Factors influencing recruitment patterns of Golden Perch (*Macquaria ambigua orientalis*)
within a hydrologically variable and regulated Australian tropical river system.

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Abstract

The links between river flows, water temperature, river regulation and recruitment variability of Golden Perch, *Macquaria ambigua orientalis*, were investigated from the Fitzroy Basin, Queensland. The dominant age classes determined by interpreting growth marks observed in otoliths were variable among rivers. Positive correlations between the age frequency and monthly river flow volumes were greatest in summer (December-March) conversely, autumn, winter and spring river flows correlated poorly for most rivers. Water temperature exhibits strong seasonality across the basin with mean monthly temperatures > 23 °C generally occurring between October and April. These data indicate the combination of water temperature and increased river flows are important factors for recruitment. The degree of river regulation is also suspected of contributing to increased variability in dominant age classes within rivers. This assessment highlights the importance of timing of river flows in mitigating the negative effects of river regulation on golden perch populations.

Keywords: floods, river flows, river regulation, recruitment, Fitzroy River.

Introduction

Australian fish have developed unique and flexible life-history strategies to cope with the highly variable environmental and river flow conditions that many rivers in semi-arid and tropical regions exhibit (Puckridge et al. 1998; Humphries et al. 1999; Thoms & Sheldon 2000). Fish populations may respond to variation in river flows, including floods and droughts, by moving between habitats and spawning and recruiting over a wide range of flow conditions (Bishop et al. 1995; Mallen-Cooper 1999, Balcombe et al.

35 2006). However, improved management of regulated flow regimes will be critical to the long term maintenance of fishes adapted for rivers with natural flow regimes classified as among the most variable in the world (Walker 1985; Thoms & Sheldon 2000; Pusey et al. 2004).

Golden perch, *Macquaria ambigua* Percichthyidae (Richardson), is one Australian freshwater fish species with flexible spawning strategies adapted for naturally variable river flows. The species is relatively long-lived and has been recorded up to 26 years old (Mallen-Cooper & Stuart 2003), but is more commonly 10 years old and up to 60 cm long and < 5 kg in weight (Anderson et al. 1992a, McDowall 1996). Golden perch are highly fecund and the semi-buoyant eggs from a single 2.2 kg female can number up to 500,000 (McDowall 1996). In early pond experiments, spawning was associated with water temperatures above 23 °C and flooding of dry ground (Lake 1967). This spawning model was generally consistent with the ‘flood pulse concept’ in which summer inundated floodplains provide suitable spawning conditions for fish and these inundated habitats then provide suitable feeding grounds for larvae (Junk et al. 1989). Early studies also added further evidence of flood mediated recruitment for golden perch (Mackay 1973; Reynolds 1983; Harris & Gehrke 1994).

50 Recently, studies on golden perch within temperate rivers of the southern Murray-Darling Basin system have provided evidence that golden perch have a much more flexible breeding strategy with spawning and recruitment occurring during both flood conditions and rising winter /spring flows contained within the river banks (Mallen-Cooper & Stuart 2003; King et al. 2005; Stuart & Jones 2006; Balcombe et al. 2006). Additionally, the southern populations of golden perch appear to spawn at much lower water temperatures than previously document by Lake (1967) at approximately 19 °C (King et al. 2005; Stuart & Jones 2006). It is increasingly apparent that for golden perch, the influence of river flow and temperature on recruitment is highly variable, with fish displaying opportunistic spawning behaviour and recruitment variation across the geographic distribution of the species.

60 The Fitzroy Basin in central Queensland (Fig. 1) is the northern most natural distribution of the golden perch in Australia with other natural populations occurring in the Murray-Darling, Lake Eyre and Bulloo River systems (McDowall 1996; Pusey et al. 2004). Golden perch from the Fitzroy catchment represent a genetically and morphologically distinct sub-species, *M. ambigua oriens* (Musyl & Keenan 1992) and they are distributed widely throughout the sub-catchments (Long & Berghuis 1999), however, in contrast to southern populations, relatively little is known of their biology (Pusey et al. 2004).

Riverine impoundments and changes to natural flow regimes often exert negative pressures on fish populations including reductions in water quality, habitat loss, inhibited migration, alteration of spawning triggers, reduction in average river flow volumes and changes to the timing and periodicity of flows (Cadwallader 1978; Walker 1985; Faragher & Harris 1994; Maheshwari et al. 1995). Given the variability in rainfall and environmental conditions across the Fitzroy Basin, variable recruitment patterns in golden perch were likely a natural feature of the basin. The degree to which recruitment patterns have changed as a result of anthropogenic flow regulation, changes to natural flow patterns and other factors such as raised turbidity levels, toxicants and artificial fish stocking, is unknown.

