Monitoring Murray cod spawning & recruitment in response to spring 2020 Macquarie River environmental water flows

A report prepared for the Commonwealth Environmental Water Office by NSW Department of Primary Industries - Fisheries

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More information

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Executive summary

Water for the environment was used during Spring 2020 in the mid-Macquarie River providing stable flows to support Murray cod nesting during the peak breeding period. Successful spawning and juvenile recruitment were observed during the 2020/21 watering year within the mid-Macquarie River. This can be attributed to the spring environmental water delivery specifically targeted to promote Murray cod spawning and recruitment. From this study, 'real time' data was provided to Fisheries Managers and the Macquarie Environmental Flows Reference Group (EFRG) on the timing of the spring 2020 Murray cod spawning season. This information was used to inform river management options to maximise Murray cod recruitment outcomes; specifically relating to the delayed release of a flow pulse to the Macquarie Marshes that could have inhibited Murray cod nesting.

Murray cod larvae accounted for 88% (n=645) of the total larval catch from October 2020 into early November 2020. The larvae and eggs of other species captured included freshwater catfish, golden perch, silver perch, common carp, yabbies and mussels. Sampling conducted in early 2021 indicated that Murray cod larvae had successfully recruited to the juvenile life-stage; indicating that flow conditions post the spawning period were conducive to support larval survival and juvenile recruitment. Juvenile recruitment strength was compared to earlier years where data were available. Recruitment strength was greatest during the 2014/15 watering year when CEWO and NSW environmental watering was used to promote Murray cod recruitment. Flow characteristics for each stage of the Murray cod recruitment process were also examined in relation to recruitment strength for the three years of available data. Stable flows during the nesting period appeared to be the predominant drivers of Murray cod recruitment strength based on the limited data set.

Based on outcomes of the current study, a refined hydrograph was designed to support Murray cod spawning and recruitment in future watering years. Key components of the hydrograph included pre-nesting bank-full flows or flooding to enhance productivity and availability of spawning habitat and minimal flow variability during the core spawning period to reduce the risk of disturbing nests. We recommend that monitoring of Murray cod spawning and recruitment should continue over multiple breeding seasons and varied hydrological scenarios. This will provide information that can be used to compare larval and recruitment strength across years and help to refine the hydrograph to most efficiently use water for the environment to promote Murray cod spawning and recruitment.

Introduction

Fish assemblages in dryland rivers have evolved life-history strategies attuned to environmental triggers, particularly water temperatures and flow regimes. However, the regulation of rivers through the construction of dams, weirs and other water diversion structures has altered natural flow regimes and affected the associated ecological processes of many river systems throughout the world. Given the extensive literature detailing the importance of river flows to fish diversity, abundance and recruitment, the restoration of riverine ecosystems is being addressed in part by providing water for the environment in regulated systems. To help refine the use of water for the environment in the Macquarie River, we designed and tested a hydrograph in spring 2020 with the aim being to promote spawning and recruitment of Murray cod in the mid-Macquarie River.

Between September 2020 and February 2021, 137.5 GL (100 GL NSW; 37.5 GL CEW) of water for the environment was delivered to Marebone Weir via the mid-Macquarie River to support the recovery of native fish and core wetland vegetation in the Macquarie Marshes following drought-of-record in 2017 – 2019 (Figure 1). Rainfall provided additional flows in the river making flows more variable than planned. Translucent Environmental Water Allowance was triggered, delivering flows of up to 2,000 $ML.day^{-1}$ (Figure 2). Without deliveries of water for the environment, flows in the Mid-Macquarie River around Dubbo and Narromine would have fallen below the target threshold of 1,000 $ML.day^{-1}$ throughout most of September and October 2020; reducing available nesting habitat for Murray cod and freshwater catfish and causing potential nest abandonment and nest desiccation (Figure 2).

This study aimed to examine the spawning and recruitment response of Murray cod to the spring 2020 Macquarie River environmental water flows. For managers, an improved understanding of the timing of spawning events and transition of early life stages downstream will improve the ability to manage flow events in ‘real time’ and enable consideration of river management options to maximise recruitment outcomes. Annual recruitment strength was also compared between years with varied flow characteristics. Recruitment data were available from: 2014 – 15 where drought conditions limited water availability in the system; 2016 – 17 that experienced widespread flooding and dam spill, and; 2020 – 21 that experienced wetter conditions and numerous tributary flow events that was preceded by extreme drought, river cease-to-flow, fish deaths and fish rescues in 2019 and early 2020.

The findings of this study will contribute to the development of adaptive flow management plans and the increasing body of knowledge required in the effective use of environmental water to benefit native fish communities.

