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Reproduction and recruitment of golden perch (*Macquaria ambigua ambigua*) in the southern Murray–Darling Basin in 2013–2014: an exploration of river-scale response, connectivity and population dynamics

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PREMIUM FOOD AND WINE FROM OUR CLEAN ENVIRONMENT
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EXECUTIVE SUMMARY

Restoring flow regimes to benefit aquatic ecosystems, including fish, requires an empirical understanding of relationships between hydrology, life history and population dynamics. Spawning and recruitment of golden perch (*Macquaria ambigua ambigua*) in the southern Murray–Darling Basin (MDB) corresponds with overbank flooding and increased discharge that remains in-channel. As such, golden perch is considered a candidate species for measuring ecological response to environmental water allocations.

To understand the hydrological requirements of flow-cued spawning fish and measure reproductive response, there is a need to be able to accurately determine the hydrological conditions at the time and place of spawning. This can be achieved by the *in situ* collection of eggs, immediately post-spawning, or by retrospectively determining the spatio-temporal origin of larval, juvenile and adult fish (i.e. *when* and *where* a fish was spawned).

In spring/summer 2013–14, over 1000 GL of environmental water was allocated to the southern MDB, which incorporates the Murray and lower Darling rivers, and tributaries including the Edward–Wakool, Murrumbidgee and Goulburn rivers. This provided an opportunity to investigate the spawning and recruitment of golden perch, in association with flow, at sites across the southern MDB. We aimed to retrospectively determine the time and place of spawning of larval and young-of-year (YOY) fish, and the movement of larval, juvenile and adult golden perch between regions, using otolith microstructure and geochemistry, specifically strontium isotope ratios ($^{87}Sr/^{86}Sr$). Dissolved strontium isotope ratios in rivers and streams are an artefact of catchment geology and can provide a geographically distinct natural marker in fish otoliths. Importantly, Sr isotope ratios are not biologically modified; therefore $^{87}Sr/^{86}Sr$ values measured in otoliths are generally similar to those measured in ambient waters.

Water samples were collected at sites across the southern MDB in spring–summer 2013–14 to develop a spatio-temporal 'isoscape' of $^{87}Sr/^{86}Sr$ in water to provide a template for determining the spatial origin of early-life-stage golden perch. Sampling of golden perch eggs and larvae was conducted at sites in the lower and mid River Murray, and Goulburn, Murrumbidgee and Edward–Wakool rivers and otolith microchemistry was used to retrospectively determine the spatio-temporal origin (i.e. birth time and place) of larval and YOY fish. Otoliths were also collected from a representative subsample of the golden perch population at each location to enable determination of age structures and facilitate future investigation of the natal origin of strong cohorts.

There was a clear distinction in dissolved $^{87}Sr/^{86}Sr$ in water between various locations in the southern MDB in 2013–14, with many locations exhibiting minimal intra-seasonal variation. Distinct and relatively stable $^{87}Sr/^{86}Sr$ was recorded in the River Murray at Barmah, and the Goulburn, Murrumbidgee and Darling rivers. Sites in the mid River Murray, between the confluence of the Goulburn River and Lock 11 at Mildura, were also temporally stable but showed a clear attenuation of $^{87}Sr/^{86}Sr$ in a downstream direction from Barmah to Lock 11 (Mildura). The lower River Murray, downstream of the Darling River junction, exhibited high spatio-temporal variability in $^{87}Sr/^{86}Sr$ due to substantial temporal variation in the magnitude of discharge from its parent rivers, the Darling and Murray. Despite this temporal variation, $^{87}Sr/^{86}Sr$ in the lower Murray was distinctly lower and greater than the mid–River Murray and Darling rivers, respectively.

In the southern MDB in 2013–14, golden perch spawning, as indicated by the collection of eggs, and retrospective determination of age and spawning location of larvae and YOY, was identified in the Goulburn River, mid River Murray at Barmah and Hattah, Darling River and lower River Murray. Spawning occurred primarily from October–December and coincided with both the rising and descending limbs of within-channel and overbank flows and water temperatures ≥17°C.

Recruitment of golden perch to YOY (i.e. age 0+), following spawning from October–December 2013, was only apparent in the lower Murray and Darling rivers, and analysis of otolith microchemistry indicated these fish were spawned either in the lower Murray or Darling River. The fate of eggs and early life stage golden perch spawned in the River Murray at Barmah and Hattah, and the Goulburn River, remains unresolved.

Assessment of the resilience of golden perch populations requires an understanding of survivorship and population demographics. In 2014, a broad range of age classes of golden perch were collected in the southern MDB, with fish ranging from age 0+ to 20+ years. Throughout the lower River Murray, lower Darling River and mid River Murray, however, populations were dominated by age 4+ fish. Otolith $^{87}Sr/^{86}Sr$ indicated this cohort was spawned in the Darling River in 2009–10 during the Millennium Drought but in a year with a substantial summer flow in the lower Darling River. By measuring otolith $^{87}Sr/^{86}Sr$ from the core to edge, and integrating this with annual increments in otolith microstructure, we established that age 4+ golden perch collected in the lower and mid River Murray in 2014 moved out of the Darling River at age 1+ in association with extensive flooding in the southern MDB in 2011.

In the Goulburn River, age 4+ and 5+ fish, spawned in 2009–10 and 2008–09, respectively, were most prevalent, yet these fish may not have been spawned in the Goulburn River. Flows in the Goulburn River in 2008–09 and 2009–10 were extremely low, and no golden perch eggs or larvae were collected in either year. This raises the possibility that these fish migrated into the Goulburn River from the River Murray, or are stocked fish. Transects of otolith $^{87}Sr/^{86}Sr$ on juvenile and adult golden perch from the Goulburn River support this assertion, showing evidence of migration into the Goulburn River for an adult (age 6+) fish and, in the case of juvenile (age 1+ and 2+) fish, abrupt changes in $^{87}Sr/^{86}Sr$ early in the fishes life history, indicating stocking.

Management and restoration of freshwater fish populations at relevant spatio-temporal scales requires knowledge of the movement of juvenile and adult life stages and the spatial scale at which population processes occur. The present study constitutes a preliminary exploration of connectivity between regions in the southern MDB and demonstrates that larval, juvenile and adult golden perch move passively and actively over 100–1000s km including between the lower Darling River and lower and mid Murray rivers (larvae, juveniles and adults), and potentially the Murray and Goulburn rivers (adults). The results of this study support the notion that variability in within-channel flows in conjunction with appropriate water temperature can promote golden perch spawning. Nevertheless, in some regions of the southern MDB this may not lead to *in situ* recruitment of YOY fish. For example, spawning, as evidenced by the collection of golden perch eggs, occurred in the lower Goulburn River and the River Murray at Hattah in October–December 2013 but no YOY fish were collected at these sites in March–April 2014.

Golden perch age structures in any one region of the southern MDB may be dependent on movement/dispersal from regions hundreds of kilometres away. Indeed, specific spawning events and locations may influence golden perch population dynamics at large spatial scales (1000s km) thus reinforcing the importance of hydrological and biological connectivity throughout the rivers of the southern MDB and the need for a river-scale perspective for the management of golden perch. Further investigations are required, however, to determine the level of connectivity between regions and the importance of immigration and emigration, stocking, and natural and angling mortality in influencing population demographics and the resilience of golden perch populations.

INTRODUCTION

Fish are prominent indicators of the impacts of altered flow regimes on aquatic ecosystems and in Australia's Murray–Darling Basin (MDB) river regulation and water abstraction have contributed to significant reductions in native fish populations (Barrett 2004). Restoring flow regimes with environmental water allocations has become a key aspect of ecosystem management in the MDB (MDBA 2012; Koehn *et al.* 2014). To be effective, however, flow restoration to benefit aquatic ecosystems, including fish, requires an understanding of relationships between hydrology, life history and population dynamics (Arthington *et al*. 2006).

Golden perch (*Macquaria ambigua ambigua*) is one of only two fish species (along with silver perch, *Bidyanus bidyanus*) in the southern MDB that is considered to require increased discharge to initiate spawning (Humphries *et al.* 1999). Spawning and recruitment of golden perch in the River Murray corresponds with both increased flow contained within the river channel and overbank flooding (Mallen-Cooper and Stuart 2003; King *et al*. 2009; Zampatti and Leigh 2013a). As such, golden perch is considered a candidate species for measuring ecological response to environmental water allocations (King *et al*. 2009).

In spring/summer 2013–14, over 1000 GL of environmental water was allocated to the southern MDB, which incorporates the Murray and lower Darling rivers, and tributaries including the Edward–Wakool, Murrumbidgee and Goulburn Rivers (Figure 1). Environmental water allocations were generally delivered to meet specific ecological objectives at site- (e.g. Barmah–Millewa Forest and the Coorong, Lower Lakes and Murray Mouth) or river reach-scales (e.g. the Goulburn River and lower River Murray channel) although these locations were ultimately connected as water flowed along the River Murray to the sea. Consequently, flow-related ecological responses may have occurred over 1000s of kilometres of river. Integration of monitoring and research projects at specific sites provides an opportunity to investigate river-scale responses to large spatial scale environmental flows.

To understand the hydrological requirements of flow-cued spawning fish, such as golden perch, and measure a reproductive response, there is a need to be able to accurately determine the hydrological conditions at the time and place of spawning. This can be achieved by the *in situ* collection of eggs immediately post-spawning or by retrospectively determining the spatio-temporal provenance of larval, juvenile and adult fish (i.e. *when* and *where* a fish was spawned). Yet, to date, few investigations relating golden perch egg/larval presence and/or recruitment to flow have considered precisely when or where fish were spawned (although see Mallen-Cooper and Stuart 2003; Ebner *et al*. 2009; King *et al*. 2009; Zampatti and Leigh 2013a).

Fish otoliths (earstones) are calcareous structures that are formed by the sequential addition of layers of calcium carbonate from birth to death. The chemical composition of the otolith reflects, at least in part, the chemistry of ambient water at the time of deposition (Campana and Thorrold 2001). Consequently, the migration history of a fish, including its place of birth and death, can potentially be determined by comparing geochemical signatures in otoliths with ambient signatures in water, if there is geographic variability in water chemistry.

Dissolved strontium isotope ratios (i.e. $^{87}Sr/^{86}Sr$) in rivers and streams are an artefact of catchment geology and can provide a geographically distinct natural marker in fish (Gillanders 2005). Importantly, Sr isotope ratios are not biologically modified; therefore $^{87}Sr/^{86}Sr$ values measured in otoliths are generally similar to those measured in ambient waters. As a result, spatio-temporal 'isoscapes' of dissolved $^{87}Sr/^{86}Sr$ in water can provide a fundamental template for determining the spatial origin of freshwater fish (Barnett-Johnson *et al.* 2008; Muhlfeld *et al*. 2012).

In spring/summer 2013–14, it was expected that overbank flooding in the Barmah region and within-channel rises in flow in the main-channel, and tributaries of the Murray and Darling rivers, would promote spawning and facilitate recruitment of golden perch (King *et al*. 2009; Zampatti and Leigh 2013b). Numerous projects (funded by the Murray–Darling Basin Authority, Commonwealth Environmental Water Office and State agencies) were proposed to investigate the spawning and recruitment of golden perch in relation to environmental flow delivery. Consequently, a significant opportunity existed to integrate data from these projects to investigate the river-scale response of golden perch to flow restoration in the southern MDB.

By integrating projects being undertaken in the Goulburn River, lower and mid River Murray, Murrumbidgee River and Edward–Wakool system, and including additional sites in the Darling River, we aimed to compare the spawning and recruitment response of golden perch at sites across much of the southern MDB. Using otolith geochemistry, specifically strontium isotope ratios ($^{87}Sr/^{86}Sr$), we also aimed to investigate the movement of various life stages of golden perch (e.g. larvae and juveniles) between these regions and hence examine the level of connectivity among populations. We also collected age-structure data to contrast population demographics between regions.

Our overall aim was to determine golden perch spawning and recruitment responses to flow in the southern MDB in 2013–14 in order to facilitate an understanding of the interrelatedness of golden perch life histories and connectivity between regions. This knowledge is integral to guide the restoration of flow regimes to improve the health of native fish populations and in turn aquatic ecosystems, a central goal of the Basin Plan (MDBA 2012). Our specific objectives were to:

1) Develop a spatio-temporal ‘isoscape’ of $^{87}Sr/^{86}Sr$ in water across the southern MDB in spring/summer 2013–14 to provide a template for determining the natal origin (spawning location) of early life-stage golden perch.
2) Integrate the data from sampling of golden perch eggs/larvae (an indicator of spawning) and young-of-year (YOY) recruits from sites across the southern MDB to determine where reproduction occurred.
3) Use otolith microstructure and geochemistry to retrospectively determine the spatio-temporal provenance (i.e. birth time and place) of golden perch larvae and juveniles from each location and relate this to environmental conditions (e.g. flow and water temperature) at the time and place of spawning.
4) Integrate these data to develop a system-scale understanding of golden perch life history and response to flow.
5) Collect otoliths from a representative subsample of the golden perch population at each location to enable determination of age structures and facilitate future investigation of the natal origin of strong cohorts.

STUDY REGION

The Murray–Darling Basin (MDB) drains an area of 1 073 000 km^2 or 17% of the Australian continent. The combined length of the two major rivers, the Murray and the Darling, is ~5500 km and both flow through predominantly semi-arid or arid landscapes. In their natural states, they experienced highly variable flow regimes (Walker *et al*. 1995; Puckridge *et al*. 1998). River regulation, in the form of large headwater storages, weirs, floodplain levees and tidal barrages, and consumptive use for irrigation and domestic supply, has had a profound impact on the magnitude and variability of discharge in the River Murray (Maheshwari *et al*. 1995) and many of its tributaries (Cottingham *et al*. 2003; Kingsford 2003).

This study was conducted in the lower and mid reaches of the River Murray, the lower Darling River, and three tributaries of the mid-River Murray; the Murrumbidgee, Edward-Wakool and Goulburn rivers. The lower River Murray extends downstream from the Darling junction to the river mouth (Figure 1). In this region 10 low-level (~3 m) weirs fragment 830 km of river into a series of contiguous weir pools. Unlike the regulated but free flowing mid and upper-reaches of the River Murray, the weirs transform a historically highly dynamic lotic system into a homogenous series of lentic environments under low flows (Walker 2006). For the purpose of this investigation we consider the lower Murray as two distinct geomorphic regions (Walker and Thoms 1993): 1) the *floodplain* region, extending from the Darling River confluence to Lock 3 and 2) the *gorge* region, extending from Lock 3 to Mannum (Figure 1). The mid Murray extends upstream from the Darling River junction to Yarrawonga (Figure 1). This region is less fragmented by weirs and still retains long reaches (100s km) of lotic habitats; nevertheless, it is impacted by highly regulated discharge and in some reaches, particularly upstream of Torrumbarry Weir, seasonal inversion of flow (Maheshwari *et al*. 1995).

The Goulburn River is a tributary of the mid River Murray that drains the north-western slopes of the Great Dividing Range. Sites in this study were located in the lower Goulburn River between Goulburn Weir and the River Murray junction (Figure 1). Much of the catchment is cleared agricultural land although some areas of forest remain, particularly in the lower reaches which flow through the Lower Goulburn National Park. Flow in the lower Goulburn River is highly regulated by several upstream dams and weirs, which in particular have reduced winter–spring flows.

The Murrumbidgee River is ~1700 km long and originates in the alpine region of south eastern Australia, flowing in a northerly direction until downstream of Canberra and then predominantly west. The Murrumbidgee is regulated by two large capacity water storages, Blowering Dam on the Tumut River and Burrinjuck Dam on the main stem, both of which are situated in the mid-upper reaches of the catchment. Flows are highly regulated and a further seven weirs on the main river channel re-regulate water and aid in supplying irrigation channels throughout the warmer months. Median annual flows at Balranald represent 20% of natural inflows primarily due to abstraction and diversion for irrigation, as well as evaporation losses. Within the study area, channel widths are typically ~70 m, maximum river depths are commonly 3–5 m and river red gum (*Eucalyptus camaldulensis*) represents the dominant in-stream habitat. The study was undertaken in the Murrumbidgee River between Wagga Wagga and Balranald, New South Wales (Figure 1).

The Edward-Wakool system is a large anabranch system of the River Murray. The system begins upstream of the Barmah choke, and travels northwest through a series of river red gum forests before discharging back into the River Murray downstream of Kyalite (Figure 1). It is a complex network of interconnected streams, ephemeral creeks, flood-runners and wetlands including the Wakool River, Yallakool Creek, Colligen-Niemur Creek and Merran Creek. Like many areas of the Murray-Darling Basin, the Edward-Wakool anabranch system has suffered from the effects of river regulation, migration barriers and degradation of water quality. The flow regime within the Edward-Wakool system has been significantly altered by river regulation, with changes to both the timing and volume of flows. Substantial modification of the flow regime results from the use of the system as a diversionary delivery channel for the lower River Murray; large volumes of water are sent through the system to bypass the Barmah Choke to avoid over-bank flooding at Barmah.