In the Fitzroy Basin, the management of regulated flow regimes is currently being reviewed and an improved understanding of the breeding biology of golden perch and the influence of river flow, the degree of river regulation and water temperature, may be important factors in water management planning. For some fish, such as barramundi (*Lates calcarifer*), flooding in the Fitzroy River estuary is an important prerequisite for strong recruitment (Staunton-Smith et al. 2005). However, for freshwater fish inhabiting this large semi-arid tropical river, the patterns of recruitment and flooding are less clear and this represents an important management objective.

This study examined the age distribution of golden perch from four major rivers in the Fitzroy Basin to investigate the effect of variability in river flow, seasonal water temperature, and the degree of river regulation on recruitment patterns.

Materials and Methods

Study Location

The Fitzroy Basin is the largest drainage system on the east coast of Australia occupying an area of 142,645 km² spanning the Tropic of Capricorn, with a tropical, semi-arid climate (Noble et al. 1997). Of all the Australian east coast rivers, the Fitzroy discharges the second largest mean annual volume of ~6.08km³ (Furnas & Mitchell 2001). There are six major sub-catchments in the Fitzroy Basin; the Connors/Isaac, Nogoia, Comet, Mackenzie, Dawson and Fitzroy Rivers (Fig. 1). These rivers are characterised by extensive floodplains, often with many anabranches. The longest tributary, the Dawson River, flows for 483 km from the source in the Carnarvon Range to the confluence with the Mackenzie River to form the Fitzroy River which flows an additional 480 km to the river mouth at Keppel Bay in the Coral Sea. The river gradient is relatively low at only 0.26 m km⁻¹ and there is high turbidity (Kelly & Wong 1996). Rainfall and flow in the Fitzroy River and its tributaries are highly variable and subject to

periodic summer monsoonal floods in summer (18.5×10^6 ML in 25 days in 1991), however, there are extended periods of low to zero flow in winter and rivers regularly dry up into a series of pools (Connell et al. 1981; O'Neill et al. 1992).

105 The Fitzroy Basin is highly regulated with fifteen impoundments with a total combined storage capacity of 1.67×10^6 ML (Department of Natural Resources 1998) with the largest being Fairbairn Dam on the Nogoa River. A number of additional large dams have been proposed for the Comet and Dawson rivers. The Mackenzie and lower Dawson rivers are the most regulated reaches which has led to a reduction in the frequency and total volume of low and medium flows in the system (Department of Natural Resources
110 1998). The Isaac and Connors rivers in the north of the catchment are currently unregulated.

Fitzroy River golden perch

Golden perch were collected from eight locations within the Fitzroy, Dawson, McKenzie and Nogoa Rivers (Fig. 1) between August 1996 and May 1997. Fish were caught using single and multi-panel gill
115 nets (50, 100, 150 mm stretched mesh) and single wing fyke nets (25 mm stretched mesh). Nets were set in a variety of habitat types including deep pools and shallow runs in an effort to sample a wide size range of fish. Traps on fishways on the lower Fitzroy River and angling supplemented samples, at Eden Bann Weir (Stuart et al. 2007) and at the Fitzroy tidal barrage (Stuart & Mallen-Cooper 1999). All fish were measured for total length, (TL), weighed (g) and the stage of gonad maturation noted.

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Ageing technique

The use of sectioned otoliths to age golden perch has been validated for golden perch up to a maximum of 22 years with known age stocked specimens (Anderson et al. 1992a; Stuart 2006). In the present study, sagittal otoliths were dissected from specimens and a section approximately 0.5 mm thick was cut
125 through the core along the dorso-ventral plane of the left otolith using a Buehler Isomet low-speed cutting saw. Sections were mounted on a microscope slide and examined under a dissecting microscope using reflected light against a black background to highlight the pattern of opaque zones (annuli). Sectioned otoliths were read 'blind' on two separate occasions and to reduce reader bias, the identification of each otolith was obscured during both age estimations. Estimation of the ageing precision was calculated using
130 the index of average percentage error (IAPE) method (Beamish & Fournier 1981).

To confirm the annual formation of annulus marks, the Fitzroy River samples were used to measure the timing of the annulus formation for a range of fish ages collected in the lower catchment at the Eden Bann

Weir collection site each month between August 1996 and January 1997. A qualitative score for the outermost annulus and otolith margin was employed to assign a nominal birthday for golden perch from the Fitzroy Basin. As per convention, the estimated ages were corrected to the nominal birth date to ensure all fish hatched in the same spring/summer spawning period were counted among the corresponding age-class group (Anderson et al. 1992b). The nominal birth date was determined as the month in which the greatest proportion of samples showed a new annulus forming on the otolith margin. These qualitative scores included; forming (f) when a new annulus mark had commenced forming around the otolith margin; new (n) when a complete marginal annulus was observable but was <25 % of the width of the previous hyaline zone; plus (p) when a complete marginal annulus was observable but was <75 % of the width of the previous hyaline zone; and due (d) when a hyaline zone on the leading edge of the otolith was >75 % of the previous hyaline zone width with no marginal annulus forming.