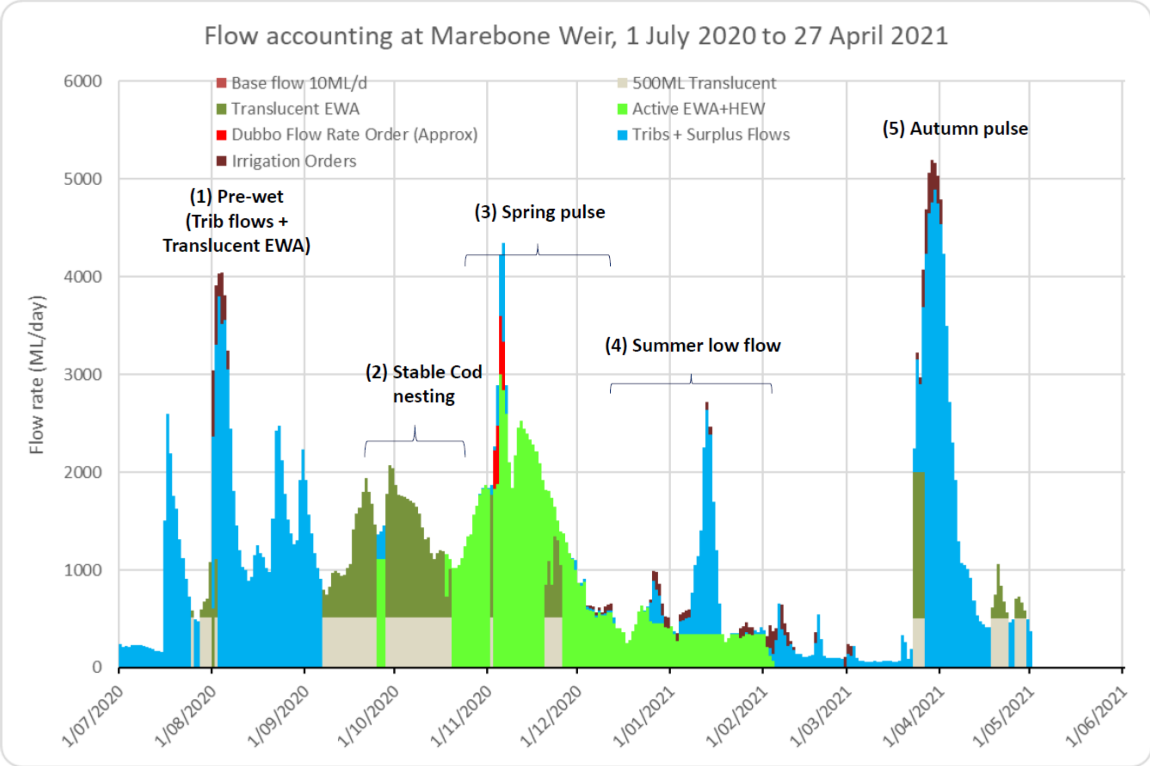


Figure 1. Flow accounting at Marebone Weir from July 1st, 2020 to April 27th, 2021.

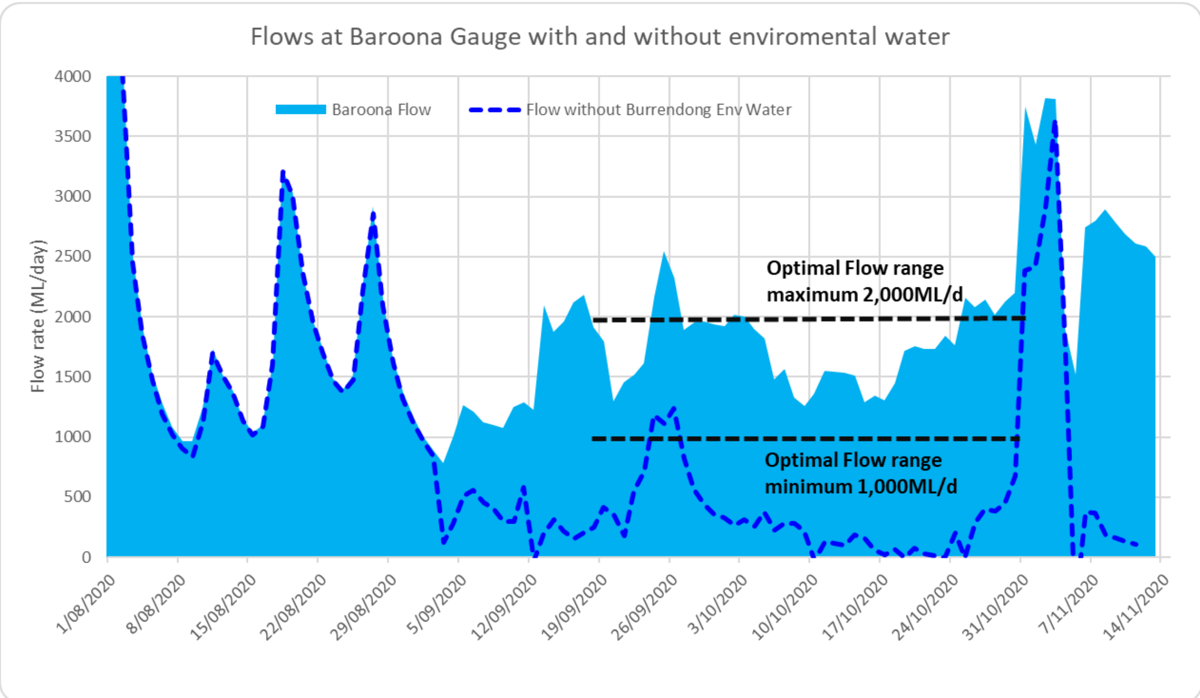


Figure 2. River discharge at Baroona Gauge Station during the spring 2020 Murray cod breeding season and discharge that would have occurred without the delivery of environmental water. Dashed horizontal lines indicate the targeted flow range to promote successful Murray cod breeding and recruitment.