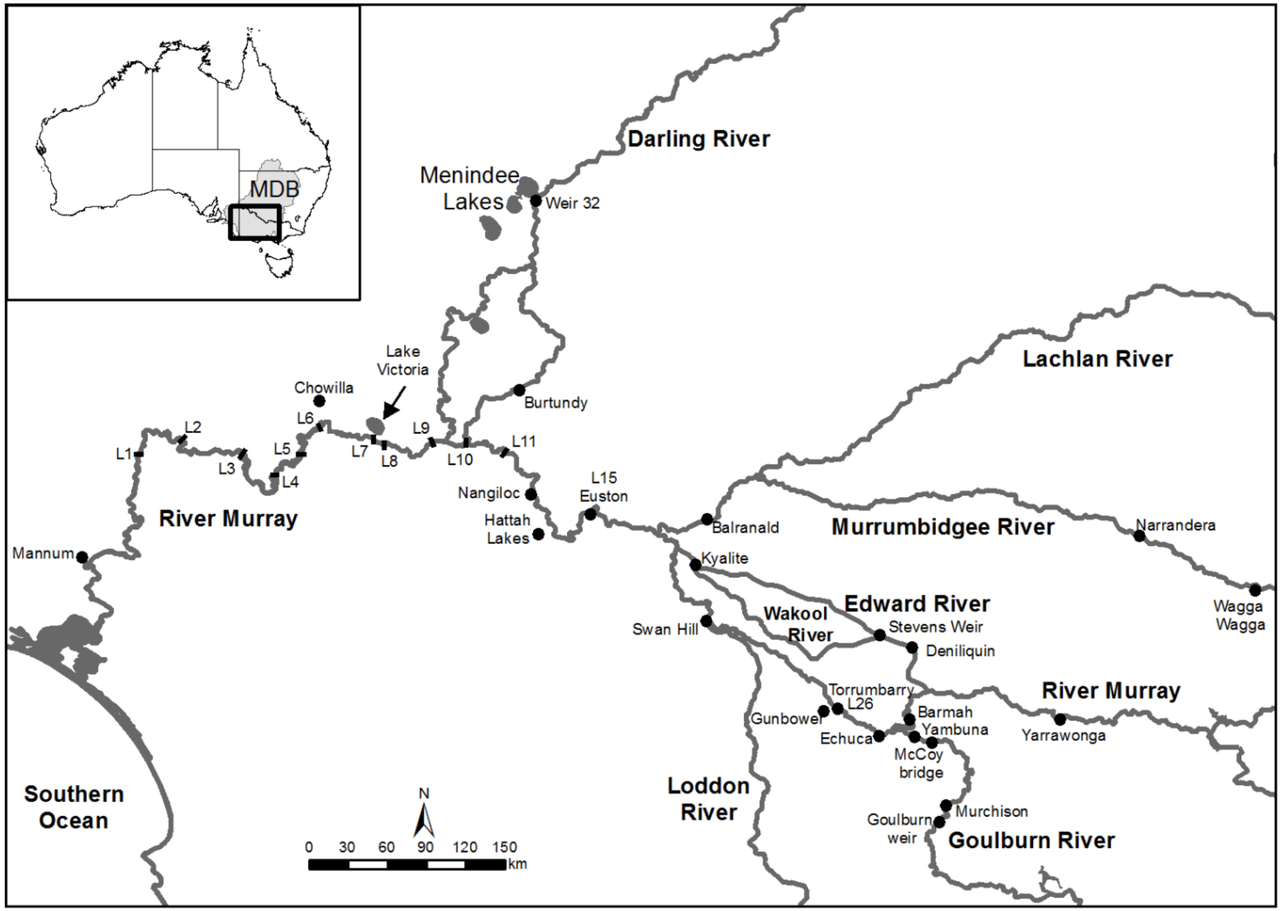

Figure 1. Map showing the location of the Murray–Darling Basin and the major rivers that comprise the southern Murray-Darling Basin, showing the numbered Locks and Weirs (up to Lock 26, Torrumbarry), the Darling, Lachlan, Murrumbidgee, Edward–Wakool, Loddon and Goulburn rivers and Lake Victoria, an off-stream storage used to regulate flows in the lower River Murray.

METHODS

Hydrology

Daily mean flow (ML day^{-1}) and water temperature (°C) for the period August 2013 to April 2014 were obtained for the River Murray at the South Australian border (18 km upstream of Lock 6), Euston, Torrumbarry and Barmah, the Darling River at Burtundy, Goulburn River at McCoy's Bridge, Murrumbidgee River at Narrandera and the Edward–Wakool at Deniliquin (MDBA, unpublished data).

Analysis of water $^{87}Sr/^{86}Sr$ at sites across the southern MDB

To determine spatio-temporal variation in water $^{87}Sr/^{86}Sr$ over the spring/summer of 2013/14, water samples were collected fortnightly–monthly from 12 sites across the study region (Table 1).

Table 1. Location of water sample collection for $^{87}Sr/^{86}Sr$ analysis.

River	Location	Sampling period	Total number of samples
Murray	Lock 1	16/09/13–17/02/14	12
Murray	Lock 6	17/09/13–04/02/14	11
Murray	Lock 9	01/10/13–21/01/14	9
Murray	Lock 11	23/09/13–03/02/14	10
Murray	Swan Hill	30/09/13–13/02/14	10
Murray	Torrumbarry	29/09/13–30/01/14	5
Murray	Echuca	22/10/13 –16/12/13	5
Murray	Barmah	16/10/13–17/12/13	6
Darling	Weir 32	04/11/13–26/02/14	9
Edward–Wakool	Deniliquin	24/09/13–11/02/14	11
Murrumbidgee	Narranderra	17/09/13–04/02/14	11
Goulburn	Yambuna	07/10/13–17/12/13	6

Aliquots (20 ml) of each water sample were filtered through a 0.2 µm Acrodisc syringe-mounted filter into a clean polystyrene beaker and dried overnight in a HEPA-filtered fume cupboard. Previous analyses have shown that filtering after transfer to the laboratory, rather than after sample collection in the field, has no influence on measurement of $^{87}Sr/^{86}Sr$ (e.g. Palmer and Edmond 1989).

Strontium was extracted using a single pass over 0.15 ml (4 x 12 mm) beds of EICHROMTM Sr resin (50–100 µm). Following Pin *et al*. (1994), matrix elements were washed off the resin with 2M and 7M nitric acid, followed by elution of clean Sr in 0.05M nitric acid. The total blank, including syringe-filtering, is ≤0.1 ng, implying sample to blank ratios of ≥4000; no blank corrections were therefore deemed necessary. Strontium isotope analyses were carried out on a “Nu Plasma” multi-collector inductively coupled plasma mass spectrophotometer (ICPMS) (Nu Instruments, Wrexham, UK) interfaced with an ARIDUS desolvating nebulizer, operated at an uptake rate of ~40 µL min^{-1}. Mass bias was corrected by normalizing to ^{88}Sr:^{86}Sr = 8.37521 and results reported relative to a value of 0.710230 for the SRM987 Sr isotope standard. Internal precisions (2SE) based on at least 30 ten-second integrations averaged ± 0.00002 and average reproducibility (2SD) was ± 0.00004.

Sampling golden perch eggs and larvae

Fish eggs and larvae were sampled at sites in the southern Murray-Darling Basin using a combination of plankton tows (lower River Murray only), drift nets (all sites except lower River Murray) and quatrefoil light traps (Murrumbidgee only). Plankton tows were conducted using a pair of square-framed bongo nets with 500 µm mesh; each net was 0.5 x 0.5 m and 3 m long. Drift nets consisted of 500 µm mesh and were 1.5 m long with a 0.5 m diameter mouth opening. The volume of water (m^3) filtered through each net was determined using a calibrated flow meter (General Oceanics™, model 2030R) placed in the centre of the mouth openings. Drift nets were set in the late afternoon (after 1600 hrs.) and retrieved in the morning (before 1100 hrs.). Fish in all samples were euthanased (Alfaxan or Benzocaine) and preserved (70-95% ethanol) in the field and returned to the laboratory for processing. Samples were sorted using a dissecting microscope. Larvae and eggs were identified, and where possible, classified as pre-flexion (i.e. early stage larvae with notochord predominately straight) or post-flexion (i.e. the start of upward flexion of the notochord and appearance of fin rays and fin fold) following Serafini and Humphries (2004).

Lower River Murray

Larval fish sampling was conducted at two sites in the lower River Murray, 5 km downstream of Lock 1 (34°21.138' S, 139°37.061' E) and 5 km downstream of Lock 6 (33°59.725' S, 140°53.152' E) (Figure 1), approximately fortnightly between October 2013 and early February 2014. Three day-time and three night-time plankton tows were undertaken on the same day at each site, with both sites sampled within a two-day period.

Mid River Murray (Hattah)

Fish eggs and larvae were sampled in the mid River Murray at four sites near Chalka Creek in the Hattah Lakes region (Figure 1; Table 2) using 4 drift nets (2 surface, 2 bottom) set at each site. Sampling was conducted fortnightly from early November to early December 2013.

Table 2. Details of larval sampling sites in the mid River Murray at Hattah**.**

Site	Latitude	Longitude
1200 m downstream of pumping station	-34.72892	142.50891
500 m downstream of pumping station	-34.73223	142.50377
500 m upstream of pumping station	-34.74071	142.50412
950 m upstream of pumping station	-34.74051	142.50867

River Murray at Barmah

Fish eggs and larvae were sampled at three sites in the River Murray in the Barmah region using three drift nets set at each site (Figure 1; Table 3). Sampling was conducted fortnightly, from the 16th October to 3rd December 2013 with an additional sampling trip conducted during the week of the 18th November to coincide with a small fall and rise in discharge and water level as part of the environmental water delivery.

Table 3. Details of larval sampling sites in the River Murray at Barmah**.**

Site	Latitude	Longitude
Murray River @ Morning Glory	S36.08	E144.947
Murray River @ Barmah Lake	S35.95	E144.954
Murray River @ Ladgroves	S35.86	E145.344

Goulburn River

Fish eggs and larvae were sampled at three sites in the lower Goulburn River using two drift nets set at each site (Table 4). Sampling was conducted fortnightly from October–December 2013, with additional sampling conducted twice per week coinciding with environmental flow releases.

Table 4. Details of larval sampling sites in the lower Goulburn River**.**

Site	Latitude	Longitude
Yambuna	S36.131	E145.003
Pyke Road	S36.427	E145.357
Murchison (Cable Hole)	S36.69	E145.230

Murrumbidgee River

Fish eggs and larvae were sampled fortnightly from late August 2013–early January 2014 at five in-channel sites (n = 11 sampling events per sites; Table 5) using a combination of eight larval drift nets and ten light traps set overnight at each site.

Table 5. Details of larval sampling sites in the Murrumbidgee River**.**

Site	Latitude	Longitude
Berry Jerry	S35.0169	E147.0232
Gooragool	S34.6311	E146.1055
Sunshower	S34.587	E146.0498
Yarrada	S34.5591	E145.8216
McKennas	S34.4371	E145.5142

Edward-Wakool system

Targeted drift net sampling was undertaken in the Edward-Wakool River system in November 2013 to assess the spawning response of golden perch to an environmental flow delivered to Yallakool Creek (Watts *et al.* 2014). Larval drift nets were set at two sites in Yallakool Creek, as well as two sites in the Wakool River and Colligen Creek (Table 6); two nearby rivers which did not receive environmental water. Three, 500 µm conical drift nets (1.5 m long, with a 0.5 m diameter mouth opening) were set in each of the three rivers over 3 nights before (5–7 November 2013), during (13–15 November 2013) and after (20–21 November 2013) the delivery of the in-channel fresh, resulting in a total of 9 sampling nights.

Table 6. Details of larval sampling sites in the Edward-Wakool River system.

River/Creek	Site	Latitude	Longitude
Yallakool Creek	Hopwoods	-35.487°	144.645°
Yallakool Creek	Cumnock Park	-35.493°	144.639°
Wakool River	Many Waters	-35.497°	144.878°
Wakool River	Yalloke	-35.493°	144.860°
Colligen Creek	Bowen Park	-35.431°	144.639°
Colligen Creek	Bowen Park	-35.430°	144.688°

Sampling young-of-year golden perch and population age-structure

Adult and juvenile golden perch were sampled by boat electrofishing using either a 5 kW or 7.5 kW Smith Root (Model GPP 5 or 7.5) electrofishing unit. Sampling was undertaken in March–April 2014 to maximise the chance of collecting young-of-year (YOY) golden perch spawned in the spring–summer 2013–14 spawning season. Electrofishing for golden perch in the Edward–Wakool system and the Barmah region of the River Murray was scheduled to be undertaken outside of the timeframe of the current project (August 2013–April 2014) so results from these regions were unavailable.

Electrofishing was conducted during daylight hours and all available littoral habitats were fished. At each site the total time during which electrical current was applied ranged from approximately 1000 to 1800 seconds. All fish were measured to the nearest mm (total length, TL) and a subsample, proportionally representing the length-frequency of golden perch collected, were retained for ageing.

Lower River Murray and Darling River

Electrofishing was conducted at eight sites in the main channel of the South Australian River Murray, 22 sites in the Chowilla Anabranch system and adjacent River Murray, and four sites in the lower Darling River (downstream of Weir 32) in autumn (March/April) 2014 (Table 7). A subsample of fish (*n* = 49–67) proportionally representing the length-frequency of golden perch collected from the gorge and floodplain geomorphic regions of the lower River Murray and the lower Darling River was retained for ageing. Additional juvenile fish were obtained from plankton tows conducted as part of larval fish sampling in December 2013–February 2014 and from *ad hoc* fyke net sampling in the wetlands connected to the lower River Murray main channel (floodplain geomorphic region) in December 2013.

Table 7. Details of boat electrofishing sites in the lower Murray and Darling rivers.

River	Site	Latitude	Longitude
Murray	Murtho Forest	S34.07974	E140.75085
Murray	Plushes Bend	S34.22775	E140.74009
Murray	Rilli Island	S34.39145	E140.59164
Murray	Cobdogla	S34.21724	E140.36522
Murray	Lowbank	S34.16490	E140.03611
Murray	Morgan	S34.05534	E139.68784
Murray	Swan Reach	S34.55317	E139.60809
Murray	Caurnamont	S34.83723	E139.57341
Darling	Pomona	S34.00913	E141.90374
Darling	Lethro	S33.59618	E142.43884
Darling	Pooncarie (downstream)	S33.37666	E142.56178
Darling	Pooncarie (upstream)	S33.37972	E142.55553

Mid River Murray (Mildura to Torrumbarry)

Electrofishing was conducted at six sites in the mid-River Murray between Gunbower and Nangiloc during March 2014 (Table 8). A subsample of 49 fish was retained for ageing.

Table 8. Details of boat electrofishing sites in the mid-River Murray.

Site	Latitude	Longitude
Nangiloc	S34.477	E142.376
Wemen	S34.761	E142.545
Boundary Bend	S34.711	E143.146
Tooleybuc	S35.020	E143.335
Benjeroop	S35.486	E143.877
Gunbower	S35.739	E144.253

Goulburn River

Electrofishing was conducted at 13 sites in the lower Goulburn River during March 2014 (Table 9). A subsample of 19 fish was retained for ageing.

Table 9. Details of boat electrofishing sites in the lower Goulburn River.

Site	Latitude	Longitude
Murchison (Cable Hole)	S36.69	E145.230
Cemetary Bend	S36.516	E145.322
Pyke Road	S36.427	E145.357
Mooroopna	S36.392	E145.369
Shepparton	S36.381	E145.394
Shepparton Weir	S36.354	E145.353
Loch Garry	S36.242	E145.287
Pogues Road Undera	S36.203	E145.268
Kotupna	S36.164	E145.222
McCoys Bridge	S36.177	E145.123
Murrumbidgee Road Pederick	S36.156	E145.035
Yambuna	S36.131	E145.003
Kanyapella	S36.095	E144.925

Murrumbidgee River

Electrofishing was conducted at 23 sites on the Murrumbidgee River in February and March 2014, including two sites on Old Man Creek and sites overlapping with those sampled for larval fish (Table 10). Possible YOY golden perch (n = 2) were retained for ageing.

Table 10. Details of boat electrofishing sites in the Murrumbidgee River.

Site	Latitude	Longitude
Baupie escape	S34.63837	E143.60730
Bernofy	S35.02480	E146.98830
Berry Jerry Station	S35.01688	E147.02317
Birdcage Reserve	S34.52260	E145.71130
Carrathool	S34.44846	E145.41882
Cookoothama	S34.55864	E145.93520
Euroly Bridge	S34.63651	E146.37006
Glen Avon - Redgum Mill	S34.57740	E143.64364
Gooragool river site	S34.63113	E146.10548
Gum Creek	S34.88449	E146.77655
Hay Boatramp	S34.51565	E144.83373
Maude	S34.47676	E144.30320
Mckennas river site	S34.43711	E145.51423
Mucklebar	S35.10894	E147.44567
Nap Nap	S34.43822	E144.15225
Narrandera Boatramp	S34.75537	E146.55126
Pevensey Reserve	S34.55951	E144.66071
Redbank Weir	S34.37867	E143.78315
Sunshower river site	S34.58701	E146.04975
Willow Isles	S34.71658	E143.38386
Wyreema	S34.48586	E144.99724
Wyvern	S34.46738	E145.69093
Yarrada river site	S34.55908	E145.82159

Ageing

Larvae and young-of-year (YOY)

To estimate the spawn date of larval and YOY golden perch, daily increment counts in otolith microstructure were examined in 38 fish collected from the lower River Murray and lower Darling River. Golden perch larvae/juveniles were measured to the nearest millimetre and sagittal otoliths were removed. Otoliths were mounted individually in Crystalbond^{TM}, proximal surface downwards, and polished down to the primordium using a graded series of wetted lapping films (9, 5, and 3 µm). Sections were then polished using 0.3 µm alumina slurry to a thickness of 50–100 µm.

