FISH BODY CONDITION AND RECRUITMENT RESPONSES TO ANTECEDENT FLOWS IN DRYLAND RIVERS ARE SPECIES AND RIVER SPECIFIC

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ABSTRACT

Dryland rivers in arid and semi-arid regions drain approximately one-third of the Earth's land area yet basic aspects of their ecology are poorly documented and many are threatened by excessive water use leading to alterations of the flow regime. Management of dryland rivers imperilled by changes to the flow regime requires quantitative hydro-ecological relationships and models to support environmental flow restoration strategies, and to define ecological response indicators for assessment of trends in ecological health. Fish living in dryland rivers experience highly variable levels of food resources associated with 'boom and bust' productivity patterns driven by highly irregular episodes of rainfall, runoff and floodplain inundation followed by busts associated with drying of remnant aquatic habitats. To cope with variable food resource levels, fish store energy as fat during productivity booms, enabling them to breed at a later date or to survive through extended periods of limited food resources. This study tracked temporal patterns of body condition and recruitment success of the four most abundant fish species in two Australian dryland river systems with contrasting patterns of flow variability, Cooper Creek and the Moonie River. We found consistent responses to flow magnitude and timing for body condition and/or recruitment success in Cooper Creek but fewer responses in the Moonie River. Results suggest that the fish metrics and relationships to flow established for Cooper Creek may apply in similar dryland rivers exhibiting clear boom and bust patterns while the Moonie River results could be applicable to rivers with less variable flow patterns and fewer spells of zero-flows. Our study demonstrates that simple, non-destructive methods based on fish length and weight provide useful biological indicators of response to flow variability provided that care is taken with species selection and that hydro-ecological relationships are calibrated for each contrasting type of hydrologic regime.

KEY WORDS: fish body condition, recruitment, hydrologic variability, biological indicators, hydro-ecological relationships, flow regime

INTRODUCTION

Dryland rivers in arid and semi-arid regions (drylands, Tooth 2000) drain approximately one-third of the Earth's land area (Walker *et al.*, 1995) and service around 20% of the world's population (Bull and Kirby, 2002). These distinctive systems are found in large areas of Australia, Africa, Asia, the Americas, and Mediterranean Europe (Kingsford and Thompson, 2006; Welcome *et al.*, 2006). Despite their widespread distribution, ecological values and societal importance, the dynamics of dryland rivers are not as well understood or studied as rivers in wetter climates (Nanson *et al.*, 2002; Kingsford and Thompson, 2006; Arthington and Balcombe, 2011). Furthermore, many dryland rivers are under increasing threat from development of their water resources to support human activities and settlements (Wishart, 2006; Tockner *et al.*, 2008).

Dryland rivers with well-developed floodplains share one vital characteristic: their biota exist in states of 'boom and bust', exhibiting high productivity (the boom) associated with channel flows and floods, and low productivity (the bust) in drying aquatic habitats without flow (Bunn *et al.*, 2006; Arthington and Balcombe, 2011). Populations of dryland river fish are able to persist through unpredictable cycles of boom and bust and the associated fluctuating availability of food resources by virtue of resistance and resilience traits. Resistance to harsh physico-chemical conditions during the dry times (Kingsford *et al.*, 2006; Arthington *et al.* 2010; Wager and Unmack, 2000), flexible feeding strategies (Balcombe *et al.*, 2005; Sternberg *et al.*, 2008), spawning strategies attuned to flow conditions (Balcombe *et al.*, 2007; Balcombe and Arthington, 2009; Kerezszy *et al.*, 2011), high vagility and opportunistic responses to flooding (Kerezszy *et al.* 2013) are vital traits of fish species living in dryland floodplain rivers.

Given that inundated floodplain habitats represent areas of high food resource potential (Balcombe *et al.*, 2005) whereas drying river channels and waterholes do not generally provide resource rich habitats (Bunn *et al.*, 2003, 2006; Fellows *et al.*, 2009), it follows that the body condition of individual fish can be expected to vary with hydrologic conditions that range from zero-flow and variable in-channel flows to overbank flows and extensive floodplain inundation. Flow has indeed been found to be a significant driver of fish body condition in hydrologically variable streams (Spranza and Stanley, 2000; Oliva-Paterna *et al.*, 2003). In addition to an increased potential for higher body condition after significant flow events, fish recruitment success is also likely to be enhanced (Balcombe *et al.*, 2006; Balcombe and Arthington, 2009). This has been confirmed by a short-term study showing that body condition and recruitment success of two generalist fish species were enhanced after recent flows compared to long periods of time without flows (Balcombe *et al.*, 2012).

