location	Pre-2007 distribution	Impacts 2007–2010	Status 2011	Translocation	Alien species control	*In situ* habitat works	Environmental watering	Rescue and/or captive breeding	Artificial refuges	Reintroduction (>2011)
RBF	(1) Bremer River	Rodwell Creek	Two pools (500-m stream)	One pool was lost and other close to dry (0.5 m) March 2008; low dissolved oxygen, moderate salinity	D	X		X	X		X	
	(2) Marne River	Black Hill	1-km spring fed stream	High salinity, thick anoxic white cloud at bottom of pools, no recent breeding events (>5 years)	C							
	(3) Angas River	Angas Gauge	2-km spring fed stream	Groundwater flow ceased during summer, high salinity peaks, some fish in poor condition	B							
	(4) Tookayerta Creek	Tookayerta	Well distributed ($\sim$20 km^2)	Minimal change, baseflow slowed in summer	A							
MHH	(1) Lower Lakes	Hindmarsh Island	Widespread channels ($\sim$20 km^2)	Most habitat dried by February 2008 (some shallow habitat)	D		X	X	X	X	X	X
		Dunns Lagoon	Throughout wetland ($\sim$2 km^2)	All habitat dried by summer 2009	C							
		Milang area	Patchy lake edge ($\sim$20 km^2)	Extensive habitat drying, small wetland and drain pockets	C		X	X	X			
		Lower Murray	Patchy three wetlands ($\sim$4 km^2)	Two wetlands dried, remaining (Rocky Gully) became fragmented and anoxic	D			X	X	X	X	X
	(2) Riverland	Disher Creek	Widespread in Basin ($\sim$1 km^2)	Main basin extremely saline, small pocket of habitat near drain infall	C	X	X		X	X		X
		Berri Basin	Feeder creek to Basin ($\sim$0.1 km^2)	Became very shallow and fresh	C	X	X		X	X		X

Opportunistic removal of alien species was undertaken at seven sites, with the aim of suppression rather than elimination, at least for short periods that may have assisted spawning and recruitment of native species (Table 2). This was undertaken during previous long-term monitoring, as part of DAP monitoring, and as supplementary DAP actions at Boggy Creek and Turvey's Drain to reduce the abundance of eastern Gambusia in winter 2010. Typically, this involved low numbers of fish, but included the removal of >60 000 eastern Gambusia at Dishers Creek over six monitoring events in 2008–2011 (Bice *et al.* 2011).

In situ *habitat maintenance*

Specific on-ground works to preserve fish habitats *in situ* ranged from small scale (e.g. 30-m-long pool) and simple, to medium scale (e.g. 1-km^2 wetland) with complex infrastructure and logistics. Actions included three broad categories, namely, habitat modification, delivery of water to sites and water quality enhancement.

Two small-scale habitat modifications were trialled. Cages filled with local limestone were placed into the last small remaining habitat of southern purple-spotted gudgeon. This provided the only physical structure for a period before the wetland dried completely. In response to a noted recruitment failure for river blackfish at Black Hill Springs on the Marne River, spawning tubes consisting of 1-m sections of 90-mm-diameter and 50-mm-diameter rigid plastic pipe were attached to star pickets and placed near the benthos in winter 2009. This species is known to spawn in hollow logs (Lintermans 2007) and it was hypothesised that limited spawning-site availability may have led to diminished recruitment. In spring 2009, eggs were found attached to the inner surface of a spawning tube; however, this did not translate into any noticeable recruitment by autumn 2012.

Larger-scale habitat modifications involving temporary earthworks to preserve manageable sections of habitat proved effective. Turvey's Drain is used as an irrigation supply channel leading off the edge of Lake Alexandrina, and the through-flow effect of pumping has paradoxically maintained suitable refuge habitat for southern pygmy perch in a highly modified landscape. Site management to maintain pumping for irrigation, and hence fish habitat, involved construction of a ~2-m-high levee to preserve the drain at the long-term lake height, and then pumping over the structure from the receding lake, which necessitated the excavation of a ~1-km-long channel to reach the water's edge in 2008. Earthen levees ~20 m in width were constructed as specific DAP actions at Boggy Creek and the outlet channel of Rocky Gully wetland. All three levees were removed because Lower Murray water levels rose from late 2010.

