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Riverine flow and spawning requirements of *Macquaria ambigua oriens*: implications for conservation and management

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Abstract. Understanding the life-history attributes of aquatic species is integral to the development of environmental-flow strategies in regulated river systems. This is particularly important when species are under continual and increasing pressure from water-resource development. In this study, the water temperature and flow requirements for spawning of the Fitzroy River golden perch (*Macquaria ambigua oriens*) were investigated over 4 years at 22 sites in the Fitzroy River catchment. Eggs, larvae and young-of-year (YOY) *M. ambigua oriens* were sampled on a variety of flow events to determine the environmental requirements for spawning. Eggs and larvae of *M. ambigua oriens* were detected during natural flow events generally with a minimum of 1.5 m river rise and duration of 7 days. Spawning was associated with the peak and/or recession of the first or second post-winter flow event where water temperatures exceeded 24°C. Our data suggests that it is important to protect a range of flows, not just flood flows, as previously documented for this species. The interaction of spawning flows with existing and future water-resource development should be considered to ensure maintenance of the population viability of *M. ambigua oriens*.

Additional keywords: environmental flows, Fitzroy River, golden perch, regulation, water-resource development, water temperature.

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Introduction

Hydrological alteration of riverine ecosystems, and concomitant impacts on biodiversity, not only threaten ecological integrity and sustainability, but also the spectrum of human dependence on services provided by these ecosystems (Arthington *et al.* 2006, 2010). Recognition of these issues has led to significant resources being directed towards integration of water science, policy and management (Poff *et al.* 2003; Tharme 2003; Webb *et al.* 2010); with the ultimate aim of consolidating environmental flows in water-resource management. Development of environmental-flow strategies requires an understanding of the aspects of flow that are critical in supporting aquatic ecosystems (Boulton and Brock 1999; Thoms and Sheldon 2002). Specifically, knowledge regarding the influence of timing, duration, magnitude and frequency of the flow regime on ecological responses is fundamental (Welcomme and Halls 2001, 2005; Bunn and Arthington 2002; Welcomme *et al.* 2006). Absence of spatially explicit ecological information has inherent risks and can compromise the development and overall success of environmental-flow strategies (Arthington *et al.* 2004). Monitoring and evaluation are therefore important to ensure that targeted ecological outcomes of environmental-flow strategies are achieved (King *et al.* 2010).

Fish play an important role as flagship species for environmental-flow programs due to their critical dependence on the natural flow regime (Poff and Zimmerman 2010). Environmental flows developed to protect specific requirements of fish species or communities require data on the relationship between river hydrology and key aspects of fish biology. Arthington *et al.* (2003) suggested that preliminary data should include species composition and distribution, habitat preferences and water quality tolerances. Further investigations into movement and passage requirements, diet and foraging behaviour, reproductive biology, spawning habitats and larval/juvenile requirements should follow. In Australia, many environmental-flow programs have included strategies to protect the flow-spawning cues of fish species (e.g. MDBC 2002*a*, 2002*b*). The design and implementation of such environmental flows are often developed using best available science at the time; however, very few of these studies investigate the causal mechanisms behind hydro-ecological relationships.

For the Fitzroy River Basin in central Queensland, environmental-flow strategies have been specifically developed with the intent of supporting the endemic fish species, Fitzroy River golden perch (*Macquaria ambigua oriens*). One such strategy, the 'first post-winter flow event', specifically aims to minimise the impact of water-resource development on first post-winter flows where water temperatures exceed 23°C (Queensland Government 2010, 2011). Importantly, this strategy was developed when the available literature focussed solely on the Fitzroy River golden perch's allopatric species (*M. ambigua ambigua*); whose own spawning strategy has been subsequently significantly revised (King *et al.* 2003; Mallen-Cooper and Stuart 2003; Balcombe *et al.* 2006; Ebner *et al.* 2009; Kerezsy *et al.* 2011). What was initially considered a flood-spawning species (Lake 1967*a*; Mackay 1973; Reynolds 1983), has since met with alternative spawning models that have challenged its flood-flow dependence.

This study reports on the results of a 4-year study investigating the hydrological spawning requirements of *M. ambigua oriens* populations in the Fitzroy River Basin, and in turn determines whether current environmental-flow strategies are providing these critical water requirements.

Methods

Study area

The Fitzroy River Basin is the largest east coast drainage system of Australia, occupying an area of ~142 600 km^2 (FBA 2008). There are six major river sub-basins: the Fitzroy, Dawson, Mackenzie, Nogoa, Comet and Isaac/Connors (Fig. 1; 23°47′25.18″S, 149°45′42.55″E). Rainfall and stream flow are highly variable, with a distinct wet season in the summer months. The remainder of the year (dry season) has low rainfall and rivers regularly recede to a series of disconnected turbid waterholes.

The Fitzroy River Basin is heavily regulated: 11 large weirs, one major dam and one barrage impound 44% of the Fitzroy River length, 48% of the Dawson River length and 49% of the Nogoa/Mackenzie River length (Fig. 1; Queensland Government 1998). The Fitzroy, Mackenzie, lower Dawson, Comet and lower Nogoa rivers are the most regulated sections, with median annual flow estimated to be 50% to 79% of pre-development conditions (Queensland Government 1998). The Isaac/Connors, upper Nogoa (upstream Fairbairn Dam) and upper Dawson (upstream Glebe Weir) rivers are relatively unregulated, with median annual flow estimated to be 95% to 99% of pre-development conditions (Queensland Government 1998). Low flows are significantly affected, with sites downstream of impoundments receiving supplemented flows for irrigation (predominantly cotton), mining and industrial use (Queensland Government, 1998). Medium to high flows are less impacted; however, flood flows in the Lower Nogoa are greatly reduced by the presence of Fairbairn Dam, which can accommodate 1.3 GL at full supply (Queensland Government 1998).

