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Population dynamics of Murray cod (*Maccullochella peelii*) in the South Australian reaches of the River Murray: a synthesis of data from 2002–2013

B. P. Zampatti, C. M. Bice, P. J. Wilson and Q. Ye

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EXECUTIVE SUMMARY

Murray cod (*Maccullochella peelii*) is Australia's largest freshwater fish; it is an iconic species of the Murray-Darling Basin and has a long history of human utilisation. Murray cod populations have declined as a result of barriers to movement, cold water pollution, changes to the natural flow regime, habitat loss and over-harvesting. As such the species is listed as '*vulnerable'* under the Australian *Environment Protection and Biodiversity Conservation Act 1999* and as '*critically endangered'* by the International Union for the Conservation of Nature.

Fisheries and conservation management of Murray cod require an understanding of population status and dynamics. Given the progression from extensive drought to sequential high flow years in the River Murray since the publication of the last Murray cod stock status report (2007), a review of the current status of Murray cod populations in the lower River Murray was timely. Furthermore, data are required to inform considerations regarding potential Murray cod stock enhancement in the lower River Murray. In the absence of a commercial fishery and/or dedicated fishery-independent Murray cod monitoring program, the aim of the current project was to interrogate data from fish monitoring and research projects undertaken in the lower River Murray from 2002–2013 to provide an overview of the current status of Murray cod populations. We analysed data from three long-term (8–11 year) fish monitoring projects conducted in the South Australian reaches of the lower River Murray over a period of hydrological extremes, incorporating seven years of drought and unprecedented low flow in the lower River Murray, followed by three years of over bank or elevated within-channel flow.

Murray cod relative abundance remained low and recruitment was minimal in the predominantly lentic main channel habitats of the lower River Murray during drought (2001–2010). At the same time, consistent recruitment was evident in the lotic habitats of the Chowilla system. Low numbers of juvenile fish (<500 mm total length) were collected in main channel habitats in years following increases in flow contained within the river channel and overbank. Elevated flow increases water velocities and promotes hydraulic complexity in the regulated weir pools of the lower River Murray. These hydrodynamic characteristics are permanent features of the free-flowing reaches of the mid–upper River Murray and lotic anabranches where broad size structures of Murray cod are observed, and appear fundamental to promoting the survival of early life stage Murray cod and providing habitat for juveniles and adults.

Overbank flows in 2010/11 were associated with an extensive anoxic blackwater event that caused substantial mortalities of adult Murray cod. Despite this, data from anabranch and main channel habitats indicated recruitment associated with spawning in 2010. Nevertheless, fish spawned during both within-channel and overbank increases in flow were generally not detectable until fish were 300–400 mm total length and 2–3 years of age. Thus, monitoring the population dynamics of Murray cod and relating responses to flow is a long-term proposition that needs to consider time lags in the detectability of recruitment.

In addition to long-term monitoring there remain a number of key deficiencies in our understanding of the ecology of Murray cod, including factors contributing to the survival of early life stages, reproductive potential of large/old fish, main channel micro-habitat use of juveniles and adults, and the importance of connectivity to main channel and anabranch habitats upstream of South Australia. Developing an understanding of these factors will be crucial to the conservation and restoration of Murray cod populations in the lower River Murray.

Even though the majority of Murray cod collected in main channel habitats of the lower River Murray were generally large, these fish may represent a broad range of age classes (e.g. fish ≥800 mm could range in age from 8 to 46 years). Murray cod have a potential life span of greater than 40 years; consequently, whilst relative abundances remain low, but reasonably stable, Murray cod do not appear at imminent risk of being extirpated from the lower River Murray. This should not, however, preclude the need for action to address the factors inhibiting Murray cod recruitment, particularly the conservation and restoration of perennial and seasonal lotic habitats.

INTRODUCTION

Murray cod (*Maccullochella peelii*), a member of the Perchichthyidae family, is Australia's largest freshwater fish, growing to lengths of >1.4 m and weights >40 kg, with a life span of up to 48 years (Rowland 1989; Anderson *et al*. 1992; Lintermans 2007). Murray cod is an iconic species of the Murray-Darling Basin (MDB) and has a long history of human utilisation; it forms an integral part of Aboriginal dreaming stories, once maintained a substantial commercial fishery and continues to support an important recreational fishery (Rowland 1989; Henry and Lyle 2003; Koehn and Todd 2012).

Like many species of freshwater fish in the MDB, Murray cod populations have declined as a result of anthropogenic impacts such as barriers to movement, cold water pollution, changes to the natural flow regime, habitat loss and over-harvesting (Lintermans and Phillips 2005). As such the species is listed as '*vulnerable'* under the Australian *Environment Protection and Biodiversity Conservation Act 1999* and '*critically endangered'* by the International Union for the Conservation of Nature (IUCN 2011). Population decline of Murray cod has been documented for over 100 years (Dannevig 1903) and early commercial harvesting, following European colonisation of the MDB, potentially had significant immediate impacts on Murray cod populations (Humphries and Winemiller 2009).

Until mid-2003, data on the population demographics and dynamics of Murray cod in the South Australian (SA) reaches of the River Murray were collected from a commercial fishery (Ye and Zampatti 2007). In the absence of these data post-2003, Murray cod size/age structure and abundance data have been collected via a targeted monitoring program (Ye and Zampatti 2007) or indirectly through a range of large spatio-temporal scale research and monitoring projects of fish populations in the lower River Murray (e.g. Barrett 2008; Wilson *et al.* 2012). Specific research on Murray cod biology and ecology has also been conducted in main channel and anabranch habitats at Chowilla in the floodplain geomorphic region of the lower River Murray (e.g. Zampatti *et al*. 2011; Leigh and Zampatti 2011; 2013).

Despite commercial fishery data being collected for Murray cod for over 50 years (from the early 1950s) it was not until 2000 when data were comprehensively integrated into a fishery assessment report (Ye *et al.* 2000). This was followed by a stock status report in 2007 (Ye and Zampatti 2007) incorporating additional data from the end of the commercial fishery (2000 to mid-2003) and limited fisheries independent data from targeted and non-targeted sampling conducted in the first six years (2001 to 2007) of an extensive drought and corresponding low-flow period in the MDB (van Dijk *et al.* 2013).

The *millennium* drought ended in late 2010 (Leblanc *et al.* 2012) with wide-spread flooding in the lower River Murray. Flooding would have been expected to promote Murray cod recruitment (Rowland 1989) but was also associated with an extensive hypoxic blackwater event that caused substantial mortality of large (>900 mm, total length, L_T) Murray cod (Leigh and Zampatti 2013). This event, however, was followed by two subsequent years (2011/12 and 2012/13) of bank-full or significant within-channel rises in flow in the lower River Murray which would also be considered to have been conducive to Murray cod recruitment.

Due to concern over apparent declines in Murray cod abundance in the River Murray in South Australia, fishing regulations have undergone several changes in the last two decades. Notably in 2003, the South Australian Government closed the commercial river fishery (including Murray cod) in the lower River Murray, but the recreational take of Murray cod (2 fish per person per day) was allowed, outside of an annual four month closed season (September-December). In January 2009, due to concerns over a lack of Murray cod recruitment in the lower River Murray (Ye and Zampatti 2007), a moratorium was implemented on the take of Murray cod by recreational fishers, to protect those fish that remained and ensure sufficient reproductive potential when environmental conditions (i.e. river flow) improved. This was followed in January 2011 by a limited annual catch and release fishery (1 January to 31 July) with a closed season and ban on trolling lures (1 August to 31 December). This management arrangement remains in effect. No formal monitoring of Murray cod population demographics and dynamics has been undertaken in association with changes to fisheries policy and management.

Fisheries and conservation management of Murray cod need to be underpinned by an understanding of population status and dynamics. Given the progression from extensive drought to sequential high flow years in the River Murray since the publication of the last Murray cod stock status report (Ye and Zampatti 2007), a review of the current status of Murray cod populations in the lower River Murray was timely. Furthermore, these data are also required to inform considerations regarding potential Murray cod stock enhancement (i.e. stocking of artificially propagated fish) in the lower River Murray (PIRSA 2013). The absence of a commercial fishery and/or dedicated fishery-independent Murray cod monitoring program makes such a task challenging, but some insight may be gleaned from existing fish monitoring and research projects conducted in the lower River Murray.

The aim of the current project was to interrogate data from fish ecology projects undertaken in the lower River Murray from 2002–2013 to endeavour to provide an overview of the current status of Murray cod populations in the SA reaches of the lower River Murray. Our objectives were to:

1. Review long-term fish monitoring and research projects conducted in the lower River Murray to determine the availability of long-term, fishery-independent data on Murray cod population dynamics (i.e. spatio-temporal variation in length/age-structure and abundance).
2. Where appropriate, consolidate and analyse Murray cod length/age-structure and abundance data, including association with environmental variables (e.g. flow), and provide comment on the current population status of Murray cod in the SA reaches of the lower River Murray.

MURRAY COD BIOLOGY AND ECOLOGY

Murray cod has a broad natural distribution, occurring throughout much of the low and mid-altitude reaches of the MDB and is found in a variety of aquatic habitats from small, clear rocky streams to large, turbid lowland rivers. Considerable research has explored aspects of Murray cod biology and ecology, particularly in the mid–upper reaches of the River Murray and its tributaries (e.g. Anderson *et al*. 1992; Rowland 1998b; Humphries 2005; Koehn and Harrington 2006; Baumgartner 2007; Kaminskas and Humphries 2009; Koehn 2009; Koehn *et a*l. 2009; Rourke *et al*. 2011), but investigations in the hydrodynamically distinct lower River Murray in SA have been a relatively recent endeavour (e.g. Leigh and Zampatti 2013).

Habitat

Murray cod occur across a wide range of aquatic ecosystems, from upland streams to lowland rivers, yet aspects of habitat use are similar in these disparate environments. From a macro-habitat perspective Murray cod favour the main channel of rivers, anabranches and creeks, rather than permanent wetlands and temporarily inundated floodplains (Humphries *et al.* 1999; King 2004; Koehn 2009; Leigh and Zampatti 2013). Within main channels and anabranches, both juvenile and adult Murray cod have an affinity for hydraulically diverse lotic (i.e. flowing) habitats with abundant physical habitat cover, particularly large woody debris (Boys and Thoms 2006; Jones and Stuart 2007; Koehn 2009; Koehn and Nicol 2013).

Diet

Murray cod is an apex predator and as an adult may feed on a variety of organisms, particularly fish and crustaceans, but also amphibians, reptiles, birds and mammals (Harris and Rowland 1996; Ebner 2006; Baumgartner 2007). Murray cod larvae are well-developed at time of first feeding and have a large mouth gape (Humphries *et al.* 1999) enabling them to consume larger prey items than the larvae of other native fishes (King 2005). Studies of larval Murray cod diets in the Broken River, Victoria, indicated that large benthic zooplankton (i.e. Macrotrichid Cladocerans and Cyclopoid Copepods) and aquatic insects (i.e. Chironomidae larvae, Trichoptera and Emphemeroptera) comprised the majority of the diet (King 2005; Kaminskas and Humphries 2009). The diet of juvenile Murray cod is not well understood, but potentially involves an ontogenetic transition towards the adult diet, with crustaceans and fishes likely to be important prey items.

Movement

Early studies of fish movement in the lower River Murray suggested that Murray cod were non-migratory and predominantly sedentary (Reynolds 1983). More recent studies, however, utilising radio-telemetry and tag-recapture in the mid–upper (i.e. Murray and Ovens rivers, including Lake Mulwala) and lower Murray regions (i.e. Chowilla and Lindsay-Mullaroo regions) indicate more complex movement patterns (Koehn *et al*. 2009; Saddlier *et al*. 2009; Leigh and Zampatti 2013). In each of these regions, Murray cod exhibit high levels of site fidelity and extended sedentary periods, but also undertake large-scale riverine movements of 100s km, potentially in association with increasing flows, and with evidence of return movements. Specifically within the Chowilla region of the lower River Murray, Murray cod also exhibit regular movements between favoured anabranch habitats within Chowilla and the adjacent River Murray (Leigh and Zampatti 2013), with an apparent increase in the frequency of these movements in winter-spring prior to the spawning season. In concurrence, Koehn *et al*. (2009) observed increased frequency of upstream movements within the Ovens River immediately prior to the spawning season, suggesting these migrations may occur for the purpose of locating favourable spawning sites and compensating for downstream larval drift, and may thus represent a critical life-history process.