Monitoring objectives

Two sampling components monitored for: 1) spawning, and; 2) successful juvenile recruitment in response to the spring 2020 Macquarie River hydrograph. Sampling for drifting larvae was undertaken to identify spawning events; this was followed by young-of-year (YOY) sampling to determine if spawning resulted in successful juvenile recruitment.

Spawning objectives: Monitor for Murray cod reproduction within the mid-Macquarie River.

1. In the spring of 2020 did Murray cod spawn within the mid-Macquarie River?
2. When did spawning occur in the mid-Macquarie River and what were the abiotic drivers associated with spawning (i.e. hydrology & water temperature)?
3. Use the presence of drifting fish larvae to inform real time river management to maximise fish recruitment outcomes. An example is releasing a late spring pulse for Macquarie Marshes vegetation, an early release of the flow pulse can disrupt Murray cod nesting inhibiting spawning and recruitment.

Recruitment objectives: Assess the juvenile recruitment response of Murray cod to the delivery of a 2020 spring pulse within the Macquarie River.

4. Did spawning in the mid-Macquarie River result in successful juvenile recruitment of Murray cod? (i.e. did the flow conditions allow larvae to survive to juveniles).
5. What were the abiotic drivers associated with successful juvenile recruitment (i.e. hydrology & water temperature)?

Methodology

Study sites

The Macquarie River is a large regulated inland freshwater river system located in the central-northern Murray-Darling Basin of New South Wales (NSW), Australia. The headwaters of the system originate in the foothills of the Great Dividing Range and flow in a north-westerly direction for approximately 650 km before joining the Barwon River in northern NSW (Figure 3). Flows within the mid-Macquarie River, Macquarie Marshes, and lower Macquarie River are primarily dictated by the flow regulating activities of Burrendong Dam. Four study sites between Narromine and Warren (Figure 3) on the mid-Macquarie River were monitored for spawning (larval fish & egg sampling) and recruitment (YOY juvenile sampling). This zone has previously been identified as a strong-hold for Murray cod recruitment within the Macquarie River (Stocks et al., 2015).

Spawning

To allow for integration with existing monitoring studies throughout the Murray-Darling Basin, larval fish sampling followed the LTIM/TLM methodology. At four sites in the mid-Macquarie River larval sampling was conducted weekly between October 12th and November 12th, 2020. At each site, 6 larval drift nets were set overnight. Samples were live picked on site, to examine for the presence/absence of drifting larvae. Live picking was used to inform real time management of the spring flow event. After live picking, samples were preserved for more intensive quantitative laboratory sorting.

The total abundance of larval fish captured was compared between species using analysis-of-variance (ANOVA). Assumptions of ANOVA, including normality and homogeneity of variance were investigated. Data were $\log_{10}$ transformed to meet ANOVA assumptions. To examine pairwise comparisons between species, Tukey's HSD (honest significant difference) tests were performed. The percentage composition of the total larval catch was calculated for each species.

Existing size-at-age growth models were used to estimate the age of Murray cod larvae (Serafini and Humphries, 2003). Length frequency plots of larval Murray cod were constructed for each of the five weeks of larval sampling, incorporating larval age class data. Larval abundance was plotted against abiotic variables including discharge and water temperature, providing a means to determine if a specific feature of the hydrograph promoted successful spawning.

A collaborative project 'NSW Fisheries Fish Screening Project' commenced within this projects study reach in late November 2020. This project provided a significant 'value add' to the current project; extending the temporal resolution of larval sampling to March 2021.

Recruitment

Standardised fish community sampling was used to examine for the presence of YOY Murray cod in January and March 2021. These periods were chosen as juveniles were expected to be of a size susceptible to capture by boat electrofishing. Standardised fish sampling followed the Sustainable Rivers Audit (SRA) sampling protocol (Davies, 2008). This method is the primary standardised protocol employed by NSW Fisheries throughout the Murray-Darling Basin and by earlier studies conducted within the Macquarie River (Stocks et al. 2015). A combination of 12x 90 second boat electrofishing shot, 10x bait traps and 5x opera house traps were deployed at four sites. Additional electrofishing effort was undertaken to increase catches of YOY Murray cod at selected sites.

Recruitment strength, calculated as catch-per-unit-effort (CPUE) of YOY Murray cod <120mm was compared between three years of monitoring within the mid-Macquarie using ANOVA. Assumptions of ANOVA, including normality and homogeneity of variance were investigated. Data were $\log_{10}$ transformed to meet ANOVA assumptions. CPUE of YOY Murray cod was compared between March/April sampling conducted in 2015, 2017 and 2021. The Murray cod recruitment process was divided into three key life-history stages. Stage 1: Pre-spawning (August 1st – September 15th); Stage 2: Nesting (September 16th – December 1st), and; Stage 3: Recruitment (December 2nd – April 1st). The timing of each stage of the recruitment was based on data from the current study and earlier studies conducted within the mid-Macquarie River (Stocks et al., 2015, Stocks et al., 2021). Characteristics of the hydrograph were examined for each of the three stages of the Murray cod recruitment process and linked to the success or failure of each stage.