Predicted future high demands for the water resources of the Fitzroy River Basin have resulted in several large dam and weir proposals for the upper Dawson (Nathan Dam), Connors (Mt Bridget Dam) and lower Fitzroy rivers (Rookwood and Riversleigh Weirs) (Queensland Government 2006). It is expected that these proposed dams and weirs will significantly impact on the flow regimes of these rivers, particularly on those that are relatively unregulated at present (e.g. upper Dawson and Connors rivers).

Study sites

In total, 22 sites were sampled on 85 separate occasions for *M. ambigua oriens* eggs, larvae and young-of-year (YOY) fish (Table 1; Fig. 1). Sites were located in the unregulated upper reaches of the Nogoa and Dawson rivers, and in the regulated reaches of the Dawson, Mackenzie, Fitzroy and Comet Rivers. Sites were located in close proximity to stream gauging stations owned by the Queensland Department of Natural Resources and Mines (DNRM). Sites were sampled over four seasons (2004/5, 2005/6, 2006/7, 2007/8) during flow events between October and April, and also during no/low flow spells. Efforts were made to ensure a consistent and standardised sampling regime; however, highly variable flows and poor site access (due to flooded roads and/or poor road conditions) often prevented sampling. This resulted in a more opportunistic sampling program whereby sites were sampled when conditions allowed.

Sample collection

Drift nets were used to sample *M. ambigua oriens* eggs and larvae during flow events driven by rainfall. Flow events that were proposed to be sampled were those with discharges that were thought to inundate the river channel by at least 1.5 m based on upstream gauge station data. Since the sites span over many hundreds of kilometres, the decision to sample was based on several factors including whether it was the first flow for the season, whether the site had been previously sampled and the probability of access to the site. All attempts were made to sample across the whole flow event from the first day of flow at site through to the receding limb of the hydrograph. At each site, three to six conical larval drift nets (500-µm mesh, circular, 1.5-m deep, 400-mm opening; T & L Netmaking, Melbourne) were suspended in surface waters of the main channel. Nets were fitted with flow meters (2030 series, General Oceanics Inc., Miami, FL, USA) to determine volume sampled, and net entrances were covered with mesh (40 mm) to prevent entry of debris and larger predators (Gilligan and Schiller 2003). Nets were deployed for between 6 to 15 h (12 h average). When available, subsamples of live eggs and larvae were placed in 20-L aerated carboys and transported to the laboratory for rearing and identification. Remaining samples were rinsed through a 500-µm mesh and preserved in 70% ethanol.

Sampling over the first season showed that velocities during low-flow periods were generally too low to allow the effective use of drift nets. Drift-net tows were also trialled; however, the