Spawning

Murray cod is a circa-annual spawner, spawning over a well-defined period in spring to early summer in response to increasing photoperiod and water temperature (>15˚C) and irrespective of flow (Rowland 1998b; Humphries 2005; Koehn and Harrington 2006). In the lower River Murray, larvae are present annually in October/November in both main channel and anabranch habitats (Leigh and Zampatti 2011; Zampatti *et al.* 2011; Cheshire *et al.* 2012) with spawning, based on back-calculated ages of larvae, occurring in late September–mid November (Zampatti unpublished data).

Estimates of size and age at maturity vary with geographic location, but are typically 500–600 mm L_T and around 5 years of age for both sexes (Rowland 1998b). Murray cod form breeding pairs, with large adhesive eggs laid onto hard substrate, which are then guarded by the male (Rowland 1998b). Relative fecundity is approximately 5000 eggs per kg of body weight (Rowland 1985). There is some conjecture regarding decreased fecundity and ‘reproductive performance’ with age but detailed studies are lacking (Rowland 2005; Stuart and Koehn 2007).

Larvae hatch after a period of 5–13 days (Lintermans 2007) before undergoing downstream drift for periods of up to 7 days (Humphries 2005; Koehn and Harrington 2005). Despite spawning annually, recruitment is typically episodic, particularly in the highly regulated lower River Murray, where the population is characterised by a small number of dominant age classes (Ye and Zampatti 2007).

Recruitment

Length and age data indicate that recruitment in the main channel of the lower River Murray is positively associated with years of elevated flow (contained within the river channel and overbank) with little recruitment during low flow years (Ye and Zampatti 2007). Recent evidence from the Barmeh-Millewa region in the mid-Murray also suggests an association between enhanced recruitment and elevated flow (King *et al*. 2009). Whilst strong recruitment is only evident in the main channel of the lower River Murray following years of elevated flows, in contrast, regular recruitment of Murray cod is commonly observed in the Chowilla system near Lock 6 (Wilson *et al.* 2012) and the nearby Lindsay-Mullaroo system (Henderson *et al.* 2012), irrespective of broader hydrological conditions. These systems are unique within the lower River Murray in that they contain permanent lotic habitats, now absent from the main channel under regulated flows. Lotic characteristics are shared by other regions of the MDB where more consistent Murray cod recruitment is observed (e.g. the River Murray downstream of Yarrawonga, Jarod Lyon, Arthur Rylah Institute, pers. comm.) suggesting a causal link between flowing water environments and recruitment.

Threats to Murray cod and population decline

Historical accounts of early European explorers described Murray cod as one of the most abundant fishes in the rivers of the MDB; whereas now they are one of the rarest (Humphries and Winemiller 2009). Reasons for decline are multi-factorial and the key threatening processes generally cited for Murray cod in the MDB are altered flow regimes, loss of early life-stages to irrigation diversions (i.e. pumps and channels), altered water quality (including cold-water pollution from headwater dams), habitat loss, barriers to movement, interactions with alien species, and commercial and recreational harvest (Lintermans and Philips 2005). Other factors such as disease and the genetic implications of stocking should also be considered.

In the lower River Murray the primary threats to Murray cod are:

1) The direct and indirect impacts of river regulation and water extraction (i.e. inhibition of upstream and downstream movements by weirs, removal of early life-stages by pumps and diversions, and altered hydrology and hydraulics).
2) Habitat alteration, most notably the removal of large wood (snags) from the main channel and anabranches.
3) Over-harvesting.

The majority of these threats have been acting on Murray cod populations for over 100 years. Indeed, by the late 1920s commercial fishers were voicing concerns regarding the scarcity of Murray cod in the lower River Murray and cautioning the impact of weirs and river regulation on Murray cod, including the inhibition of movement (lateral and longitudinal), decreased river flow (i.e. discharge) and stationary water behind weirs (i.e. conversion of lotic to lentic habitats) (*The Register News-Pictorial* 2nd July 1929). Commercial fishing itself was also likely to be having a significant impact (Humphries and Winemiller 2009). Declines in Murray cod populations in the MDB have been stark and 20th century decline, post the major impacts of river regulation in the lower River Murray, is best demonstrated by historical commercial fisheries data (Figure 1). These data show a dramatic decline in the early 1960s, 30–40 years post completion of the 10 locks and weirs in the lower River Murray and after nearly a century of commercial fishing.

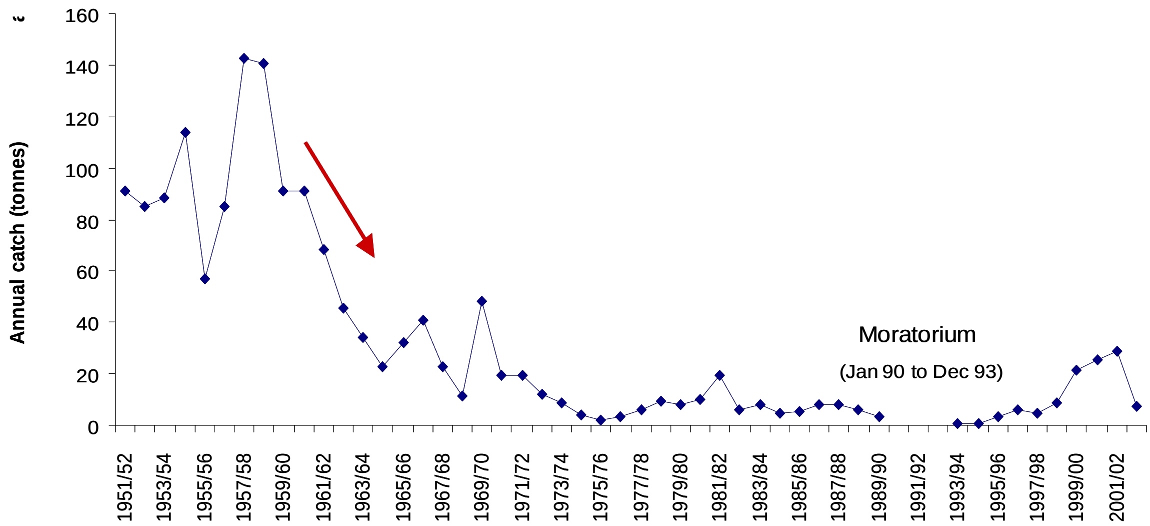

Figure 1. Murray cod commercial catch from the South Australian inland fishery 1951/52 to 2002/03.

Efforts to mitigate population decline of Murray cod in the lower River Murray have primarily targeted barriers to movement and harvesting. Fishways to facilitate the passage of juvenile and adult Murray cod are nearing completion on all locks and weirs on the main channel of the River Murray (Barrett and Mallen-Cooper 2007) and harvesting has been minimised by the closure of the SA River commercial fishery for native fish in July 2003 and a moratorium on recreational take in 2009. Habitat, hydrological and hydrodynamic rehabilitation, however, remain little explored.

STUDY REGION

This study concerns the lower River Murray, downstream of the SA/NSW border (Figure 2). In this region, a series of five tidal barrages and six low-level (~3 m) weirs regulate flow released by upstream dams and diverted by irrigation, and fragment >600 km of river into a series of contiguous weir pools. Unlike the regulated, but free flowing mid-reaches of the River Murray, the weirs in the lower River Murray transform a historically highly dynamic lotic system into a homogenous series of lentic environments under low flows (Walker 2006). Ultimately, extraction of water for irrigated agriculture and consumptive use, results in only ~36% of the natural mean annual discharge (12 300 GL) of the River Murray reaching the sea.

Data on Murray cod abundance and length were sourced from studies conducted in main channel and anabranch habitats in two distinct geomorphic regions (Walker and Thoms 1993): (i) gorge (Mannum–Lock 3) and (ii) floodplain (Lock 3–SA/NSW border) (Figure 2).

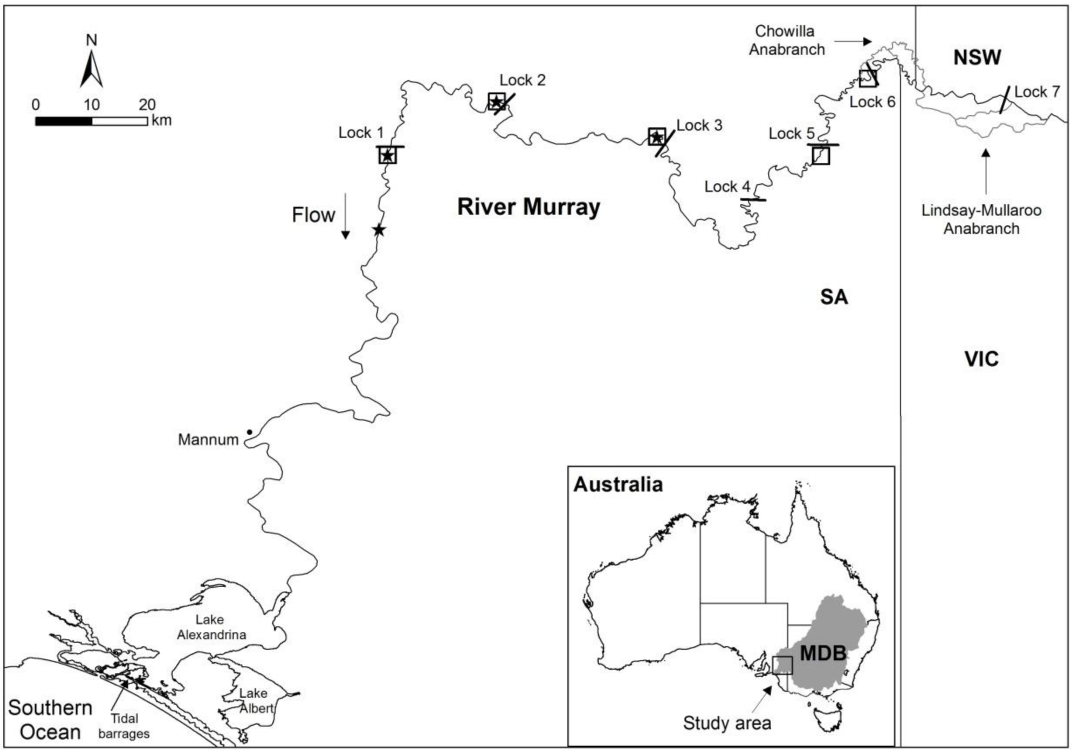

Figure 2. Map of the study region highlighting the Murray–Darling Basin, the River Murray to immediately upstream of the South Australian Border (including the location of Locks and Weirs Nos 1–7), and the Chowilla and Lindsay-Mullaroo Anabranch systems. Black stars represent Murray River Fishway Assessment Program sampling sites and open black squares represent Native Fish Monitoring Program sampling sites.

HYDROLOGY

The period 2002–2013 was characterised by hydrological extremes in the MDB. From 2001–2010, the MDB experienced its most severe drought on record (van Dijk *et al.* 2013) resulting in a prolonged period of highly regulated, low-volume (<15 000 ML.day^{-1}) in-channel flows in the lower River Murray (Figure 3). This anthropogenically exacerbated hydrological drought resulted in regulated flow to SA reaching a record low of <1000 ML.day^{-1} in winter 2007 and the Murray ceased flowing to the sea from March 2007–September 2010.

The drought was broken in late 2010 by the largest overbank flow since 1993, peaking at 93 000 ML.day^{-1} and causing extensive overbank flooding in the lower River Murray. The following three years were characterised by elevated within-channel flows in spring/summer (Figure 3).