Fish Community

Standardised fish community sampling was conducted in January 2021 at five sites within the mid-Macquarie River (accompanying the January recruitment sampling). Historical standardised fish community sampling within the same river reach was available for January 2015, January 2016 and January 2017 (Stocks et al., 2015, Stocks et al., 2021). The abundances of each species caught were compared between sampling years using ANOVA. Assumptions of ANOVA, including normality and homogeneity of variance were investigated. Data were $\log_{10}$ transformed to meet ANOVA assumptions. To examine pairwise comparisons within a species between years, Tukey's HSD (honest significant difference) tests were performed. Length frequency distributions were constructed for all species captured during the 2021 sampling year. Length frequency distributions of Murray cod were also constructed for each sampling year.

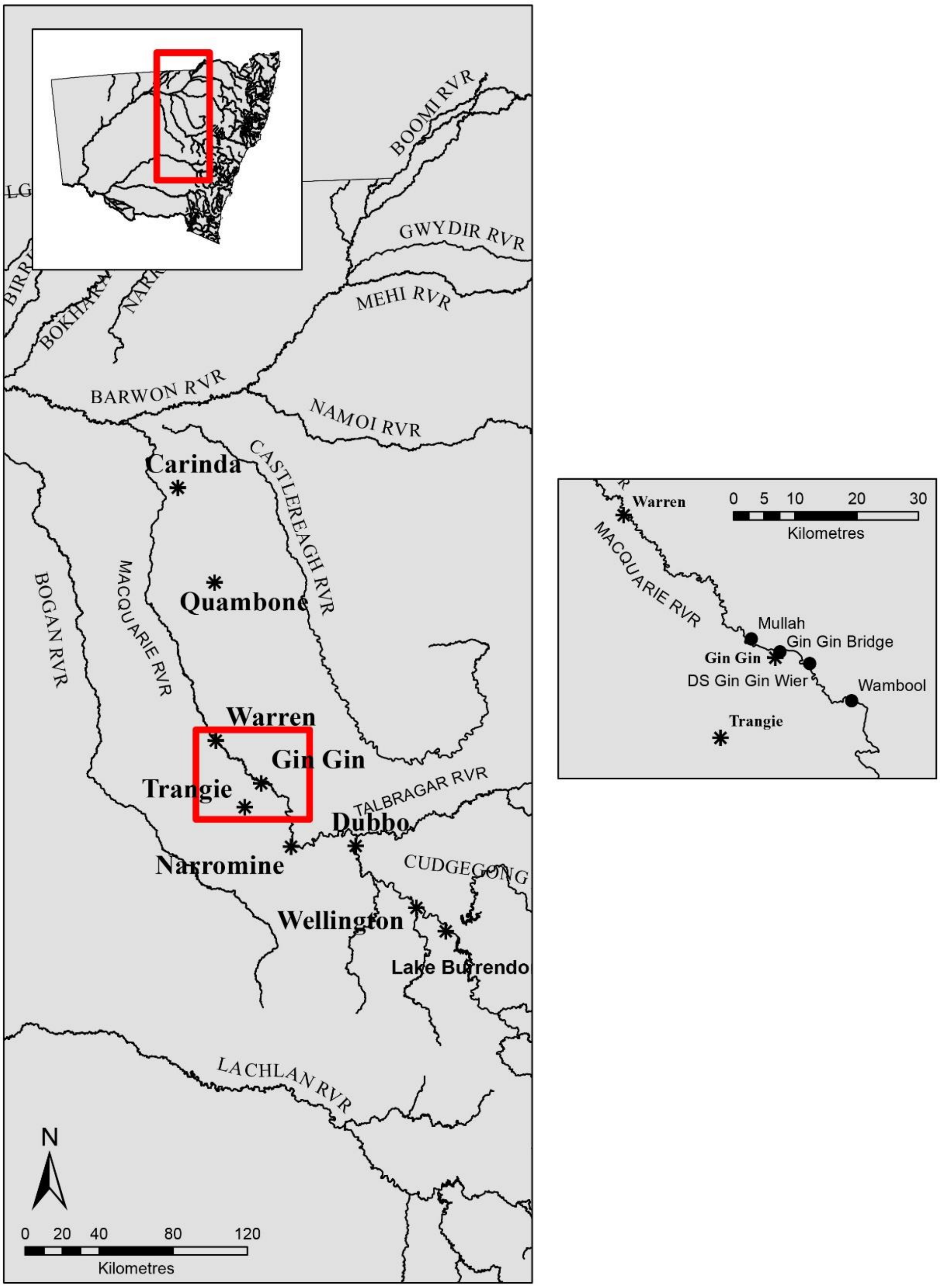


Figure 3. Sampling reach and sites (black circles) that larval and recruitment monitoring was conducted between October 2020 and March 2021.