Sections were examined using a compound microscope (x 600) fitted with a digital camera and Optimas image analysis software (version 6.5, Media Cybernetics, Maryland, USA). Increments were counted blind with respect to fish length and capture date. Estimates of age were determined by counting the number of increments from the primordium to the otolith edge. Three successive counts were made by two readers for one otolith from each fish. If these differed by more than 10%, or differed by more than 3 days in the case of very young fish (<30 days), the otolith was rejected, but if not, the mean was used as an estimate of the number of increments. Increment counts were considered to represent true age of larval and juvenile golden perch (Brown and Wooden 2007) and spawn dates were determined by subtracting the estimated age from the capture date (Zampatti and Leigh 2013b).

Juveniles and adults

Golden perch exhibit considerable variation in length-at-age in the MDB (Anderson *et al.* 1992). Therefore to accurately assess the age structure and year-class strength of golden perch, we investigated both length and age-frequency distributions in the lower River Murray, lower Darling River, mid River Murray (Mildura–Torrumbarry) and Goulburn River. Fish retained for ageing (n = 305) were euthanized and sagittal otoliths were removed. Whole otoliths were embedded in clear casting resin and a single 400 to 600 µm transverse section was prepared. Sections were examined using a dissecting microscope (x 25) under transmitted light. Estimates of age were determined independently by three readers by counting the number of discernible opaque zones (annuli) from the primordium to the otolith edge. YOY (<1 year old) fish were defined as individuals lacking clearly discernible annuli.

$^{87}Sr/^{86}Sr$ analysis

Larvae and young-of-year otolith preparation

Sagittal otoliths of 23 larval and YOY fish collected from the lower River Murray and lower Darling River were dissected and mounted individually in Crystalbond™, proximal surface downwards, on an acid-washed glass slide and polished down to the primordium using a graded series of wetted lapping films (9, 5 and, 3 µm). The slide was then reheated and the polished otolith transferred to a 'master' slide, on which otoliths from all collection sites were combined and arranged randomly to remove any systematic bias during analysis. The samples were rinsed in Milli-Q water (Millipore) and air dried overnight in a class 100 laminar flow cabinet at room temperature.

Juveniles and adults otolith preparation

Whole sagittae from 35 juvenile/adult fish (i.e. ≥ age 1+) collected from the lower River Murray, lower Darling River, mid River Murray (Mildura–Torrumbarry) and Goulburn River were embedded in clear casting resin and a single 400 to 600 µm transverse section was prepared. The transverse sections were mounted individually on acid-washed glass slides using Crystalbond™ and polished using wetted lapping film (9 µm). The slide was then reheated and the polished otolith transferred to a 'master' slide, on which otoliths from all collection sites were combined and arranged randomly to remove any systematic bias during analysis. The samples were rinsed in Milli-Q water (Millipore) and air dried overnight in a class 100 laminar flow cabinet at room temperature.

LA-ICPMS

Laser ablation – inductively coupled plasma mass spectrometry (LA-ICPMS) was used to measure $^{87}Sr/^{86}Sr$ in the otoliths of larval, juvenile and adult fish. The experimental system consisted of a ''Nu Plasma'' multi-collector LA-ICPMS (Nu Instruments, Wrexham, UK), coupled to a HelEx laser ablation system (Laurin Technic, Canberra, Australia, and the Australian National University) constructed around a Compex 110 excimer laser (Lambda Physik, Gottingen, Germany) operating at 193 nm. Otolith mounts were placed in the sample cell and the primordium of each otolith was located visually with a 400× objective and a video imaging system. The intended ablation path on each sample was then digitally plotted using GeoStar v6.14 software (Resonetics, USA). Each otolith was ablated along a transect from the primordium to the dorsal margin at the widest radius using a 6 × 100 µm rectangular laser slit. The laser was operated at 90 mJ, pulsed at 10 Hz and scanned at 5 or 10 µm sec^{-1} (depending on the size of the otolith) across the sample. Ablation was performed under pure He to minimise the re-deposition of ablated material, and the sample was then rapidly entrained into the Ar carrier gas flow. A pre-ablation step using reduced energy (50 mJ) was conducted along each transect to remove any surface contaminants and a 20–30 sec background was measured prior to acquiring data for each sample. Corrections for Kr and Rb interferences were made following closely the procedures of Woodhead *et al*. (2005) and mass bias was then corrected by reference to an $^{86}Sr/^{88}Sr$ ratio of 0.1194. Iolite Version 2.13 (Paton *et al*. 2011) that operates within IGOR Pro Version 6.2.2.2 (WaveMetrics, Inc., Oregon) was used to process data offline, with data corrected for potential Ca argide/dimer interferences.

A modern marine carbonate standard composed of mollusc shells ($^{87}Sr/^{86}Sr$ value of 0.70916 according to long-term laboratory measurements, identical to the accepted modern seawater value of 0.709160, MacArthur and Howarth 2004) was analysed after every 10 otolith samples to allow for calculation of external precision. Mean (±1 SD) values of $^{87}Sr/^{86}Sr$ values in the modern marine carbonate standard (n = 24) run throughout the analyses were 0.70918 ± 0.00017, with external precision (expressed as ± 2 SE) calculated as ± 0.00006. Mean within-run precision, measured as ± 2 SE, was ± 0.00005.

RESULTS

Water $^{87}Sr/^{86}Sr$ and hydrology

Water sample collection commenced in late September/early October 2013 and extended through until February 2014 at most sites. Overall, $^{87}Sr/^{86}Sr$ at most locations remained reasonably stable throughout the period of collection, with the highest ratios (>0.7190) measured in the River Murray at Barmah and the Edward River, and the lowest (<0.7080) in the Darling River (Figure 2). Water $^{87}Sr/^{86}Sr$ generally decreased longitudinally along the River Murray as tributaries with distinct and relatively temporally stable $^{87}Sr/^{86}Sr$ (e.g. Goulburn and Murrumbidgee rivers) contribute to discharge. At sites in the lower River Murray (downstream of the Darling River junction) $^{87}Sr/^{86}Sr$ was highly variable due to substantial temporal variation in water source (i.e. from the mid Murray, Darling River and Lake Victoria), although $^{87}Sr/^{86}Sr$ at Lock 1 remained reasonably stable (Figure 2).

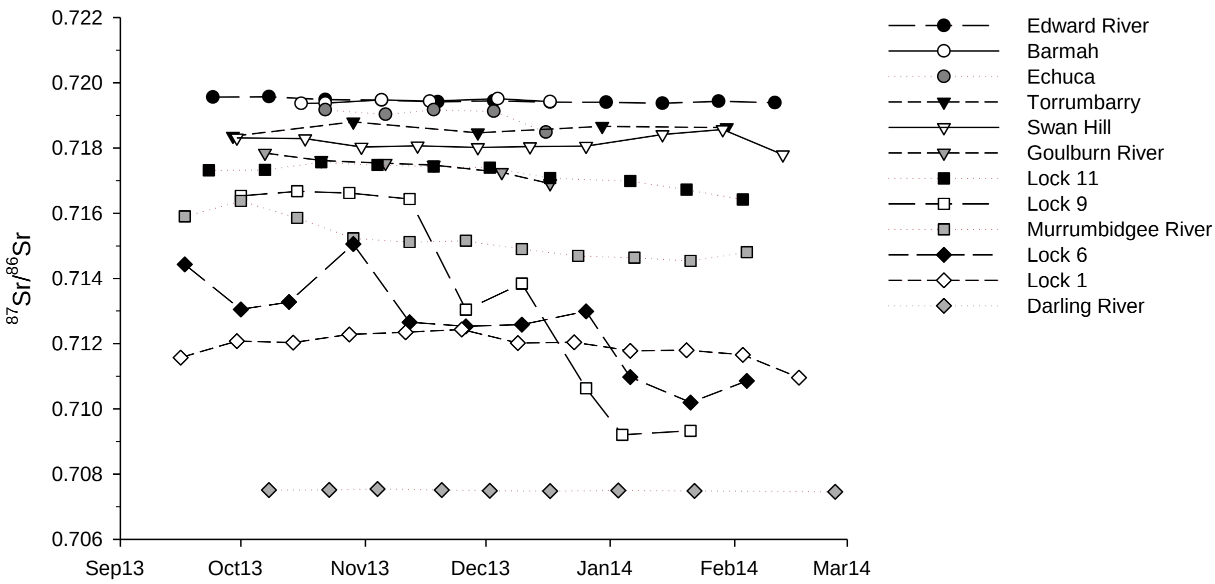

Figure 2. $^{87}Sr/^{86}Sr$ ratios in water samples collected from mid-September/early-October 2013 to February 2014 in the River Murray (Lock 1, 6, 9, 11, Swan Hill, Torrumbarry, Echuca and Barmah), and the Darling, Goulburn, Edward and Murrumbidgee rivers.

Lower River Murray and Darling River

From August 2013 to early January 2014, flow in the lower River Murray (discharge at the South Australian border, QSA) generally reflected flow in the mid-reaches of the Murray at Euston. In both reaches, flows increased from approximately 8000 ML day^{-1} in mid-August 2013 to a peak of approximately 25 000–27 000 ML day^{-1} in late September–mid October 2013. Flows then gradually decreased to approximately 8000 ML day^{-1} in early January 2014, with some variation in the descending limb of the hydrograph in December 2013 (Figure 3). In early January, flow in the River Murray at Euston decreased to approximately 5000 ML day^{-1} while flow in the lower Murray ranged 7000–10 000 ML day^{-1} as a result of flow from the Darling and water released from Lake Victoria (Figure 3). Flow in the Darling River at Burtundy was <1000 ML day^{-1} until early December 2013 when flow increased to a maximum of approximately 3000 ML day^{-1} through late December and early January before gradually decreasing to <1,000 ML day^{-1} by late March 2014 (Figure 3).

$^{87}Sr/^{86}Sr$ in water samples collected from Lock 9 and 6 in the lower River Murray was highly variable exhibiting a trend from higher ratios (0.7140–0.7170) representative of the mid-Murray in October–mid-November 2013 before decreasing as a result of the influence of increasing Darling flows and decreasing flow from the mid Murray from December 2013 (Figure 3). From September 2013–February 2014, $^{87}Sr/^{86}Sr$ in water samples collected from Lock 1 remained relatively stable ranging 0.7110–0.7125 and from October 2013–February 2014, $^{87}Sr/^{86}Sr$ in the Darling River at Menindee (Weir 32) remained constant at approximately 0.7075 (Figure 3).

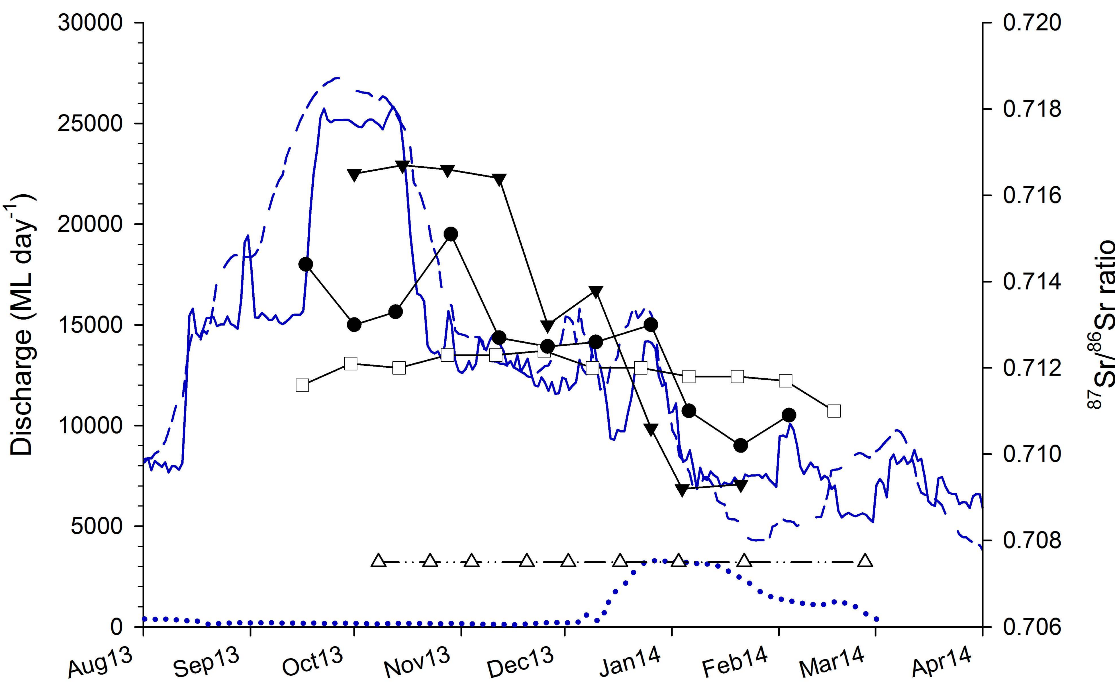

Figure 3. Mean daily discharge (ML day^{-1}) in the River Murray at the South Australian border (solid blue line) and Euston (dashed blue line), and Darling River at Burtundy (dotted blue line). $^{87}Sr/^{86}Sr$ in water samples collected from mid-September 2013 to late-February 2014 in the River Murray at Lock 9 (solid triangles), Lock 6 (solid circles) and Lock 1 (open squares), and the Darling River at Menindee (Weir 32) (open triangles).

Mid River Murray

Flow at Euston generally reflected flow at Swan Hill, with a slight time delay (Figure 4). At Euston, flows increased from approximately 8000 ML day^{-1} in August 2013 to a peak of approximately 27 000 ML day^{-1} in late September 2013. Flow at Swan Hill increased from approximately 6000 ML day^{-1} in August to a peak of approximately 20 000 ML day^{-1} in early October (Figure 4). Flows at Euston peaked higher than flows at Swan Hill due to increased flow from the Murrumbidgee River in early August 2013 (Figure 4; Figure 8). Flows then gradually decreased to approximately 13 000 ML day^{-1} in late November 2013 and reduced further to approximately 5000 ML day^{-1} by late January 2014 (Figure 4).

$^{87}Sr/^{86}Sr$ in water samples collected from Lock 11 and Swan Hill remained relatively stable from mid-September to mid-December (Lock 11 ranging from 0.7171–0.7176; Swan Hill ranging from 0.7180–0.7183) before decreasing slightly to approximately 0.7160 at Lock 11 and 0.7175 at Swan Hill by February 2014 (Figure 4).

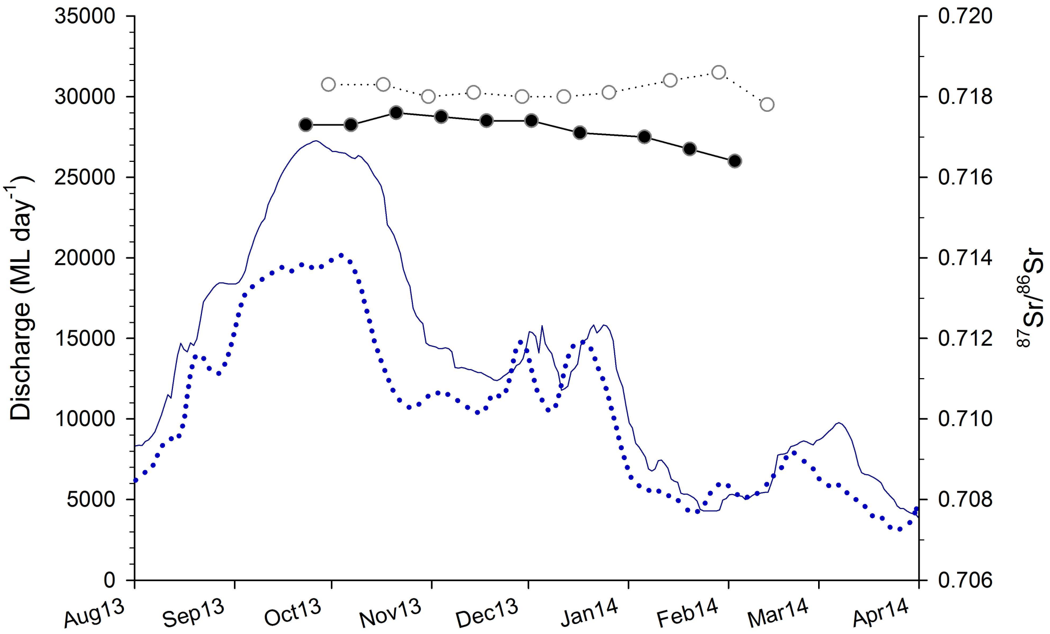

Figure 4. Mean daily discharge (ML day^{-1}) in the River Murray at Swan Hill (dotted blue line) and Euston (solid blue line). $^{87}Sr/^{86}Sr$ in water samples collected from mid-September 2013 to February 2014 in the River Murray at Swan Hill (open circles) and Lock 11 (Mildura) (solid circles).

Flow at Torrumbarry increased from approximately 7000 ML day^{-1} in early August 2013 to a peak of approximately 24 000 ML day^{-1} in early September (Figure 5). Flows then decreased to approximately 18 000 ML day^{-1} by mid-September before increasing again to approximately 23 000 ML day^{-1} by the end of the month (Figure 5). Flows then decreased slowly to approximately 11 000 ML day^{-1} in mid-October 2013 and then further to 5000 ML day^{-1} by January 2014.