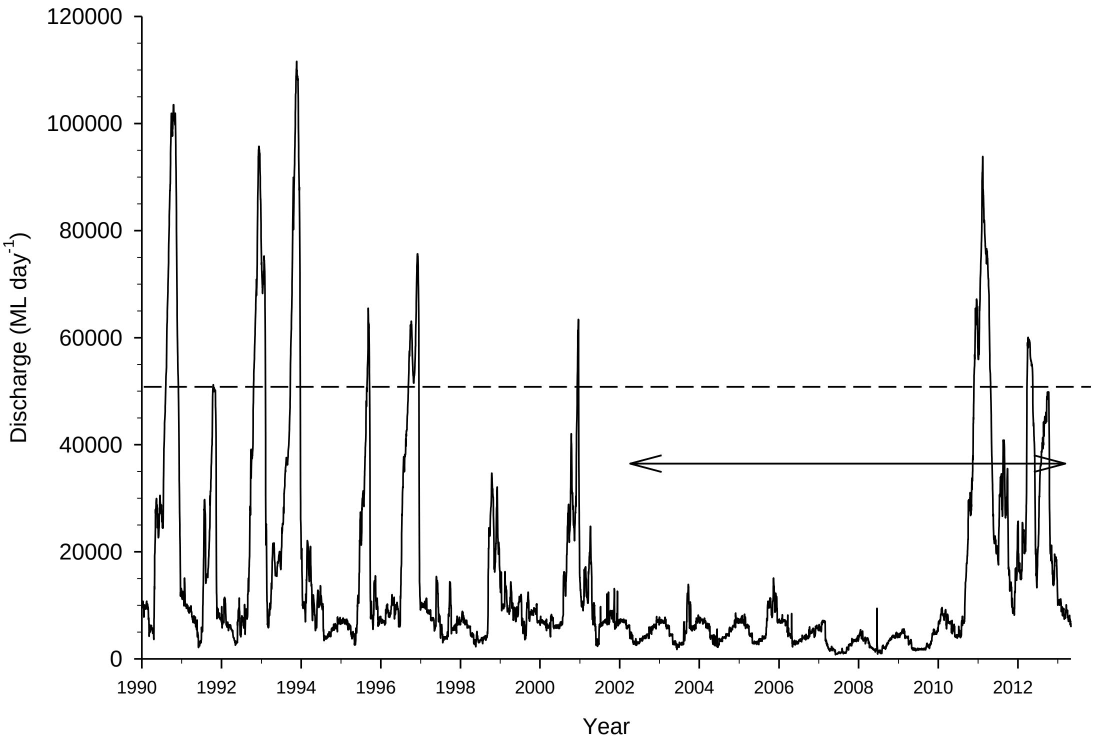

Figure 3. River Murray flow (discharge into South Australia, ML.day^{-1}) from 1990 to 2013. Black arrow represents the study period and dashed line represents the approximate discharge at which overbank flows occur in the lower River Murray.

METHODS

We used 2 key criteria to select datasets for this project. Fish sampling programs needed to:

1. use methods that would target Murray cod (e.g. drum netting and boat electrofishing) in main channel and anabranch habitats of the lower River Murray in SA; and
2. be undertaken annually, for at least 5 years, in a consistent, standardised and quantifiable manner (e.g. same sites, same techniques and effort recorded).

All sampling programs that had collected Murray cod in the lower River Murray were considered but due to the specific nature of most sampling programs, many lacked adequate temporal replication or consistency in sampling techniques and sites to enable analysis of Murray cod population dynamics. The three monitoring programs deemed suitable for further analysis are outlined below.

Chowilla Fish Assemblage Condition Monitoring

Fish assemblage ‘condition monitoring’ has been undertaken annually from 2005 to 2013 in the permanent anabranch and main-channel habitats of the Chowilla Anabranch system in the floodplain geomorphic region of the lower River Murray (Figure 2) (Wilson *et al*. 2012). This monitoring has been funded by the Murray-Darling Basin Authority (MDBA), through the South Australian Department of Environment, Water and Natural Resources (DEWNR). The Chowilla Anabranch system (hereafter Chowilla) is a complex of anabranches on the northern floodplain of the River Murray that circumvent Lock and Weir No. 6, 620 km from the river mouth. As a result of the head differential created by the weir, flow is diverted through the anabranches and creates permanent lotic habitats in a region where such habitats are now rare in the main river channel.

With the exception of 2011, condition monitoring was conducted in March/April in order to maximise the likelihood that young-of-year (YOY) individuals of all species, from the preceding spring/summer spawning season, were represented in the catch, enabling the recruitment of individual fish species to be assessed. Due to high river levels and extensive floodplain inundation in 2011, surveys were delayed until May when flow had decreased substantially (~45 000 $ML.day^{-1}$), in an effort to ensure that a comparable (standard) area was sampled at each site to previous surveys (2005 – 2010). Murray cod are consistently collected in specific mesohabitats in the Chowilla region, i.e. flowing anabranch and main channel habitats (Wilson *et al*. 2012);

consequently for these analyses, we selected a subset of condition monitoring sites that represented these habitats (Table **1**, Figure 4).

Table 1. Sites sampled in the Chowilla Anabranch and River Murray main channel from 2005–2013 as part of the Chowilla fish assemblage condition monitoring program (* denotes year sampled; u/s = upstream; d/s = downstream; Ck = creek)

Site No.	Name	2005	2006	2007	2008	2009	2010	2011	2012	2013
1	Chowilla Ck u/s Boat Ck	*	*	*	*	*	*	*	*	*
2	Chowilla Ck d/s Slaney Ck	*	*	*	*	*	*	*	*	*
3	Salt Creek @ Tareena B'bong	-	-	-	-	*	*	*	*	*
4	Slaney Ck Lower	*	*	*	*	*	*	*	*	*
5	Little Slaney Ck d/s weir	*	*	*	*	*	*	*	*	*
6	Pipeclay Ck	*	*	*	*	*	*	*	*	*
7	River Murray 10km d/s Lock 6	*	*	*	*	*	*	*	*	*
8	Boat Ck u/s bridge	*	*	*	*	*	*	*	*	*
9	Salt Creek Bank K	-	-	-	*	*	*	*	*	*
10	Swiftys Ck	*	*	*	*	*	*	*	*	*
	Total sites	**8**	**8**	**8**	**9**	**10**	**10**	**10**	**10**	**10**

Sampling was conducted using a boat mounted 5kW Smith Root Model GPP electrofishing system. At each site, 12 (6 on each bank) x 90 second (power on time) electrofishing shots were undertaken during daylight hours. All fish were dip-netted and placed in holding tanks. Fish from each shot were identified, counted and measured for length (± 1 mm, caudal fork length, L_F or total length, L_T).

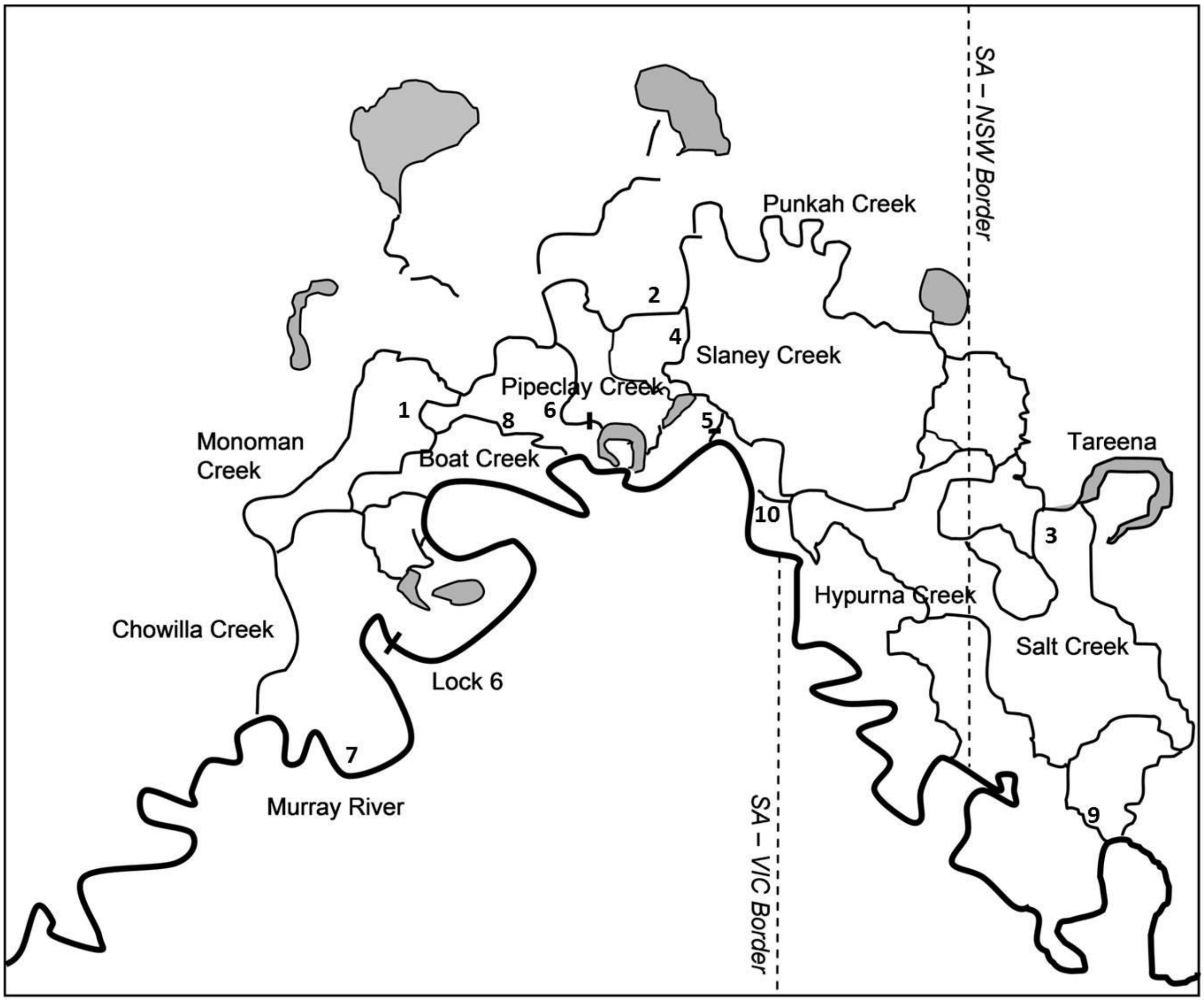

Figure 4. Map of the Chowilla Anabranch system and the adjacent Murray River main channel showing the numbered fish condition monitoring sites listed in Table 1.

Murray River Fishway Assessment Program Lock 1–3 fish sampling

In order to improve fish passage to over 2000 km of the River Murray, from the sea to Hume Dam, fishways are being constructed on all locks and weirs along the main channel of the river (Barrett and Mallen-Cooper 2007). As part of a long-term (>10 year) assessment program of the effectiveness of newly constructed fishways in decreasing accumulations of fish downstream of the weirs, fish assemblages were sampled annually in the vicinity of Locks 1–3. This assessment program was funded by the MDBA. Fish were sampled monthly (September–February) between 2002 and 2013 at three sites immediately below Lock 1, Lock 2 and Lock 3 and an additional site five kilometres downstream of Lock 1 using a boat mounted 7.5kW Smith-Root Model GPP 7.5 H/L electrofishing system. Each site was sampled over a diel period with the same method used during the day and night.

Sampling consisted of 18 replicate 90-second (on-time) electrofishing ‘shots’ with eight shots performed on each bank, downstream of each weir and two shots across the weir face. Electrofishing shots were evenly spaced and commenced approximately 600 m downstream of the weir proceeding in an upstream direction. During each shot, fish were collected by dip net and placed into a live well to recover prior to identification and measurement (± 1 mm, caudal fork length, L_F or total length, L_T).

Native Fish Monitoring Program

A long-term fishery-independent monitoring program (Native Fish Monitoring Program) was implemented in the SA lower River Murray in 2005 (Ye and Zampatti 2007). Until 2010, this monitoring program was funded by Primary Industries and Regions South Australia (PIRSA) with the aim of collecting biological information for key native fish species (Murray cod and golden perch) and to measure biological performance indicators (i.e. relative abundance and size/age structure) for stock assessment. Post 2010, the monitoring program was funded by the Commonwealth Environmental Water Office (CEWO) and whilst the aims of the monitoring program varied the techniques remained consistent. The Murray cod data presented in this report were a selected subset of data collected between 2005 and 2012 using consistent methods from four main channel sites in the lower River Murray; two in the gorge (below Locks 1 and 2) and two in the floodplain geomorphic region (below Locks 5 and 6) (Figure 2). Sampling was undertaken by commercial fishers monthly from September–December in each year. On each occasion, 10 or 15 small mesh drum nets (0.9 m hoop diameter, 3.5 m wings, 50 mm mesh) were set overnight for 2–3 consecutive nights for a total of 30 net nights sampling effort at each site.