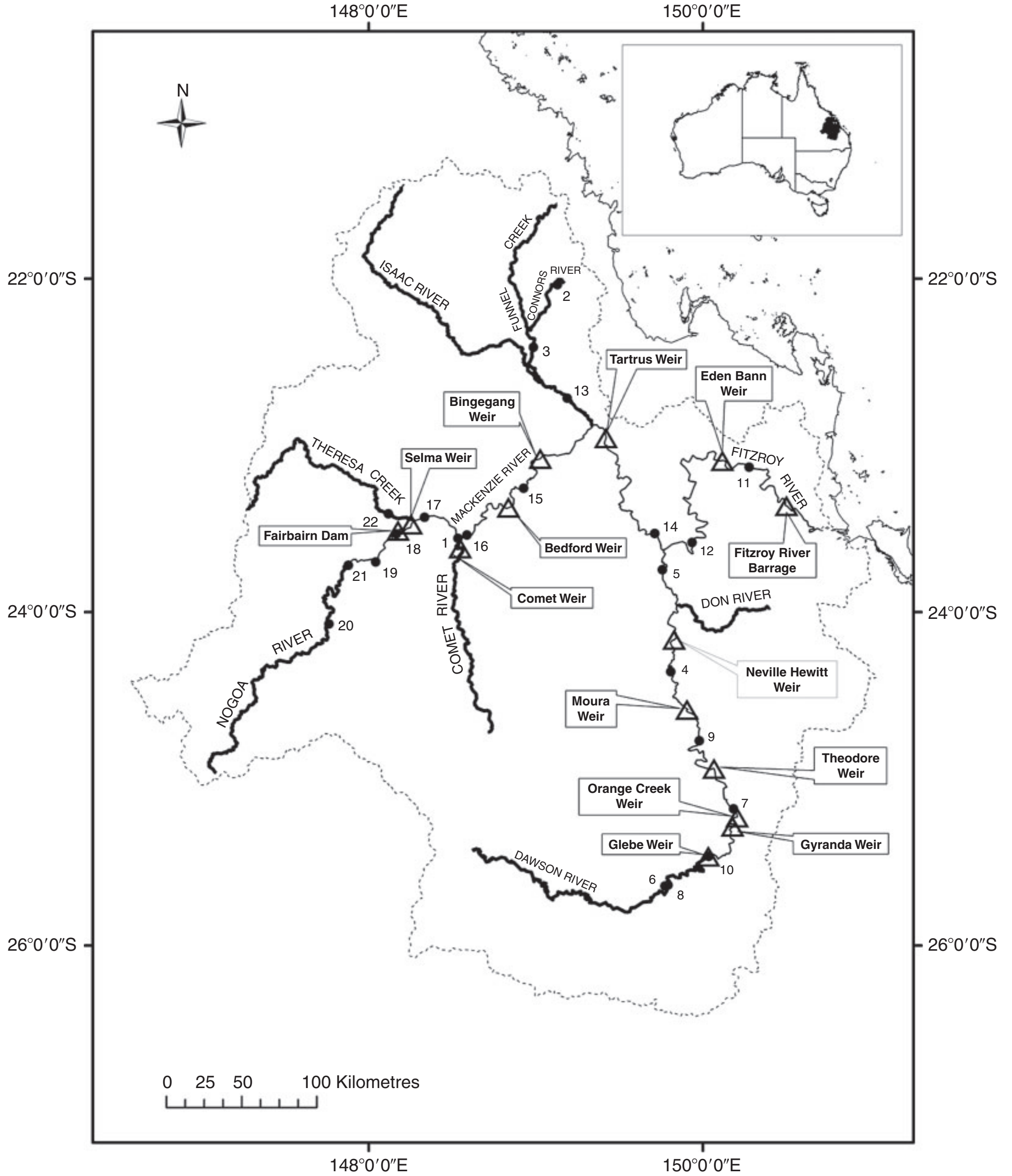

Fig. 1. Location of study sites sampled for Fitzroy River golden perch (*Macquaria ambigua oriens*) eggs, larvae and young-of-year (YOY) fish. Triangles represent major river impoundments. Emboldened river reaches represent unregulated sections.

associated data was excluded as this method could not be carried out consistently due to difficulties gaining boat access to sites.

Young-of-year (YOY) fish sampling was conducted to provide further evidence of spawning events of *M. ambigua oriens* in years where there is successful recruitment. It is acknowledged that this technique, however, may not be able to detect spawning events when recruits are not sampled. Back-calculating the age of YOY fish from daily growth increments in otolith microstructure not only confirms the timing of spawning, but also highlights environmental conditions evident during spawning events. YOY fish were sampled using boat (2.5 GPP, Smith-Root, Inc., Vancouver, WA, USA) and backpack (LR-24, Smith-Root, Inc.) electrofishing. Voltage and frequency (Hz) were adjusted at each site according to local conditions, and to minimise harm to biota. Effort was maximised at all sites by targeting complex habitats (e.g. structural woody habitat, rocks, undercut banks) favoured by *M. ambigua oriens*. Sampling time and effort were recorded for individual locations with each site/trip varying between 131 and 39 180 s (average 7767 s). Fish were anaesthetised using Aqui-S© (Lower Hutt, New Zealand) and preserved in 70% ethanol for

Table 1. Periods of egg and larval sampling (as indicated by D) and young-of-year (YOY) fish sampling (as indicated by E) for each of the 22 monitoring sites

* and shading indicates samples where eggs/larvae or YOY were collected respectively. Emboldened sites denote unregulated sites. TW = tailwater/below dam or weir

River/Site no./name	2004				2005												2006												2007											
	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Comet River																																								
1. CometWeir TW																																							D	
Connors River																																								
2. Mt Bridget gauge					D																																			
3. Twin bridges				E																									DD											
Dawson River																																								
4. Bindaree																											DD													
5. Boolburra																											D						E			E		E		D*
6. Glebe Weir									E					D																			E							
7. Isla Delusion																																								D*
8. Taroom	E		D	D										D		D	E			E*							D				D		E			E		E	D*D	
9. Waddington Park																																	E			E		E		D*
10. Glebe Weir TW			E						E					D	D	E				E*													E							
Fitzroy River																																								
11. Eden Bann TW									E																															
12. Riversleigh																											D													
Isaac River																																								
13. May Downs Rd																													D											
Mackenzie River																																								
14. Duaringa-Apis Rd									E																											E		E		D
15. Jelinbah																																								D
16. Rileys Crossing																												D					E			E		E		D
Nogoa River																																								
17. Bridge Flat Rd																																								D
18. Emerald						E			E																															D
19. Fairbairn Dam	E																																							
20. Glenlees	E			D*		D		E						D		D				E							D		D*D*	DE*					E	E		E	D*	D*
21. Norwood				D*				E						DD		DD				E																				
Theresa Creek																																								
22. Main Rd														D																										

laboratory-based identification and enumeration. Non-target species were released at point of capture.

Sample processing

In the laboratory, preserved drift-net samples were rinsed through a 250-μm sieve, and coarse fractions (e.g. large leaves, twigs and rocks) removed. Drift-net samples containing a small amount of debris were completely sorted (100%), whereas samples containing a large amount of debris were sub-sorted (10%) using a modified Marchant sub-sampler (Marchant 1989). *M. ambigua oriens* eggs and larvae were identified, and larval stages assessed according to *M. ambigua ambigua* descriptions (Lake 1967*b*; McDowall 1996; Neira *et al.* 1998; Serafini and Humphries, 2004) and observations of laboratory-reared *M. ambigua oriens* specimens. Egg diameter and larvae total length (TL) were measured using a dissecting microscope, and life stages were estimated, as follows, to aid in the back-calculation to spawning events:

- Eggs: 0–1 day (diameter 2.8–4.2 mm)
- Protolarvae: 1–5 days (2.4–5.1 mm TL)
- Flexion: 4–9 days (4.6–7.5 mm TL)
- Post–flexion: 7–12 days (6.1–7.9 mm TL)
- Metalarvae: 13–21 days (11.0–17.0 mm TL)

Abundance of eggs and larvae were standardised by volume for each site (e.g. number of eggs/larvae ML^{-1}) according to the General Oceanics User Manual.