Results

Spawning

In total 732 larval fish and 4 fish eggs were captured during the 5 weeks of larval sampling between October 12th and November 12th, 2020 within the mid-Macquarie River (Table 1). Five larval fish species and the drifting eggs of one species, silver perch, were captured. Murray cod was the most abundant larvae, comprising 88% of the total catch. Common carp were the second most abundant larvae captured, making up 8% of the total catch (Table 1 & Figure 4). Drifting larval yabbies and mussels were also captured though were not quantified (Plate 3).

Sampling week had a significant effect on the total catch of larval Murray cod ($F_{4,15}$=2.134*;* P=0.1). The highest mean abundance per site of larval Murray cod was captured in the first week of sampling (October 12 – 15th), (Table 1 & Figure 5). The species composition of larval fish captured varied temporally throughout the 5 weeks of sampling (Table 1 & Figure 5). Murray cod larvae were captured during each week of sampling whereas larval common carp and freshwater catfish were not captured until weeks 4 and weeks 5 respectively. The first captures of common carp larvae were associated with a rise in discharge (2,000 ML.day^{-1} increasing to 4,000 ML.day^{-1}) due to tributary inflows. The first captures of freshwater catfish larvae were associated with water temperatures above 20˚C (Figure 5). A collaborative project within the same river reach continued the larval sampling from November 2020 through until March 2021 (NSW DPI Screens for Streams Project). Figure 6 combines the larval drift netting data from the two projects, showing the presence of larval species by month. Murray cod larvae were first captured in October 2020 and continued to be captured into December 2020. Freshwater catfish breeding season commenced approximately a month later than Murray cod and continued into January 2021 (Figure 6).

Growth models were used to assign the daily age of larval Murray cod based on standard length (Serafini and Humphries, 2003). During the five weeks of sampling, all age classes from 1 – 6 days up to 16+ days old were identified (Figure 7).

Species identification- genetic validation

Ninety-three larval fish and four eggs were sent to the Australian Genomic Research Facility (AGRF) for DNA sequencing to determine species. Of the 57 larval fish sub-sample sent to AGRF that were identified as Murray cod by macroscopic examination, 100% of these fish were confirmed to be Murray cod by genetic analysis. Thirty-eight larval fish and eggs were unable to be identified by macroscopic examination. The four unidentified eggs captured in larval drift nets were confirmed to be silver perch eggs, the unidentified fish were Australian smelt, freshwater catfish, golden perch and Murray cod.

Table 1. Total catch by species for each week of larval drift and light trap sampling within the mid-Macquarie River. Week 1 = Oct 12th, 2020; Week 2 = Oct 19th, 2020; Week 3 = Oct 26th, 2020; Week 4 = Nov 2nd, 2020; Week 5 = Nov 9th, 2020.

Common Name	Week 1	Week 2	Week 3	Week 4	Week 5	Species total	% of catch
Australian smelt	0	1	0	0	1	2	0
Common carp	0	0	0	50	10	60	8
Freshwater catfish	0	0	0	0	19	19	3
Golden perch	0	1	0	0	0	1	0
Murray cod	285	86	36	102	136	645	88
Silver perch (eggs)	0	0	0	4	0	4	1
Unidentified fish	4	1	0	0	0	5	1
Total	289	89	36	156	166	736	