Data analysis

Data analyses were undertaken using the statistical software package PRIMER v. 6.12 and PERMANOVA+ (Anderson *et al*. 2008). Temporal variation in Murray cod abundance was investigated using single factor (year) univariate PERMANOVA (permutational multivariate analysis of variance) (Anderson 2001). This analysis was performed on Euclidean distance similarity matrices and prior to all analyses, total numbers of Murray cod were standardised as catch per unit effort (CPUE; fish.minute of electrofishing^{-1} or fish.net night^{-1}).

Additional data

Length-at-age and growth

No comprehensive investigation has been undertaken on the age demographics or age-related growth of Murray cod in the lower River Murray. Nevertheless, numerous individual Murray cod have been collected in an ad hoc manner over the past 10 years and aged using either thin sectioned otoliths or broken and burnt otoliths. These otolith preparation and ageing techniques are described by Anderson *et al*. 1992 and Gooley 1992, respectively. Murray cod (n = 28) were sampled by either electrofishing, drum netting or gill netting, measured for length (L_T, mm) and weighed (g), sex determined and otoliths removed. These fish were generally aged using thin sectioned otoliths. Otoliths and length measurements were also collected for 106 moribund/dead fish found drifting or in the littoral zone of the lower River Murray. Murray cod mortalities are commonly observed during spring/early summer in the lower River Murray but the cause of these deaths is unknown. These fish were aged using broken and burnt otoliths. For the purpose of this report we have consolidated all available length-at-age data for Murray cod collected in main channel and anabranch habitats of the lower River Murray and fitted a von Bertalanffy growth curve using a non-linear, least squares estimation technique as per Rowland (1998a).

Chowilla Murray cod targeted sampling 2008 and 2013

In 2008 and 2013, intensive targeted sampling for Murray cod was undertaken in the Chowilla region to collect fish for the implantation of radio transmitters to investigate Murray cod movement patterns. Sampling effort was approximately 45 days and 30 days in 2008 and 2013, respectively. Sampling was undertaken using a boat mounted 5kW Smith Root Model GPP electrofishing system (the same as that used for annual fish assemblage condition monitoring in the region). The 2008 sampling was undertaken during the *millennium* drought and the 2013 sampling was undertaken two years post extensive flooding in the lower River Murray. Total length (mm) was recorded for all Murray cod collected and is presented in this report to enable comparison of length-frequency distributions of Murray cod, as an indicator of population demographics, in two hydrologically distinct periods. A Kolmogorov-Smirnov 'goodness-of-fit' test was used to determine differences in length-frequency distributions between 2008 and 2013 (Zar 1984).

RESULTS

Relative abundance

Chowilla Condition Monitoring

Murray cod were consistently collected at sites in the Chowilla region from 2005–2013, with total numbers ranging 6–21 fish per year (Table 2). Mean relative abundances remained constant from 2005–2010, but appeared to decrease post 2010 (Figure 5). Nevertheless, PERMANOVA detected no significant differences in Murray cod abundance between years ($Pseudo\text{-}F_{8,82}$ = 0.87, p = 0.54).

Table 2. Total numbers of Murray cod captured at sites sampled as part of fish assemblage condition monitoring in the Chowilla region from 2005 to 2013. (NS = not sampled; u/s = upstream; d/s = downstream; Ck = creek).

Site Number	Site	2005	2006	2007	2008	2009	2010	2011	2012	2013
1	Chowilla Ck u/s Boat Ck	2	3	3	1	4	4	1	0	1
2	Chowilla Ck d/s Slaney Ck	0	0	0	0	0	1	1	0	1
3	Salt Creek @ Tareena B'bong	NS	NS	NS	NS	6	0	0	1	1
4	Slaney Ck Lower	4	3	7	2	1	2	0	3	3
5	Little Slaney Ck d/s weir	2	1	1	3	3	4	1	3	1
6	Pipeclay Ck	1	0	1	0	0	0	0	1	0
7	River Murray 10km d/s Lock 6	0	0	1	0	2	0	3	1	0
8	Boat Ck u/s Bridge	1	2	1	0	0	1	0	0	0
9	Salt Creek Bank K	NS	NS	NS	8	5	4	0	0	0
10	Swiftys Ck	2	2	1	1	0	0	0	0	0
	Total	**12**	**11**	**15**	**15**	**21**	**16**	**6**	**9**	**7**

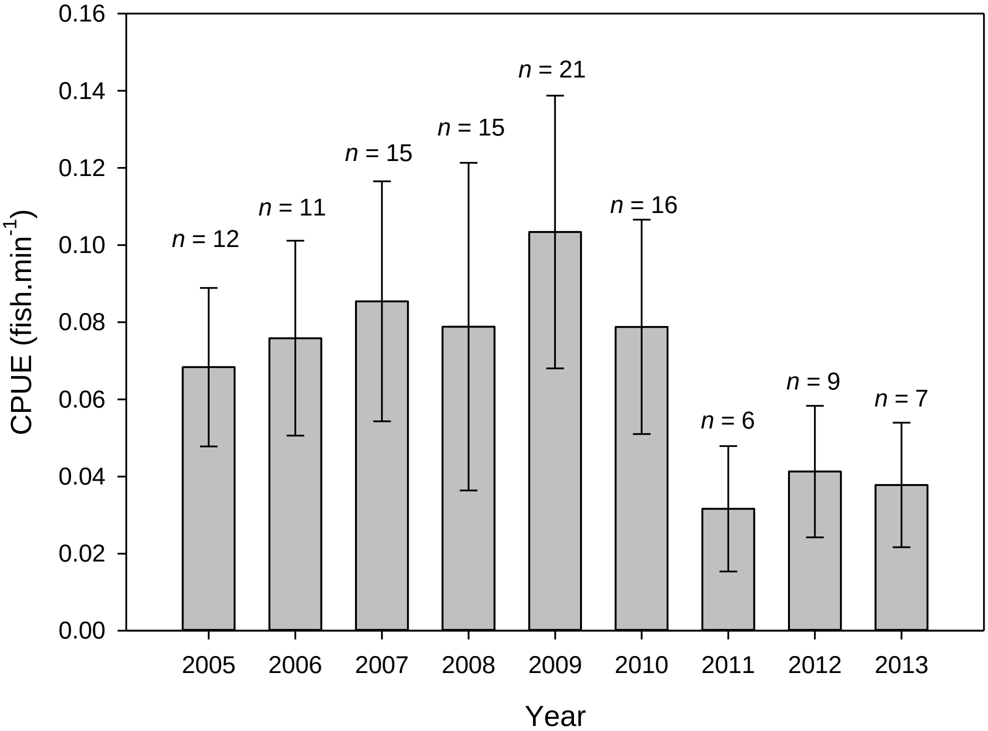

Figure 5. Mean (± SE) catch-per-unit-effort (CPUE) (fish.min^{-1}) of Murray cod collected annually during standardised boat electrofishing surveys from 2005 to 2013 at 10 sites in the Chowilla Anabranch system and adjacent River Murray (*n* = total number of Murray cod collected).

Murray River Fishway Assessment Program Lock 1–3 fish sampling

Murray cod were consistently collected at sites in the lower River Murray main channel in the vicinity of Locks 1–3 from 2002–2013 with total numbers ranging 10–118 fish per year (Table 3). Mean relative abundances remained relatively consistent with the exception of a significant increase in 2010/11 (PERMANOVA $Pseudo\text{-}F_{9,39}$ = 5.20, p = 0.001) (Figure 6).

Table 3. Total numbers of Murray cod captured at sites sampled downstream of Locks 1–3 for the Murray River Fishway Assessment Program from 2002 to 2013 (d/s = downstream). Data were collected monthly from September to February hence data presented for given years (e.g. 2003) were collected from September the preceding year (e.g. 2002). No sampling was conducted in 2005/06.

Site	2003	2004	2005	2007	2008	2009	2010	2011	2012	2013
Lock 1 (0 km d/s)	0	2	2	3	1	0	0	35	0	0
Lock 1 (5 km d/s)	8	12	20	13	4	8	6	15	9	7
Lock 2 (0 km d/s)	1	1	2	0	6	2	3	49	0	1
Lock 3 (0km d/s)	2	0	3	1	1	0	2	19	1	2
Total	**11**	**15**	**27**	**17**	**12**	**10**	**11**	**118**	**10**	**10**

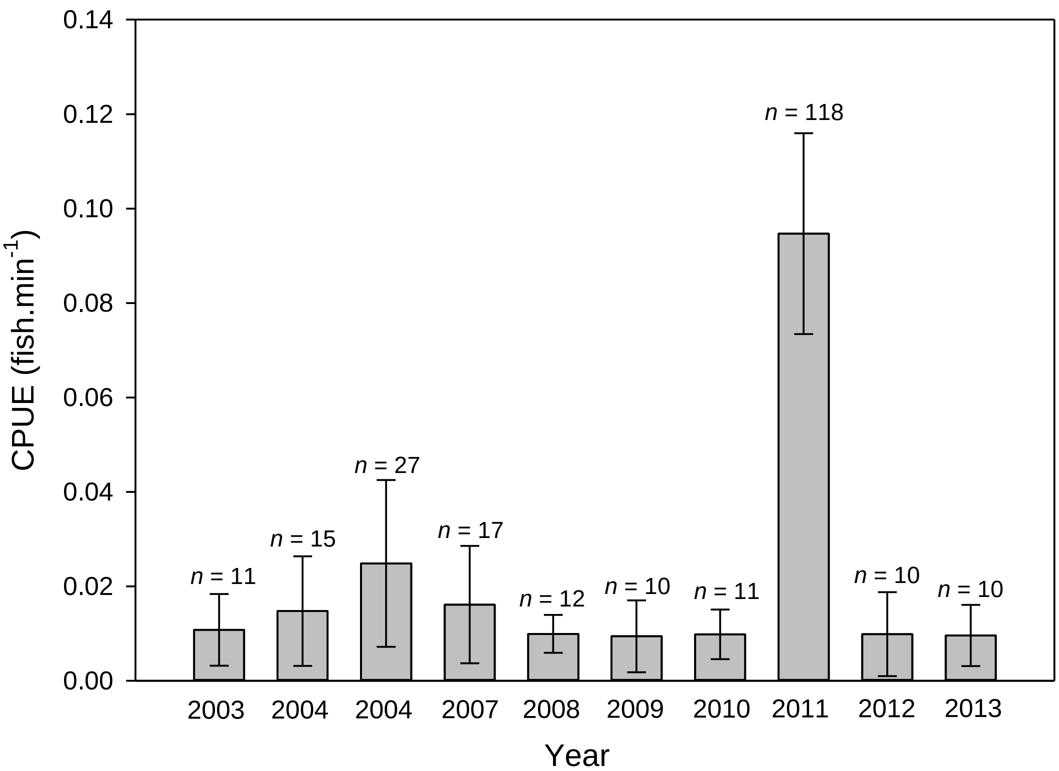

Figure 6. Mean (± SE) catch-per-unit-effort (CPUE) (fish.min^{-1}) of Murray cod collected annually during standardised boat electrofishing surveys from 2002 to 2013 at sites in the River Murray downstream of Locks 1–3 (*n* = total number of Murray cod collected). Data were collected monthly from September to February hence data presented for given years (e.g. 2003) were collected from September the preceding year (e.g. 2002). No sampling was conducted in 2005/06.

Native Fish Monitoring Program

Low numbers of Murray cod (2–10 fish per year) were collected by drum netting downstream of Locks 1, 2, 5 and 6 from 2005–2012 (Table 4). Relative abundance peaked in 2010 (Figure 7) although PERMANOVA detected no significant difference in the relative abundance of Murray cod between years ($Pseudo\text{-}F_{7,31} = 1.38$, $p = 0.21$).

Table 4. Total numbers of Murray cod captured at four sites sampled in the River Murray for the Native Fish Monitoring Program from 2005 to 2012.