The delivery of environmental water allocations (DFW 2010) maintained core refuge habitat at the sites with earthworks, and threatened fish persisted through the critical period at each site (Bice *et al.* 2011). Specific details of environmental water delivery included the following: (1) Turvey's Drain; 30 ML during 2008–2010 from Lake Alexandrina; further and projected increased salinity of source water in Lake Alexandrina prompted arrangements for connection to an irrigation supply line to deliver environmental water of lower salinity (<1); (2) Boggy Creek; the site dried to cracks in the mud in late 2009, with 11.5 ML delivered during 2009–2010, 3 km of piping was required to reach water suitable for pumping; and (3) Rocky Gully; major algal blooms, hypoxic conditions and high salinities (>35) prompted delivery of 19 ML from 2008 to 2010, via piping from the nearby River Murray channel.

Given the almost complete lack of wetland habitat along the lower River Murray as a result of drying, a restored wetland was targeted as a drought refuge and reintroduction site for southern purple-spotted gudgeon. Piawalla Wetland near Murray Bridge occurs within the natural floodplain of the River Murray and is separated by levees that normally aim to keep wetlands dry for agriculture; at low river levels, the levees facilitated retention of environmental water in the wetland (38 ML delivered).

Rodwell Creek provides an example of watering aimed to maintain a stream refuge pool (~30 × 3 m). Triggers (see Monitoring methods) were based on critical thresholds of depth (i.e. >1 m) and dissolved oxygen (>mg L^{-1}), and sought to also reduce salinity and temperature. Water delivery required installation of large water tanks (total volume of 30 KL), which were filled by commercial water-tanker delivery (water chemically analysed for suitability), and gravity-fed to the pool. An outlet was fitted with a large spray bar to diffuse flow velocity and provide aeration. Total volume delivered was 0.6 ML in 39 events between 2008 and 2011 (Fig. 5). Intensive direct monitoring of pool conditions informed the need for and effectiveness of watering, with 122 site visits occurring across 2008–2012 (monthly to weekly, depending on the pool condition).

Despite meeting water-level triggers with environmental watering, dissolved oxygen levels remained critically low at Rodwell Creek in 2009. High biological oxygen demand followed a short period of stream flow that flushed significant organic carbon into the pool. To mitigate this threat, a large pond aerator (6600 L h^{-1}) was installed at the nearest electricity source and connected to 250 m of 12-mm flexible plastic pipe and trenched to the pool, with delivery by three evenly spaced 10-cm air stones. This successfully maintained the concentration of dissolved oxygen above critical thresholds (Fig. 5). The strategy to protect a core population through critical water shortage allowed a natural population response, with the return of favourable conditions in 2011; an increase in estimated population size from 10s to 100s of individuals and a range expansion across >10 additional pools was noted.

Fish rescue and captive breeding

Removing fish from the wild was treated as a last resort option when *in situ* species conservation was not possible because conditions could not be maintained above critical thresholds. Initially, rescued fish were planned to be housed in captivity only temporarily to overcome short-term critical risk. However, the sheer scale of the critical water shortage (i.e. all populations of some species were affected), levels of impact to habitat (i.e. often desiccation caused loss of key habitat elements even on rewetting) and the length of time habitats remained affected relative to the lifespan of the target species (i.e. >3 years) quickly shifted the focus from short-term catch, hold, and then release, to longer-term captive breeding and reintroduction. Establishment of at least one *ex situ* population was attempted