$^{87}Sr/^{86}Sr$ in water samples collected from Torrumbarry remained relatively stable from late September 2013 to early January 2014 ranging 0.7184–0.7188 (Figure 5). $^{87}Sr/^{86}Sr$ in water samples from Echuca remained relatively stable ranging 0.7190–0.7192 from late October to early December 2013 before decreasing to 0.7185 in late December 2013 as a result of increasing Goulburn River flows (Figure 7).

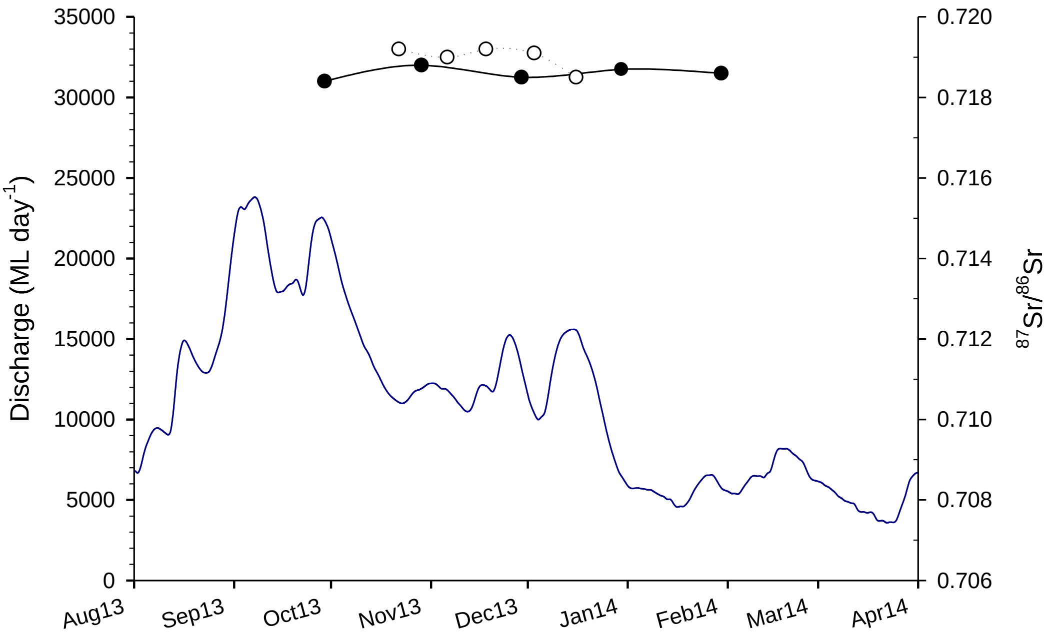

Figure 5. Mean daily discharge (ML day^{-1}) in the River Murray at Torrumbarry (Weir 26) (solid blue line) and $^{87}Sr/^{86}Sr$ in water samples collected from the River Murray at Echuca (open black circles) and Torrumbarry (solid black circles).

In the River Murray at Yarrawonga flows increased from approximately 12 000 ML day^{-1} in early August to 45 000 ML day^{-1} by late August 2013. Flows then decreased to approximately 20 000 ML day^{-1} by mid-September before increasing to approximately 30 000 ML day^{-1} by late September. Flows then decreased abruptly to 17 000 ML day^{-1} by early October and gradually decreased to 10,000 ML day^{-1} by mid-December (Figure 6). $^{87}Sr/^{86}Sr$ in water samples collected in the River Murray at Barmah remained stable during this time, ranging from 0.7194–0.7195 (Figure 6).

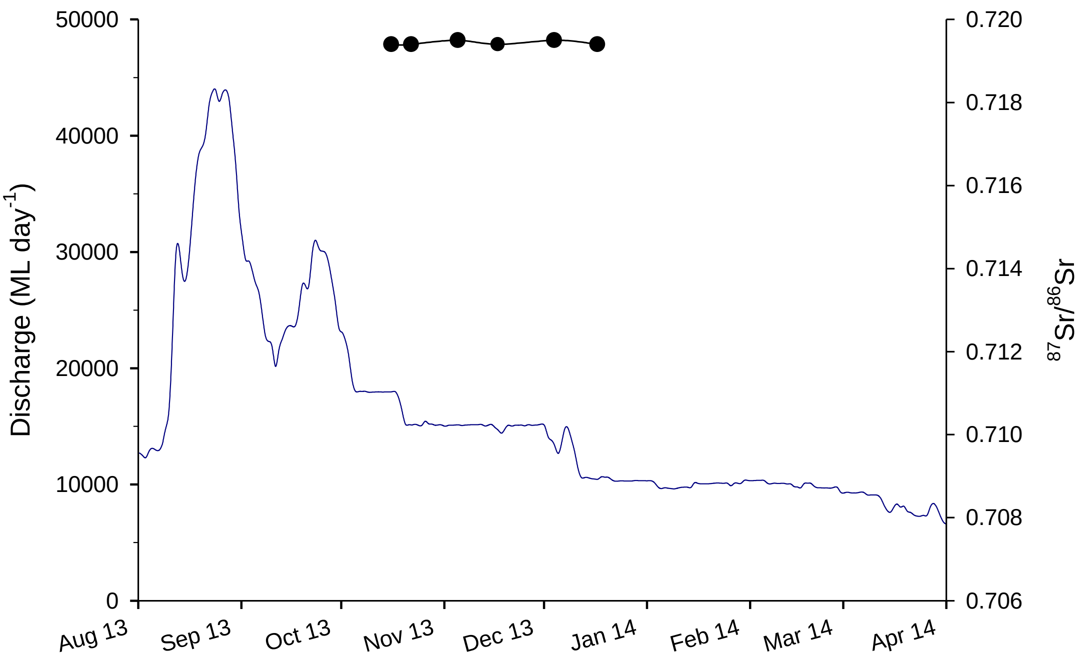

Figure 6. Mean daily discharge (ML day^{-1}) (solid blue line) in the River Murray at Yarrawonga and $^{87}Sr/^{86}Sr$ (solid black circles) in the River Murray at Barmah.

Goulburn River

Flow in the Goulburn River fluctuated from approximately 1000 ML day^{-1} to 10 000 ML day^{-1} from early August to late December 2013 (Figure 7). From late October to late December flows pulsed between 1000 ML day^{-1} and 7000 ML day^{-1} due to the delivery of environmental flows. In particular, environmental water was delivered over about 3 weeks from late October to early November (maximum discharge ~ 3170 ML day^{-1}), about 2 weeks from mid-November to early December (maximum discharge ~ 7052 ML day^{-1}), and about 3 weeks from early to late December (maximum discharge ~7411 ML day^{-1}). $^{87}Sr/^{86}Sr$ in water samples collected from the Goulburn slowly decreased from 0.7178 in October to 0.7169 in December (Figure 7).

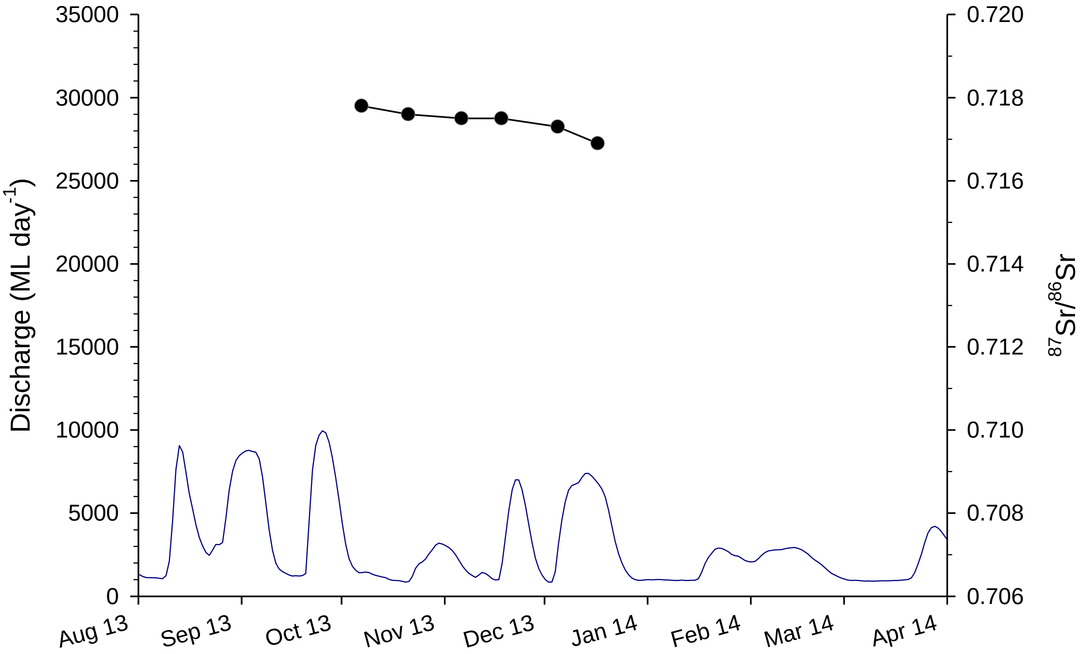

Figure 7. Mean daily discharge (ML day^{-1}) (solid blue line) in the Goulburn River at McCoys Bridge and $^{87}Sr/^{86}Sr$ (solid black circles) in the Goulburn River at Yambuna.

Murrumbidgee River

Flow in the Murrumbidgee at Balranald peaked at approximately 4000 ML day^{-1} in early August 2013 before decreasing to approximately 1500 ML day^{-1} by late August. Flow remained at <2000 ML day^{-1} until March 2014 when it increased slightly to approximately 3000 ML day^{-1} (Figure 8).

$^{87}Sr/^{86}Sr$ in water samples collected from the Murrumbidgee at Narrandera initially decreased from 0.7164 to 0.7152 from mid-September to late October 2013, then remained relatively stable (ranging 0.7145–0.7152) from late October 2013 to early February 2014 (Figure 8).

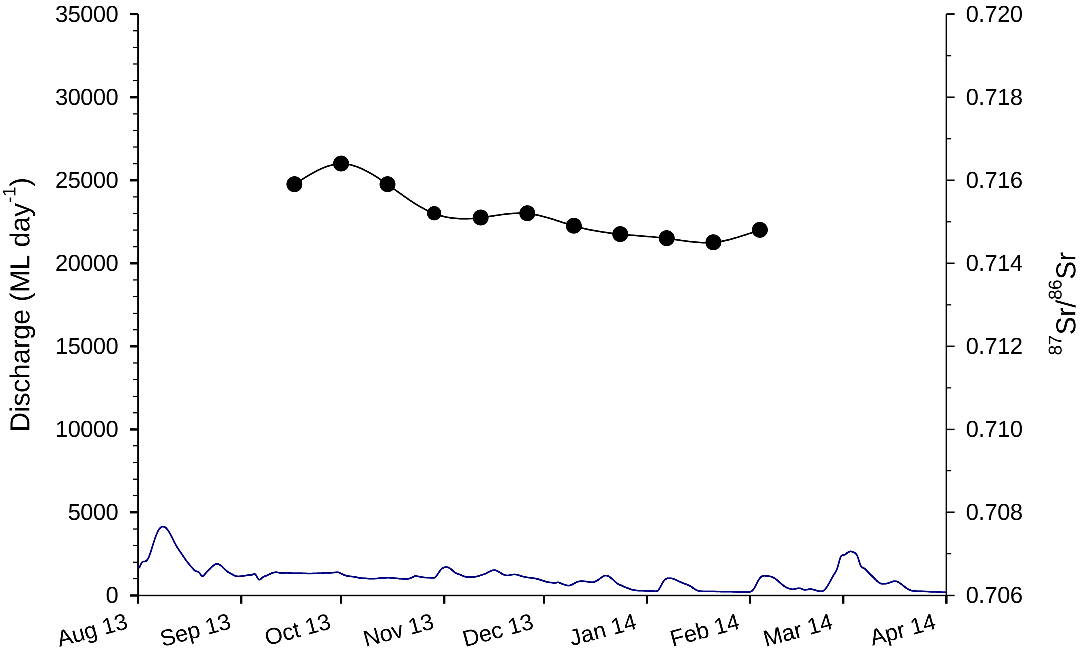

Figure 8. Mean daily discharge (ML day^{-1}) (solid blue line) in the Murrumbidgee River at Balranald and ^{87}Sr/^{86}Sr (solid black circles) in the Murrumbidgee River at Narrandera.

Edward-Wakool system

Flow in the Edward River downstream of Stevens Weir increased from approximately 1000 ML day^{-1} in early August 2013 to a peak of approximately 10 000 ML day^{-1} in early September 2013. Flows then gradually decreased to approximately 1000 ML day^{-1} by late October 2013 (Figure 9). Flow remained relatively stable at approximately 1000 ML day^{-1} from late October onwards with the exception of slight increases in discharge to approximately 2000 ML day^{-1} in early and late December 2013 and late March 2014 (Figure 9). ^{87}Sr/^{86}Sr in water samples collected at Deniliquin remained constant at approximately 0.7195 (Figure 9).

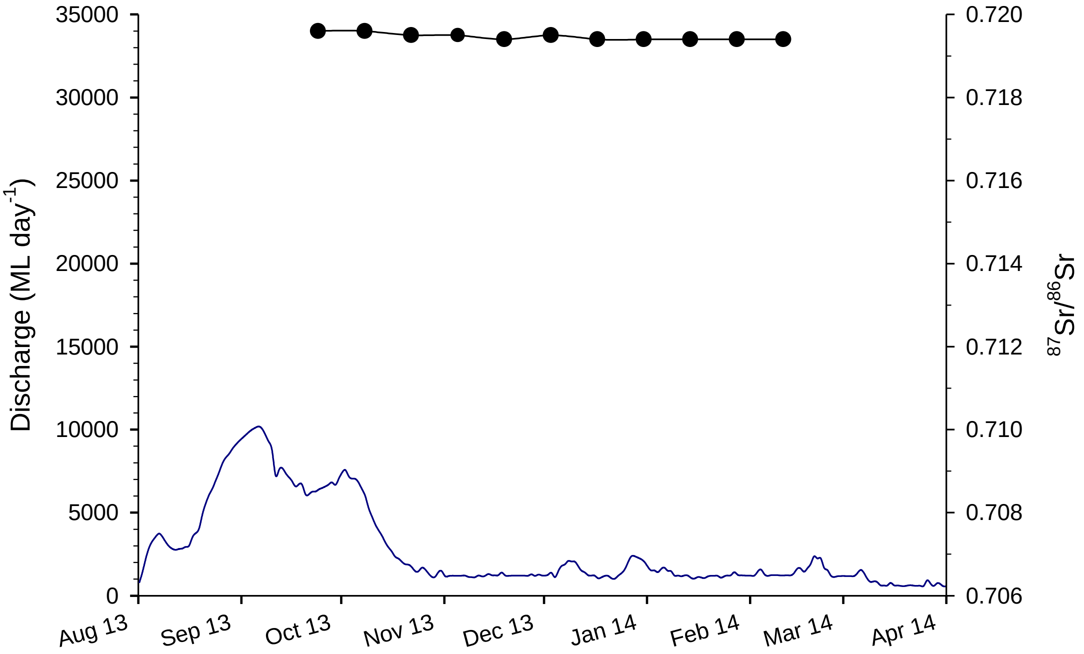

Figure 9. Mean daily discharge (ML day^{-1}) (solid blue line) in the Edward River downstream of Stevens Weir and $^{87}Sr/^{86}Sr$ (solid black circles) in the Edward River at Deniliquin.

Golden perch eggs and larvae

Lower River Murray

A total of 123 and 31 golden perch larvae were collected at Lock 1 and Lock 6, respectively, in 2013–14. At Lock 1, larvae were first collected in early October when water temperature reached ~19°C. Larval abundance peaked in mid-December 2013 and larvae continued to be collected until early February 2014 (Figure 10). All golden perch larvae collected at Lock 1 were pre-flexion. At Lock 6, golden perch larvae were collected from early October 2013 to mid-January 2014, with the majority being post-flexion. Larval abundance peaked in mid-October and again in late December 2013 but larvae continued to be present until mid-January (Figure 10).

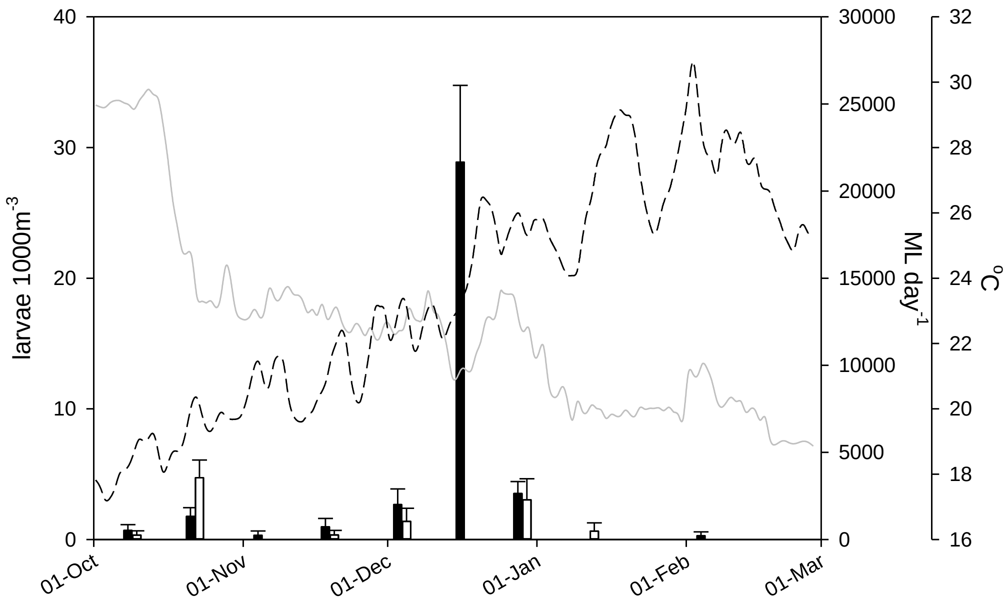

Figure 10. Mean (±S.E.) standardised abundance of golden perch larvae collected in the River Murray at Lock 1 (solid black bars) and Lock 6 (open bars) in 2013/14, plotted against discharge (ML day^{-1}) in the River Murray at the South Australian border (solid grey line) and water temperature (°C) (dashed black line). Sampling was undertaken fortnightly from 9 October 2013–5 February 2014.