Site	2005	2006	2007	2008	2009	2010	2011	2012
Lock 1	0	0	0	0	0	1	3	0
Lock 2	1	0	0	0	0	6	1	1
Lock 5	0	3	1	0	2	3	0	0
Lock 6	1	2	1	0	2	0	0	2
Total	**2**	**5**	**2**	**0**	**4**	**10**	**4**	**3**

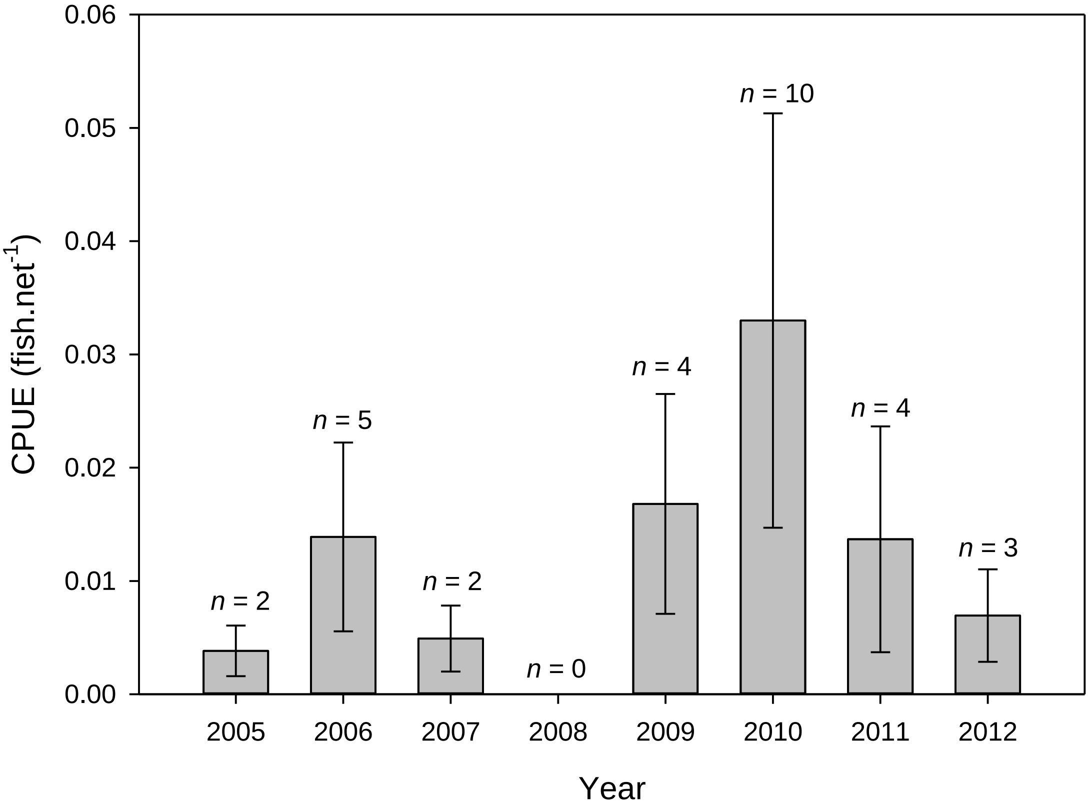

Figure 7. Mean (± SE) catch-per-unit-effort (CPUE) (fish.net night^{-1}) of Murray cod collected annually during standardised drum netting from 2005 to 2012 at Locks 1, 2, 5 and 6 on the River Murray (*n* = total number of Murray cod collected).

Length-frequency distribution

Chowilla Condition Monitoring

Length-frequency data from electrofishing sites in the Chowilla system and adjacent River Murray main channel generally show a broad size distribution of Murray cod each year, despite relatively small sample sizes in some years (e.g. *n* = 6 in 2005 and 2013) (Figure 8). This includes the consistent presence of juvenile fish (i.e. ≤500 mm L_T).

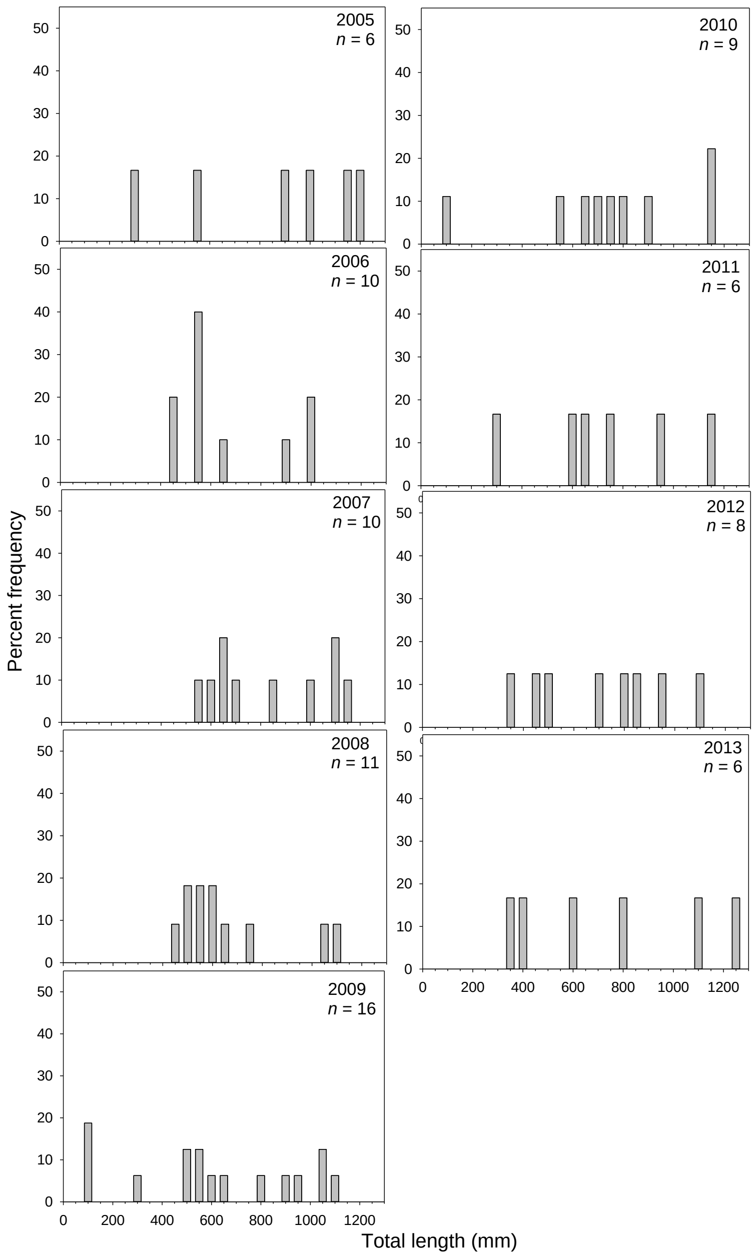

Figure 8. Length-frequency distributions of Murray cod collected annually during standardized electrofishing surveys at sites in Chowilla Anabranch system and adjacent River Murray main channel from 2005–2013 (*n* = sample size).

Murray River Fishway Assessment Program Lock 1–3 fish sampling

Length-frequency data from main channel electrofishing sites in the vicinity of Lock 1–3 show a predominance of fish >800 mm L_T with low numbers (1–2 fish) of potentially juvenile fish (≤500 mm) collected in 20005, 2010, 2012 and 2013 (Figure 9).

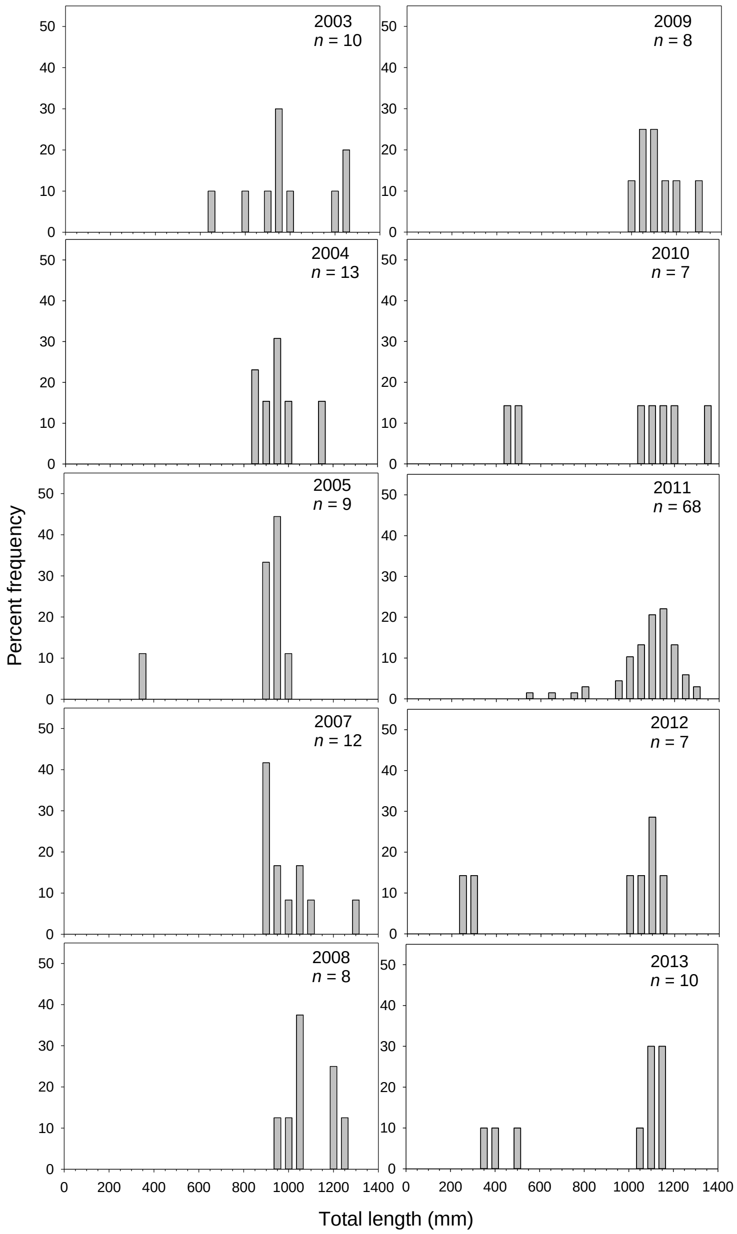

Figure 9. Length-frequency distributions of Murray cod collected annually during standardised electrofishing surveys at four sites in the River Murray main channel downstream of Locks 1–3 from 2002–2013 (*n* = sample size). Data were collected monthly from September to February hence data presented for given years (e.g. 2003) were collected from September the preceding year (e.g. 2002). No sampling was conducted in 2005/06

Native Fish Monitoring Program

Length-frequency data from the Native Fish Monitoring program are based on low sample sizes, but show a predominance of fish >800 mm L_T with low numbers (1–2 fish) of potentially juvenile fish (≤500 mm L_T) collected in 2005, 2006 and 2012 **(**Figure 10).