Otolith extraction and reading

Sagittal otoliths were removed from preserved *M. ambigua oriens* in the laboratory, according to McDougall (2004). Samples were cleaned in distilled water and placed in vials to dry. Each sample was mounted in Crystalbond™ 509 (West Chester, PA, USA) transparent adhesive on a microscope slide and polished to expose the primordial region. Daily increments were counted at a magnification of 250×. A 25% random otolith re-count was conducted to provide an estimate of the average percentage error (APE) (Beamish and Fournier 1981).

Data analysis

Estimated spawning dates were calculated using two approaches. The first approach involved back-calculating the known average number of days of each egg/larval life-stage, from the date the eggs and larvae were collected in drift nets. The second approach involved back-calculation of sagittal otolith daily increments from YOY fish at the date of capture. First increment formation was assumed to occur when otoliths were first observed, which, based upon laboratory rearing of eggs collected in the field and examination of field-preserved protolarvae, occurred within one day of hatching. A YOY-data linear regression equation (fish TL: estimated daily otolith count) was calculated using Statistica 7.1 (Tulsa, OK, USA).

Calculated spawning dates were plotted against mean daily river discharge (ML day^{-1}) and water temperature (°C), obtained from the department's existing gauging station network (DNRM Hydstra database). The water temperatures and river discharge at which spawning occurred was determined for the back-calculated spawning periods, and statistically (i.e. mean, minimum and maximum) and graphically (i.e. histograms) summarised. River discharge and water temperature were corrected for sites without gauged data, based on known flow-transfer times (P.Voltz, Department of Natural Resources and Mines, Queensland, pers. comm.).

Results

Of 85 sampling events, 45 of these targeted eggs/larvae during naturally occurring flows between October and March (Table 1; see Supplementary Figs S1 and S2). The magnitude of flow events sampled ranged between 500 ML day^{-1} (Glenlees, November 2006) and 41 500 ML day^{-1} (Taroom, December 2005). Water temperatures during the sampled flow events ranged from 20.7°C (Taroom, November 2005) to 29°C (Taroom, December 2005). The majority (68%) of the 39 electrofishing trips occurred during no flows; a maximum flow was recorded at 200 ML day^{-1} (Glenlees, March 2007). Water temperatures during these periods ranged from 10.3°C (Glenlees, July 2008) to 26.6°C (Glenlees, March 2007).

Spawning was only detected during periods of elevated flow events (Table 1; see Supplementary Figs S1 and S2). Eggs/larvae or YOY fish were collected on 13 of the 85 sampling events (~15%) from seven of the 22 sites (~32%). Spawning occurred in the catchment during each of the 4 years and only between the months of November and January.

Spawning observations: eggs/larvae

Ten spawning events were identified via collection of drifting eggs/larvae (Table 1; see Supplementary Figs S1 and S2). Abundance of eggs/larvae varied considerably between spawning events, with mean egg/larval abundances ranging from 5 to 7 373 ML^{-1} (Table 2). Highest egg/larval abundances were collected from the unregulated sites of the Nogoa River (Norwood and Glenlees) and Dawson River (Taroom), followed by sites in the regulated reaches of the Dawson River (Boolburra, Waddington, Isla Delusion). No spawning was detected in the regulated sections of the Nogoa/Mackenzie, Fitzroy or Comet rivers or the unregulated Isaac/Connors River.

The collection of drifting eggs/larvae only occurred over one or two flow events per season for any particular site, with most of spawning occurring over the first significant post-winter flow event where water temperature exceeded 24°C. In the Upper Nogoa River, this spawning strategy was most notable during the 2006/07 and 2007/08 seasons. Only one spawning occasion was detected during the 2004/05 season. No eggs/larvae were collected during the 2005/06 season, when river flows were comparatively lower than the other years in the post-winter period. In the Dawson River, drifting eggs/larvae were only collected during the 2007/08 season, where spawning was detected at four sites and over two sampling periods.

Back-calculation of egg/larval ages revealed that *M. ambigua oriens* predominantly spawned on the peak and/or recession of a flow event (i.e. 8 of 10 spawning events) (Table 2). The remaining two spawning events yielded a low abundance of eggs (up to 10 eggs ML^{-1}) collected on the rise of the flow event; however, these samples were collected on the rise of the same flow events that yielded abundant eggs/larvae upon its recession and may be indicative of spawning further up the catchment. Eggs of

Table 2. Standardised abundance of eggs and larvae (ML^{-1}) of Fitzroy River golden perch (*Macquaria ambigua oriens*)

Site no.	Site name	Sample date	Eggs ML^{-1}		Protolarva ML^{-1}		Flexion ML^{-1}		Post flexion ML^{-1}		Meta larvae ML^{-1}		Total ML^{-1}		Spawning location in flow event
			mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.	
21	Norwood	14-Dec-2004			7338	1826	35	36					7373	1861	peak/fall
20	Glenlees	15-Dec-2004	146	96	5726	2384	31	25					5903	2504	peak/fall
20	Glenlees	10-Jan-2007	838	663	3122	1894							3960	2557	peak/fall
20	Glenlees	17-Jan-2007					5	2					5	2	fall
20	Glenlees	29-Nov-2007	6	0									6	0	rise
20	Glenlees	4-Dec-2007	4390	1721	36	50							4426	1770	fall
8	Taroom	28-Nov-2007	10	2									10	2	rise
5	Boolburra	6-Dec-2007	2634	304									2634	304	fall
9	Waddington Pk	10-Dec-2007			977	520	106	23	95	39			1178	581	peak/fall
7	Isla Delusion	10-Dec-2007			1698	459	409	158	296	251	20	28	2423	895	fall

M. ambigua oriens hatch after approximately 1 day (K. Burndred, unpub. data), which, based upon known flood travel times, potentially exposes eggs to up to 60 km of upstream river length before hatching (P. Voltz, Department of Natural Resources and Mines, Queensland, pers. comm.).