River Murray at Barmah

A total of 121 golden perch eggs, but no larvae, were collected from drift samples in the River Murray within Barmah-Millewa Forest (B-MF) from October to December 2013. Eggs were collected from all three sites: Morning Glory (*n* = 3), Barmah Choke (*n* = 40) and Ladgroves Beach (*n* = 78). The majority (71%) of eggs were collected in mid-late October during the descending limb of a moderate over bank flow (discharge at first capture = 17 950 ML day^{-1}) at a water temperature of ≥16°C (Figure 11). This was despite environmental water delivery maintaining floodplain inundation until mid-December.

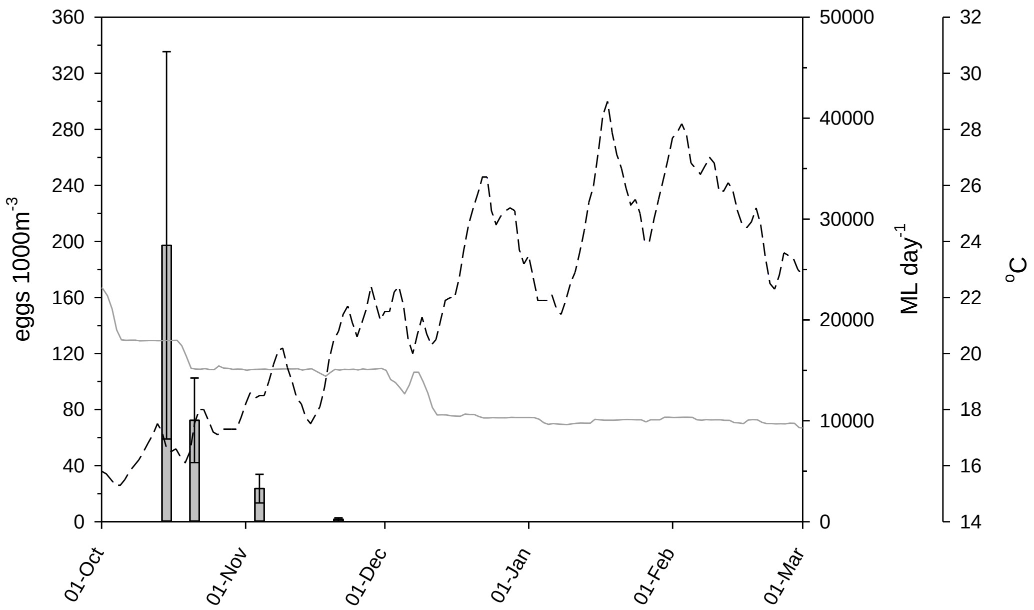

Figure 11. Mean (±S.E.) standardised abundance of golden perch eggs collected in the River Murray at Barmah in 2013–14, plotted against discharge (ML day^{-1}) in the River Murray at Yarrawonga (solid grey line) and water temperature (°C) at Tocumwal (dashed black line). Sampling was conducted fortnightly from October–December 2013.

Goulburn River

A total of 282 golden perch eggs were collected in the lower reaches of the Goulburn River (Yambuna) in mid-November 2013, coinciding with the rising limb of a flow pulse that peaked at ~7000 ML day^{-1} and a water temperature of ~20˚C (Figure 12) . Four pre-flexion golden perch larvae were also collected in the Goulburn River in mid-November 2013 but were not available for ageing or Sr isotope analysis.

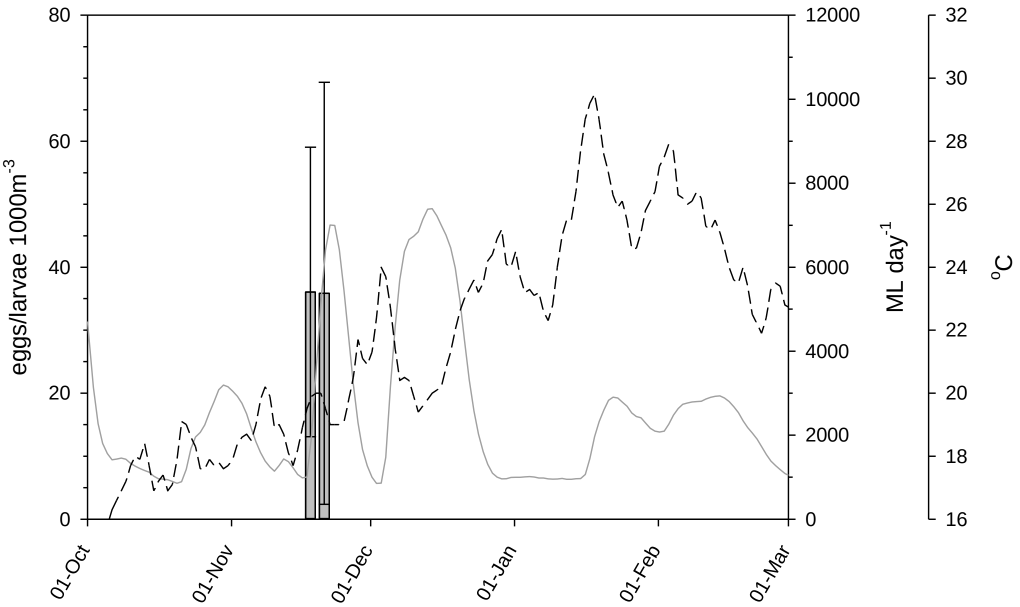

Figure 12. Mean (±S.E.) standardised abundance of golden perch eggs/larvae collected in the lower Goulburn River at Yambuna in 2013–14, plotted against discharge (ML day^{-1}) (solid grey line) and water temperature (°C) (dashed black line) in the Goulburn River at McCoys Bridge. Sampling was conducted fortnightly from October–December 2013, with additional sampling conducted twice per week coinciding with environmental flow releases in late November 2013.

River Murray at Hattah

A total of 53 eggs and 7 larvae of golden perch were collected in the drift sampling in the mid-River Murray in the Hattah region in 2013 (Figure 13). Eggs/larvae were collected in early November in association with the descending limb of the hydrograph, and in December during a within-channel rise in flow. Water temperature around this time was 21-23°C (Figure 13). Golden perch larvae were not available for ageing or Sr isotope analysis.

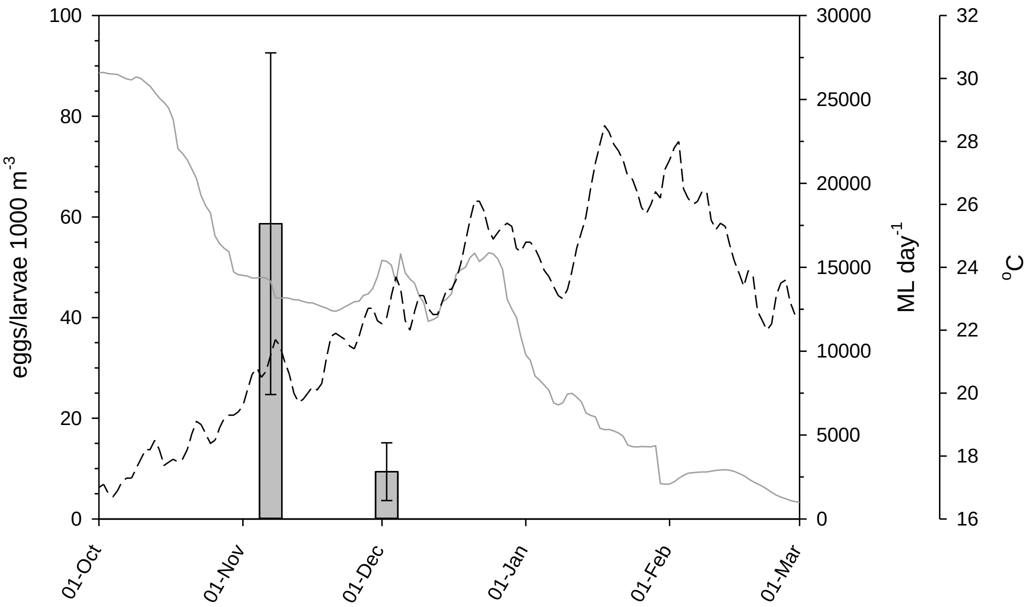

Figure 13. Mean (±S.E.) standardised abundance of golden perch eggs/larvae collected in the mid River Murray at Hattah in 2013–14, plotted against discharge (ML day^{-1}) (solid grey line) and water temperature (°C) (dashed black line) in the River Murray at Hattah. Sampling was conducted fortnightly from November–December 2013

Edward-Wakool System and Murrumbidgee River

No identifiable golden perch eggs or larvae were collected in the Murrumbidgee or Edward–Wakool systems (Watts *et al*. 2014).

Spawn dates and Otolith $^{87}Sr/^{86}Sr$ of larval and young-of-year golden perch

In 2013–14, larval and YOY golden perch were predominantly collected in the lower River Murray, although one YOY fish was also collected in the lower Darling River. We were able to determine daily ages and hence estimate spawn dates for 38 larval and YOY fish collected from the lower River Murray. Ages ranged 4–115 days for fish collected from 4 December 2013 to 4 March 2014 indicating a spawning period from 14 October 2013 to 24 December 2014 (Table 11; Figure 14).

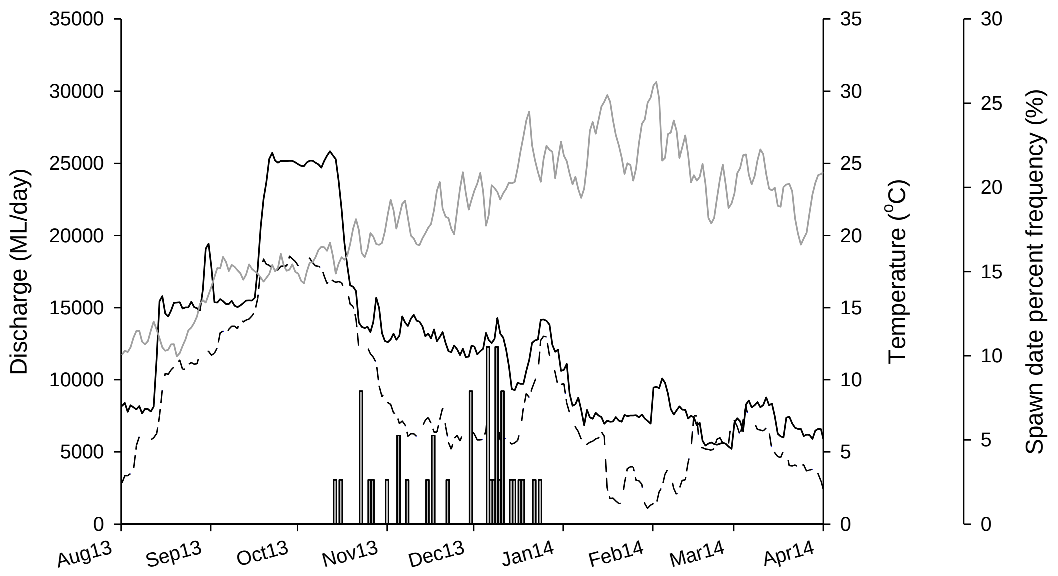

Figure 14. Back-calculated spawn dates for larval and young-of-year golden perch (grey bars; *n* = 38) captured from the lower River Murray during 2013–14, plotted against discharge (ML day^{-1}) in the River Murray at the South Australian border (solid black line) and Euston (dashed black line) and water temperature (°C) (grey line).

Pre-flexion larvae collected in larval tows in December 2013 at Lock 1 ranged in length from 4–7 mm and age from 4–12 days (Table 11). At Lock 6, larval and early juvenile golden perch collected in larval tows from October 2013–January 2014 ranged in length from 9–27 mm and age from 5–43 days (Table 11). Juvenile golden perch collected by electrofishing and fyke netting in December 2013 and March 2014, at locations throughout the floodplain geomorphic region of the lower Murray, ranged in length 21–53 mm and age from 37–115 days (Table 11)

Of the 38 larvae/YOY for which we could determine daily age, 18 were analysed for $^{87}Sr/^{86}Sr$ (Table 11). Seventeen age 0+ fish spawned between 23 October and 24 December 2013 had otolith core $^{87}Sr/^{86}Sr$ indicative of the lower River Murray, downstream of Lock 9 (i.e. >0.7090 and <0.7170) (Table 11; Figure 15). One fish, collected in Salt Creek at Chowilla on 20 March 2014 was spawned on the 14 December 2013 and exhibited otolith core $^{87}Sr/^{86}Sr$ indicative of the Darling River (~0.7075) (Figure 15).

Table 11. Capture location and date, length (mm), age (days) and spawn date of 38 larval/young-of-year golden perch collected from the floodplain and gorge geomorphic regions of the lower River Murray, including otolith core $^{87}Sr/^{86}Sr$ values measured from 18 larval/young-of-year fish.

Region	Capture location	Capture date	Length (mm)	Age (days)	Spawn date	$^{87}Sr/^{86}Sr$
Floodplain	Lock 6	13/01/2014	27	43	30/11/2013	0.7136725
Floodplain	Lock 6	21/10/2013	11	7	14/10/2013	-
Floodplain	Lock 6	21/10/2013	9	5	16/10/2013	-
Floodplain	Lock 6	30/12/2013	18	23	6/12/2013	0.7138749
Floodplain	Lock 6	30/12/2013	19	24	6/12/2013	0.7134529
Floodplain	Lock 6	12/01/2014	12	20	22/12/2013	-
Floodplain	Lock 6	30/12/2013	20	23	7/12/2013	-
Floodplain	Lock 6	3/12/2013	14	16	17/11/2013	0.7163424
Floodplain	Lock 6	3/12/2013	11	15	17/11/2013	0.7135185
Floodplain	Lock 6	30/12/213	18	24	6/12/2013	0.7138883
Floodplain	Lock 6	12/01/2014	13	19	24/12/2013	0.7109106
Floodplain	Lock 6	30/12/2013	16	21	9/12/2013	0.7134128
Floodplain	Lock 6	30/12/2013	20	24	6/12/2013	0.7138498
Floodplain	Lock 6	30/12/2013	13	20	10/12/2013	-
Floodplain	Lock 6	30/12/2013	15	21	9/12/2013	-
Floodplain	Lock 6	30/12/2013	9	12	18/12/2013	-
Floodplain	Martin's Bend	12/12/2013	22	37	5/11/2013	0.7143233
Floodplain	Martin's Bend	13/12/2013	23	51	23/10/2013	0.7127532
Floodplain	Martin's Bend	13/12/2013	22	38	5/11/2013	0.7162591
Floodplain	Martin's Bend	13/12/2013	23	42	1/11/2013	0.7127598
Floodplain	Martin's Bend	12/12/2013	30	49	23/10/2013	0.7130439
Floodplain	Martin's Bend	12/12/2013	25	47	26/10/2013	-
Floodplain	Martin's Bend	12/12/2013	24	50	23/10/2013	-
Floodplain	Martin's Bend	13/12/2013	21	47	27/10/2013	-
Floodplain	Martin's Bend	22/12/2013	22	43	8/11/2013	-
Floodplain	Monoman Ck	11/03/2014	53	115	15/11/2013	0.7131053
Floodplain	Salt Creek	20/03/2014	43	96	14/12/2013	0.7076807
Floodplain	Border Cliffs	4/03/2014	41	101	22/11/2013	0.7125680
Floodplain	Chowilla Ck	15/03/2014	52	90	15/12/2013	0.7111782
Gorge	Lock 1	4/12/2013	5	4	30/11/2013	-
Gorge	Lock 1	4/12/2013	5	4	30/11/2013	-
Gorge	Lock 1	17/12/2013	6	8	8/12/2013	-
Gorge	Lock 1	17/12/2013	6	7	9/12/2013	-
Gorge	Lock 1	17/12/2013	4	6	11/12/2013	-
Gorge	Lock 1	29/12/2013	7	12	17/12/2013	-
Gorge	Lock 1	17/12/2013	6	7	9/12/2013	-
Gorge	Lock 1	17/12/2013	5	6	11/12/2013	-
Gorge	Lock 1	17/12/2013	5	6	11/12/2013	-