River flow, water temperature and artificial stocking

River flow and water temperature data for each of the rivers studied were obtained from the Queensland Department of Natural Resources and Water (DNRW). The data were sourced from the official DNRW gauging station located closest to the fish sampling sites. In an effort to assess the likely effect of artificial stocking of fingerlings on the golden perch population, stocking numbers were sourced from the Department of Primary Industries.

Statistical analyses

Pearson correlation coefficients were determined between the number of fish observed in each age class and a range of river flow statistics including the total monthly, annual, winter (June-August), spring (September-November), summer (December-February), autumn (March-May) and wet season (September-February) periods for each of the four rivers. In addition to these flow statistics derived from delineations of the calendar year, three additional total flow statistics were calculated to represent flows where water temperature might influence the number of fish observed in each age class. These included the total flow for all months in which the average monthly temperatures exceeded 21 °C, 23 °C and 25 °C respectively. Correlations were determined using SPSS Graduate Pack 13.0, 2004. Regression equations were then calculated for the largest positive correlations for each river to assess how well the regression explained the relationship between age frequency and river flow. The river flow data used for the analyses of the spring period were from the months preceding the theoretical birth date and for summer, autumn and winter periods, following the birth date.

To assess the global trend between age class strength and river flow from all rivers combined, the flow data for the period chosen in each river was standardised by dividing the total flow by the median flow values for the corresponding period (Bonvechio & Allen 2005) and correlation and regression analysis were performed.

In the present study the collection of small 1 year old golden perch was possibly affected by a combination of sampling equipment and habitat biases. Specifically the gill net mesh sizes used would have been ineffective for collecting small golden perch and the fyke nets typically require fish to be actively moving. Additionally, the chances of collecting the less abundant older fish were greatest in the Fitzroy River where there were more potential sample days because fish were available from a seven month fishway assessment at Eden Bann Weir (Stuart et al. 2007). Hence to limit potential bias, the data analyses were restricted to age classes 2 - 12 for the Fitzroy and 2 - 9 for the remaining rivers. The 9 year age class was chosen as the upper limit for group analysis as these ages were represented in the Nogoa, Dawson and Mackenzie river samples where there were similar habitat types sampled. The absence of an age class in the data was retained in the analysis as we assumed these represented poor or failed recruitment events rather than inadequate field sampling.

Assumptions of the linear regression model were assessed before analysis for flow and age frequency data. In the case of river flow data, log transformation ($x+1$) was used to address the skewed nature of the data prior to analyses. A von Bertalanffy growth function was used to analyze the age at length data using the NLIN procedure of Statistical Analysis System (SAS). Comparisons of von Bertalanffy growth functions among rivers was performed using the analysis of the residual sum of squares (ARSS) method (Chen et al. 1992).

Results

Ageing errors and birth date determination

The thin-sectioned otoliths had clearly discernible patterns of opaque and hyaline zones when viewed under a microscope using reflected light and there was a high precision (IAPE 2.9% error) of age estimates between the two readers. Examination of the otolith margin revealed the percentage of fish forming a new annulus was greatest in the months of spring (September and October) with a small proportion of fish forming a new annulus in August and November (Fig. 2). No golden perch was recorded forming an annulus on the outer edge of the otolith in December or January, although the sample sizes were smaller. This indicated that the otolith banding patterns were annual and most often formed in

200 spring. In determining the nominal birth date, the percentage of fish with a new band forming was greatest in both September and October. As the September sample size was larger, the 1st of September was assigned as the theoretical birth date.

Age and Growth

205 Otoliths from 182 golden perch, ranging in size from 163 to 511 mm TL were sectioned, including 72 fish from the Fitzroy River, 54 fish from the Nogoa River, 33 fish from the Dawson River and 22 fish from the Mackenzie River. Table 1 provides the parameters of the von Bertalanffy growth function and Figure 3 depicts the growth curves with 95% confidence intervals shown for fish samples that converged to a maximum theoretical length estimate (L_{∞}) following a maximum of 50 iterations of the non-linear procedure in SAS. The growth rate of golden perch for both males and females was highly variable as indicated by the difference in growth between the oldest estimated fish of 12 years old measuring 402 mm (TL), compared to a larger fish of 511 mm (TL) estimated to be 8 years old. No significant differences were observed between the growth rate of all fish from the Fitzroy and Dawson rivers ($P>0.05$, $F=0.98$, $df=3, 99$) (Fig. 3a). In contrast, significant differences in the growth rate were found between males from 210 the Fitzroy and Nogoa rivers ($P<0.001$, $F=12.35$, $df=3, 46$) (Fig. 3b) and among females from the Fitzroy, Dawson and Mackenzie rivers ($P<0.05$, $F=2.57$, $df=6, 79$) (Fig. 3c). For all samples, based on a qualitative assessment of gonad stage, the minimum size and age at maturity was 173 mm TL and 2.3 years for males, and 277 mm TL and 5.1 years for females.