Recruitment observations: YOY fish

Forty sampling periods targeted YOY fish, which occurred throughout the year during periods of no/low flow (i.e. <100 ML day^{-1}) (Table 1; see Supplementary Figs S1 and S2). Both the highly turbid water and steep, muddy banks made access and safe operation of electrofishing equipment problematic. Sampling was therefore restricted to provision of safe access.

One-hundred and sixty-two (162) YOY fish were collected from four sites (Taroom, Glenlees and Glebe Weir TW) (4.5 to 165 mm TL). The first two sites are unregulated reaches where spawning has been detected, with the latter being a weir immediately below sites where eggs and larvae have been collected. Daily-age estimates were reliably determined from 112 fish (APE < 1%). The remaining 50 fish had too diffuse or irregular daily increments to accurately count and hence were subsequently excluded from further analysis.

The 112 YOY fish were collected from two separate sampling events over three sites. In April 2006, 24 YOY fish were collected from Dawson River at Taroom and Glebe Weir TW (~55km downstream), with an estimated daily age between 28 and 45 days (15 to 53 mm TL). In February 2007, 87 YOY fish were collected from Nogoa River at Glenlees, with fish-age ranging from 5 to 27 days (4.5 to 22 mm TL). Estimated daily age and fish total length was positively related ($r^2 = 0.9133$, $P < 0.0001$; Daily age $= -0.1624 + 0.9755 \times$ fish TL).

Both YOY spawning periods were back-dated and aligned with the peak and fall of preceding flow events (Fig. 2). Spawning of the Taroom/Glebe Weir TW YOY fish were back-calculated to a flow event in November 2005 (Fig. 2*a*), whilst Glenlees YOY fish were back-dated to January 2007 (Fig. 2*b*). Importantly, for the Glenlees sample, recruits were back-dated to a flow event where eggs and larvae had been previously collected, highlighting the viability of the hydraulic habitat provided by the flow event for both spawning and recruitment.

Flow and water temperature conditions during spawning events

Spawning occurred in flow events ranging from 522 to 18 992 ML day^{-1}, with the majority (67%) occurring at flows between 4000 to 10 500 ML day^{-1} (Fig. 3*a*, see Supplementary Table S1). Water temperatures on these flows ranged from 21.5 to 29.5°C, with the majority of spawning (over 83%) occurring when water temperatures exceeded 24°C (Fig. 3*b*, see Supplementary Table S1). River height during these flow events ranged from 0.19 m to 6.71 m above cease-to-flow, with the most spawning occurring at flows greater than 1.5 m above cease-to-flow (Fig. 3*c*, see Supplementary Table S1).

Discussion

Our study provides further resolution on the links between river flow, water temperature and spawning and recruitment of