The conservation of dryland river systems depends upon protection of their unusual dynamic characteristics, embracing hydrologic, geomorphic, sedimentary, biogeochemical, ecological and evolutionary processes (Kingsford and Thompson, 2006; Arthington and Balcombe, 2011; Leigh *et al.*, 2010). An important focus of

management is to avoid or reduce human disturbances of these natural regimes, in particular, alterations to natural hydrologic variability brought about by dam and weir construction, river flow regulation, water diversions and groundwater pumping. These activities typically remove or dampen the dynamic hydro-ecological processes that define dryland rivers (Walker *et al.*, 1995; Wishart, 2006). In circumstances where flow regimes have been altered to serve human needs, the provision of environmental flows is an important management response (Richter *et al.* 2006; Hirji and Davis, 2009). Quantitative hydro-ecological relationships and models are essential to development of environmental flow restoration strategies, and to define ecological response indicators for assessment of trends in ecological health (Sheldon *et al.*, 2012; Poff *et al.*, 2010).

Numerous environmental flow assessments have been undertaken in individual river basins or tributaries, each generating river-specific recommendations for flow management and ecological response monitoring (e.g. Richter *et al.*, 2006; King *et al.*, 2010). An important question is whether hydro-ecological relationships for individual rivers can be transferred to other river basins, thereby facilitating cost-effective implementation of flow management ‘rules’ and indicators of ecological response (Kennard *et al.*, 2010; Poff *et al.*, 2010). In this paper we examine fish responses to hydrologic conditions in two Australian dryland river systems to test the specificity, or generality of response of four abundant species in terms of simple, non-destructive metrics – body condition and juvenile recruitment. Our specific aims are 1. To test the hypothesis that fish body condition and recruitment success will be responsive to both the magnitude and timing of flow events; and 2. To assess whether body condition and recruitment responses are species specific, river-specific or transferable across dryland river systems.

METHODS

Study area

The Cooper Creek catchment (approximately 290 000 km², Fig. 1) has a semi-arid to arid climate, receiving a mean annual rainfall varying from 400-500 mm in the headwaters to <100 mm at its entry to Lake Eyre (Bunn *et al.*, 2003). Most stream flow is generated by summer monsoon rainfall in the headwaters of the Thomson and Barcoo rivers, and by variable local rainfall. Mean daily maximum air temperatures at Windorah range from 38.1 °C in January to 21.4 °C in July and mean daily minima from 24 °C in January to 7 °C in July. Mean annual evaporation exceeds 3 m and, together with evapotranspiration, drainage diffusion and infiltration, results in transmission losses below Windorah accounting for more than two-thirds of the discharge by the time it reaches the South Australian border (Knighton and Nanson 1994). Cooper Creek has the most variable hydrological regime of any of the world’s large rivers of comparable discharge (Puckridge *et al.*, 1998), driven by the unpredictable timing and volume of rain events in the catchment. While large floods in this system cover vast tracts of land, such events occur irregularly and the river persists for most of the time as a series of disconnected waterholes separated by dry anastomosing channels. Extended dry periods may last up to 21 months without flow, causing many waterholes to dry completely (Bunn *et al.*, 2003). This study presents data on fish condition and recruitment patterns collected on eight sampling occasions from four waterholes selected on the basis of availability of access and being semi-

permanent in the Windorah region (Fig. 1). The sampling periods spanned a range of hydrological conditions (Balcombe and Arthington, 2009), with the first three sampling occasions interspersed between large overbank flow events and the final four occasions following a large overland flood (Fig. 1).

The Moonie River, east of Cooper Creek, sits within the northern Murray-Darling Basin in southern Queensland (Fig. 1). The Moonie River catchment (14870 km²) has a semi-arid climate, with average rainfall between 450 - 600 mm year⁻¹ and mean annual pan evaporation between 1800 - 2200 mm year⁻¹. As with most dryland rivers, there is considerable annual variation in temperature and inter-annual variation in rainfall which combine to generate irregular and infrequent flow events. The maximum recorded no-flow spell for the system was 13 months at Nindigully gauge in 1979 and 1980 (Biggs *et al.* 2005), whilst the 100-year modelled maximum no flow spell is approximately two years (Department of Environment and Resource Management, unpublished data). Thus, similar to Cooper Creek, the Moonie River exists for most of the year as a series of disconnected waterholes, although the duration of zero flow is longer in Cooper Creek (Balcombe and Sternberg, 2012). The data analysed in this study derive from 13 sampling occasions in the Moonie River from ten waterholes selected as per the Cooper Creek waterholes and covered both in-channel and overland flow events (Sternberg *et al.*, 2012). The first sampling occasion (T1, Feb 2006), occurred some six weeks after a high channel flow event and the most recent overland flood event (14000 MLday⁻¹) occurred some three years prior to T1 (Sternberg *et al.*, 2012). Throughout the study period (T1 –T13) there were three overland flood events (17000 MLday⁻¹ in Feb 2008; 13500 MLday⁻¹ in May 2009 and 81000 MLday⁻¹ in March 2010 just prior to T13). Hence, all other flow events were confined within the river channel (Fig. 1).