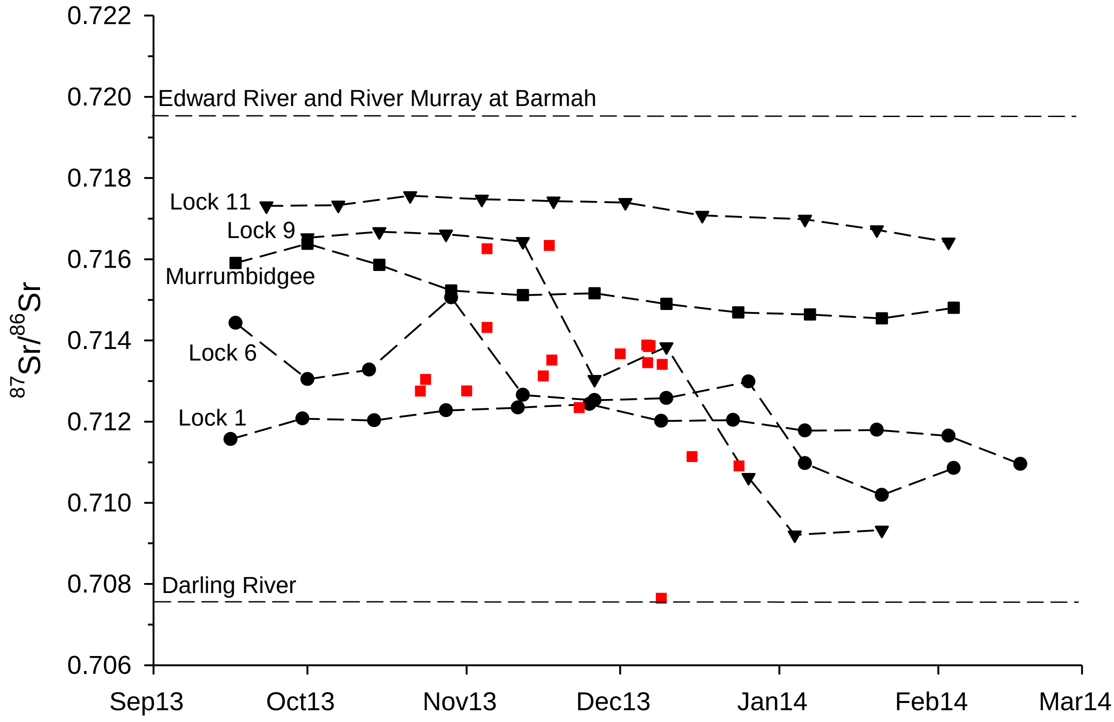

Figure 15. $^{87}Sr/^{86}Sr$ in water samples collected from late September/early October 2013 to February 2014 at sites in the southern MDB. $^{87}Sr/^{86}Sr$ in the Darling River and Edward River/River Murray at Barmah are presented as dashed straight lines as these were temporally stable and represent the maximum and minimum $^{87}Sr/^{86}Sr$ measured in water samples in the southern MDB in 2013/14. Closed red squares represent spawn date and otolith core $^{87}Sr/^{86}Sr$ of larval/YOY golden perch (*n* = 18) collected in the lower River Murray from October 2013 to April 2014.

Transects of $^{87}Sr/^{86}Sr$ from the otolith core to edge can elucidate the movement history of early life stage golden perch but may also reflect temporal variability in ambient $^{87}Sr/^{86}Sr$ in water. Here we provided preliminary examples of life-history profiles for two YOY golden perch, based on transects of $^{87}Sr/^{86}Sr$ from the otolith core to edge. Transects of $^{87}Sr/^{86}Sr$ show that two fish, captured at Chowilla (Lock 6) and Martin's Bend (upstream of Lock 4) in the lower River Murray, were spawned in the Darling River and River Murray respectively. Both fish exhibit modulation of $^{87}Sr/^{86}Sr$ as they move downstream (passively and/or actively) (Figure 16). The fish spawned in the Darling River in December 2013, and captured upstream of Lock 6 in early March 2014, shows an increase in $^{87}Sr/^{86}Sr$ as it transitions into the lower River Murray (Figure 16). In contrast, the fish spawned in the lower River Murray in early November 2013, and captured upstream of Lock 4 in mid-December 2013, shows decreasing $^{87}Sr/^{86}Sr$ across the otolith transect (Figure 16). Whilst this fish may have been moving downstream in the lower Murray, the modulation in otolith $^{87}Sr/^{86}Sr$ was most likely due to dissolved $^{87}Sr/^{86}Sr$ in the lower River Murray decreasing substantially over this period due to increasing Darling River flow (Figure 3).

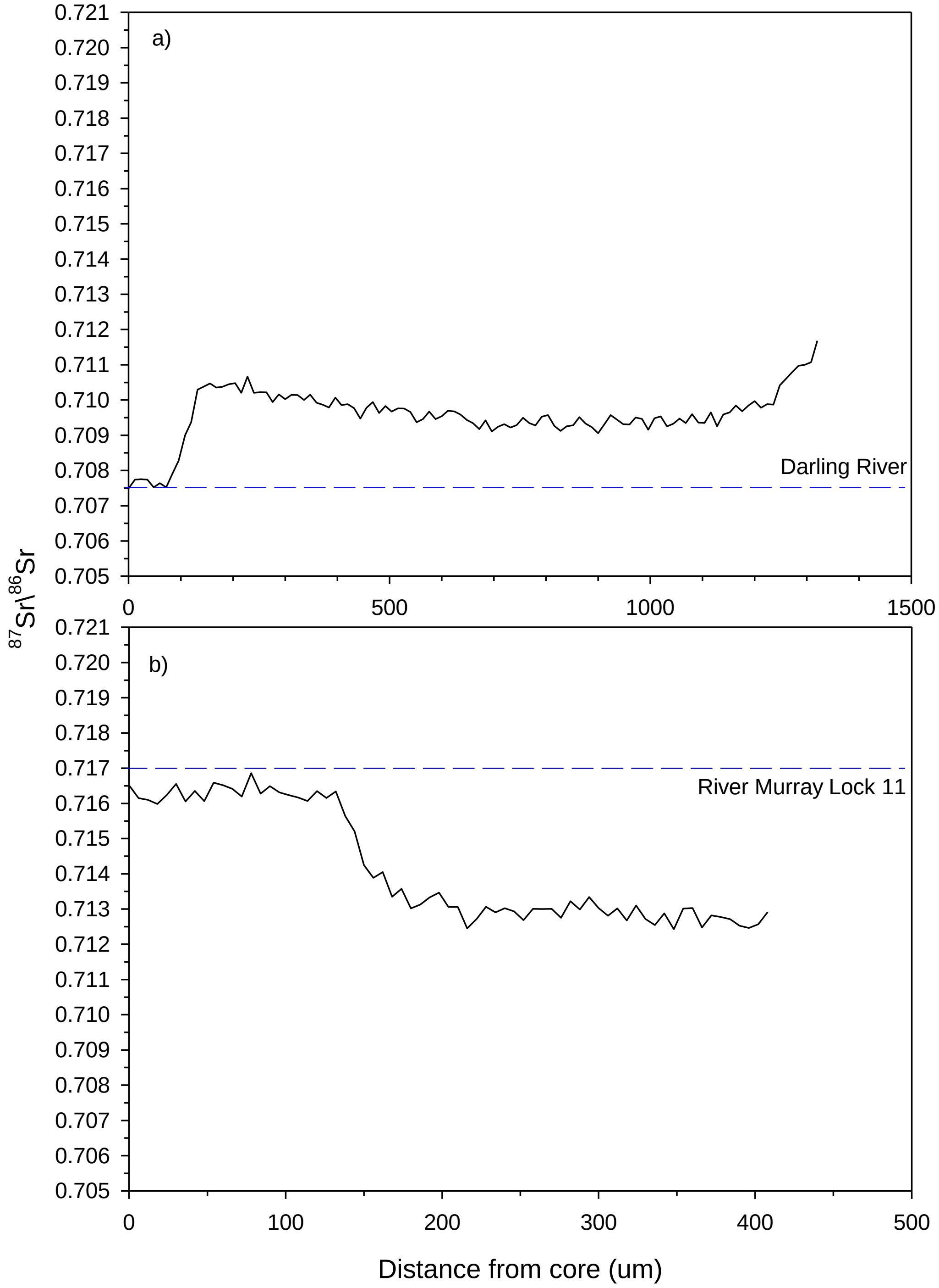

Figure 16. Individual life history profiles based on otolith Sr isotope transects (core to edge) for two juvenile golden perch aged (a) 101 and (b) 38 days collected at Chowilla and Martin's Bend (upstream of Lock 4) respectively in the floodplain region of the lower River Murray. Dashed blue line denotes $^{87}Sr/^{86}Sr$ ratio in (a) the Darling River and (b) River Murray at Lock 11.

Otolith core $^{87}Sr/^{86}Sr$ was also determined for five age 0+ golden perch that were collected from the floodplain geomorphic region of the lower River Murray and the lower Darling River in April 2014 but for which spawn dates were unable to be accurately determined. The fish collected in the lower River Murray exhibited core $^{87}Sr/^{86}Sr$ values indicative of a lower River Murray origin (i.e. >0.7080 and <0.7170) and the fish collected at Pooncarie on the Darling River exhibited a core $^{87}Sr/^{86}Sr$ signature indicative of a Darling River origin (~0.7075) (Table 12).

Table 12. Otolith core $^{87}Sr/^{86}Sr$ measured in 5 young-of-year golden perch collected from the floodplain geomorphic region of the lower River Murray and the lower Darling River.

Region	Capture location	Capture date	Length (mm)	Age (yrs)	Spawned	$^{87}Sr/^{86}Sr$
Floodplain	Chowilla Ck	6/03/14	42	0+	2013/14	0.7104077
Floodplain	Salt Ck (Chowilla)	20/03/14	63	0+	2013/14	0.7150462
Floodplain	Downstream Lock 4	30/04/14	63	0+	2013/14	0.7118915
Floodplain	Downstream Lock 4	30/04/14	80	0+	2013/14	0.7096538
Darling	Pooncarie	1/04/14	88	0+	2013/14	0.7073955

Golden perch length and age structure

In 2014, golden perch sampled in the gorge and floodplain geomorphic regions of the lower River Murray (including the Chowilla anabranch system) ranged in age from 0+ to 18+ years, with a dominant cohort of age 4+ fish comprising 52, 64 and 45% of the sampled population in the Chowilla, floodplain and gorge geomorphic regions respectively (Figure 17). The second most abundant cohort in Chowilla, and the broader floodplain geomorphic region of the lower River Murray, was age 3+ fish spawned in 2010–11 (Figure 17). In the gorge geomorphic region, the second most abundant cohorts were age 3+ and 13+ fish spawned in 2010–11 and 2001–2 and comprising 18 and 19% respectively of the sampled population (Figure 17).

In the lower Darling River and mid River Murray, golden perch ranged in age from 0+ to 8+ and 1+ to 15+ years, respectively (Figure 18). In both regions the dominant cohort was age 4+ fish (spawned in 2009–10) comprising approximately 40% of the population. The next strongest cohorts were age 2+ fish (2011–12) in the lower Darling (28%) and age 8+ (2005–06) and 10+ fish (2003–04) in the mid Murray (18 and 16%) (Figure 18).

The golden perch population sampled in the lower Goulburn River in 2014 ranged in age from 1–20 years (Figure 18). The most prominent cohorts were age 4+ and 5+ fish spawned in 2009–10 and 2008–09 respectively, with these cohorts each representing approximately 20% of the population. The remainder of the population was comprised of individual fish from many year classes, although 12–17 year old fish were conspicuously absent (Figure 18).

Age 0+ fish, spawned in 2013–14, comprised less than 1% of the sampled populations in the floodplain (including Chowilla) and gorge geomorphic regions of the lower Murray and the Darling River (Figure 17; Figure 18). This age class was absent from populations sampled in the mid Murray and Goulburn Rivers (Figure 17; Figure 18).

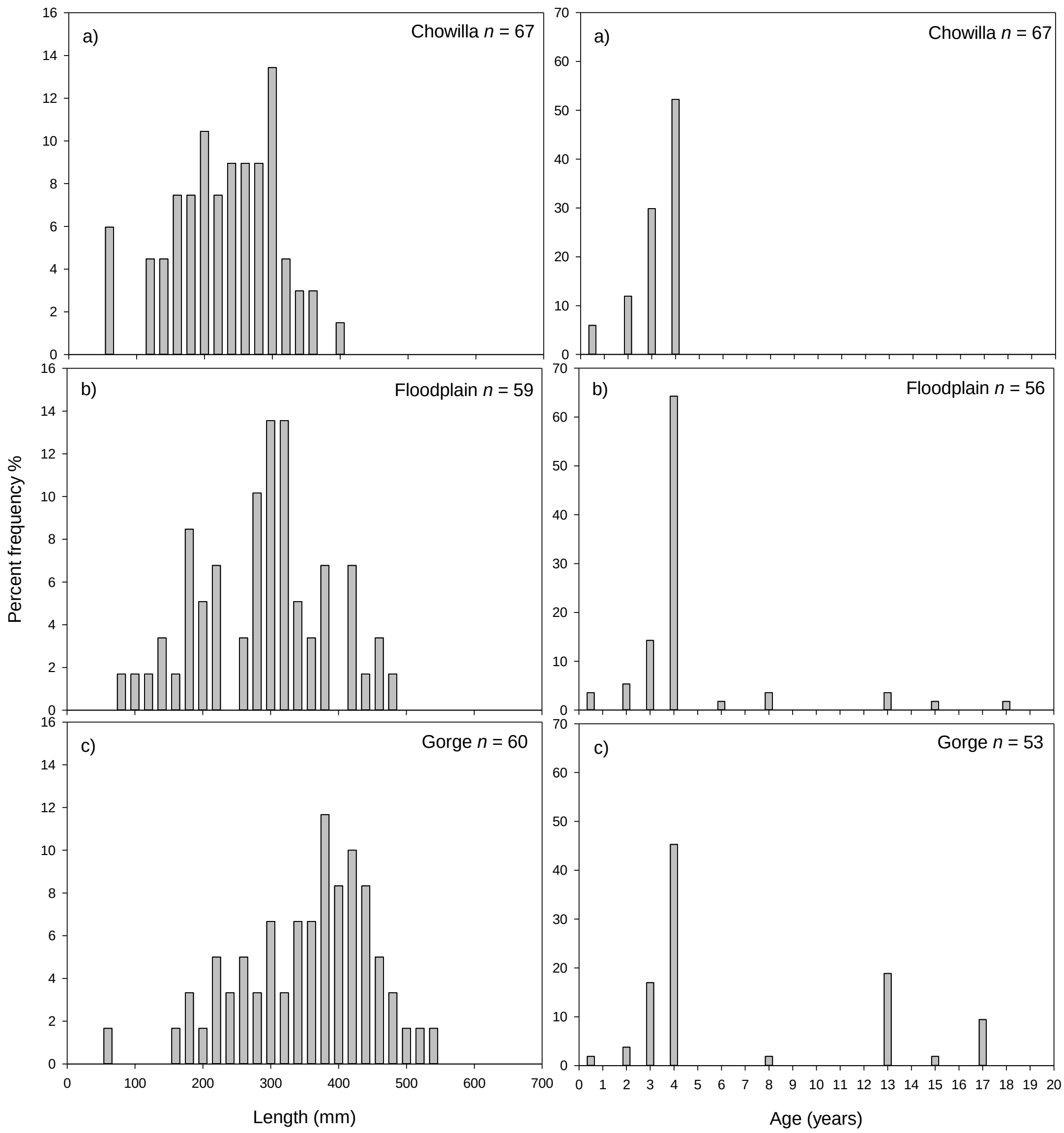

Figure 17. Length (left column) and age (right column) frequency distribution of golden perch collected by boat electrofishing from the a) lower River Murray at Chowilla and b) the floodplain and c) gorge geomorphic regions in March–April 2014.