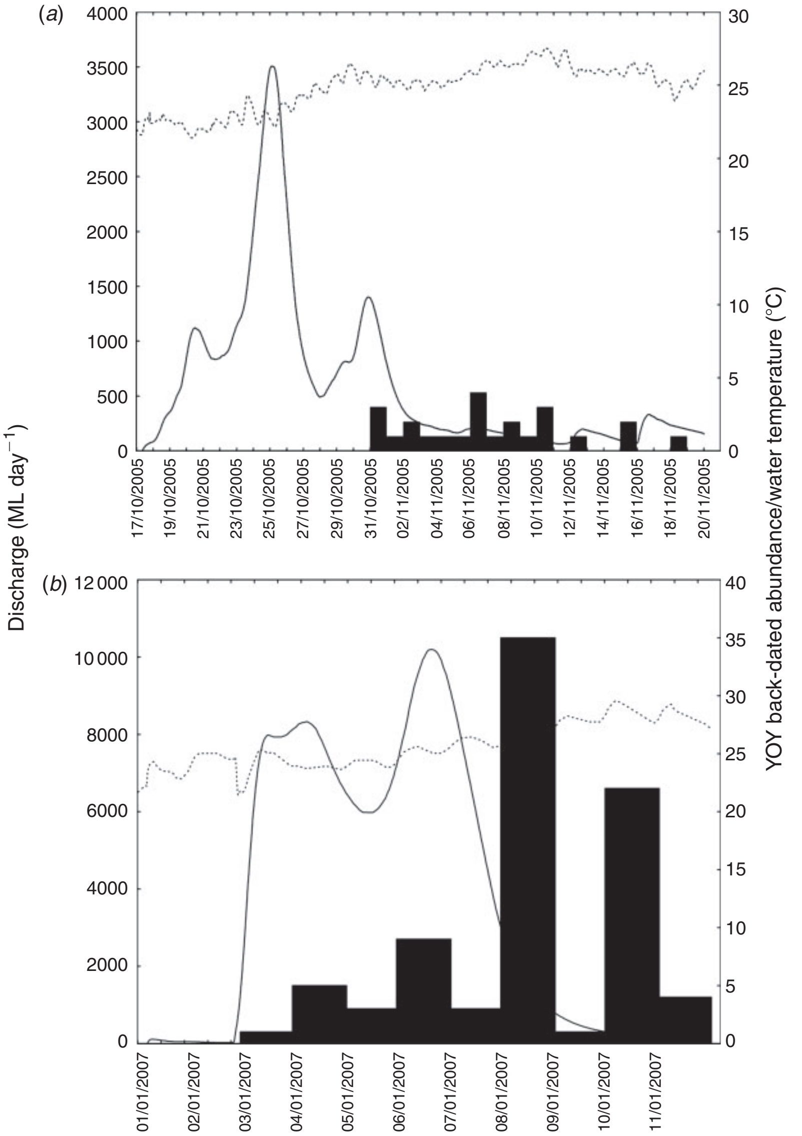

Fig. 2. Back-dated young-of-year fish abundance (solid column), mean daily discharge (ML day^{-1}) (solid line) and water temperature (°C) (dashed line) collected from Dawson River at Taroom in April 2006. (*a*) Discharge and water temperature data taken from Dawson River at Taroom gauge (130302a)) and Nogoa River at Glenlees in February 2007. (*b*) Discharge and water temperature from Nogoa River at Craigmore (130209a)).

Fitzroy River golden perch, *Macquaria ambigua oriens*. We propose important refinements to the spawning model for this species (Fig. 4); one that highlights the requirement for seasonal, yet variable, in-channel flows, and also the importance of early season (Spring) connectivity flows.

Spawning of Fitzroy River golden perch predominately occurred on the peak and/or fall of the first or second flow events of the season, where water temperatures exceeded 24°C. During this study, this was between November and January. We observed spawning in association with river rises generally greater than 1.5 m above cease-to-flow, but never during periods of low/no flow.

The magnitude of flow-spawning events ranged from minor inundation of the first bench, to moderate within-bank events that filled and ran through a series of low to medium level billabongs, alluvial terraces and anabranches (B. Cockayne, pers. obs.). Floodplain inundation has been postulated to underpin spawning and recruitment of a variety of native Australian fish species (e.g. Lake 1967*a*); however, supporting evidence is scant and its broad applicability subsequently questioned (Humphries *et al.* 1999; King *et al.* 2003; Mallen-Cooper and Stuart 2003; Kerezsy *et al.* 2011). Floodplain flows in the region are generally uncommon, occurring approximately once every 3–8 years (DNRM Hydstra database 2010). This indicates that

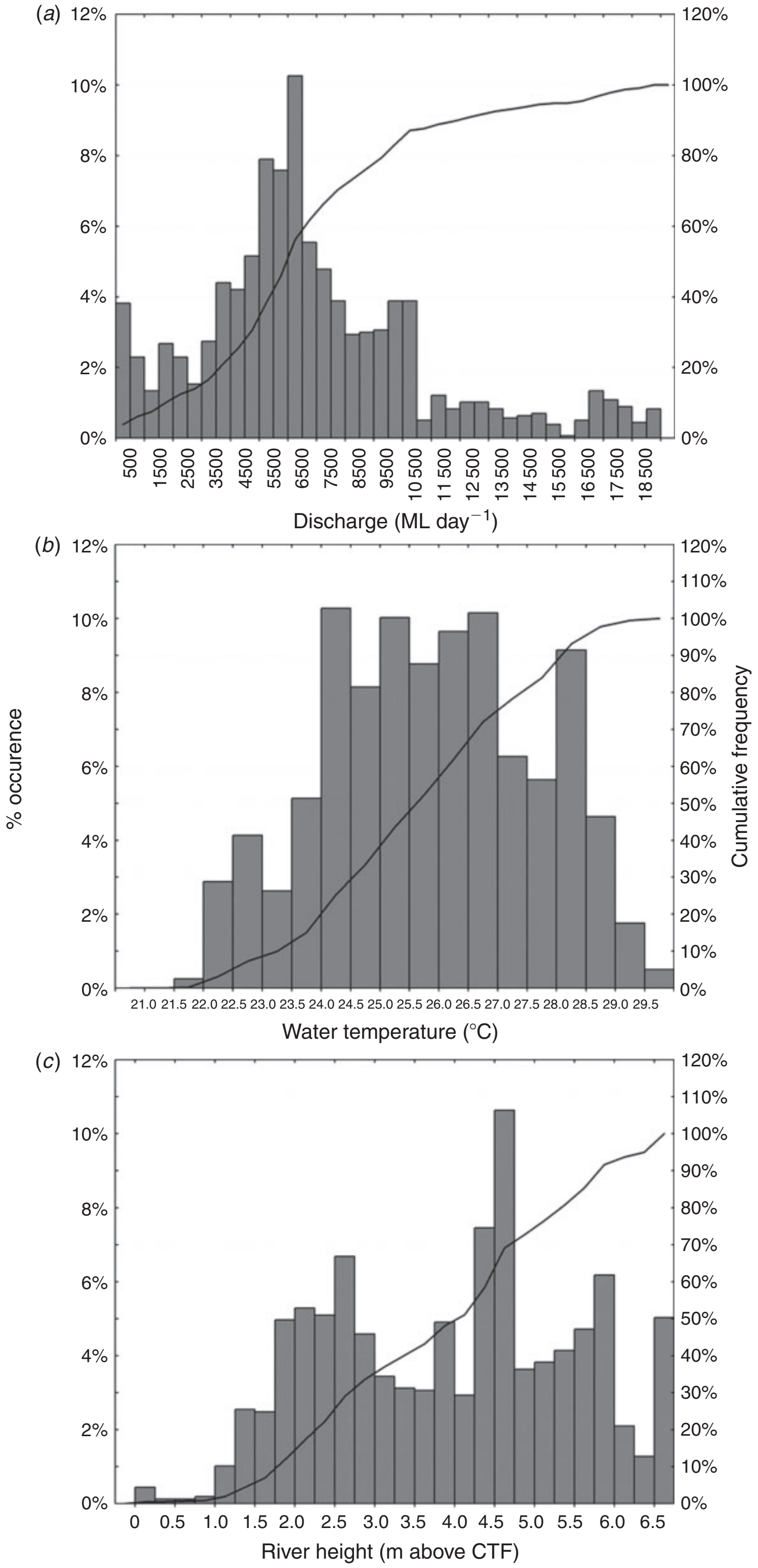

Fig. 3. Percentage occurrence of all recorded Fitzroy River golden perch (*Macquaria ambigua oriens*) spawning over given (*a*) flows, (*b*) water temperature and (*c*) river height. Data collected at 30 min intervals. CTF = cease to flow.