Fish collection and metrics

Fish were sampled in both rivers using fyke and seine nets (as per Arthington *et al.*, 2005). There had been an intention to measure fish standard length (mm) and weight (to the nearest 0.1 g) of all species captured, however this was not always possible due to time constraints or equipment malfunction. Hence this paper is focused on all fyke and seine net catches of the four most abundant species in each river (see Table 1 for species involved). Owing to the potential for measurement error associated with weighing small fish under field conditions we excluded small-sized individuals from the body condition analyses as per Table 1. The raw data was used to calculate metrics based on length-weight measures (body condition) and length only data (juvenile recruitment).

Body condition was represented by the relative mass index (W_r) following Beesley *et al.* (2012). This index is calculated using the formula $W_r = (W/W_s)100$, where W_s is the length-specific standard weight predicted from length-mass relationships for a given species (Pope and Kruse, 2007). Length weight relationships calculated for the estimation of body condition in each of the two rivers is provided in Table 2. These relationships were derived from data collected from both this study and unpublished data collected from previous studies within each of the two catchments. Each individual sampling occasion was subsequently summarised to mean W_r (condition) for each species for subsequent analyses.

Our recruitment index represented the percentage of juveniles within the entire length-frequency histogram prepared from fyke net data only as per Balcombe

and Arthington (2009). The cut-off lengths representing fish likely to have been less than six months old were based on those of Balcombe and Arthington (2009) and Pusey *et al.* (2004). These lengths are given in Table 1. Due to limitations of field sampling and numbers caught it was not possible to acquire data points for body condition and recruitment across all sampling sites or species, hence there were 14 such fish metric tests that could be applied; all sites and numbers used in analyses are listed in Table 1. Mean ($\pm$ S.E.) values of body condition and the percentage of recruits (juveniles) used for all times, and species given in Table 1 are presented in Table 2.

Flow metrics

Based upon our knowledge of fish recruitment and condition response to aspects of flow (e.g. Balcombe and Arthington, 2009; Arthington and Balcombe, 2011; Balcombe *et al.*, 2012) we set out to test some simple, readily calculated, ecologically meaningful flow metrics. Seven metrics were estimated, three representing time elapsed since flow (timing) and four representing volume (magnitude) of flow. Flow timing metrics (measured in days) were time since low in-channel flows (TSLF), time since high in-channel flow (TSHF) and time since floodplain flow (TSFPF). Flow magnitude metrics were the maximum daily discharge (ML/D) of the most recent flow event (MAXDIS), the total volume (ML) of the most recent flow event (TOTV), total discharge (ML) in the previous three months (DIS3MO) and total discharge (ML) in the previous six months (DIS6MO).

In Cooper Creek discharge was measured by summing the discharge from the Stonehenge and Retreat gauges (see Figure 1) as per Balcombe and Arthington (2009). Low flow for both rivers was set to any flow less than 2000 MLDay^{-1} , while high channel flow cut-offs were set at $<10000 \text{ MLDay}^{-1}$ for both rivers. All overland flood events were verified by authors or landowner observations in both catchments.

Data analyses

We analysed our fish metrics (dependant variables) against flow metrics (independant variables) with Simple Linear Regression to examine whether flow (hydrological) and fish metric associations were consistent. Following this, fish metrics were further analysed using interactive forward-stepping multiple linear regression (Systat 11, 2006) to examine whether fish recruitment and condition was better described by a combination of flow variables. Hydrological variable entry was set at $P < 0.15$ and variables were only retained in the final models if they were significant at ($p < 0.05$) or where they added greater than 5% to the overall model's explanatory power. Residual plots of final models for both simple and multiple regressions were examined to ensure they met the assumptions of both simple and multiple regression (Quinn and Keogh, 2005). Prior to running models all data were screened to meet the assumptions of regression and, subsequently it was necessary to transform some variables. Where transformation was needed, $\text{Log}_{10}(x+1)$ was found to be suitable for a number of hydrological metrics. We checked for co-linearity among hydrological metrics prior to running models. Where two or more metrics were correlated (at $r > 0.75$), only one variable was inserted into the model. However, to ensure that we had not rejected the wrong variable, alternative models were also run with rejected variables. The final variable retained (if significant) was determined by the model fit. Although by running multiple tests (98 in total; 14 fish metrics and seven flow metrics) for the simple linear regressions there was an increased likelihood