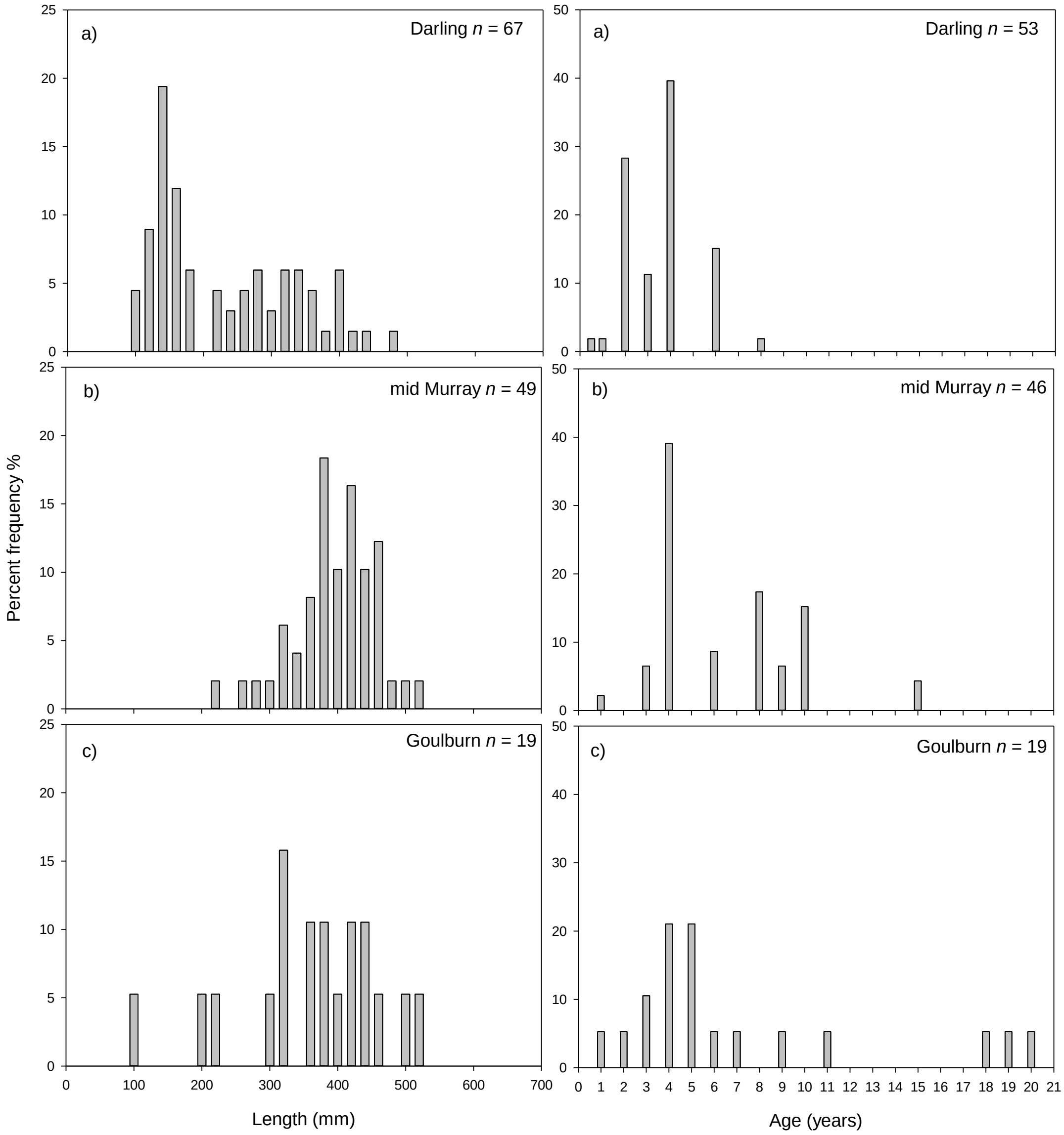

Figure 18. Length (left column) and age (right column) frequency distributions of golden perch collected by boat electrofishing from a) the lower Darling, b) mid Murray and c) Goulburn rivers in March–April 2014.

$^{87}Sr/^{86}Sr$ life-history transects of juvenile and adult golden perch

To investigate the origin and movement of a small subsample of juvenile and adult golden perch collected in the lower and mid River Murray, Darling River, Murrumbidgee and Goulburn River we analysed $^{87}Sr/^{86}Sr$ along transects from the otolith core to edge. Here we present preliminary data on the origin and movement of 1) three age 4+ golden perch collected in the lower and mid-River Murray, and the Darling River (Figure 19), 2) three golden perch aged 1+, 2+ and 6+, collected in the lower Goulburn River (Figure 20) and 3) two age 1+ golden perch collected in the Murrumbidgee River (Figure 21).

Otolith $^{87}Sr/^{86}Sr$ profiles for the three age 4+ golden perch collected in the lower and mid-River Murray, and Darling River indicate a Darling River origin for all three fish (Figure 19). The fish that were collected in the Chowilla system in the lower River Murray and at Cohuna in the mid River Murray exhibit an abrupt change in $^{87}Sr/^{86}Sr$ approximately 1/3 of the way along their otolith transects, corresponding with an age of approximately 1+. At this point, the fish that was collected at Chowilla exhibits a transition to a variable lower River Murray $^{87}Sr/^{86}Sr$ profile (i.e. >0.7080–<0.7170) whilst the fish collected at Cohuna (in the mid-Murray) exhibits a transition to the higher, more temporally stable, $^{87}Sr/^{86}Sr$ signature of the mid-Murray (i.e. ≥0.7180). The fish collected in the Darling River at Pooncarie shows that the fish was spawned in the Darling River and spent the remainder of its life there (Figure 19).

$^{87}Sr/^{86}Sr$ life history profiles of two golden perch, aged 1+ and 2+, from the Goulburn River showed abrupt changes in $^{87}Sr/^{86}Sr$ early in the fishes life history (<100 days old) from a signature indicative of the Murrumbidgee River to a signature indicative of the Goulburn River (Figure 20). The $^{87}Sr/^{86}Sr$ life history profile of a single golden perch, aged 6+, indicates an origin and long period of residence outside of the Goulburn River with a transition into the Goulburn River later in life (Figure 20).

Otolith $^{87}Sr/^{86}Sr$ profiles for the two age 1+ golden perch collected in the Murrumbidgee show no substantial variation from the Murrumbidgee water $^{87}Sr/^{86}Sr$ for the entire life-history profile (Figure 21).

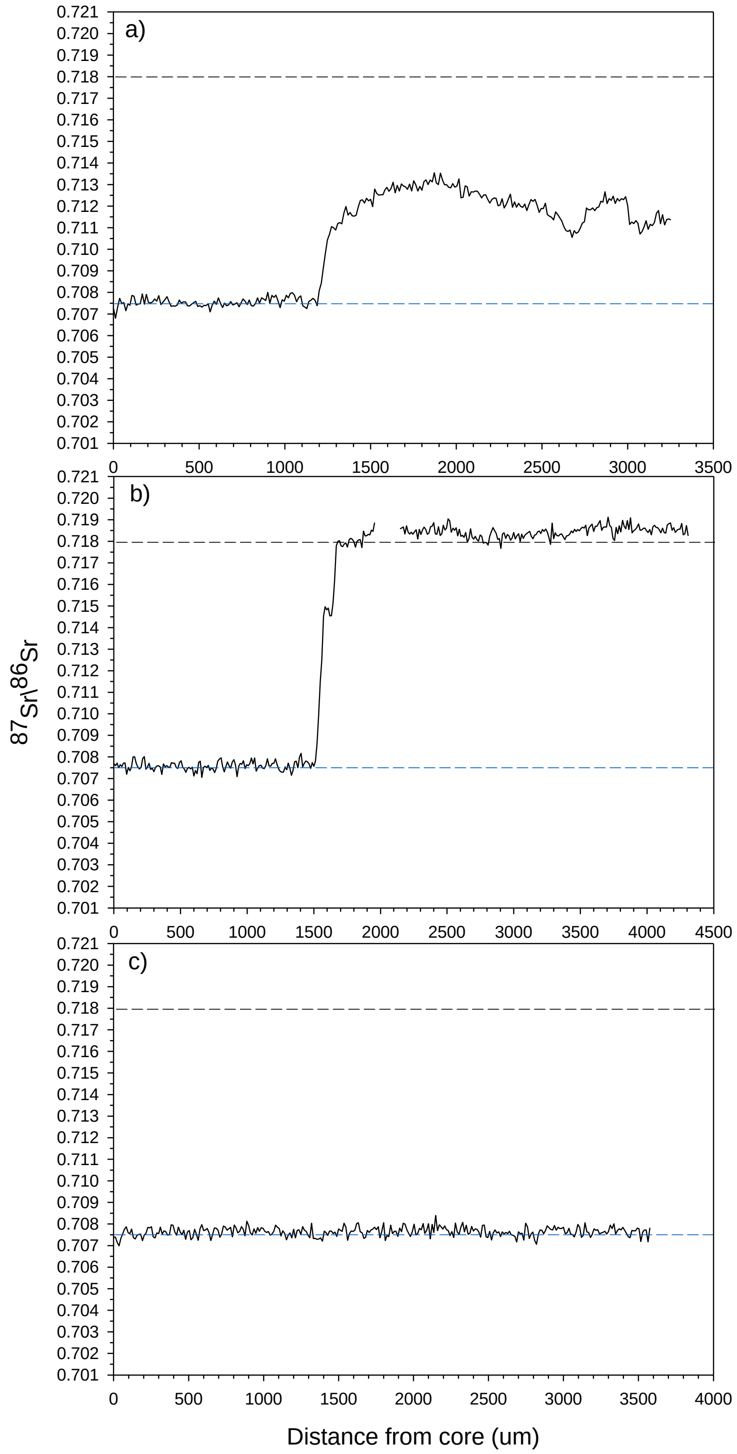

Figure 19. Individual life-history profiles based on analysis of $^{87}Sr/^{86}Sr$ along transects from the core to edge of otoliths from age 4+ golden perch collected in (a) Chowilla Creek in the lower River Murray, (b) mid-River Murray at Cohuna and (c) Darling river at Pooncarie. Blue dashed line indicates the temporally stable $^{87}Sr/^{86}Sr$ ratio of the lower Darling River and the black dashed line represents the lower range of $^{87}Sr/^{86}Sr$ signatures of the mid-Murray (i.e. ≥0.7180).

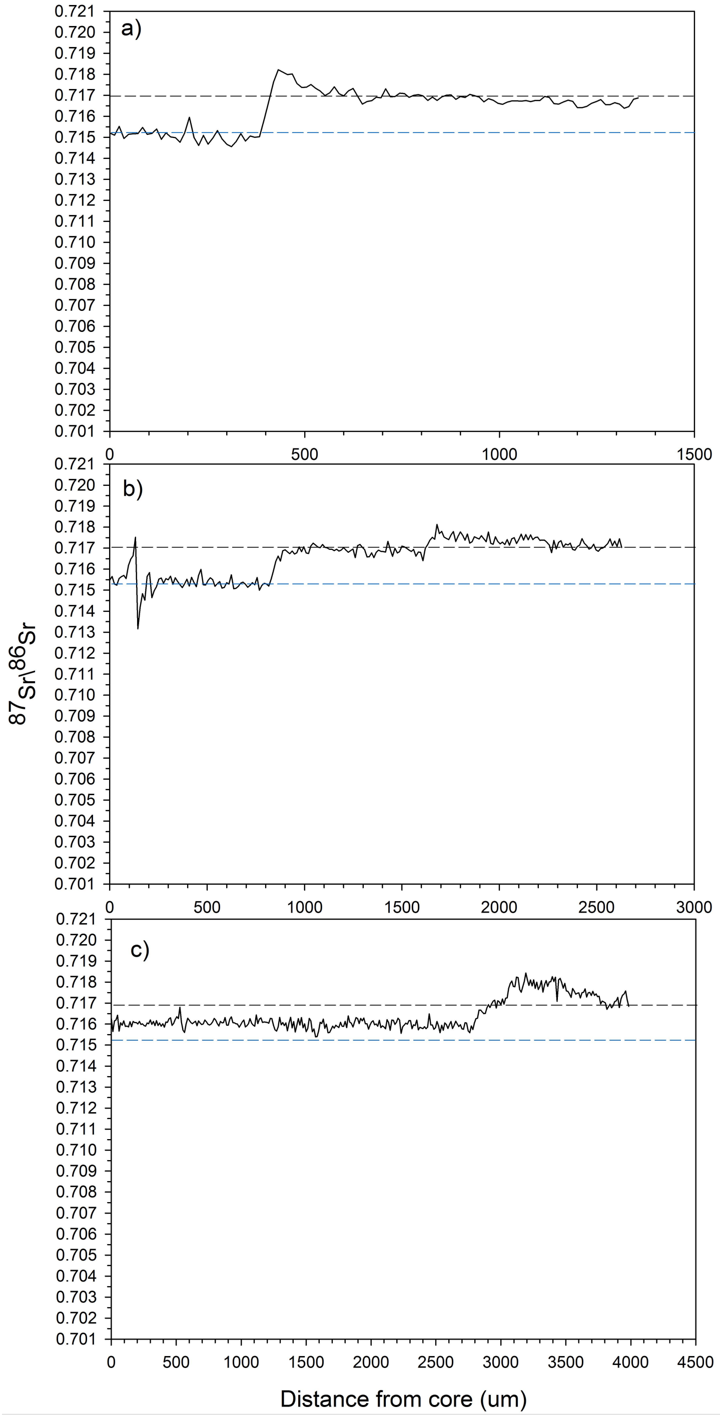

Figure 20. Individual life-history profiles based on analysis of $^{87}Sr/^{86}Sr$ along transects from the core to edge of otoliths from golden perch collected in the lower Goulburn River in March 2014. (a) Age 1+ fish, (b) age 2+ fish and (c) age 6+ fish. Blue dashed line indicates $^{87}Sr/^{86}Sr$ measured in the Murrumbidgee River in 2013–14 and black dashed line indicates $^{87}Sr/^{86}Sr$ measured in the Goulburn River in 2013–14.

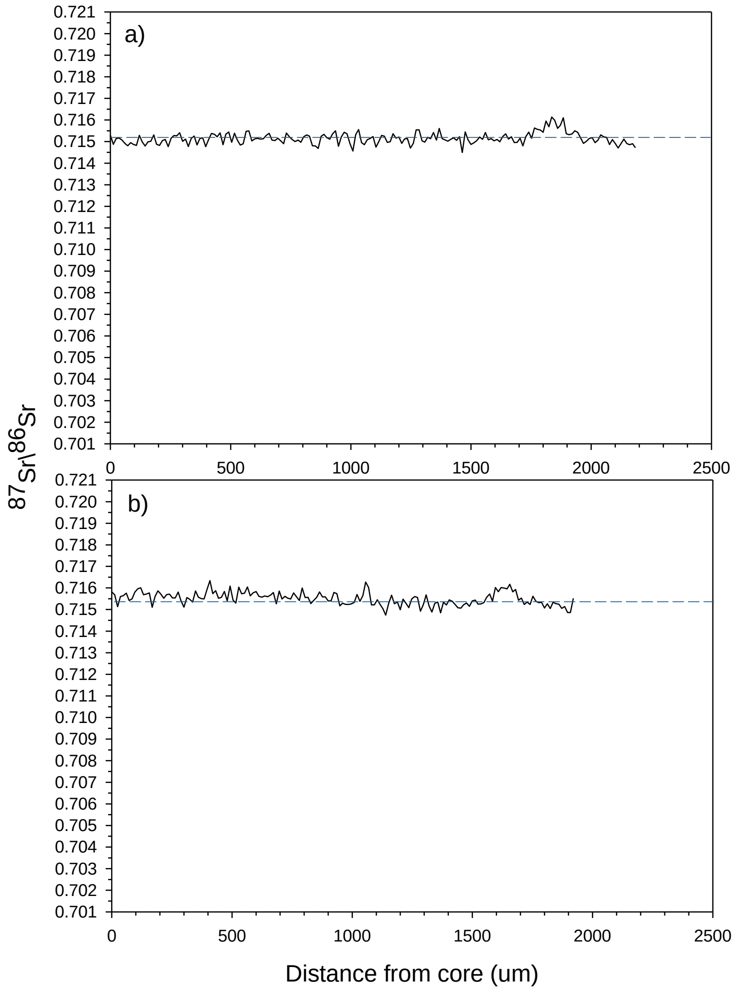

Figure 21. Individual life-history profiles based on analysis of $^{87}Sr/^{86}Sr$ along transects from the core to edge of otoliths from age 1+ golden perch collected in the Murrumbidgee catchment at (a) Gum Creek site on Old Man Creek and (b) Gooragool on the Murrumbidgee River. Blue dashed line shows the approximate $^{87}Sr/^{86}Sr$ ratio recorded in the Murrumbidgee River from September 2013–February 2014.

DISCUSSION

Restoring flow regimes to benefit aquatic ecosystems, including fish, requires an empirical understanding of relationships between hydrology, life history and population dynamics. We integrated studies of spawning and recruitment of golden perch at sites across the southern MDB in 2013–14 to facilitate an understanding of the connectivity and interrelatedness of golden perch life histories between regions and their association with flow. In particular we used otolith microstructure and chemistry to 1) determine the spatio-temporal origin (i.e. time and place of birth) of early life stage (larval and YOY) golden perch, and 2) the population age structure, spatial origin and migration history of a representative sub-sample of golden perch collected from the lower and mid River Murray, and Darling, Murrumbidgee and Goulburn rivers.

Developing an $^{87}Sr/^{86}Sr$ isoscape

Spatio-temporal isoscapes of dissolved $^{87}Sr/^{86}Sr$ in water constitute an essential template for determining the spatial origin of freshwater fish (Barnett-Johnson *et al.* 2008; Muhlfeld *et al*. 2012). In this study there was a clear distinction in $^{87}Sr/^{86}Sr$ between various locations in the southern MDB in 2013–14, with many locations exhibiting minimal intra-seasonal variation. Distinct and relatively stable $^{87}Sr/^{86}Sr$ was recorded in the River Murray at Barmah, and the Goulburn, Murrumbidgee and Darling rivers. $^{87}Sr/^{86}Sr$ measured in the Edward River at Deniliquin was equivalent to that measured in the River Murray at Barmah due to this region being the source of discharge for the Edward River. Sites in the mid River Murray between the confluence of the Goulburn River and Lock 11 at Mildura were also relatively temporally stable in 2013–14 and showed a clear attenuation of $^{87}Sr/^{86}Sr$ in a downstream direction from Barmah to Lock 11 (Mildura) due to inflow from the Goulburn and Murrumbidgee rivers, which had distinctly lower $^{87}Sr/^{86}Sr$ than the River Murray at Barmah. Depending on the annual discharge from tributaries in the mid-Murray (e.g. the Goulburn, Campaspe, Loddon, Wakool and Murrumbidgee rivers), $^{87}Sr/^{86}Sr$ may exhibit inter-annual variation. Indeed, inter-annual variation in $^{87}Sr/^{86}Sr$ has been shown to be substantial in the Lachlan River sub-catchment of the MDB, particularly in association with hydrological variability (Crook *et al*. 2013). As such, further exploration of inter-annual variability in $^{87}Sr/^{86}Sr$ and relationship with hydrology (volume and source) is required in the mid reaches of the River Murray and its tributaries.