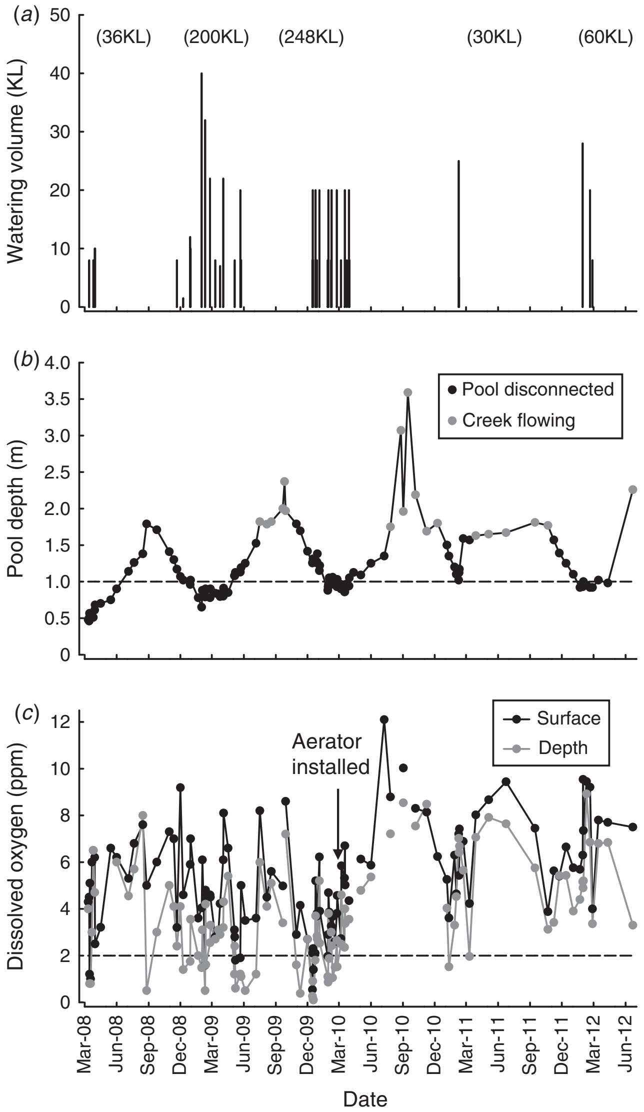

Fig. 5. Rodwell Creek (*a*) environmental watering (KL), (*b*) pool depth (m) and (*c*) dissolved oxygen (ppm) reflecting habitat maintenance of the only catchment refuge for river blackfish during 2008–2012. Critical thresholds used for management action are shown as dashed horizontal lines.

for each of the five species (Table 2), and their individual suitability for captive breeding is discussed.

The southern purple-spotted gudgeon has a long history of cultivation in captivity, with traits well suited to survival and spawning in aquaria (e.g. Gale 1914). A rescue of 55 fish was undertaken in 2007, immediately before and during the drying of its single known remaining wetland. Captive maintenance and breeding was hindered by an outbreak of disease triggered by poor environmental conditions in the wild, confirmed as epizootic ulcerative syndrome, and a 2 : 1 ratio of male to female broodstock that reflected an observed bias in the wild. Fish were initially transferred to makeshift holding facilities, before two small dedicated temperature controlled hatcheries were developed. Two other support hatcheries were developed in schools that served the complimentary roles of increasing environmental awareness and involvement, and practical application in reintroduction programs (Hammer *et al.* 2012).

In 2007, low numbers of Yarra pygmy perch were located within small remnant patches of emergent vegetation in larger channel environments of Lake Alexandrina, with 200 fish rescued from three discrete locations representing a fraction of the standing population a short time earlier (Hammer *et al.* 2010). There was little information on captive husbandry. Moderate success in rearing fish was achieved with outside aquaculture tanks that simulated wild habitat, including a display at a wildlife park. Several hundred juveniles were produced using this method up to 2010. Remaining broodstock then founded a specific genetic-based breeding program at Flinders University.

Little was known of captive husbandry of southern pygmy perch, but pond spawning had previously been achieved (Llewellyn 1974). Three populations were rescued; one from the Angas River MU (2008), and two sites from the Lake Alexandrina MU, namely Mundoo Drain on Hindmarsh Island (2008) and Turvey's Drain (2010). Captive breeding in ponds was small scale because of limited capacity, producing $<$100 juveniles by 2010. Thereafter, Lake Alexandrina fish were also included in the genetic-based breeding program.

River blackfish is known as an aggressive species difficult to maintain in captivity, with some notes available on successful spawning (Jackson 1978). A single small rescue was undertaken for the sole remaining site of the Bremer River MU at Rodwell Creek in autumn 2008. Nine fish were transferred to large aquaculture holding tanks in a temperature-controlled environment, and later incorporated into a captive-breeding trial (Westergaard and Ye 2010). Spawning was achieved in the first year but problems were encountered rearing the eggs and fry. Nevertheless, eight captive-reared juveniles were produced. Subsequent attempts to spawn fish were unsuccessful.