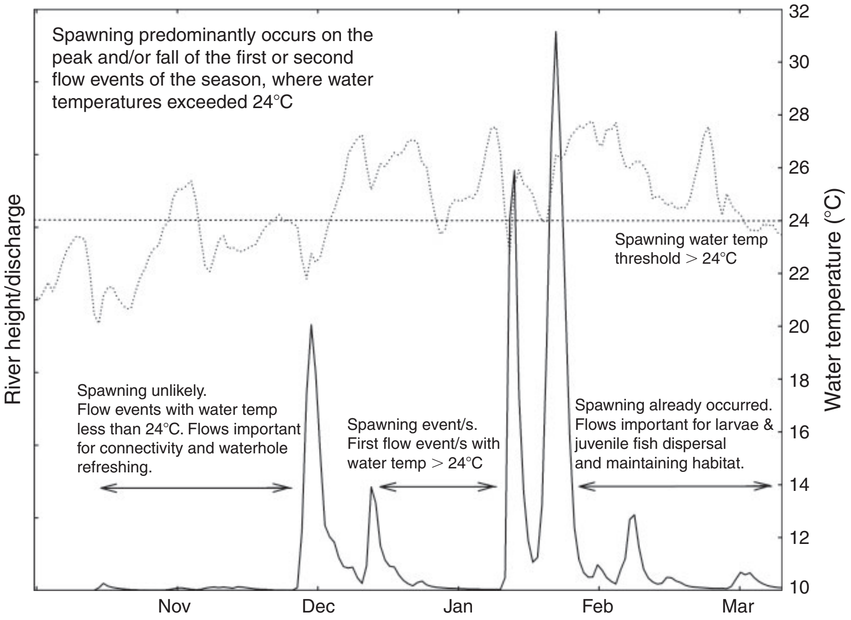

Fig. 4. Proposed spawning model for Fitzroy River golden perch (*Macquaria ambigua oriens*).

floodplain inundation is not a critical requirement for Fitzroy River golden perch spawning and recruitment, but rather the ecological response occurs on flow events that typically occur annually.

These results support previous findings linking flows and Fitzroy River golden perch spawning and recruitment. Roberts *et al.* (2008) established a link between river flows and Fitzroy River golden perch recruitment, with positive correlations between annual age structure and total discharge volume for months within years with an average water temperature above 23°C. They found flow events contributing to strong year classes were variable, but strongest around 9000 ML day^{-1}, which is consistent with results from this study.

The timing of flow events during the warmer months of the year is a critical component of the Fitzroy River golden perch spawning strategy and emphasises the important role of water quality, which should be considered alongside flow parameters, when developing environmental-flow strategies. In this study, no eggs or larvae were sampled in early season (i.e. September to October) or late season (i.e. February to April) flow events, and no YOY recruits were back-dated to these periods. These results concur with those of Roberts *et al.* (2008), who found flow events that occurred before November and after March generally resulted in poor annual recruitment, regardless of flow event magnitude. A lack of spawning early in the season is likely to be linked to water temperatures being lower than the spawning trigger of 24°C. Although late-season flows were generally above the 24°C spawning trigger, no evidence of spawning was detected, and we expect that this is likely due to spawning having already occurred during prior flow events.

The natural shape and duration of a spawning flow event can have a major influence on spawning and recruitment success of Fitzroy River golden perch. The initial rise of a flow event has long been proposed as a reproductive stimulus for golden perch (Lake 1967*a*; Mackay 1973; Battaglene 1991; Mallen-Cooper and Stuart 2003), with connectivity created by such rises providing access to spawning habitat, which is a fundamental requirement of the golden perch spawning migration strategy (O'Connor *et al.* 2005). Collection of eggs around the peak of flow events, in this study, would suggest that *M. ambigua oriens* responds similarly. Purging of semi-buoyant eggs during the peak of the event is likely to aid in egg dispersion and improve chances of larvae entering nursery habitat. The duration of an event recession is also important for larval development and recruitment with slow-flowing backwaters and inundated billabongs, anabranches and alluvial terraces providing a warm, safe and potentially food-rich refuge for larvae (Humphries *et al.* 1999; Tonkin *et al.* 2011). Such conditions would be provided for by the slowly receding tail of a flow event.

We propose that low-flow events before the Fitzroy River golden perch spawning season improve Fitzroy River golden perch spawning and recruitment success. A majority of significant spawning events in this study were preceded by small-flow events. Flow events before the spawning season can be linked to several ecological functions such as an increase in hydraulic connectivity (particularly where isolated waterholes exist), improvement in condition of spawning habitat, improved nutritional sources subject to the 'low-flow recruitment hypothesis', and therefore improved physiological conditioning of adult fish (Collins and Anderson 1999; Humphries *et al.* 1999).