The lower River Murray, downstream of the Darling River junction, exhibited high spatio-temporal variability in $^{87}Sr/^{86}Sr$ due to substantial temporal variation in the magnitude of discharge from its parent rivers, the Darling and Murray. Despite this temporal variation, $^{87}Sr/^{86}Sr$ in the lower Murray in 2013–14 was distinctly lower than the mid–upper River Murray, due primarily to discharge from the Darling River which has the lowest $^{87}Sr/^{86}Sr$ (~0.7075) yet recorded for any river in the southern MDB. Consequently, fish originating in, or moving between, the lower and mid River Murray should be discernable based on otolith $^{87}Sr/^{86}Sr$. Nevertheless, the level of interannual variability in $^{87}Sr/^{86}Sr$ remains to be explored and determining the natal origin of golden perch, or migration history of early life-stage golden perch, within the lower or mid-Murray would require water samples to be collected annually over the duration of the spawning season (October–February) at the spatial resolution of interest. Additionally, a combined multi-elemental and isotopic otolith chemistry approach may provide greater spatial resolution in water and otolith chemistry and be useful in elucidating the spawning origin at the intra-regional scale e.g. within the lower River Murray (Walther *et al*. 2008; Crook *et al.* 2013).

Spawning of golden perch and recruitment to young-of-year

Golden perch in the southern MDB are considered to spawn in association with increased flow contained within the river channel or overbank floods, when water temperatures exceed approximately 17°C (Humphries et al. 1999; King *et al.* 2009; Zampatti and Leigh 2013a). The drifting eggs and larvae of golden perch have previously been used as an indicator of spawning and related to the antecedent flow regime (King *et al.* 2005; 2009; Koster *et al*. 2012). Golden perch eggs hatch within approximately 30 hours at water temperatures exceeding 20°C so the collection of eggs provides a reasonable indicator of the approximate location of spawning (i.e. within 10s of kilometres) which can be associated with local hydrology. Larval and early juvenile golden perch, however, can remain drifting in the water column for several weeks (Humphries *et. al*. 1999). Consequently, by knowing the age and spatial origin of early life stage golden perch, hydrology can be more closely associated with the timing and location of spawning (Zampatti and Leigh 2013b).

In 2013–14, golden perch eggs were collected in the River Murray at Barmah and Hattah and in the Goulburn River at Yambuna. In the River Murray at Barmah, golden perch eggs were first collected in mid-October 2013 on the descending limb of a moderate over bank flow (discharge at first capture = 17 950 ML day^{-1}) at a water temperature of approximately 16°C. Low abundances of eggs continued to be collected through until early December coinciding with minor variations in flow (12 000 to 15 000 ML day^{-1}). Higher numbers of golden perch eggs were collected in 2013 compared with surveys of eggs conducted from 2008–2012 in the River Murray at Barmah. In these previous surveys, eggs were only collected in 2010 and in low abundances (i.e. average density = 6.7 individuals per 1000 m^3). The low levels or failure of golden perch spawning in the River Murray at Barmah from 2008–2012 was considered a result of either low or stable flows (including overbank) during the peak spring spawning period (see King *et al*. 2009) or disruption of spawning the year following the 2010/11 blackwater event (Raymond *et al*. 2013). Thus the return of more variable overbank flows in 2013 may have resulted in increased golden perch spawning.

In the mid River Murray at Hattah, golden perch eggs, and low numbers (n = 7) of larvae, were collected in November 2013 in association with the descending limb of the hydrograph, and in December 2013 during a small (12 500–16 000 ML day^{-1}) within-channel rise in flow, at water temperatures ≥20°C. In the Goulburn River at Yambuna, golden perch eggs, and low numbers (n = 4) of larvae, were collected in mid-November 2013 coinciding with the rising limb of the hydrograph during an increase in flow (1110 to 7052 ML day^{-1}) associated with an environmental flow release. Water temperature at this time was 19–20°C.

In the lower River Murray, golden perch larvae were collected between October 2013 and February 2014 in association with decreasing (from a peak of 25 000 ML day^{-1} in October 2013 to ~7000 ML day^{-1} in February 2014) but variable within-channel flows and water temperatures ≥19°C. No identifiable golden perch eggs or larvae were collected in the Murrumbidgee and Edward-Wakool rivers.

Sampling was conducted for YOY golden perch in the Goulburn, mid Murray, Murrumbidgee, Darling and lower Murray in March/April 2014, but YOY were only collected in the Darling River and lower River Murray. The spatio-temporal provenance (i.e. timing and location of spawning) of larvae and YOY golden perch collected in the lower Murray and Darling rivers were determined retrospectively using daily increments in otolith microstructure and otolith chemistry. Larvae and YOY golden perch collected in the lower Murray and analysed for $^{87}Sr/^{86}Sr$ (n = 22) predominantly (95%) exhibited otolith core $^{87}Sr/^{86}Sr$ indicative of the lower River Murray, suggesting these fish were spawned in the River Murray downstream of the Darling River junction. Two YOY fish collected in the lower River Murray and Darling River respectively exhibited otolith core $^{87}Sr/^{86}Sr$ indicative of a Darling River origin.

Overall, in the southern MDB in 2013–14, golden perch spawning, as indicated by the collection of eggs, and retrospective determination of the age and spawning location of larvae and/or YOY fish, was identified in the Goulburn River, mid River Murray at Barmah and Hattah, Darling River and lower River Murray. Spawning occurred primarily from October–December and coincided with water temperatures ≥19°C, with the exception of the River Murray at Barmah where spawning occurred at water temperatures ≥16°C. Spawning in the Darling and Goulburn rivers occurred in association with the rising limb of the hydrograph (within-channel flow pulses) in late November/December. In the mid River Murray at Barmah and Hattah and the lower River Murray, spawning occurred across a broad period (October-December), generally on the prolonged descending limb of a within-channel flow pulse that peaked in September–October 2013 or, in the case of Barmah, an overbank flow that peaked in August–September 2013. The timing of spawning and association with hydrology and water temperature concurs with previous investigations (King *et al*. 2009; Koster *et al*. 2012; Zampatti and Leigh 2013a).

In the southern MDB in 2014, recruitment of golden perch to age 0 was only apparent in the lower Murray and Darling rivers, and analysis of otolith microchemistry indicated these fish were spawned either in the lower Murray or Darling River. The fate of eggs and early life stage golden perch spawned in the River Murray at Barmah and Hattah, and the Goulburn River, remains unresolved. Whilst it is likely that early life stage golden perch from these regions drifted downstream in the lotic reaches of the mid River Murray, electrofishing surveys in the region between Mildura and Torrumbarry failed to collect YOY golden perch. Furthermore, none of the YOY fish collected in the lower Murray or Darling River exhibited otolith core $^{87}Sr/^{86}Sr$ characteristic of the Goulburn River or River Murray at Barmah. The fate of golden perch spawned in locations such as the Goulburn River and the mid–upper River Murray is an important area for future research.

Population demographics of golden perch at sites in the southern MDB

Resilient populations of long-lived native fish necessitate multiple age classes to maximise population viability in light of environmental perturbations and anthropogenic impacts (Gunderson 2000). Consequently, assessment of population resilience requires an understanding of survivorship and population demographics. In 2014, a broad range of age classes of golden perch were collected in the southern MDB, with fish ranging from age 0+ to 20+ years. Throughout the lower River Murray, lower Darling River and mid River Murray, however, populations were dominated (38–64%) by age 4+ fish, spawned in 2009/10 during the Millennium Drought. In the lower River Murray, the second most abundant cohort was age 3+ fish spawned in 2010/11 during extensive overbank flooding in the southern MDB. This cohort, however, was not prominent in the Darling River, mid River Murray or Goulburn River.

In the lower River Murray and lower Darling River, age structure data indicate episodic recruitment of golden perch during the period of the Millennium Drought (2001–2009), reflecting the absence of within-channel and overbank flows in these regions during this time (Zampatti and Leigh 2013a). Post-2009, recruitment in both regions has been more consistent with consecutive year-classes from 2010–2014 spawned in association with in-channel and overbank increases in flow, thus improving the resilience and hence health of golden perch populations in the lower River Murray.

In the mid River Murray in 2014, golden perch populations sampled between Mildura and Torrumbarry were dominated by age 4+ fish but also showed multiple cohorts of fish spawned during the Millennium Drought, particularly age 8+ and 10+ fish spawned in 2005–06 and 2003–04, respectively. More consistent golden perch recruitment in the mid River Murray, compared to the lower Murray and Darling rivers, may result from more seasonal flow variability in this region. In the mid River Murray, within-channel rises in flow in spring, remain a feature of the hydrograph, whilst in comparison, these flows are generally regulated out of the flow regime of the lower River Murray by the operation of Lake Victoria (MDBA unpublished data; Zampatti and Leigh 2013a). Golden perch (*Macquaria ambigua oriens*) recruitment in coastal catchments has also been shown to be more consistent in rivers that retain facets of natural flow regimes (Roberts *et al.* 2008).

In the Goulburn River only a small sample of fish (*n* = 19) was collected for ageing. Nevertheless, a broad range of age classes (1–20 years old) was collected. Age 4+ and 5+ fish, spawned in 2009–10 and 2008–09, respectively, were most prevalent, yet it is possible that these fish were not spawned in the Goulburn River. Flows in the Goulburn River in 2008–09 and 2009–10 were extremely low, and sampling conducted with drift nets collected no golden perch eggs or larvae, in either year (Koster *et al.* 2012). This raises the possibility that these fish migrated into the Goulburn River from the River Murray, or are possibly stocked fish. A recent acoustic telemetry study revealed that adult golden perch regularly move between the mid-Murray and Goulburn Rivers (Koster *et al.* 2014), whilst a recent stocking evaluation in the Goulburn River revealed that about 10-20% of golden perch in the Goulburn River are stocked fish (Ingram *et al*., in press). Determining the contribution of immigration to population dynamics in the Goulburn River, as well as the timing and associated environmental conditions, are research questions that require further consideration.

In both the mid River Murray and Goulburn River, the influence of stocking on population structure also cannot be discounted and warrants further investigation, potentially using otolith chemistry techniques (e.g. natural chemical tags or artificial markers such as calcein, Crook *et al.* 2009). Indeed, a more complete picture of the population demographics of golden perch in the southern MDB could be obtained by investigating the age structures of populations in the Murrumbidgee, Edward–Wakool and mid-upper River Murray (i.e. Barmah and upstream) and also collecting larger samples of fish from the Goulburn River. An integral component of such an investigation would be the use of otolith chemistry to investigate the natal origin and migration history of individual fish.

Population dynamics and connectivity

Combining otolith chemistry and biochronology enables a fish to be retrospectively positioned in space and time throughout its life (Campana and Thorold 2001). A primary aim of the present investigation was to elucidate the natal origin and spawn date of larval and age 0+ golden perch in the southern MDB in 2013/14. In conjunction, we combined otolith chemistry and biochronology to also conduct a preliminary investigation of the natal origin and movement history of a small sample of juvenile and adult golden perch from the lower Murray and Darling rivers, the mid River Murray and Goulburn River.

In 2014, a cohort of age 4+ fish dominated golden perch populations in the lower and mid River Murray and Darling River. This cohort was spawned in the Darling River in 2009–10, during the Millennium Drought, but a year with a substantial summer flow (~10 000 ML day^{-1}) in the lower Darling River. Equivalent flows were absent in the mid River Murray and did not transpire in the lower River Murray due to reregulation of flow in Lake Victoria. By measuring otolith $^{87}Sr/^{86}Sr$ from core to edge, and integrating this with annual increments in otolith microstructure, we established that age 4+ golden perch moved out of the Darling River at age 1+ in association with extensive flooding in the southern MDB in 2011. When fish moved out of the Darling River they then moved both upstream and downstream in the River Murray. This finding supports the hypothesis of Zampatti and Leigh (2013b) that this cohort, which appeared as a dominant cohort of age 1+ fish in the lower River Murray, following extensive flooding in 2010–11, was actually spawned in the Darling River in 2009–10.

Population dynamics of golden perch in the Goulburn River may also be influenced by the movement of fish from other catchments. In support of tagging studies of golden perch movement (e.g. Koster *et al.* 2014), the $^{87}Sr/^{86}Sr$ life history profile of a single golden perch, aged 6+, examined in this study provides retrospective evidence of movement between the Goulburn River and other systems. Stocking may also influence population structure of golden perch in the Goulburn River. $^{87}Sr/^{86}Sr$ life history profiles of two golden perch, aged 1+ and 2+, from the Goulburn River showed abrupt changes in $^{87}Sr/^{86}Sr$ early in the fishes life history (<100 days old), from a potential Murrumbidgee River to a Goulburn River signature. We suggest this rapid transition in otolith $^{87}Sr/^{86}Sr$ was due to these fish being artificially propagated in a hatchery in NSW that utilised Murrumbidgee water, and then translocated to the Goulburn River. Indeed, one of these fish was confirmed as stocked based on the presence of an otolith calcein mark.

Management and restoration of freshwater fish populations at relevant spatio-temporal scales requires knowledge of the movement of juvenile and adult life stages and the spatial scale at which population processes occur. The present study constitutes a preliminary exploration of connectivity between regions in the southern MDB and demonstrates that larval, juvenile and adult golden perch move passively and actively over 100–1000s km including between the lower Darling River and lower and mid-Murray rivers (larvae, juveniles and adults), and potentially the Murray and Goulburn rivers (adults). Furthermore, adult and juvenile golden perch may undertake extensive (100–1000s km) active movements in both an up and downstream direction. These findings concur with, and expand on, previous investigations of adult golden perch movement using mark-recapture techniques and radio-telemetry, and studies of the movement of golden perch through fishways (Reynolds, 1983; Mallen-Cooper 1996; O’Conner *et al*.2005)

CONCLUSIONS

The results of the present study support the notion that variability in within-channel flows in conjunction with appropriate water temperatures can promote golden perch spawning in the southern MDB. In some regions, however, this may not lead to *in situ* recruitment of young-of-year fish. Spawning, as evidenced by the collection of golden perch eggs, occurred in the lower Goulburn River and the River Murray at Hattah in October–December 2013, but no young-of-year fish were collected in these regions in March–April 2014. It is possible that eggs and early stage larvae are transported downstream from these source populations and that later upstream movement of juvenile and adult fish influence population demographics in these regions. Stocking also cannot be discounted as influencing population structures.

These observations support the findings of long-term monitoring of golden perch population sizes and structure in a 50 km reach of the River Murray between Yarrawonga Weir and Tocumwal where no young-of-year and very few juvenile (<200 mm TL) golden perch, have been collected during 15 years of intensive electrofishing surveys (Lyon *et al*. 2014; Tonkin *et al*. 2014). The authors suggest fluctuations in golden perch populations in the region are largely driven by influxes (and emigration) of adult and sub-adult fish rather than in-situ recruitment, despite evidence of golden perch spawning in the reach (Tonkin *et al*. 2009).

Our results also demonstrate that the collection of eggs/larvae must be integrated with investigations of recruitment to understand the response of golden perch populations to flow restoration, including specific environmental flow releases. Determining the age and natal origin of early life-stage golden perch enables quantitative association of spawning with hydrology. Furthermore, understanding the age structures of populations provides insight into the resilience (i.e. health) of golden perch populations and the long-term influence of hydrological regulation and restoration.

We suggest that golden perch populations in the southern MDB form a meta-population with potential source and sink populations or a hybrid of patchy population and source-sink models (Schlosser and Angermeier 1995), with considerable movement between these populations by early life stages, juveniles and adults. Age structure in any one region may be dependent on movement/dispersal from regions hundreds of kilometres away. Indeed, specific spawning events and locations (e.g. the lower Darling River) may influence golden perch population dynamics at large spatial scales (1000s km) thus reinforcing the importance of hydrological and biological connectivity throughout the rivers of the southern MDB and the need for a river-scale perspective for the management of golden perch. Further investigations are required, however, to determine the level of connectivity between regions and the importance of immigration and emigration, stocking, and natural and angling mortality in influencing population demographics and the resilience of golden perch populations in the southern MDB.

Future Research

Key research questions that arise from this investigation and which will assist in a more comprehensive understanding of golden perch population dynamics and the relevance of flow on population processes in the southern MDB include determination of:

1. Inter-annual variability in dissolved $^{87}Sr/^{86}Sr$ in water and association with hydrology (i.e. volume and source) in the mid reaches of the River Murray and its major tributaries, including the Murrumbidgee, Goulburn, Campaspe and Loddon rivers.
2. The Influence of stocking on the population demographics and dynamics of golden perch in the southern MDB.
3. The movement of juvenile and adult golden perch between rivers/regions in the southern MDB, in particular the influence of immigration and emigration on population dynamics.
4. The fate of golden perch eggs and larvae originating across the southern MDB, including factors influencing survival.
5. The influence of natural and angling mortality on population dynamics.

Developing an understanding of these factors, in association with long-term monitoring of golden perch population size and demographics at selected sites in the southern MDB, would aid in the development of models of golden perch population dynamics that would assist in environmental water allocation.

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