of committing Type 1 errors (Keppel, 1991), owing to the exploratory nature of the work we were more concerned with committing Type II errors. Therefore, while keeping the acceptable level of significance at $P < 0.05$, final models were accepted only if there was a consistency of pattern, whereby flow metrics had to have significant associations with more than one fish metric or individual models had a high explanatory power ($R^2 > 0.6$). All analyses were undertaken using Systat for Windows 11.00.01 (SSI 2004).

RESULTS

Body condition relationships with flow

Simple linear regressions revealed that there were more significant associations between body condition and flow metrics in Cooper Creek (6) compared to the Moonie River (3). Furthermore the strength of association for these relationships was also stronger as reflected by higher r-squared values, particularly for the best-fit relationships (Table 4). Of the nine significant associations, however, there was a lack of consistency in either individual flow metrics being found associated with fish condition or indeed, if a flow metric was found on more than one occasion the direction of the relationship was opposite. For example, *Maquaria* spB condition was positively associated with MAXDIS, while *Carrassius auratus* condition declined with MAXDIS. Similarly, while *M. sp B* condition was reduced with a longer duration since low in-channel flows (TSLF), the opposite was the case for *Tandanas tandanas*. It must be noted that these opposite relationships occur in the two different rivers and in each case different species. Additionally, in each catchment only two of the four species showed any response in body condition to flow magnitude or timing.

For three species, model fits for body condition were improved with additional flow metrics compared to single metrics alone (Table 5). For the medium-bodied generalist *Nematolosa erebi*, in Cooper Creek, body condition was related to time since both high (negative) and low (positive) flows with a strong model fit (adjusted $R^2 = 0.91$). In the same system the body condition of the large-bodied *M. sp. B*, was associated with both time since high flow (negative) and total volume of the most recent flow event. In the Moonie River, the final model fit for the condition of the exotic *C. auratus* using multiple regression was largely driven by both maximum discharge of the most recent flow event (negative) and the previous three month discharge (negative).

Recruitment relationships with flow

Similar to the results for body condition there were more significant relationships between fish recruitment and single flow variables in Cooper Creek (5) compared to the Moonie River (2) and the relationships were stronger in the former system (Table 4). Interestingly most of the variables associated with recruitment were those related to timing of flows with six of the seven associations being flow timing metrics. In

contrast to the patterns for recruitment however, there was some consistency in that all six of these associations showed fish recruitment was reduced in relation to time since various flow events (Table 4).

For three species across the two rivers fish recruitment was better explained by a combination of flow metrics (Table 5). For the two catfish species in Cooper Creek a combination of both timing and magnitude was found to produce the strongest models for recruitment. In the Moonie River, *N. erebi* recruitment was reduced in relation to both time since high in-channel flows and overbank (floodplain) flows.

Utility of flow metrics

Of the seven flow metrics tested, significant relationships were more likely when the flow metric was measured by time elapsed (10/16) compared to discharge magnitude (6/16) (Table 3). In general, fish metrics tended to be negatively associated with flow timing, and positively associated with flow magnitude (apart from *C. auratus* in the Moonie River) (Table 4).

DISCUSSION

Body condition and recruitment relationships with flow

Our primary hypothesis that fish body condition and recruitment success will be responsive to both the magnitude and timing of flow events was found to be true. However, the derived relationships were not uniform among species nor consistent for the same species across rivers. Generally relationships between fish body condition or recruitment and flow metrics were more likely to be significant in Cooper Creek than the Moonie River, with significant relationships most likely driven by a flow-timing metric. These results likely demonstrate the contrasts in flow regimes of these rivers. As Cooper Creek rarely exists as a flowing river, but mostly as disconnected drying waterholes, the contrast between boom and bust conditions is pronounced, with strong ecological responses (improved condition, growth, recruitment) when flows do occur (Bunn *et al.*, 2006; Kerezszy *et al.*, 2011). The flow regime of the Moonie River is much less variable such that a sharp delineation between boom and bust conditions is less obvious and there is a more subdued response to flow conditions than in Cooper Creek (Sternberg *et al.*, 2012).