220 Year class strength

Figure 4 shows the differences in the dominant age classes observed between each of the four rivers. In the Fitzroy River, the dominant age classes were six (32 %) and eight (29 %) years old. The next most abundant age class (three years old) comprised only 8 % of the total sample. The sample from the Nogoa River was dominated by the four (28 %), five (24 %) and six (22 %) year old classes whereas the Dawson and Mackenzie Rivers were dominated by the three year old age class (24 % and 50 % respectively). 225 There were also reasonable proportions of fish in age classes five and six in the Dawson River and six in the Mackenzie River. From these data it is apparent that the six year old age class was consistently present in reasonably high frequencies across all rivers. However, the sample size for the Dawson and Mackenzie Rivers was relatively smaller with 33 and 22 fish, respectively. In contrast to the other rivers, 230 the Nogoa River sample contained a higher proportion of four year old fish and a relatively high proportion of five year old fish compared to the Fitzroy and Mackenzie Rivers and to a lesser degree the Dawson River. This indicates that conditions conducive to recruitment of golden perch were present in

those years corresponding to the four and five year old age classes in the Nogoia River and less so for the remaining rivers.

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Artificial stocking

The number of artificially stocked golden perch fingerlings varied considerably between sites and years ranging from 7,000 to 42,000 in any one year. The only river not stocked was the Nogoia River upstream of Fairbairn Dam. Correlations between the number of fish stocked and the corresponding age class frequencies from each river indicated a relatively weak non-significant relationship ($R = 0.46$, $r^2 = 0.22$, $P > 0.1$). Although stocked golden perch were likely to be present in the natural population, we assumed that the contribution of stocked fish to the stronger age classes was likely to be relatively low in comparison to naturally recruited fish.

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River flow and water temperature

River flows throughout the Fitzroy Basin are typically greatest during the summer wet season (December to February), decreasing during autumn and the least during the winter/spring period (July to November) (Fig. 5). This flow pattern was highly variable from year to year, with periods of low flow also occurring during summer and considerable flows extending well into the autumn period (March to May). Figure 6 shows the seasonal pattern of average monthly water temperatures for the four rivers. Water temperatures varied across the Fitzroy basin, with the Nogoia and Dawson Rivers experiencing lower temperatures, warming later in the year and cooling earlier in autumn. The Fitzroy River, on average, was warmer throughout the year compared to the other rivers.

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Significant flow regulation occurs in the Fitzroy Basin due to the many weirs and dams in the system. Table 2 summarises the three separate measures used to characterize the degree of river regulation; the Average Proportional Flow Deviation (APFD), the frequency of weir drown-out events and the percent of inundated stream length. The APFD is a measure of change away from the natural river flow regime, with an increase representing greater deviation from natural. The frequency of weir drown out events is used to indicate the reduction in opportunities for spawning and dispersal migrations along the river length and the percent of stream length inundated is used to indicate the amount of natural riverine habitat lost due to flooding from impoundments. These measures for the Nogoia River relate to the stretch of river upstream from Fairbairn Dam. This stretch of the Nogoia River is the least regulated stretch of river sampled within the Fitzroy Basin with no appreciable flow regulation, no impoundments upstream of Fairbairn Dam and approximately 17 % of the stream length inundated as a result of Fairbairn Dam.

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River flow, temperature and age frequency

The results of the correlation analyses between river flow statistics and golden perch age class frequency found that generally the warmer periods of the year contained the greatest number of positive correlations and the highest correlation coefficients for any given river (Table 3, Fig. 7). The strongest correlation, $r = 0.82$, was obtained for the total flow in the months with an average temperature $>21^{\circ}\text{C}$ in the Fitzroy River ($P < 0.001$, $n = 11$). Correlations between age class frequency and both the total summer flow (December to February) and the total wet season flow (September to February) were positive for all rivers, however only the Fitzroy River results were significant ($P < 0.006$ and $P < 0.003$ respectively). With the exception of the Fitzroy River, all flows occurring prior to November and after March were typically associated with negative or low correlations coefficients (Fig. 7). Conversely correlations between November and March were largely positive with 14 out of the 20 possible correlation combinations being positive. Out of the 6 negative correlations, four of those were from the Nogoa River.

The correlations between the total flow values for months exceeding 21°C , 23°C or 25°C and age frequency, with the exception of the Nogoa River, were all high and in 7 out of 9 cases were significant (Table 3). Additionally, for the Fitzroy, Dawson and Mackenzie Rivers, the correlations between the total flows occurring in months with average water temperatures exceeding 25°C were all significant ($r = 0.80$, $P < 0.002$; $r = 0.75$, $P < 0.01$; $r = 0.74$, $P < 0.01$ respectively). These results suggest that the timing of flows have important implications for recruitment success and the threshold of this timing may be related to increasing water temperatures.