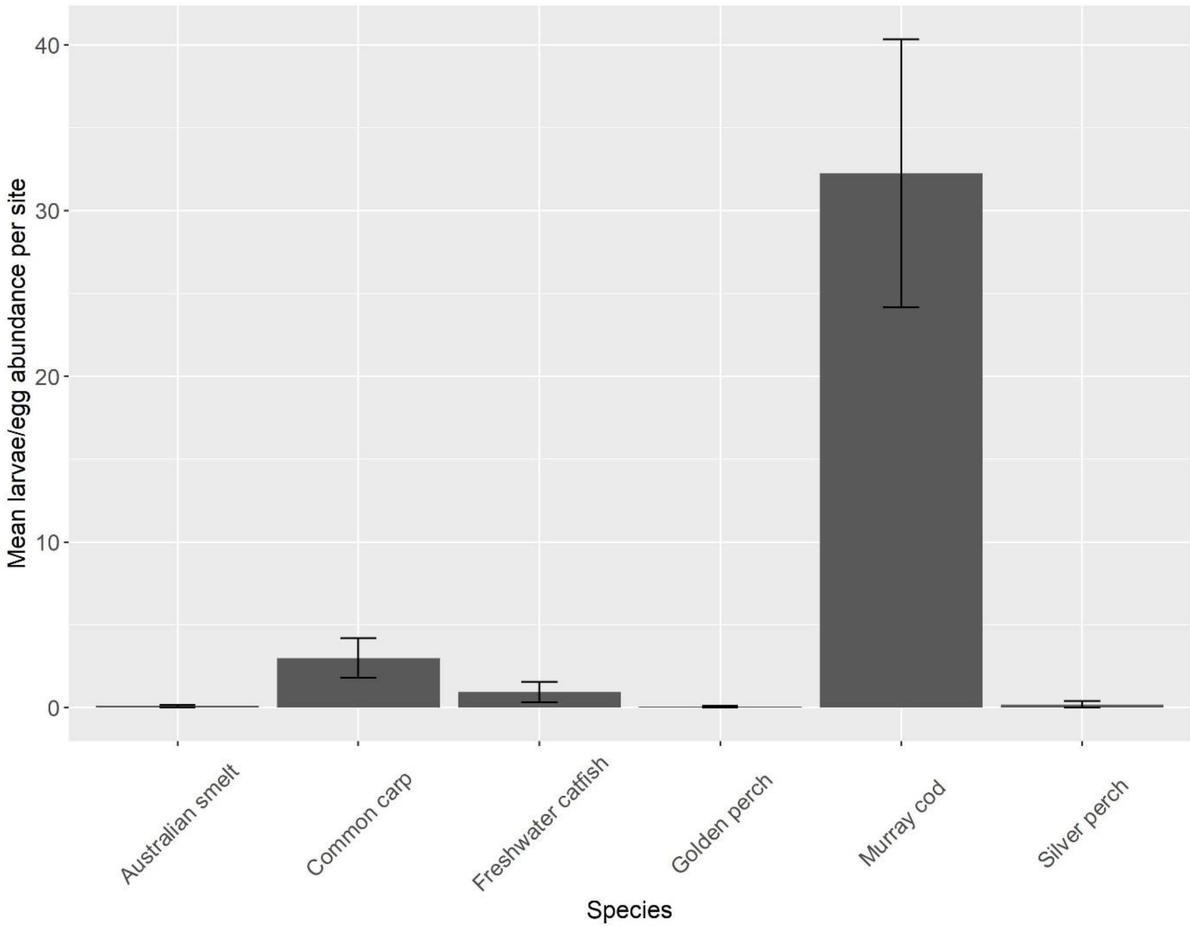


Figure 4. Mean abundance per site of larval fish captured in the mid-Macquarie River from 5 weeks of sampling between October 12th and November 12th. Note abundance of silver perch are eggs.

Figure 5. Mean abundance per site of larval fish captured each week of sampling in the mid-Macquarie River. Black line graph is water temperature at Baroona gauging station. Red line graph is river discharge at Gin Gin gauging station. Note: Larval sampling commenced on October 12th, 2020 and concluded November 11th, 2020 under the current project (https://realtimedata.waternsw.com.au/). Note abundance of silver perch are eggs.