For *N. erebi* in Cooper Creek, the strong positive relationship of body condition with time elapsed since the last overland flood levels started to increase may suggest that floods have a negative impact. However, this is more likely to be a response to drying and stability coupled with a reduction in other species during drying conditions. Balcombe and Arthington (2009) found that *N. erebi* typically went through population booms after significant waterhole isolation and drying, and Arthington *et al.* (2010) showed how most fish species exhibited significant population losses after initial booms following floods. Owing to this major multi-species decline in abundance, bony bream would have been released from competition for algal resources, a major food resource for this species (Balcombe *et al.*, 2005; Sternberg *et al.*, 2008). Even more pertinent is that as time elapsed since high flows increased, especially through 2004, it is likely that the littoral band ('bath-tub ring') of benthic algae that forms the main driver of secondary production in Cooper Creek (Bunn *et al.*, 2003) was likely to have become well-established, thus providing a significant in-channel energy subsidy to *N. erebi* (Bunn *et al.*, 2006). Paukert and Rogers (2004) also found a strong correlation between the body condition of flannelmouth suckers and algal productivity in the Colorado River. Due to the variable nature of benthic algal productivity in Cooper Creek we suggest that species such as *N. erebi* are unlikely to represent a good indicator of boom and bust processes as they can also proliferate during dry periods by feeding on established biofilms or alternatively by switching to poor quality foods such as detritus to compensate for the absence of algae (Balcombe *et al.*, 2005).

In contrast to *N. erebi*, *Macquaria* sp. B body condition appears to represent a good metric of response to flow timing and magnitude. The negative relationship between its condition and time since both low and high flow combined with its positive response to a number of flow magnitude metrics demonstrate that its condition is highly contingent on both flow timing and magnitude. These results can be explained by the huge energy subsidies derived from floodplain inundation which are subsequently transferred back into the waterholes on flood drawdown (Balcombe *et al.*, 2005; Burford *et al.*, 2008), therein supporting large abundances of species such

as *Macquaria* sp. B. The larger the flood the greater the energy subsidy provided back into waterholes (Arthington *et al.*, 2005; Welcomme *et al.*, 2006). However, as the duration of drying increases the waterholes cannot sustain such large fish populations and they lose condition and subsequently die as environmental conditions deteriorate (Arthington *et al.*, 2005; 2010). Similar patterns of declining fish condition and/or mortality have been observed in dry-season pools of a Mediterranean stream (Pires *et al.*, 2008), in prairie drainages (Spranza and Stanley, 2000) and in rivers with fluctuating flows (Encina and Granado-Lorencio, 1977).

It is notable that recruitment success but not the body condition of two catfish species was strongly affected by flow timing and magnitude in Cooper Creek. Both of these species are flow-spawning specialists (Balcombe and Arthington, 2009; Kerezszy *et al.*, 2011), with spawning linked to season (temperature) and rising flow. It would be expected, therefore that body condition would be more strongly influenced by season, whereby resources would be stored and accumulated after the summer season of high productivity, and through winter to enable these catfishes to spawn and thereby capitalise on any flow events that occur in the following summer. This seasonal pattern of slow accumulation of body reserves is typical of annual seasonal-single spawning species such as barbel and Arctic charr (Encina and Granado-Lorencio, 1977; Finstaad *et al.*, 2003).

Results from the Moonie River suggest some stark contrasts with fish responses in Cooper Creek. For example, *N. erebi* and *M. ambigua* (closely related to *Macquaria* sp. B) showed no relationships between body condition and flow metrics, but recruitment success for both species was significantly reduced with increase in time elapsed since high in-channel flows were present in the Moonie River. This contrasting response demonstrates the difficulty in transferring eco-hydrological relationships from one dryland catchment to another. In another example, Balcombe *et al.* (2010) showed that biomass-habitat models derived for two fish species (*N. erebi* and *M. ambigua*) in the Moonie catchment did not reflect the same associations in the Warrego River catchment (a more arid system within the same river basin). Also in a contrast to that for Cooper Creek, the catfish present in the Moonie River (*T. tandanus*) did show a response to flow whereby as time elapsed since low flow increased so did body condition, whereas the two Cooper catfishes (different species) showed no body condition response to flow. This contrast may be a function of the greater size and longevity of *T. tandanus* and its reproductive strategy compared to the medium-bodied species (*N. hyrtlii* and *P. argenteus*) examined in Cooper Creek.