Murray hardyhead has previously been bred and successfully reared in captivity (Hammer and Wedderburn 2008). Rescues of fish were made from both the Lower Lakes and Riverland MUs and incorporated within a broader, controlled-environment breeding program that successfully produced moderate numbers of juveniles (10s to 100s per site) in aquaria (see Ellis *et al.* 2013).

Artificial refuges

Artificial refuges such as farm dams and recreated wetlands were targeted for releases of captive-bred fish before any suitable wild sites were available. They had the added advantages of potentially increasing the availability of fish for release to the wild through economies of scale, and enabling fish to be reared in more natural environmental conditions. A rigorous assessment process considered the suitability of refuge sites against species-specific criteria (e.g. habitat condition, water quality, water security, food availability, presence of other fishes, site history, management tenure) and any potential negative ecological impacts of introduced fish to receiving environments. In total, 74 sites were inspected with around a third of these being considered suitable for release (Hammer *et al.* 2009*a*).

Table 3. Summary of sites and numbers of threatened fish released in the Lake Alexandrina region in spring 2011 and autumn 2012
Refer to Table 1 for species codes. Source of reintroductions: A = artificial refuges, H = fish hatchery, F = conservation-genetics project, W = rescued wild fish. For fish-source and release-site details, see Bice *et al.* (2012)

Species	Reintroduction site	Number	Source
Spring 2011			
SPSG	Lower Finniss River	200	H
YPP	Black Swamp	400	A
	Goolwa Channel	800	A
SPP	Hindmarsh Island (Hunters Creek)	770	F
	Turvey's Drain	300	W, F
Autumn 2012			
SPSG	Lower Finniss River	400	H
YPP	Hindmarsh Island (Streamer Drain)	2200	F
	Hindmarsh Island (Shadows Lagoon)	1500	A, F
SPP	Mundoo Island (Channel 1)	280	F
MHH	Mundoo Island (Channel 2)	3500	A

Releases to 2012 included six artificial refuges, with the most successful results witnessed for Yarra pygmy perch. This species was released into three well vegetated farm dams, with survival and recruitment recorded in each; a population at one site in particular, near Mount Compass, thrived, with >2000 juvenile and adult fish recorded two years after the release of 90 first-generation offspring (Bice *et al.* 2011). Murray hardyhead was also successfully established at a saline farm dam in upper Reedy Creek. From an initial release of 241 fish over 2 years (a mix of wild fish and first-generation offspring), the population has exhibited annual recruitment and is now highly abundant (Bice *et al.* 2012).

The artificial-refuge option was not successful for all species, because no suitable site was found for river blackfish, and another site proved difficult to maintain. Piawalla Wetland showed initial positive results following release of 271 first-generation southern purple-spotted gudgeon (2010–2011), with high survival and modest recruitment (Bice *et al.* 2011). However, water quality deteriorated and could not be maintained in early 2012, with the population presumed lost (33 fish were salvaged).

Reintroductions

Sites targeted for reintroduction included those previously inhabited in 2006 that were refilled and once again suitable, and other suitable sites within the natural range of a species, which, theoretically, had high levels of water security under future scenarios (Bice *et al.* 2012; Hammer *et al.* 2012). Reintroduction planning included rigorous literature review and field-based assessment and had the following key elements: (1) identification of potential release sites via the collation of historic locations and environmental conditions, (2) field investigations to assess release-site suitability (as per artificial refuge criteria), (3) assessing methods to rear, train, transport and soft release fish (e.g. *in situ* cages) to obtain optimal wild survival (Brown and Day 2002) and (4) development of monitoring techniques including calcein marking (Crook *et al.* 2007) to adaptively assess the outcome of releases. Further refinement sought to employ genetic techniques to assess paternity and kin-relatedness for incorporation within the design of breeding programs (Carvalho *et al.* 2011, 2012*a*, 2012*b*).

Reintroductions began in the Lake Alexandrina region during spring 2011 and autumn 2012. Over 10 000 fish from four species were released at nine sites from a mixture of sources (Table 3). Following releases in spring 2011, low numbers of both southern purple-spotted gudgeon and southern pygmy perch were recaptured during monitoring in autumn 2012, indicating initial survival of at least 4 months (Bice *et al.* 2012).