Figure 8 shows the linear regression equations for the highest significant correlations between the respective river flow statistic and age class frequency for each river (from Table 3). For the Fitzroy River, the regression equation and resultant coefficient of determination (r^2) indicated that the total flow in months with average temperatures $> 21^{\circ}\text{C}$ accounts for 67 % of the variation in age class frequency. For the Dawson and Mackenzie Rivers, the most significant correlations were between total flow in the months with average temperatures $> 25^{\circ}\text{C}$ which accounted for 57 % and 54 % of the variation respectively, however, the regression for the Mackenzie River was dominated by relatively few data points. The highest correlation for the Nogoa River was for summer total flow ($r = 0.33$) and the regression only explained 11 % of the variation in age. Such low correlation and poor explanatory power of the regression relationship suggests that the Nogoa River functions somewhat uniquely compared to

the other rivers. In terms of the global relationship between flow for the period of the year with average
monthly temperatures above 25 °C and age class frequency for the Fitzroy, Dawson and Mackenzie rivers
combined (Fig. 9) the relationship is highly significant ($r = 0.73$, $r^2 = 0.53$, $P < 0.000$). The Nogoa River
was excluded from this analysis as it was established the relationship between flow and age class
frequency was quite unique compared to the other rivers examined.

Discussion

Ageing and general biology of golden perch

The combination of high precision (97%) of age estimates using thin-sectioned otoliths in this study, the
confirmation of relatively discrete periodicity of the formation of annuli and previous validation studies
from known age fish supports the use of annuli to accurately age golden perch (Anderson et al. 1992a;
Stuart 2006). The present study confirms the longevity of golden perch and highlights the variable growth
and recruitment patterns which occur across the sub-catchments possibly reflecting the broad differences
in temperature regimes, seasonal flow patterns and habitat types (Mallen-Cooper & Stuart 2003).
Longevity, flexible growth and opportunistic recruitment are likely adaptive traits for a river system with
a hydrology classified among the most variable in the world with periods of long droughts interspersed
with high magnitude summer monsoon flooding (Puckridge et al. 1998).

The growth rate (K) and theoretical maximum size (L^∞) of golden perch from the Fitzroy River appeared
slightly slower and smaller than that of southern temperate populations (Mallen-Cooper & Stuart 2003)
and the minimum size at first maturity was also smaller, although the ages at maturity were similar to the
temperate Murray River population where males matured at 2-3 years and females at 4+ years (Mallen-
Cooper & Stuart 2003). It is a common assumption that higher water temperatures translate into faster
growth and larger maximum sizes than attained in cooler climates. However the relationship between fish
growth and temperature is highly variable (McDowall 1994) suggesting there are few generalizations that
can be drawn from fish growth and size based on geographical location alone (as a surrogate for
temperature) and that a combination of endogenous and exogenous factors are likely to determine the
growth and size characteristics of a population. Higher water temperatures may actually result in reduced
growth and body size due to the negative effect of reduced oxygen content in warmer water, combined
with the increased metabolic activity with elevated body temperatures (Atkinson 1995). As the Fitzroy
Basin represents the northern most extent of the natural distribution of golden perch, the growth observed
may reflect the upper thermal limit for somatic growth as previously suggested for other fish populations
occurring at the extremities of their natural ranges (Wilde & Muoneke 2001). Alternatively, other factors

can also influence fish growth rates and maximum size including genetic differences in the species, habitat quality, food availability and quality, or competition (McDowall, 1994).

335 In the Fitzroy River system, as has been observed in other populations of golden perch (Mallen-Cooper & Stuart 2003) females grew to a larger size and took two or three years longer than males to reach maturity. This sexual dimorphism could be related to the greater energetic requirements of females during the annual formation of gametes resulting in a delay in the onset of maturity. Flow variability and the degree of flow regulation might also influence growth (Lytle & Poff, 2004). For example, if conditions
340 for spawning do not occur then golden perch might resorb gametes for growth and the frequency of this occurring might vary among regulated rivers (Mackay 1973; Collins & Anderson 1999)

Despite considerable variability, there were still differences in the growth and theoretical maximum size of golden perch between sexes and among the four sub-basins. For a large river system where flooding
345 and temperature regimes vary among sub-basins, there appears to be pervasive effects on the growth characteristics of golden perch populations. Hence, variable growth rates among rivers could be the result of interactions between local productivity in relation to flooding, regional temperature regimes and variable annual spawning effort.

350 *Relationship between river flow and recruitment*

The positive correlations between the number of fish in each age class and increased flows observed in this study support previous findings linking rising flows and flood mediated spawning and recruitment for golden perch (Humphries et al. 2008; Mallen-Cooper & Stuart 2003; Balcombe et al. 2006; King et al. 2005). In particular, river flows during the warmer months (December to March) had the greatest number
355 of positive correlations in all rivers.