The only other species to show a response to flow in the Moonie River was the introduced goldfish, *C. auratus*, where its body condition declined in relation to measures of increasing flow magnitude. This probably reflects the preference of this species for stable or zero-flow habitats in streams and lakes (Crivelli, 1995). It has also been demonstrated that there is a negative impact of larger flows and floods on *C. auratus* abundance and recruitment in dryland river systems (Costelloe *et al.* 2010), often a generalised response of exotic species to natural flows in arid-zone rivers (Propst *et al.* 2008).

Implications for management and monitoring

Investments in river conservation, restoration and ecological health monitoring require sensitive ecological indicators for monitoring long-term trends (Poff *et al.*, 2010; Bunn *et al.*, 2010; Sheldon *et al.*, 2012;). The results of the present study demonstrate the potential for using both fish body condition and juvenile recruitment success as indicators of fish response to natural flow conditions in two dryland rivers with contrasting flow regime variability and predictability, albeit that there is likely to be variation in species-specific response in rivers with contrasting flow regimes. The fundamental fish response relationships established in this study suggest that fish body condition and juvenile recruitment may also be used to monitor the outcomes/success of managed environmental flows. However, given the previous statement, there would need to be an understanding of the fish species that are likely to respond in a given hydrological setting. The advantages of using fish body condition as an indicator of response to environmental flows would be that these common and abundant species are easily captured (Balcombe and Arthington, 2009) and the methods used to gather body size and weight data are non-destructive, thus meeting ethical considerations (i.e. most fish were returned alive to the source waterhole). Additionally, given that for some species at least we were able to derive quite strong relationships using multiple linear regression we could potentially target other flow variables than the simple ones used here to target individual responses of a given species to various flow scenarios.

This study also demonstrates that body condition and recruitment responses are species-specific and that they can be interpreted in terms of specific reproductive traits, trophic ecology and/or habitat preferences. In addition, and importantly for any river health monitoring scheme, the anticipated responses of each species to flow conditions appear to be catchment specific. This is not to say that these results cannot be transferred to other dryland catchments with hydrological characteristics similar to those of the Moonie River and Cooper Creek. For example, it could be expected that the fish metrics and relationships to flow developed for Cooper Creek will apply in similar semi-arid and arid-zone rivers exhibiting clear boom and bust patterns while the Moonie River results could be applicable to dryland rivers with less variable flow patterns and fewer spells of zero-flows.

The wider use of the fish response metrics and relationships established herein to other dryland rivers will require calibration to the particular flow variability characteristics of each catchment. It may then be possible to identify suites of hydro-ecological relationships for dryland rivers with contrasting hydrological regimes, and furthermore, to predict how each type of river will be likely to respond to flow regime alterations or managed environmental flows. Hydro-ecological relationships involving aquatic and riparian vegetation, invertebrates and fish are being developed in several countries to support environmental flow management 'rules' for rivers of contrasting hydrological character (Arthington, 2012; Poff *et al.*, 2010; Kendy *et al.*, 2012; Zhang *et al.*, 2012).

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1 **Table 1** Summary of fish body condition and recruitment metrics (and relative body lengths used to calculate each metric), sample times/dates
2 and sample sizes for Cooper Creek (eight sampling times) and the Moonie River (13 sampling times). Sampling times were Cooper Creek: T1 - 04/2001,
3 T2 – 09/2001, T3 – 10/2002 T4 - 05/2003, T5 – 03/2004, T6 – 06/2003, T7 – 10/2004, T8 – 12/2004; Moonie River: T1 - 02/2006, T2 – 05/2006, T3 – 09/2006 T4 - 01/2007,
4 T5 – 04/2007, T6 – 10/2007, T7 – 03/2008, T8 – 04/2008, T9 – 09/2008, T10 - 01/2009, T11 – 03/2009, T12 – 11/2009, T13 – 04/2010. Note: empty cells indicate no fish
5 collected.
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Fish metric	Body length cut –offs (mm)	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	Total individuals measured	Total sampling occasions
Cooper Creek																
<i>Nematolosa erebi</i> recruitment	<90	81		122	570	464	387	690	2960						5274	7
<i>N.erebi</i> condition	>50			37	281	352	306	562	562						2100	6
<i>Macquaria</i> sp. B recruitment	<90	61	13	40	41	142	64	23	14						398	8
<i>Macquaria</i> sp. B condition	>50		12	30	18	134	76	65	37						372	7
<i>Neosilurus hyrtlii</i> recruitment	<100	105	44	255	17	478	17	32	133						1081	8
<i>N.hyrtlii</i> condition	>80			256	12	74		32	31						405	5
<i>Porochilus argenteus</i> recruitment	<100	100	176	199	454	314	351	28	43						4499	8
<i>P.argenteus</i> condition	>80		151	149	398	317	67	109	77						1268	7
Moonie River																
<i>N.erebi</i> recruitment	<90	252	171	52	147	65	48	537	223	77	202	177	151	304	2406	13
<i>N.erebi</i> condition	>50	67	85	42	46	25	47	339	168	65	105	169	150		1308	12
<i>Macquaria ambigua</i> recruitment	<90	103	34	33	295	70	76	206	95	163	134	210	42	131	1592	13
<i>M. ambigua</i> condition	>50	49	12	18	79	47	46	120	77	162	87	96	42		835	12
<i>Tandanus tandanus</i> condition	>80					9	31	14	16	17	25	32	34		178	8
<i>Carrassius auratus</i> condition	>50					7	31	23	23	77	19	16	29		225	8