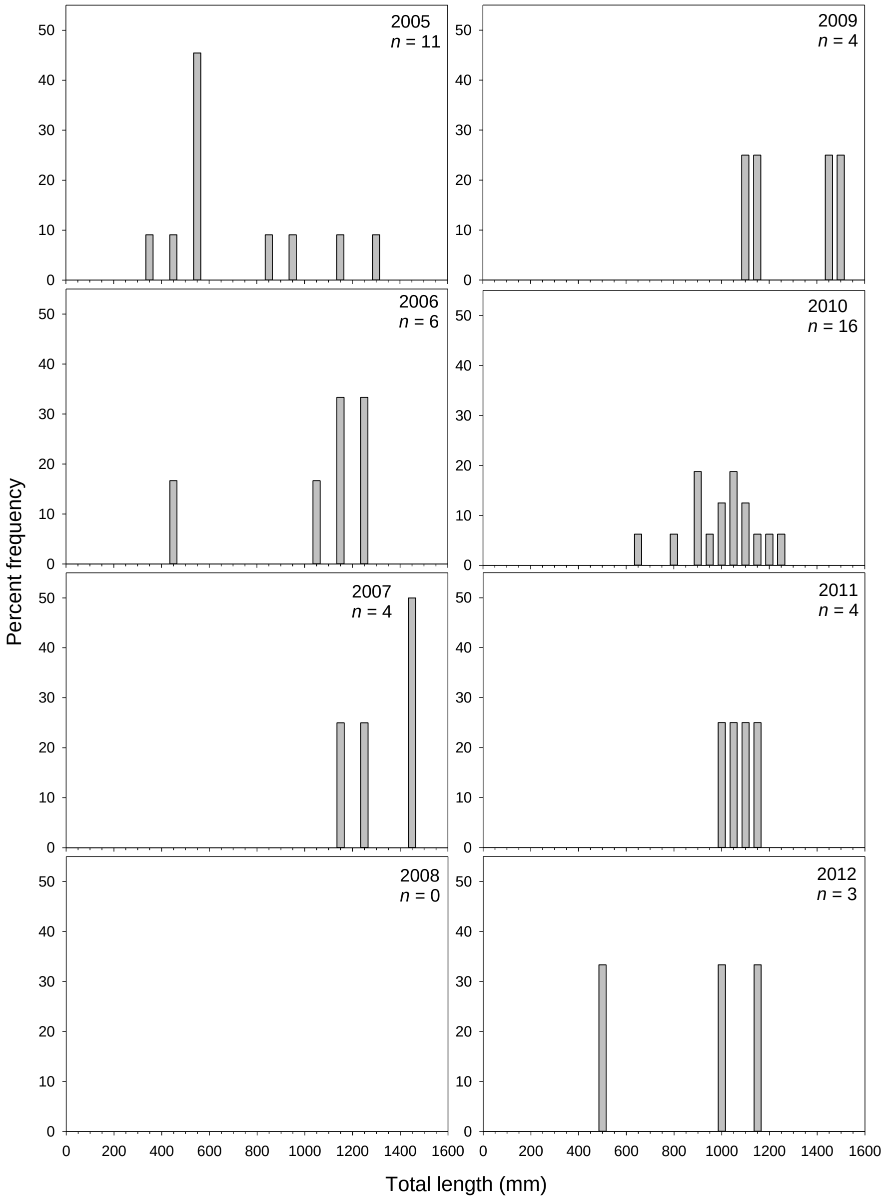

Figure 10. Length-frequency distributions of Murray cod collected annually during standardised drum netting surveys at sites directly downstream of Locks 1, 2, 5 and 6 in the River Murray main channel from 2005–2012 (*n* = sample size).

Additional data

Length-at-age and growth

Murray cod in the lower River Murray show considerable variation in length-at-age for all age classes (Figure 11). For example, 2-year-old fish may range from 240 to 420 mm L_T and 18-year-old fish from 900 to 1250 mm L_T (Figure 11). The oldest fish aged was 46 years. The von Bertalanffy growth curve for age 0.5 to 46 year old Murray cod in the lower River Murray is represented by the equation: L_t = 1240.9 (1 – exp [-0.131 { t + 0.5049 }].

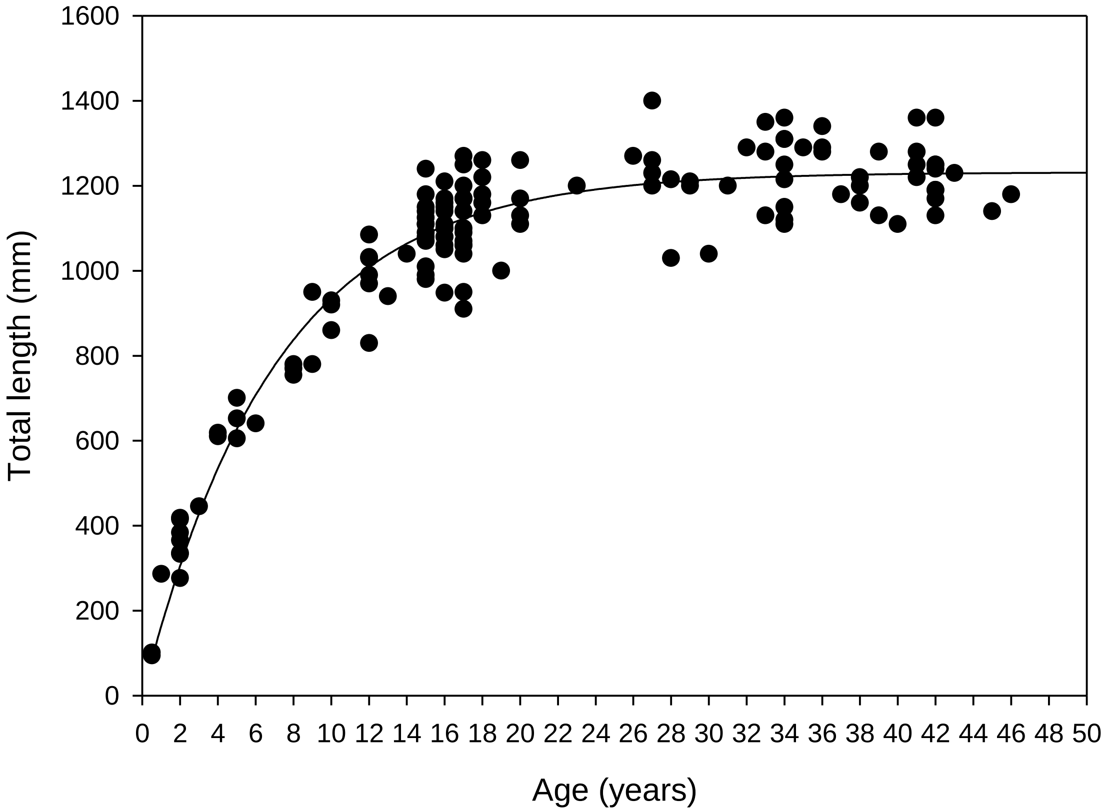

Figure 11. Length-at-age data for Murray cod collected in main channel and anabranch habitats of the lower River Murray (*n* = 134) fitted with a von Bertalanffy growth curve represented by the equation: L_t = 1240.9 (1 – exp [-0.131 { t + 0.5049}].

Chowilla Murray cod length-frequency: 2008 and 2013

Murray cod collected in 2008 and 2013 in the Chowilla region of the lower River Murray exhibited broad size distributions, ranging from 150–>1200 mm in 2008 and 100–>1200 mm L_T in 2013 (Figure 12). Length frequency distributions were significantly different between 2008 and 2013 ($D_{51, 66} = 0.4973$, $p<0.001$), likely due to the greater proportion of smaller fish (<400 mm L_T) in 2013. Otolith microstructure analyses confirmed this strong cohort of 300–400 mm L_T fish were aged 2+ (Figure 11) at the time of collection (May 2013), corresponding with a spawning period of spring 2010 (SARDI Unpublished data).

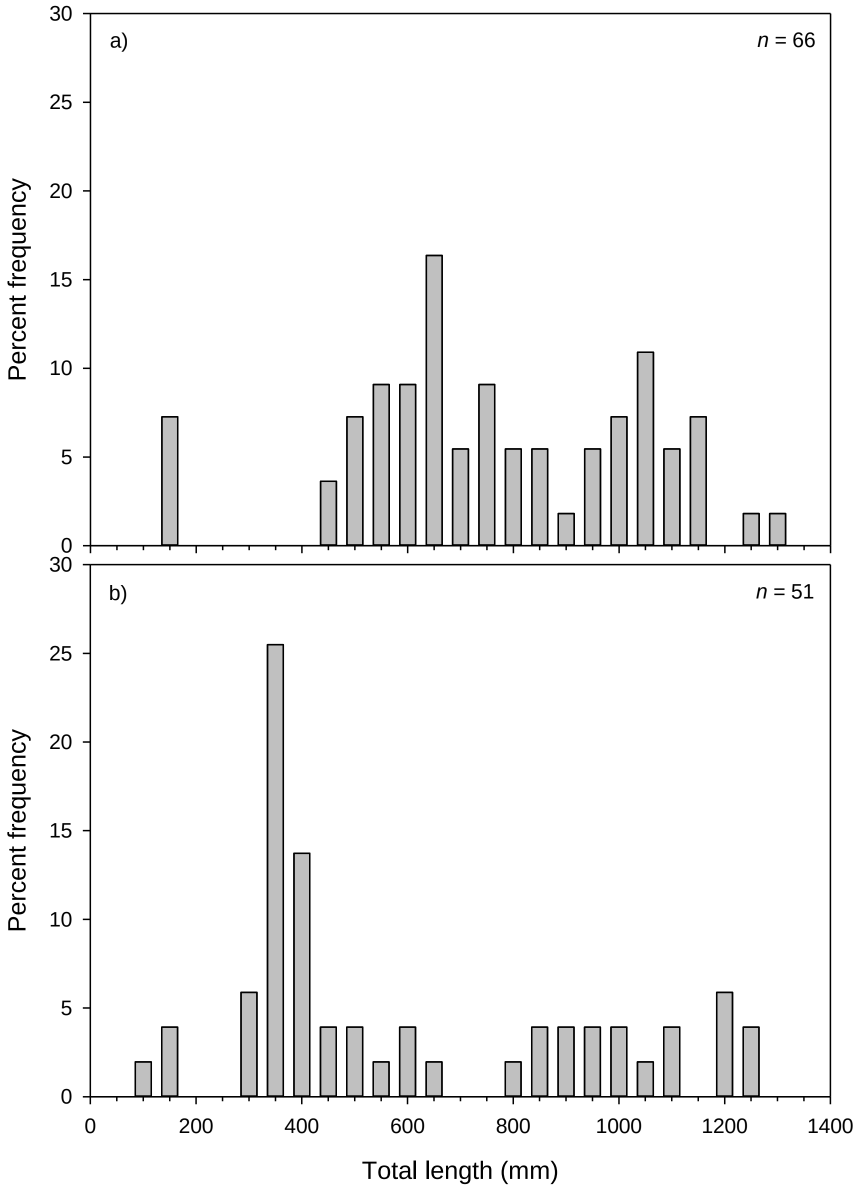

Figure 12. Length frequency distributions of Murray cod collected during targeted electrofishing in the Chowilla anabranch system and adjacent River Murray main channel in (a) 2008 and (b) 2013.

DISCUSSION

Understanding population structure and dynamics is integral to the management and conservation of freshwater fish populations. Native fish abundances in the MDB, including Murray cod, are estimated to constitute 10% of their pre-European levels (Barrett 2004). Yet despite a determination to rehabilitate native fish, and the conservation status of the iconic Murray cod, published data on the demographics and dynamics of Murray cod remain scarce. This situation is not unique to the lower River Murray as there is a general lack of monitoring and assessment of recruitment and abundance of Murray cod across the species range (Koehn 2005).

In this study we interrogated data from three long-term (8–11 year) fish monitoring projects conducted in the lower River Murray in an effort to provide an overview of the current status of SA Murray cod populations. These data were collected over a period of hydrological extremes, incorporating seven years of drought and unprecedented low flow in the lower River Murray, followed by three years of over bank or elevated within-channel flow.

<u>Relative abundance</u>

Despite substantial hydrological variability between 2002 and 2013, relative abundances of Murray cod in main channel and anabranch habitats of the lower River Murray remained relatively constant, with the exception of considerable increases in relative abundance in electrofishing and drum netting catch rates from main channel habitats in 2010. We suggest that these apparent increases in relative abundance during drought breaking floods were an artefact of increased fish movement and a spatial redistribution of Murray cod, rather than an increase in absolute abundance. Murray cod move more and over greater distances, in association with increased discharge (Koehn *et al.* 2009; Leigh and Zampatti 2013). Therefore, increased movement in the lower River Murray during flooding potentially resulted in: 1) elevated interception rates in drum nets, the effectiveness of which is reduced during low flows and 2) accumulation of fish downstream of weirs, a common impact of regulating structures (Lucas and Baras 2001), thus concentrating fish at electrofishing sites.

Whilst there were no significant differences in the relative abundances of Murray cod collected over a 9 year period (2005–2013) in the Chowilla region, there appeared to be a decrease in the total numbers collected following overbank flows in 2010. Widespread flooding in the MDB in 2010/11 was associated with an extensive hypoxic blackwater event that caused substantial mortalities of Murray cod, including in the floodplain geomorphic region of the lower River Murray (Leigh and Zampatti 2013). These mortalities likely resulted in decreased Murray cod abundance in the Chowilla region.