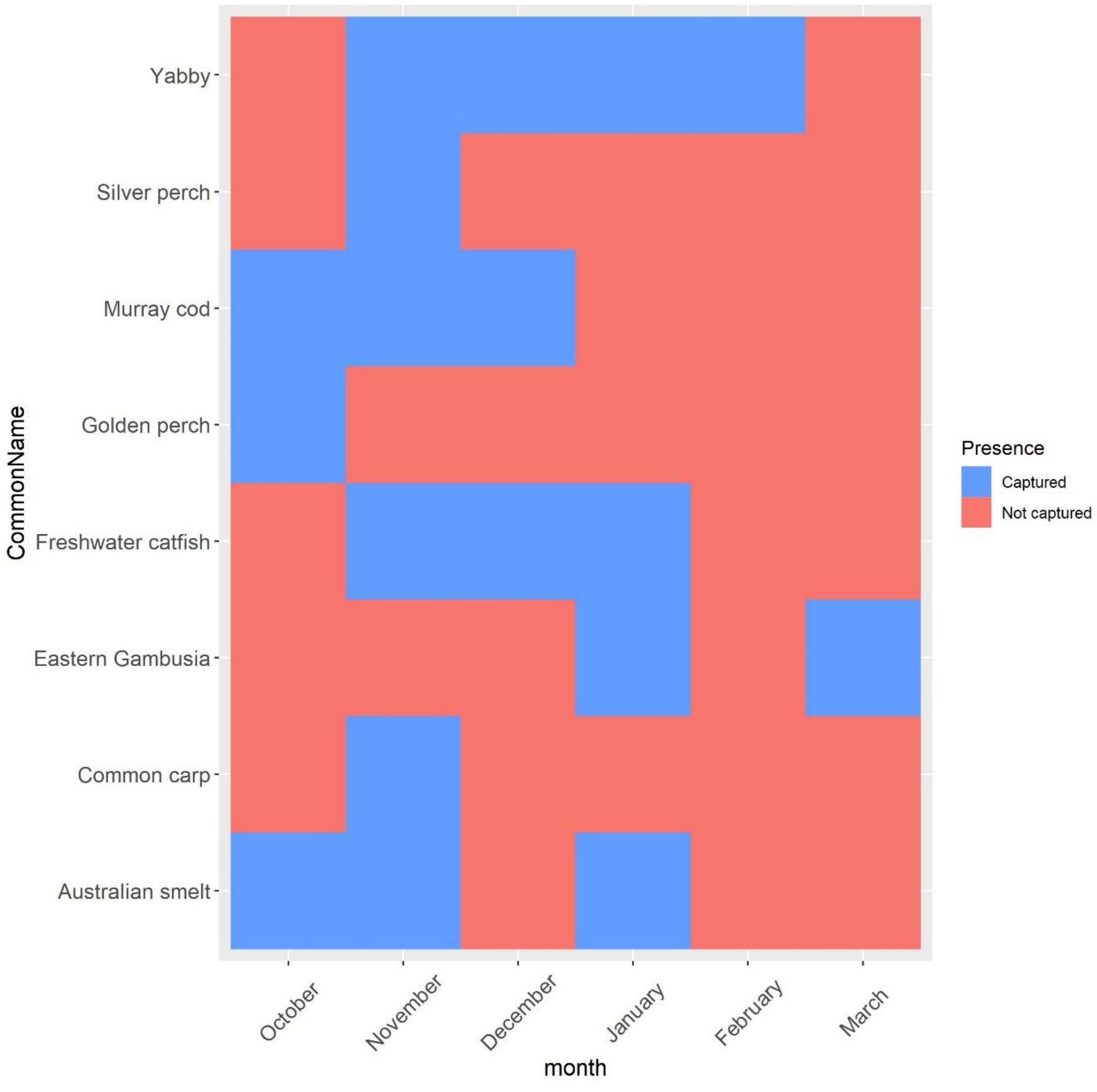


Figure 6. Presence/absence by month of larval fish captured in larval drift nets within the mid-Macquarie River between October 12th, 2020 and March 9th, 2021. Data from December to March was provided by the NSW DPI Project 'Screens for Streams'. Note: Silver perch were egg captures not larval fish.

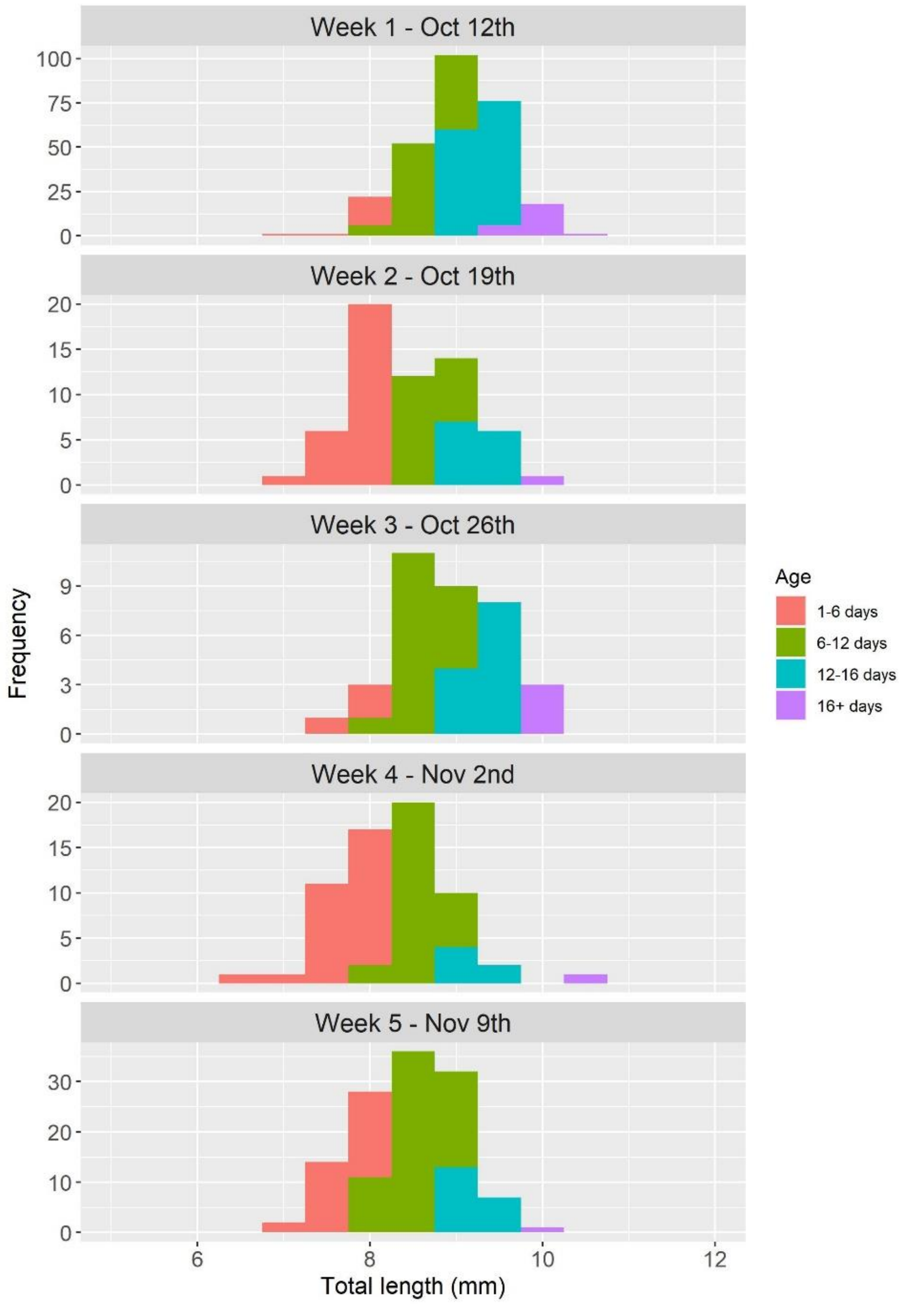


Figure 7. Length frequency distribution and daily age of larval Murray cod captured in larval drift nets and lights traps over 5 weeks of sampling within the mid-Macquarie River.