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Table 2 Length mass relationships used to calculate body condition index for fish species in Cooper Creek and Moonie River waterholes. Note: W = mass in g, L = standard length in mm. *** = P< 0.001

Species	Relationship	N	Adj R ²	P
Cooper Creek				
<i>N. erebi</i>	$W = (1.146 \times 10^{-5}) L^{3.135}$	3077	0.99	***
<i>Macquaria</i> sp. B	$W = (1.98 \times 10^{-5}) L^{3.054}$	575	0.99	***
<i>N. hyrtlui</i>	$W = (1.083 \times 10^{-5}) L^{2.954}$	620	0.98	***
<i>P. argenteus</i>	$W = (5.200 \times 10^{-6}) L^{3.085}$	1866	0.95	***
Moonie River				
<i>N. erebi</i>	$W = (5.490 \times 10^{-5}) L^{2.805}$	1874	0.96	***
<i>M. ambigua</i>	$W = (3.544 \times 10^{-4}) L^{2.459}$	1091	0.95	***
<i>T. tandanas</i>	$W = (5.870 \times 10^{-5}) L^{2.732}$	189	0.97	***
<i>C. auratus</i>	$W = (1.201 \times 10^{-4}) L^{2.766}$	234	0.96	***

Table 3 Summary of percent fish body condition (mean $\pm$ S.E.) and percent juvenile recruitment (absolute value) metrics for Cooper Creek and Moonie River across a range of sampling conditions as per Table 1.

Fish metric	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13
Cooper Creek													
<i>N. erebi</i> recruitment	17		0.1	71	0.2	45	44	92					
<i>N. erebi</i> condition			101	109	99	98.2	102	103					
			(3.0)	(0.8)	(0.7)	(0.4)	(0.7)	(0.9)					
<i>Macquaria</i> sp. B recruitment	7	0	33	0.2	31	48	30	29					
<i>Macquaria</i> sp. B condition		89.6	99	104	106	99.7	91.2	93.1					
		(3.9)	(2.4)	(2.8)	(1.7)	(1.2)	(1.3)	(1.1)					
<i>N. hyrtlui</i> recruitment	30	7	0.8	47	85	96	44	8					
<i>N. hyrtlui</i> condition			89.8	113	126		121	115					
			(0.8)	(3.2)	(3.4)		(3.2)	(2.3)					
<i>P. argenteus</i> recruitment	66	66	7	90	92	97	56	19					
<i>P. argenteus</i> condition		91.4	84.7	108	116	89.3	95.7	93.5					
		(0.9)	(3.4)	(0.4)	(1.1)	(1.1)	(1.5)	(1.2)					
Moonie River													
<i>N. erebi</i> recruitment	50	53	10	10	68	8	58	41	22	50	8	9	46
<i>N. erebi</i> condition	92	87.2	79.8	107	113	109	101	103	110	108	114	111	
	(1.1)	(0.8)	(1.5)	(1.8)	(5.3)	(2.0)	(1.5)	(1.3)	(2.7)	(2.5)	(0.9)	(3.7)	
<i>M. ambigua</i> recruitment	38	29	16	12	33	57	70	31	21	56	26	21	48
<i>M. ambigua</i> condition	91.9	93.3	83.4	95.9	113	99.8	96.4	111	115	117	107	93.7	
	(2.5)	(3.3)	(3.6)	(1.2)	(2.1)	(4.7)	(2.7)	(6.5)	(2.0)	(7.6)	(2.1)	(3.4)	
<i>T. tandanus</i> condition					90.3	107	99.6	93.4	100	92.5	92	104	
					(5.6)	(3.8)	(2.7)	(3.3)	(1.9)	(2.1)	(2.2)	(2.3)	
<i>C. auratus</i> condition					108	102	93	86	98.9	104	111	102	
					(2.9)	(2.3)	(2.9)	(3.6)	(1.7)	(2.5)	(2.0)	(1.4)	