Discussion

Over the period 2007–2010, the Lower Murray region was on the verge of ecological collapse (Kingsford *et al.* 2011; Wedderburn *et al.* 2012). Desperate and non-preferred conservation measures were required to save a suite of small-bodied threatened fish species. Initial reactive management, followed by broader strategic planning, served to secure at least one population for each of five target species. Where possible, this was in the wild, but when complete habitat elimination occurred, captive maintenance was the only option. Only a short period of opportunity was available for actions before populations were extirpated; however, in many cases where urgent interventions were undertaken, this facilitated natural response or recovery options, including later reintroductions. The different techniques, successes and lessons presented provide examples of what can be achievable across a range of habitats and scenarios and for species with different life histories, and will help guide recovery planning and urgent responses in the conservation management of freshwater fishes.

The three-stage process employed here, involving initial urgent response, coordinated multi-stakeholder planning and action, and a recovery phase, provides a successful model for dealing with critical environmental situations. A high level of pre-existing information was available as the foundation for informed decision-making. Thus, detailed inventory and knowledge of fish habitat, distribution, genetic resources, ecology and husbandry should be key preparation and objectives within conservation-management programs. Likewise, the detailed seasonal monitoring program was critical to the success of conservation efforts, in being able to identify urgent issues, restoration options and positive responses alike. However, available information, management decisions and the types of projects undertaken will likely be subject to resource limitations (e.g. prioritisation as occurred in the DAP, cost–benefit analyses). It is difficult to rank the effectiveness of the different conservation strategies employed, because each played a role under particular scenarios. We review broadly some of the strengths and issues of the different techniques and aspects of the ecology of the target species that might have influenced the relative success of the various management actions.

Translocation of fish from drying habitats to more secure locations had limited effectiveness as a result of a lack of prior conservation planning and preparedness and the rapid development and wide-reaching effects of critical water shortages. Fishes as candidates for translocation were in critically low numbers and the risk of losing populations or individuals (and representation of their genes) following translocation was of high consequence. The considerable scale of habitat loss limited the options for alternative translocation sites that matched the specific habitat requirements of threatened species, or where sites would be secure from drying. Translocation can be an effective technique to spread risk of extinction to remnant populations, but ideally is a proactive part of long-term recovery planning (Weeks *et al.* 2011).

The direct effects of the removal of alien species, with respect to minimising impacts on threatened fish populations, were difficult to quantify, but remain an interesting area for future research and assessment (Pimentel *et al.* 2005).

Artificial and heavily modified habitats ironically played a role in the persistence of some threatened fish populations (e.g. drains, stock and irrigation channels, regulated lakes, saline wetlands, levees, farm dams). Following on-ground modifications, small volumes of environmental water were delivered to restricted refuges, and successfully maintained bare-minimum habitat in wetland areas and stream pools. Actions to then protect modified habitats and physically alter more natural environments with on-ground works (e.g. small levees) can challenge some strongly held ideals and perceptions on conservation, but would appear to be an emerging reaction to conditions in highly modified riverine landscapes such as the Lower Murray region (Ellis *et al.* 2013). Longer-term water-allocation planning and water recovery should be used to avoid critical water shortages and excessive modification of the aquatic landscape (Bice and Zampatti 2011; Kingsford *et al.* 2011).

In cases of predicted or imminent catastrophe, rescues of fish into temporary *ex situ* maintenance or longer-term captive-breeding programs are likely to be a priority for risk management and future recovery planning (Minckley and Douglas 1991). Involvement by a diverse group of stakeholders in breeding and rearing Lower Murray fishes improved outputs and risk management, and highlighted that the approach can also provide opportunities for community engagement and increasing public awareness of biodiversity and conservation issues. Captive breeding should not, however, be seen as a convenient replacement for on-ground intervention, because *in situ* measures place populations in the best position for natural recovery (e.g. Rodwell Creek) and can conserve innate functional, and evolutionary links among fish, habitat and ecosystems (Frankham *et al.* 2010). Moreover, captive breeding is subject to the vagaries of husbandry (e.g. Philippart 1995; Fraser 2008), requires great dedication by hatchery operators, may require considerable research and development (e.g. river blackfish), and relies on suitability of a species for captive breeding across traits such as spawning method, larval size, diet flexibility, aggression and disease.