In the Fitzroy Basin, river flows are episodic with a seasonal bias toward larger monsoon flows in the summer and autumn months (December to March). Some fish species of the Fitzroy Basin rely on this seasonal pattern of flooding for recruitment and access to habitats (Staunton-Smith et al. 2005). For
360 golden perch in a tropical river system with a semi-arid catchment, flexible spawning strategies in response to environmental stimuli is an advantageous adaptive mechanism to succeed in a harsh environment with highly variable river flows (Thoms & Sheldon 2000; Balcombe et al. 2006). Golden perch possess a number of life history adaptations suited to these conditions, including flexible growth rates, an extended breeding season, high fecundity, high mobility, flexible spawning strategies, and wide

365 physiological tolerances (Lake 1967; Collins & Anderson 1999; Mallen-Cooper 1999; Humphries et al. 2002; Mallen-Cooper & Stuart 2003; O'Connor et al. 2005).

Despite these adaptive strategies to cope with flow variability, the regulation and alterations of the natural patterns of flows, in particular the timing, amplitude and duration of flows, and potentially water
370 temperature, has still resulted in a range of adverse impacts on golden perch (Cadwallader 1978). These include severe declines in the natural abundance and range, heightened larval mortality, interrupted migration and irregular recruitment events as observed in the age class strengths (Puckridge et al. 1998; Baumgartner et al. 2006; Mallen-Cooper & Brand 2007). In systems such as the Fitzroy Basin, the potential negative effects of river regulation might be heightened because of the inherently variable nature
375 of the natural flow regime (Puckridge et al. 1998) and the ongoing demand for further water resource management for human use in the form of additional dams and weirs.

Currently, the largest dam in the Fitzroy Basin is Fairbairn Dam on the Nogoia River (1.3×10^6 ML capacity, Department of Natural Resources 1998) which is capable of capturing a large proportion of the
380 flood volume as exemplified by the few occasion the impoundment has overtopped since its construction. Despite this, the Nogoia River upstream of the dam is unregulated and remains one of the longest reaches of unregulated river in the catchment and maintains an abundant population of golden perch (Long & Berghuis 1999) with relatively consistent recruitment between years as evidenced by the patterns in the age class frequency. The Comet and the Connors/Isaac Rivers within the Fitzroy Basin are largely
385 unregulated and would provide an interesting contrast to the recruitment patterns of golden perch from the more highly regulated rivers in the basin.

The pattern in age class frequency of golden perch from the Nogoia River suggests that recruitment occurs across a wide range of flow magnitudes. Two of the three dominant age groups in the Nogoia River (5 and
390 6 years old) corresponded to relatively large flow events in the order of 30,000 – 58,000 ML day⁻¹ for periods of three to four days. However, the flow volume coinciding with the most abundant age class (4 year old) were relatively small, with a maximum discharge of 9,072 ML day⁻¹ that lasted approximately 24 hours at this intensity. This relatively small flow would likely have been completely contained within the low flow terraces of the Nogoia River (D. Bell, DNR&W, personal communication). This apparent
395 inconsistency between flow size and recruitment as measured by age class strength was responsible for the low correlations for all flow statistics in the Nogoia River. The lack of clear flow-recruitment patterns might also be indicative of a high degree of flexibility to spawning cues and suitable conditions for

subsequent recruitment that occur in a relatively unregulated reach of river such as the upper Nogoia River. This assertion is also somewhat reflected in the regulated Dawson River, however, the sample size was relatively small and more research is needed.

These observations from the Nogoia River are in accordance with studies in the Murray-Darling system that have also found that golden perch spawn and recruit in response to a wide variety of flow conditions from floodplain inundation events, high flows that were contained within the banks of the river and possibly during minimal flow conditions (Mackay 1973; Mallen-Cooper & Stuart 2003; King et al. 2005; Balcombe et al. 2006).

Relationship between water temperature and recruitment

The importance of water temperature (nominally $>23^{\circ}\text{C}$) to promote golden perch spawning was first observed by Lake (1967) in enclosed pond environments. Jones (1974) also reported that recruitment, as judged by ageing a sample of the Murray River population, was not restricted to periods of major flooding which had inundated floodplains and concluded that water temperature was the major controlling factor. Although golden perch may actually spawn at lower water temperatures, for this study the nominal figure of 23°C , which is considered appropriate for a tropical river, was used as a basis to examine the relationship between seasonal water temperatures in the Fitzroy Basin and recruitment patterns.

The period from October to April (late spring through to autumn) across the Fitzroy Basin generally coincides with river water temperatures exceeding 23°C . However, this threshold temperature is reached as late as November or as early as March in the cooler Dawson and Nogoia rivers. Flow events that occur prior to November and after March generally result in poor recruitment in the Fitzroy Basin. This relatively narrow window of optimal temperature is highlighted in the Nogoia River where a large flow event ($\sim 239,000 \text{ ML day}^{-1}$) which commenced relatively late in the wet season (late March and continuing into April) would have coincided with a period of the year when water temperatures are rapidly cooling to below 23°C and resulted in the fewest age class (7 year olds). The mechanism for reduced recruitment in cooler water temperatures may be due to a number of factors including weaker spawning cues associated with lower water temperatures, reduced survival of larvae developing in cooler periods prior to winter, or reduced food supplies. Hence, the strength of recruitment events could have been influenced by spawning and/or larvae survival processes (Koehn & Harrington 2006).