Low flows during the *millennium* drought, followed by extensive flooding in 2010, were associated with fundamental changes to fish assemblage composition and abundance in the main channel of the lower Riiver Murray (Bice *et al.* 2014). During drought, fish assemblages in main channel habitats were characterised by small-bodied wetland species (e.g. carp gudgeon, *Hypseleotris* spp.) whilst post flooding, riverine species (e.g. golden perch, *Macquaria ambigua ambigua*) and species which spawn on inundated floodplains (e.g. common carp, *Cyprinus carpio*) dominated. Indeed, flooding was associated with large and significant increases in the abundance of age 0+ and 1+ golden perch compared to drought years (Zampatti and Leigh 2013). Similar changes were not observed in the abundance of Murray cod. Nevertheless, there may be a considerable delay (2–4 years) before Murray cod recruits from high flow years are detectable in the population. For example, it was not until May 2013 when age 2+ recruits (300–450 mm L_T), spawned during flooding in 2010, became apparent in electrofishing catches from the Chowilla region. These fish formed a strong cohort and may ultimately contribute to increases in abundance over the coming years.

<u>Size distribution</u>

Data from 2002–2010 indicate that the majority of Murray cod collected by electrofishing and drum netting in main channel habitats of the gorge geomorphic region of the lower River Murray were greater than 800 mm L_T, suggesting a minimum age of 8 years at the time of capture (Figure 11). The paucity of smaller, younger fish indicates a general lack of recruitment in the main channel of the River Murray during the millennium drought. In contrast, during the same period, the lotic anabranch habitats at Chowilla were characterised by broad size distributions of Murray cod, indicating the presence of juvenile and adult fish.

Murray cod recruitment failure has been an ongoing issue in the regulated lower River Murray, particularly during periods of low flow (Pierce 1988). The prolonged absence of juvenile Murray cod from commercial catches and fishery-independent sampling in the 1980s prompted a moratorium on the commercial and recreational take of Murray cod from January 1990 to December 1993. Following a series of high flows during the period of the moratorium juvenile fish were once again collected in 1993 and 1994 leading to the reopening of the fishery (Ye and Zampatti 2007). During the virtual absence of recruitment in the River Murray in the 1980s, recruitment was observed in Chowilla and attributed to flowing water habitats that were comparably rare in the Murray (Pierce 1990). Our data support the observations of Pierce (1990) that the Chowilla system affords conditions that promote Murray cod recruitment during periods of low flow and minimal recruitment in main channel habitats.

Despite low sample sizes there was some evidence that Murray cod recruitment in the main channel of the lower River Murray was supported by increases in discharge contained within the river channel and overbank. In particular, 400–500 mm L_T fish collected in the vicinity of Locks 1–3 in 2009 were potentially 4 years old (Figure 11) and would have been spawned in association with an in-channel rise in flow in 2005. Likewise, juvenile fish ranging 250–500 mm L_T were collected in sequential years following flooding in 2010. Importantly, however, recruits spawned in these years of elevated discharge were generally not detectable until reaching $L_T \geq 250$ mm.

Overbank flooding in 2010 would have been expected to promote strong Murray cod recruitment (Rowland 1989; Ye *et al*. 2000) ultimately leading to increased abundances. In 2010/11, however, flooding was associated with an extensive anoxic blackwater event that caused substantial mortalities of Murray cod (Leigh and Zampatti 2013). Despite this, electrofishing data from anabranch and main channel habitats (in both the floodplain and gorge geomorphic regions) indicated recruitment associated with spawning in 2010. Specifically, targeted electrofishing for Murray cod in the Chowilla region in May 2013 revealed a substantial cohort of age 2+ fish. The two year delay in the presence of this cohort, and the need for intensive targeted sampling to detect it, reinforces the need for a dedicated monitoring program to potentially detect any change in Murray cod population structure and abundance.

Concern has been raised regarding the reproductive capacity of Murray cod populations dominated by large, potentially old, fish (PIRSA 2013). From observations of hatchery brood stock, Rowland (2005) suggests that reproductive performance decreases with fish size. But limited observations of the ovaries of wild-caught fish indicate that large cod (>1 m long and >30 kg) can produce predominantly healthy and apparently viable eggs and also produce the most eggs (Koehn and Stuart 2007). There is also some evidence from other freshwater and marine species that older fish, from long-lived populations, produce more viable eggs and larvae than younger fish (Berkley *et al.* 2004; Venturelli *et al*. 2010). Consequently, these larger, older fish may produce fitter eggs and larvae which can survive under conditions inadequate for survival of progeny from younger adults (Berkley *et al*. 2004).

<u>Length-at-age and growth</u>

Murray cod sampled from the lower River Murray exhibited considerable variability in length-at-age, a trait that is common to long-lived Percicthyids (Anderson *et al.* 1992; Walsh *et al.* 2010). Consequently, in studies where an accurate birth date is required (e.g. recruitment response to hydrology or determination of population demographics) length is unlikely to be a reliable indicator of age without some form of validation.

The calculated growth rate of Murray cod in the lower River Murray (k = 0.131) was similar to those reported by Anderson *et al.* (1992) for contemporary otoliths (1990s) collected from the mid–upper reaches of the River Murray and its tributaries, and for historical collections of otoliths (1949–51) collected from the River Murray upstream of Yarrawonga. Growth rates were, however, substantially greater than historical collections of otoliths (1949–51) from the River Murray downstream of Yarrawonga (k = 0.069) and otoliths collected from the northern tributaries of the Murray (e.g. Murrumbidgee and Wakool) and Lakes Mulwala and Burrinjuck over the period 1975–84 (k = 0.060) (Rowland 1998). The reasons for spatio-temporal variation in growth rates remain unexplored, but the differences reinforce the potential importance of regional variation in the life histories and ecology of Murray cod populations and the need to consider these factors in the Basin-scale management of Murray cod.

Restoration of Murray cod populations in the lower River Murray

Riverine populations of Murray cod appear reliant on lotic habitats for the survival of larvae and habitats for adults and juveniles (Humphries 2005; Jones and Stuart 2007; Koehn and Nicol 2013). Indeed, where recruitment appears to fail in the lentic weir pools of the lower River Murray, it is sustained in flowing anabranch habitats and the perennial or seasonally lotic reaches of the mid and upper River Murray and tributaries (e.g. downstream of Yarrawonga and the lower Darling River). Restoration of lotic habitats, through the delivery of additional flow or the management of weir pool heights (i.e. decreasing pool height), will be critical to potentially rehabilitating populations of Murray cod in the lower River Murray. An important initial step would be the restoration of an annual spring flow pulse (i.e. within-channel rise in discharge). This characteristic of the hydrological regime has been predominantly regulated out of the lower River Murray, but occurred annually, even during drought, in the unregulated river (Zampatti and Leigh 2013). Importantly, even in the weir pools of the lower River Murray, an increase in discharge to ≥15 000 $ML.day^{-1}$ affords some increase in water velocities and hydraulic complexity, at least in the upper half of weir pools (Bice *et al*. 2013) and may promote increased survival of larval Murray cod.

The potential impact of weir pools and loss of lotic habitats on the recruitment of Murray cod is analogous to the recruitment of the iconic pallid sturgeon (*Scaphirhynchus albus*), endemic to the highly regulated Missouri and Mississippi rivers in the United States. This large (up to 40 kg) and long-lived (>50 years) freshwater fish depends on lotic habitats for the dispersal of larvae to rearing habitats. Where lotic habitats and hence larval dispersal is interrupted by regulating structures recruitment is poor (Kynard *et al.* 2007). Like Murray cod, the species is now considered endangered with remnant populations dominated by low numbers of large, old fish and little evidence of natural recruitment. Conservation efforts for pallid sturgeon include hydrological restoration and the stocking of artificially reared juveniles (Secor *et al*. 2002).

Stocking of artificially reared juveniles has also been proposed as a conservation measure for Murray cod populations in the lower River Murray (PIRSA 2013). Nevertheless, the regulated weir pools of the lower River Murray provide largely suboptimal hydraulic and structural habitat for riverine populations of juvenile and adult Murray cod. Consequently, carrying capacity may be limited by habitat availability, and ultimately, hydrodynamic restoration and the reintroduction of large wood may present the most viable long-term options for reinstating resilient Murray cod populations in the lower River Murray.

CONCLUSIONS

In the lower River Murray, river regulation and the loss of structural and hydraulic habitats (i.e. snags and flowing water) appears to detrimentally impact Murray cod. Harvest has been minimised since 2003, yet abundance remained low and recruitment was minimal in the predominantly lentic main channel habitats of the lower River Murray during drought (2001–2010). At the same time, however, recruitment was evident in the lotic habitats of the Chowilla system.

Low numbers of juvenile fish (≤500 mm L_T) were collected in main channel and anabranch habitats in the years following increases in flow contained within the river channel and overbank. Increased flow alters the hydrodynamics of the lower River Murray, increasing water velocities and promoting hydraulic complexity. These hydrodynamic characteristics are permanent features of the free-flowing reaches of the mid–upper River Murray and lotic anabranches and appear fundamental to promoting the survival of early life stage Murray cod and providing habitat for juveniles and adults.

Overbank flooding in 2010/11 would have been expected to promote strong Murray cod recruitment. Flooding, however, was associated with an extensive anoxic blackwater event that caused substantial mortalities of Murray cod. Despite this, data from anabranch and main channel habitats indicate recruitment associated with spawning in 2010. This was most evident from electrofishing catches at Chowilla in the floodplain geomorphic region of the lower River Murray but also apparent in the vicinity of Locks 1–3 in the gorge geomorphic region. Significantly, however, fish spawned during within-channel and overbank increases in flow were generally not detectable until fish were 300–400 mm L_T and 2–3 years of age. Thus, monitoring the population dynamics of Murray cod and measuring response to flow is a long-term proposition and needs to consider time lags in the detectability of recruitment.

Conjecture remains on the reproductive output and viability of eggs and larvae from older Murray cod, and the issue constitutes a fundamental research question. If Murray cod, like other long-lived, slow-growing fish, become more viably fecund with age, then maintaining populations of large, older fish is important from a conservation perspective. The current moratorium on catch is an effective means of doing this.

Importantly, even though the majority of Murray cod collected in main channel habitats were generally large (i.e. >800 mm L_T), these fish most likely represent a broad range of age classes. Murray cod have a potential life span of greater than 40 years; consequently, whilst relative abundances remain low, Murray cod do not appear at imminent risk of being extirpated from the lower River Murray. This should not, however, preclude the need for action to address the factors inhibiting Murray cod recruitment.

Long-term monitoring of population structure and abundance is essential to assess the effectiveness of fishery management or other interventions such as the delivery of environmental flows. Our data indicate that boat electrofishing is potentially the most effective means of collecting a broad size range of Murray cod over a range of hydrological conditions. Drum netting could be used to complement electrofishing during periods of elevated flow and provide additional data on the size/age structure of populations.

In addition to long-term monitoring there remain a number of key deficiencies in our understanding of the ecology of Murray cod in the lower River Murray:

(1) mechanisms by which Murray cod recruitment may fail, including the fate of larvae, food preferences and availability, and intra and interspecific competition;
(2) reproductive performance of older fish, including viability of eggs and survival of larvae;
(3) habitat use of juvenile and adult Murray cod in main channel habitats; and
(4) spatial scale of life history and the importance of connectivity to main channel, anabranch and tributary habitats in the River Murray and its tributaries upstream of the SA border.

Developing an understanding of these factors will be crucial to the conservation and rehabilitation of Murray cod populations in the lower River Murray. In addition, improved biological/ecological knowledge, combined with long-term monitoring data, will aid in potential modelling of population dynamics of Murray cod in the lower River Murray and determination of stock status.

REFERENCES

Anderson, J. R., A. K. Morison and D. J. Ray (1992). Age and growth of Murray cod, *Maccullochella peelii* (Perciformes: Percichthyidae), in the lower Murray-Darling Basin, Australia, from thin-sectioned otoliths. *Australian Journal of Marine and Freshwater Research* **43**: 983–1013.

Anderson, M. J. (2001). A new method for non-parametric analysis of variance. *Austral Ecology* **26**: 32–46.

Anderson, M. J., R. N. Gorley and K. R. Clarke (2008). PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods, PRIMER-E: Plymouth, UK.

Barrett, J. (2004). Introducing the Murray-Darling Basin Native Fish Strategy and initial steps towards demonstration reaches. *Ecological Management and Restoration* **5**: 15–23.

Barrett, J., Ed. (2008). The Sea to Hume Dam: Restoring Fish Passage in the Murray River, Murray-Darling Basin Commission, Canberra.