Table 4 Summary of significant Linear Regression results for fish-flow metrics in Cooper Creek waterholes on eight sampling occasions between April 2001 and December 2004, and the Moonie River on thirteen sampling occasions between February 2005 and April 2010. The best fit-relationships are highlighted in bold * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.005$. TSFF = time since floodplain flow, TSLF = time since low in-channel flow, TSHF = time since high in-channel flow, TOTV = total volume of most recent flow event, MAXDIS = maximum daily discharge of most recent flow event, DIS3MO = total discharge in previous 3 months, DIS6MO = total discharge in previous 3 months.

Species	River	Flow metric	Relationship	F ratio	Adj R^2	P
CONDITION						
<i>N. erebi</i>	C	TSFF	$Y = 0.022X + 96.2$	23.9	0.82	**
<i>Macquaria</i> sp. B	C	TSLF	$Y = -0.057X + 105.2$	9.58	0.59	*
<i>Macquaria</i> sp. B	C	TSHF	$Y = -0.049X + 106.4$	13.4	0.68	*
<i>Macquaria</i> sp. B	C	TOTV	$Y = 1.573 \log_{10} X + 80.5$	13.6	0.67	*
<i>Macquaria</i> sp. B	C	MAXDIS	$Y = 1.863 \log_{10} X + 80.8$	12.9	0.67	*
<i>Macquaria</i> sp. B	C	DIS3MO	$Y = 0.791 \log_{10} X + 92.9$	7.10	0.50	*
<i>T. tandanus</i>	M	TSLF	$Y = 0.039X + 92.1$	7.38	0.47	*
<i>C. auratus</i>	M	MAXDIS	$Y = -0.0001X + 108.9$	11.0	0.59	*
<i>C. auratus</i>	M	DIS3MO	$Y = -0.0001X + 104.7$	6.91	0.46	*
RECRUITMENT						
<i>N. hyrtlui</i>	C	TSLF	$Y = -0.003X + 0.819$	13.7	0.64	**
<i>N. hyrtlui</i>	C	TSHF	$Y = -0.002X + 0.805$	6.51	0.44	*
<i>P. argenteus</i>	C	TSLF	$Y = -0.003X + 1.005$	12.5	0.62	*
<i>P. argenteus</i>	C	TSHF	$Y = -0.003X + 1.05$	12.1	0.61	*
<i>P. argenteus</i>	C	DIS6MO	$Y = 0.051 \log_{10} X + 0.111$	37.0	0.84	***
<i>N. erebi</i>	M	TSHF	$Y = -0.073X + 55.4$	10.9	0.45	**
<i>M. ambigua</i>	M	TSHF	$Y = -0.050X + 50.4$	6.73	0.323	*

Table 5 Summary of significant Multiple Linear Regression results for fish-flow metrics in Cooper Creek and Moonie River waterholes, where relationships are better described than for one variable alone (as per Table 2). * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.005$. Key to flow metrics as per Table 4.

Species	River	Relationship	Adj R^2	P
CONDITION				
<i>N. erebi</i>	C	$Y = 0.023 \text{ TSLF} - 0.010 \text{ TSHF} + 97.306, F_{2,3} = 25.092$	0.91	*
<i>Macquaria</i> sp. B	C	$Y = -0.031 \text{ TSHF} + 0.980 \log_{10} \text{TOTV} + 92.459, F_{2,4} = 25.092$	0.87	**
<i>C. auratus</i>	M	$Y = -0.001 \text{ MAXDIS} - 0.0001 \text{ DIS3MO} + 109.035, F_{2,5} = 9.055$	0.70	*
RECRUITMENT				
<i>N. hyrtlui</i>	C	$Y = -0.002 \text{ TLF} - 0.007 \text{ THF} - 0.059 \log_{10} \text{TOTV} - 0.093, F_{3,4} = 272.64$	0.99	***
<i>P. argenteus</i>	C	$Y = -0.004 \text{ THF} - 0.068 \text{ TOTV} + 2.059, F_{2,5} = 73.52$	0.95	***
<i>N. erebi</i>	M	$Y = -0.072 \text{ THF} - 0.118 \text{ TSFPF} + 69.441, F_{2,10} = 13.793$	0.68	**

Figure Captions

Figure 1 Study locations and patterns of discharge associated with sampling periods in Cooper Creek and the Moonie River. Arrows indicate sampling occasions in relation to discharge.