430 For golden perch in the Fitzroy Basin, it appears that spawning and recruitment are closely linked to both river flow and water temperatures and in order to mitigate the effects of river regulation, flow management strategies need to be cognizant of these linkages and ensure environmental flow rules are linked with ecological relevance. Elsewhere the importance of the seasonal timing of flows and temperature in controlling the strength of recruitment in riverine fish populations has been demonstrated
435 for a range of fishes and habitats (Nilo et al. 1997; Staunton-Smith et al. 2004; Bonvechio & Allen 2005; Lobón-Cerviá & Mortensen 2005) and the optimal combination of these factors is likely to be a significant controlling factor in structuring fish populations.

Effects of River Regulation

440 The recruitment success as measured by the number of fish observed in each age class varied considerably between rivers. Although this could be an artefact of the relatively small sample size in the Dawson and Mackenzie rivers these observations may also reflect, in part, variability in hydrologic conditions and the degree of river regulation in the form of impoundments and changes to the natural flow patterns. The most variable recruitment patterns seem to occur in the Mackenzie and Fitzroy Rivers
445 whereby only one or two age classes comprise a relatively large proportion of the total sample in the order of 50% and 61% respectively. Conversely, in the Nogoia River and to a lesser extent the Dawson River, there were multiple age classes comprising a larger proportion of the total sample indicating more frequent recruitment across the period observed. The three independent measures used in this study to represent the changes in river conditions due to flow regulation indicate that the Fitzroy and Mackenzie
450 Rivers are more regulated compared to the Dawson and Nogoia Rivers. Combined, these measures might be indicative of fewer opportunities for golden perch to successfully recruit in the Fitzroy and Mackenzie Rivers which is reflected in the variability in age classes exhibited in these two rivers.

Water resources in the Fitzroy Basin are managed under a water resource plan that specifies a range of
455 flow operating principles to take into consideration environmental flow requirements of flow dependent species (Department of Natural Resources 1999). One environmental flow objective includes the provision of the “first post winter flow event”, defined as the first flow occurring in a year commencing between the 15th September and 10th April, lasts for 21 days and if commencing in September, must be at least 23 °C. Although the water resource plan in some way allows for water temperature to be considered,
460 this is only defined for the month of September. In light of the present research, it appears more appropriate, both in terms of suitability for golden perch spawning cues and optimal use of water for environmental flow objectives, that the first post winter flow rule be reconsidered to take into account the

variability in timing of the minimum water temperature of 23 °C within each river irrespective of the month of the year, as the primary trigger for the environmental flow releases.

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Despite the apparent relationship between golden perch recruitment and river flow, water temperature and the degree of river regulation in the Fitzroy Basin during this study, there are undoubtedly many other factors that would have a significant bearing on the spawning and successful recruitment of golden perch including population dynamics, food availability and migration pathways (Bye 1984; Humphries & Lake 2000; King et al. 2003; Balcombe et al. 2006), hence future research effort need to take into consideration some of these factors for fish in the Fitzroy River Basin.

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Golden perch exhibit flexible life history characteristics, which are an adaptation to a river with highly variable flow conditions with unpredictable summer monsoon flooding. Flexibility in key life-history characteristics such as longevity and high fecundity, and the capacity to recruit in response to a range of environmental factors including flow and temperature, are adaptive strategies that have contributed to the success of this species. As infrastructure for river regulation increases in the Fitzroy Basin, more appropriate flow management strategies will be needed (Arthington et al. 2006). To assist in ameliorating the adverse effects of flow modification, the existing environmental flow scenarios for the Fitzroy Basin should also consider release strategies that take into account the combined influence of flow timings and river specific temperature differences.

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Table 1. Golden perch von Bertalanffy growth parameters and the minimum and maximum length and weight for each river sampled for male (M), female (F) and all fish combined (All).