Results from our study add to the recent evidence that suggests golden perch may adopt a spawning strategy that aligns more closely with, and utilises characteristics of, localised flows rather than extensive flooding. Kerezsy *et al.* (2011) demonstrated no statistically significant flow, or seasonal, component to the spawning of the Lake Eyre sub-species of *M. ambigua,* based on a size-frequency analysis of juveniles. This same study demonstrated no difference in recruitment patterns between two river systems; one experiencing only within-channel flows, and the other experiencing channel flows and major flooding.

Subsequent review of additional gauged data for the Lake Eyre region revealed successful spawning and recruitment of the of Lake Eyre sub-species of *M. ambigua* on smaller flows (1–5 m river rises) between November and March (DNRM Hydstra database 2012).

In contrast, Ebner *et al.* (2009) found that *M. ambigua* spawned on flows in all seasons in the Menindee Lakes, a similarly variable albeit managed lake system on the floodplain of the Darling River in Western NSW. Other studies have shown golden perch to be more opportunistic and flexible spawners, with spawning occurring throughout the year but enhanced by elevated flow events and during high flow years (Balcombe *et al.* 2006, 2007; Balcombe and Arthington 2009; King *et al.* 2009; Rolls and Wilson 2010). These differences, within a genetically similar group of species, further highlight the importance of collecting locally relevant data in the development of environmental-flow strategies in regulated river systems.

The majority of spawning and recruitment events in our study occurred in the largely unregulated, upper catchments of the Nogoa and Dawson Rivers. Larvae were also collected further down the Dawson River (Isla Delusion, Waddington Park and Boolburra). However, predominant late-stage larvae combined with flow travel times indicate spawning to have occurred further upstream in the unregulated reaches. The presence of only relatively small weirs above these sites (Glebe, Orange Creek and Gyranda) enabled the eggs and larvae to be dispersed effectively over longer reaches of the Dawson River during overtopping events. This pattern was not replicated in the upper Nogoa River, which drains into the 1.3 GL Lake Maraboon (Fairbairn Dam) and which had overtopped only rarely. No eggs or larvae were collected downstream of Fairbairn Dam. These contrasting changes to the flow regime, and connectivity, have significant implications for the recruitment potential of Fitzroy River golden perch through the lower Fitzroy River Basin. Indeed, annual age-structure data from Roberts *et al.* (2008) suggests the recruitment of *Macquaria ambigua oriens* in the upper Nogoa River to be relatively consistent. In contrast, recruitment to the lower Dawson, Fitzroy and Mackenzie rivers was more closely correlated with infrequent large summer flows that provided connectivity throughout this system.

The reproductive migration strategy of golden perch has been observed (Cadwallader 1977; Mallen-Cooper *et al.* 1995), tested (Reynolds 1983; Koehn and Nicol 1998; O'Connor *et al.* 2005) and extensively discussed (Llewellyn 1968; Mallen-Cooper 2000; Barrett and Mallen-Cooper 2006). The precise locations or hydraulic habitat that accommodates spawning aggregations, however, remain unknown. Results from our study suggest the upper reaches of the Nogoa and Dawson Rivers currently provide this spatiotemporal habitat on a more frequent basis. If this pattern is indicative of process, then the interaction between the upper and lower catchments as sources and sinks for Fitzroy River golden perch eggs and larvae becomes important to the long-term viability of the population. Variability in the magnitude of spawning flows has been recognised as a primary determinant of spatial patterns of recruitment and genetic diversity (Mallen-Cooper and Stuart 2003; Faulks *et al.* 2010). The importance of large flow events to the long-range dispersal of potential recruits is warranted; however, the importance of localised recruitment from smaller annual flow events is also relevant, particularly in catchments where upstream recolonisation is artificially impeded (Brumley *et al.* 1987; Humphries *et al.* 1999).

Failure to collect fundamental data on the relationship between flow regime, critical aspects of a fishes' life history, and their combined interactions with water-resource development, will inevitably result in environmental-flow management strategies that fall short of their ecological intent (Arthington *et al.* 2010). There are many examples worldwide where flow-management strategies have been developed to protect fish spawning and recruitment (see Poff and Zimmerman, 2010 for a recent review); however, application and success of these vary. For example, King *et al.* (2009) found that spawning activity of *M. ambigua* increased during a major environmental water allocation. Whilst the exact mechanisms for the spawning success were not determined, management of these environmental water allocations were further refined to optimise and enhance fish spawning and recruitment (King *et al.* 2010). In contrast, a 13-year environmental-flow monitoring program in British Columbia failed to demonstrate a significant benefit to fish populations, despite habitat modelling and holistic instream flow approaches implying greater benefits with larger flows (Bradford *et al.* 2011). These studies highlight the importance of quantifying flow alteration and ecological response relationships, and the need to consider the key attributes of the natural flow regime in environmental-flow strategies (Poff and Zimmerman 2010).

There are potential future challenges facing the recruitment success and overall population viability of the Fitzroy River golden perch. The water resources of the Fitzroy River Basin are currently being investigated to underpin not only an expanding population, but also the agricultural, industrial and mining sectors. Currently, there are two major dams and several large weirs being considered to meet this demand (Queensland Government 2006). These have the potential to elicit major impact on the flow regime, with reduced flooding frequency, reversed flow seasonality, barriers to fish migration and water quality issues (namely cold water pollution). These impacts can increase the strain on Fitzroy River golden perch spawning, recruitment and, therefore, viability. To assist in mitigating the adverse effects of flow modification, appropriate flow-management strategies, and concomitant monitoring programs, must be developed including the hydro-ecological relationships of the Fitzroy River golden perch and other flow-dependent assets.

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