Artificial refuges provide ideal stepping stones between short-term captive maintenance and the often longer-term need for fish in reintroduction programs (Rakes and Shute 2008); however, options for suitable sites can be limited by the ecological specialisation of particular species. Thus, monitoring and research on fish ecology remain key components in assessing and adapting the ecological framework for artificial refuge populations and reintroductions (Goren 2009).

Many small-bodied fishes of the MDB (and globally) have experienced significant declines in their distribution and abundance, with the most threatened species typically occurring in isolated fragments of specific habitat (Lintermans 2007). Trapped in space and by virtue of their short life-spans, such species are exposed to chance demographic events (e.g. failed recruitment, skewed sex ratios) and environmental catastrophe (e.g. habitat drying, vegetation die-off, water-quality issues, impacts of invasive fishes) and are likely to have low resilience to new threats or resistance to chronic stressors (Angermeier 1995; Duncan and Lockwood 2001; Fagan *et al.* 2002). These vulnerabilities were reaffirmed during critical water shortages in the Lower Murray region, with specific drivers of population decline witnessed including complete elimination of habitat types, loss of refuges, low remaining abundances, concentration with alien species and conspecifics, outbreaks of disease, and an instance of strong male bias.

The contrasting ecology of the target species and their responses to critical water shortages allows some insight into the attributes of species prone to extinction (Angermeier 1995). Particular groups of fishes appear more susceptible to anthropogenic change; in the Lower Murray region, the family Percichthyidae is disproportionally threatened with extinction (eight of nine species, Hammer *et al.* 2009*b*). The threatened obligate freshwater members of the group ($n = 7$) share low fecundity and characters such as larger demersal larvae, high reliance on physical or biological cover and specialised flow or water-quality requirements (Lintermans 2007). Widespread catchment change appears to have affected this family of fishes. Two small species with highly specialised occupied habitat, namely southern purple-spotted gudgeon and Yarra pygmy perch, appeared locked into a specific part of the landscape and displayed limited resilience to pressing change (and were extirpated in the wild). Long-term preservation of minimum water level and habitat thresholds is needed to conserve species from this ecological group (Wedderburn *et al.* 2012). Murray hardyhead showed a greater level of resistance to critical water shortages, being more adaptable and mobile to shift to new refuges until these ultimately became isolated and either dried or were maintained. Maintaining regional connectivity (i.e. fish passage to and between off-channel habitats) and a mosaic of floodplain habitat types is necessary for the persistence of this type of species.

Governments in drought-prone regions of the world should be prepared for such events (Lintermans and Cottingham 2007). The critical situation experienced across 2007–2010, and the urgent need to act both broadly and at a site level, arose rapidly. Experience under these unique, but perhaps increasingly common, scenarios in the face of catchment and climate change (Kingsford 2011) demonstrated that without preparedness and dedicated programs, the timeframe of opportunity for management action can fall well short of accompanying processes, including justifications, permit and approval acquisition, procurement, and cycles for funding and environmental water prioritisation. Examples of other regions where there appears to be a strong need for such preparedness (i.e. drought-prone with major catchment changes) include an area of high freshwater endemism in south-western Australia (Beatty *et al.* 2010), Mediterranean stream fish assemblages (Magalhães *et al.* 2007), and interior and western portions of the United States (Fagan *et al.* 2002). Indeed, recent extreme drought in Texas (2011–2012) has led to impacts similar to that witnessed on the Lower

Murray, including extensive drying of streams and refuges, with the ongoing response involving rescues and captive maintenance of small-bodied threatened shiners (Cyprinidae) (Texas Water Resources Institute, unpubl. data, http://twri.tamu.edu/publications/drought/2011/december/extreme-conditions-impact-fish-populations/, accessed June 2013).

A large positive to emerge from the response for Lower Murray threatened fishes was the formation of cross-agency partnerships, collaborations, community involvement, positive media exposure and development of individual relationships among stakeholder representatives. The coordinated approach built capacity, interest, awareness, accountability and readiness for protecting fishes and aquatic habitats into the future.

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