Baumgartner, L. J. (2007). Diet and feeding habits of predatory fishes upstream and downstream of a low-level weir. *Journal of Fish Biology* **70**: 879–894.

Berkeley, S. A., C. Chapman and S. M. Sogard (2004). Maternal age as a determinant of larval growth and survival in a marine fish, *Sebastes melanops*. *Ecology* **85**: 1258–1264.

Bice, C. M., S. L. Gehrig, B. P. Zampatti, J. M. Nicol, P. Wilson, S. L. Leigh and K. Marsland (2014). Flow-induced alterations to fish assemblages, habitat and fish–habitat associations in a regulated lowland river. *Hydrobiologia* **722**: 205–222.

Bice, C. M., S. L. Leigh, J. M. Nicol and B. P. Zampatti (2013). Changes in hydraulic complexity in the lower River Murray main channel in relation to flow variability. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2013/000214-1. SARDI Research Report Series No. 709. 32 pp.

Boys, C. and M. Thoms (2006). A large-scale, hierarchical approach for assessing habitat associations of fish assemblages in large dryland rivers. *Hydrobiologia* **572**: 11–31.

Cheshire, K. J. M., Q. Ye, P. Wilson and L. Bucater (2012). From drought to flood: annual variation in larval fish assemblages in a heavily regulated lowland temperate river. Goyder Institute for Water Research Technical Report Series No. 12/6, 28 pp.

Dannevig, H. C. (1903). Summary of evidence regarding the Murray Cod fisheries, with notes. In *Murray Cod Fisheries*, Department of Fisheries, NSW, Government Printer, Sydney, NSW.

Ebner, B. (2006). Murray cod an apex predator in the Murray River, Australia. *Ecology of Freshwater Fish* **15**: 510–520.

Harris, J. H. and S. J. Rowland (1996). Family Percichthyidae: Australian freshwater cods and basses. In *Freshwater Fishes of South-eastern Australia*. R. M. McDowall, Reed, Sydney: pp 150–163.

Henderson, M., D. Wood, G. Cranston, L. Vilizzi, C. Campbell and C. Johns (2012). The Living Murray Condition Monitoring at Lindsay, Mulcra and Wallpolla 2011/12: Part A. Final report prepared for the Mallee Catchment Management Authority by the Murray-Darling Freshwater Research Centre, MDFRC Publication 26/2012, September, 151 pp.

Henry, G. W. and J. M. Lyle (2003). The National Recreational and Indigenous Fishing Survey. Final Report. Australian Government Department of Agriculture, Fisheries and Forestry, Canberra, 190 pp.

Humphries, P. (2005). Spawning time and early life listory of murray cod, *Maccullochella peelii peelii* (Mitchell) in an Australian River. *Environmental Biology of Fishes* **72**: 393–407.

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

Humphries, P. and K. O. Winemiller (2009). Historical impacts on river fauna, shifting baselines, and challenges for restoration. *Bioscience* **59**: 673–684.

IUCN (2013). IUCN Red List of Threatened Species. Version 2013.2.

Jones, M. J. and I. G. Stuart (2007). Movements and habitat use of common carp (*Cyprinus carpio*) and Murray cod (*Macullochella peelii peelii*) juveniles in a large lowland Australian river. *Ecology of Freshwater Fish* **16**: 210–220.

Kaminskas, S. and P. Humphries (2009). Diet of Murray cod (*Maccullochella peelii peelii*) (Mitchell) larvae in an Australian lowland river in low flow and high flow years. *Hydrobiologia* **636**: 449–461.

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

King, A. J. (2004). Density and distribution of potential prey for larval fish in the main channel of a floodplain river: pelagic versus epibenthic meiofauna. *River Research and Applications* **20**: 883–897.

King, A. J., Z. Tonkin and J. Mahoney (2009). Environmental flow enhances native fish spawning and recruitment in the Murray River, Australia. *River Research and Applications* **25**: 1205–1218.

Koehn, J. D. (2005). Threats to Murray cod. In *Management of Murray cod in the Murray-Darling Basin: Statements, recommendations and supporting papers*. M. Lintermans and B. Phillips, Murray-Darling Basin Commission, Canberra**:** pp 30–37.

Koehn, J. D. (2009). Multi-scale habitat selection by Murray cod *Maccullochella peelii peelii* in two lowland rivers. *Journal of Fish Biology* **75**: 113–129.

Koehn, J. D. and D. J. Harrington (2005). Collection and distribution of the arly life stages of the Murray cod (*Maccullochella peelii peelii*) in a regulated river. *Australian Journal of Zoology* **53**: 137–144.

Koehn, J. D. and D. J. Harrington (2006). Environmental conditions and timing for the spawning of Murray cod (*Maccullochella peelii peelii*) and the endangered trout cod (*M. macquariensis*) in southeastern Australian rivers. *Rivers Research and Applications* **22**: 327–342.

Koehn, J. D., J. A. McKenzie, D. J. O'Mahoney, S. J. Nicol and J. P. O'Connor (2009). Movements of Murray cod (*Maccullochella peelii peelii*) in a large Australian lowland river. *Ecology of Freshwater Fish* **18**: 594–602.

Koehn, J. D. and S. J. Nicol (2013). Comparative habitat use by large riverine fishes. *Marine and Freshwater Research*. http://dx.doi.org/10.1071/MF13011

Koehn, J. D. and C. R. Todd (2012). Balancing conservation and recreational fishery objectives for a threatened fish species, the Murray cod, *Maccullochella peelii*. *Fisheries Management and Ecology* **19**: 410–425.

Kynard, B., E. Parker, D. Pugh and T. Parker (2007). Use of laboratory studies to develop a dispersal model for Missouri River pallid sturgeon early life intervals. *Journal of Applied Ichthyology* **23**: 365–374.

Leblanc, M., S. Tweed, A. Van Dijk and B. Timbal (2012). A review of historic and future hydrological changes in the Murray-Darling Basin. *Global and Planetary Change* **80-81**: 226–246.

Leigh, S. and B. Zampatti (2011). Movement of Murray cod in the Chowilla Anabranch system and adjacent Murray River during a period of high flow into South Australia: September - December 2010. South Australian Research and Development Institute (Aquatic Sciences), Adelaide, 45 pp.

Leigh, S. J. and B. P. Zampatti (2013). Movement and mortality of Murray cod, *Maccullochella peelii*, during overbank flows in the lower River Murray, Australia. *Australian Journal of Zoology* **14**: 135–143.

Lintermans, M. (2007). Fishes of the Murray-Darling Basin: An introductory guide, Murray-Darling Basin Commission, Canberra.

Lintermans, M. and B. Phillips, Eds. (2005). Management of Murray cod in the Murray-Darling Basin: statement, recommendations and supporting papers. Murray-Darling Basin Commission, Canberra.

Lucas, M. and E. Baras (2001). Migration of Freshwater Fishes, Blackwell Sciences, Oxford.

Pierce, B. (1988). Improving the status of our River Murray fishes - a discussion paper on the potential of co-operative management. In *Proceedings of the Workshop on Native Fish Management, June 1988*, Murray-Darling Basin Commission, Canberra.

Pierce, B. (1990). Chowilla fisheries investigations. South Australian Department of Fisheries, Adelaide.

PIRSA (2013). South Australian Murray Cod Enhancement Workshop Proceedings, July 2013, Primary Industries and Regions SA, Adelaide.

Pringle, C. M., M. C. Freeman and B. J. Freeman (2000). Regional effects of hydrological alterations on riverine macrobiota: tropical-temperate comparisons. *Bioscience* **50**: 807-823.

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

Rourke, M. L., H. C. McPartlan, B. A. Ingram and A. C. Taylor (2011). Variable stocking effect and endemic population genetic structure in Murray cod *Maccullochella peeli*. *Journal of Fish Biology* **79**: 155–177.

Rowland, S. J. (1985). Aspects of the biology and artificial breeding of the Murray cod, *Maccullochella peelii* and eastern freshwater cod *M. ikei sp.* Nov. (Pisces: Percichthyidae), PhD Thesis. School of Biological Sciences. Macquarie University, Sydney. 252 pp.

Rowland, S. J. (1989). Aspects of the history and fishery of the Murray cod, *Maccullochella peelii* (Mitchell) (Percichthyidae) *Proceedings of the Linnean Society of New South Wales* **111**: 201–213.

Rowland, S. J. (1998a). Age and growth of the Australian freshwater fish Murray cod, *Maccullochella peelii peelii*. *Proceedings of the Linnean Society of New South Wales* **120**: 163–180.

Rowland, S. J. (1998b). Aspects of the reproductive biology of Murray cod, *Macullochella peelii peelii*. *Proceedings of the Linnean Society of New South Wales* **120**: 147–162.

Rowland, S. J. (2005). Overview of the history, fishery, biology and aquaculture of Murray cod (*Maccullochella peelii peelii*). In *Management of Murray cod in the Muray-Darling Basin: statement, recommendations and supporting papers*. M. Lintermans and B. Phillips, Murray-Darling Basin Commission, Canberra: pp 38–61.

Saddlier, S., J. O'Mahoney and D. Ramsey (2009). Protection and enhancement of Murray cod populations. Arthur Rylah Institute for Environmental Research Technical Report Series No. 172. Department of Sustainability and Environment, Heidelberg, Victoria.

Secor, D. H., P. J. Anders, W. Van Winkle and D. A. Dixon (2002). Can we study sturgeons to extinction? What we do and don't know about the conservation of North American Sturgeons. *American Fisheries Society Symposium*.

Stuart, I. and J. D. Koehn (2007). Big cod do breed. *Freshwater Fishing Australia* **85**: 62–64.

Van Dijk, A., H. E. Beck, R. S. Crosbie, R. A. M. de Jeu, Y. Y. Liu, G. M. Podger, B. Timbal and N. R. Viney (2013). The millenium drought in southeast Australia (2001-2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. *Water Resources Research* **49**: 1040–1057.

Venturelli, P. A., C. A. Murphy, B. J. Shuter, T. A. Johnston, P. J. van Coeverden de Groot, P. T. Boag, J. M. Casselman, R. Montgomerie, M. D. Wiegand and W. C. Leggett (2010). Maternal influences on population dynamics: evidence from an exploited freshwater fish. *Ecology* **91**: 2003–2012.

Walker, K. F. (2006). Serial weirs, cumulative effects: the Lower River Muray, Australia. In *Ecology of Desert Rivers*. R. T. Kingsford, Cambridge University Press: pp 248–279.

Walker, K. F. and M. C. Thoms (1993). Environmental effects of flow regulation on the lower River Murray, Australia. *Regulated Rivers: Research & Management* **8**: 103–119.

Walsh, C. T., C. A. Gray, R. J. West, D. E. van der Meulen and L. F. G. Williams (2010). Growth, episodic recruitment and age truncation in populations of a catadromous percichthyid, *Macquaria colonorum*. *Marine and Freshwater Research* **61**: 397–407.

Wilson, P., S. Leigh, C. Bice and B. Zampatti (2012). Chowilla icon site fish assemblage monitoring 2012. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2008/000907-4. SARDI Research Report Series No. 674. 48 pp.

Ye, Q., K. Jones and B. Pierce (2000). Murray cod (*Maccullochella peelii peelii*), Fishery Assessment Report to PIRSA for Inland Waters Fishery Management Committee. South Australian Fisheries Assessment Series 2000/17.

Ye, Q. and B. Zampatti (2007). Murray cod stock status - the Lower River Murray, South Australia. Stock Status Report to PIRSA Fisheries. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication Number F2007-000211-1, 32 pp.

Zampatti, B. P., Leigh, S. J. and Nicol, J. M. (2011). Fish and Aquatic Macrophyte Communities in the Chowilla Anabranch System, South Australia. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000719-1. SARDI Research Report Series No. 525.

Zampatti, B. P. and S. J. Leigh (2013a). Effects of flooding on recruitment and abundance of golden perch (*Macquaria ambigua ambigua*) in the lower River Murray. *Ecological Management and Restoration* **14**: 135–143.

Zampatti, B. P. and S. J. Leigh (2013b). Within-channel flows promote spawning and recruitment of golden perch, *Macquaria ambigua ambigua* – implications for environmental flow management in the River Murray, Australia. *Marine and Freshwater Research* **64**: 618–630.

Zar, J. H. (1984) *Biostatistical analysis*. Prentice-Hall, New Jersey.