Sample/ Sex	von Bertalanffy growth curve functions			Length (mm)		Weight (gm)	
	L^{∞} (mm)	K	t_0 (yr)	Min	Max	Min	Max
Fitzroy Rr (M)	513 $\pm$ 176	0.13 $\pm$ 0.1	-1.54 $\pm$ 1.9	268	431	296	1486
Fitzroy Rr (F)	463 $\pm$ 35	0.29 $\pm$ 0.1	0.47 $\pm$ 0.6	215	511	167	2820
Fitzroy Rr (All)	453 $\pm$ 35	0.28 $\pm$ 0.09	0.28 $\pm$ 0.7	190	511	115	2820
Nogoa Rr (M)	305 $\pm$ 83	0.25 $\pm$ 0.2	-0.66 $\pm$ 1.9	170	319	79	509
Nogoa Rr (F)	F/C			163	417	69	1175
Nogoa Rr (All)	F/C			163	417	69	1175
Dawson Rr (M)	306 $\pm$ 22	0.9 $\pm$ 0.6	1.33 $\pm$ 0.9	205	349	125	747
Dawson Rr (F)	421 $\pm$ 44	0.36 $\pm$ 0.2	0.52 $\pm$ 1.1	175	456	96	1712
Dawson Rr (All)	393 $\pm$ 30	0.44 $\pm$ 0.2	0.83 $\pm$ 0.9	175	456	96	1712
Mackenzie Rr (M)	F/C			179	319	93	444
Mackenzie Rr (F)	259 $\pm$ 27	0.8 $\pm$ 0.7	1.75 $\pm$ 1.2	174	273	95	285
Mackenzie Rr (All)	F/C			164	319	63	444

F/C = Non-linear regression failed to converge to a maximum within 50 iterations.

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Table 2. Measures representing the degree of river regulation within the Fitzroy Basin.

River	Average Proportional Flow Deviation	Period between weir drown-out events (yr)	Percent Inundated Stream Length ***
Nogoa	0 *	0 *	17*
Dawson	1	1.1 **	29
Fitzroy	2	2.9	39
Mackenzie	2.75	2.4 **	35

* Based on river section upstream of Fairbairn Dam.

** Represents drown-out for weir nearest sample location that the majority of fish were sampled from.

*** Stream length estimated from AMTD figures in maps in Department of Natural Resources, 1998.

Source: (Department of Natural Resources, 1998).

Table 3. Pearson correlation coefficients between the numbers of golden perch observed in each age class and various river flow statistics. Significance levels are shown in parentheses.

Flow Period ($\log_{10} + 1$)	River System			
	Fitzroy River (n = 11)	Nogoa River (n = 8)	Dawson River (n = 8)	Mackenzie River (n = 8)
Annual (July-June)	0.80 (0.001)	-0.49	0.61 (0.054)	0.41
Winter (June-August)	0.38	-0.31	-0.10	-0.59
Spring (September-November)	0.06	-0.40	-0.32	0.27
Summer (December-February)	0.73 (0.006)	0.33	0.61 (0.055)	0.15
Autumn (March-May)	0.42	-0.67	0.39	0.21
Wet Season (September-February)	0.77 (0.003)	0.12	0.55	0.17
Months with Av Temp >21 °C	0.82 (0.001)	-0.41	0.68 (0.033)	0.51 (0.09)
Months with Av Temp >23 °C	0.81 (0.001)	-0.24	0.74 (0.017)	0.51 (0.09)
Months with Av Temp >25 °C	0.80 (0.002)	-0.15	0.75 (0.016)	0.74 (0.018)

Note: Age classes used included 2-12 for Fitzroy Rr, 2-9 for Nogoa, Dawson and Mackenzie Rivers.

Fig. 1: Roberts, Position on Page 2

Fig. 2: Roberts, Position on Page 6

Fig. 3: Roberts, Position on Page 7.

Fig. 4: Roberts, Position on Page 7

Fig. 5: Roberts, Position on Page 8.

Fig. 6: Roberts, Position on Page 8.

Fig. 7: Roberts, Position on Page 9.

Fig 8: Roberts, Position on Page 9.

Fig 9: Roberts, Position on Page 9.

Fig. 1. Location of the Fitzroy River Basin, Queensland, Australia, indicating major sub-basins and fish sampling sites.

Fig. 2. Time of annuli formation, represented as the percentage of all fish sampled in that month (Number of samples per months shown).

Fig. 3: von Bertalanffy growth curves for golden perch with 95 % confidence limits for (a) all Fitzroy and Dawson River fish (b) males only and (c) females only. Juveniles were included in both male and female data sets for the calculation of growth curves.

Fig. 4. Golden perch age frequency (bars) and total discharge volume (lines) for months with an average temperature exceeding 23 °C and corresponding to the year that age class was spawned. Note that the scale of the right y-axis varies.

Fig. 5. Total monthly flows in the Fitzroy River at the Gap for the period 1985 to 1994. The number in parenthesis is the total flow estimate for January 1990.

Fig. 6. Average monthly water temperatures for the four sampled locations (between 2-8 years of data per river between 1999 and 2007).

Fig. 7. Monthly correlation coefficients between age class frequency and monthly total flow (ML) for each river sampled.

Fig. 8. Relationships for the highest significant correlations observed from Table 3 for each river between age class frequency and (a) total flow in months > 21 °C, (b) total flow in months > 25 °C and (c) total flow in months > 25 °C.

Fig. 9. Relationship between the observed age class frequency for the Fitzroy, Dawson and Mackenzie rivers combined and the standardised flow for the period of the year with average monthly temperatures above 25 °C (ratio of the median).