Juvenile Recruitment

Murray cod YOY (<120mm TL) were captured in both the January and March 2021 recruitment sampling (Figure 8). However, YOY abundances were higher in the March sampling event, likely when individuals were of a size more susceptible to capture by boat electrofishing (Figure 8).

Varied hydrological conditions were experienced during each of the years examined (Figure 9). The hydrological conditions experienced during each stage of Murray cod recruitment are displayed in Figure 10 and detailed in relation to spawning and recruitment success or failure in Figure 11. Sampling year had a significant effect on the mean YOY CPUE ($F_{2,12}$=15.7; P<0.001). A Post hoc Tukey HSD test indicated that YOY recruitment in 2015 was significantly greater than that of 2017 and 2021 (Figure 12). The 2014/15 breeding year was characterised by relatively stable flow (<1000 ML.day^{-1}) in the pre-spawning stage. The nesting/spawning stage was comprised of low flows (<300 ML.day^{-1}), that increased to stable flow of ~1000 ML.day^{-1} in the first half of nesting period. The recruitment stage was characterised by relatively stable flows from ~300 – 1000 ML.day^{-1}. In contrast the 2016/17 breeding season was significantly wetter and experienced large flow events. No recruitment was observed during this breeding year. Both the pre-spawning and nesting/spawning stage experienced large flow event >50,000 ML.day^{-1}. No spawning monitoring was conducted this year so it cannot be concluded if spawning occurred and recruitment was unsuccessful or if neither successful spawning or recruitment occurred. Successful recruitment was also observed during the 2020/21 breeding year. However, recruitment strength of Murray cod was less than the 2015/16 breeding year. For each stage of recruitment, the hydrograph was characterised by relatively stable moderate flows from 2000 – 5000 ML.day^{-1} (Figure 11).

Stocked vs Naturally recruited fish

Stocking of Murray cod and golden perch occurred in the study reach in summer 2020. All juvenile golden perch and Murray cod (40 – 150mm TL) captured during the sampling period have been sent for genetic analysis to determine if they are stocked fish or naturally recruited. This analysis is funded in-kind through the NSW Fisheries 'FishGen' project and will provide valuable data on the ratio of natural recruited to stocked Murray cod within the mid-Macquarie River. Results are expected in September 2021. Given the varied sizes of YOY Murray cod captured it is highly likely a proportion will be naturally recruited fish as a result of the flow design.

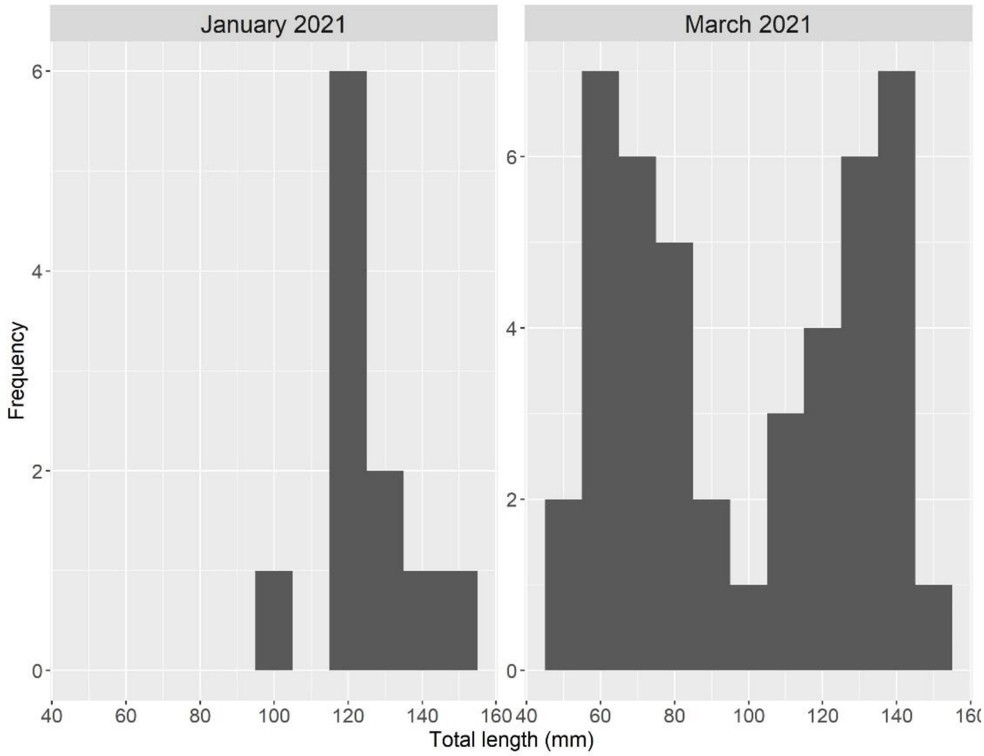


Figure 8. Length-frequency-distributions of juvenile Murray cod captured within the Macquarie River during January and March 2021 recruitment sampling.

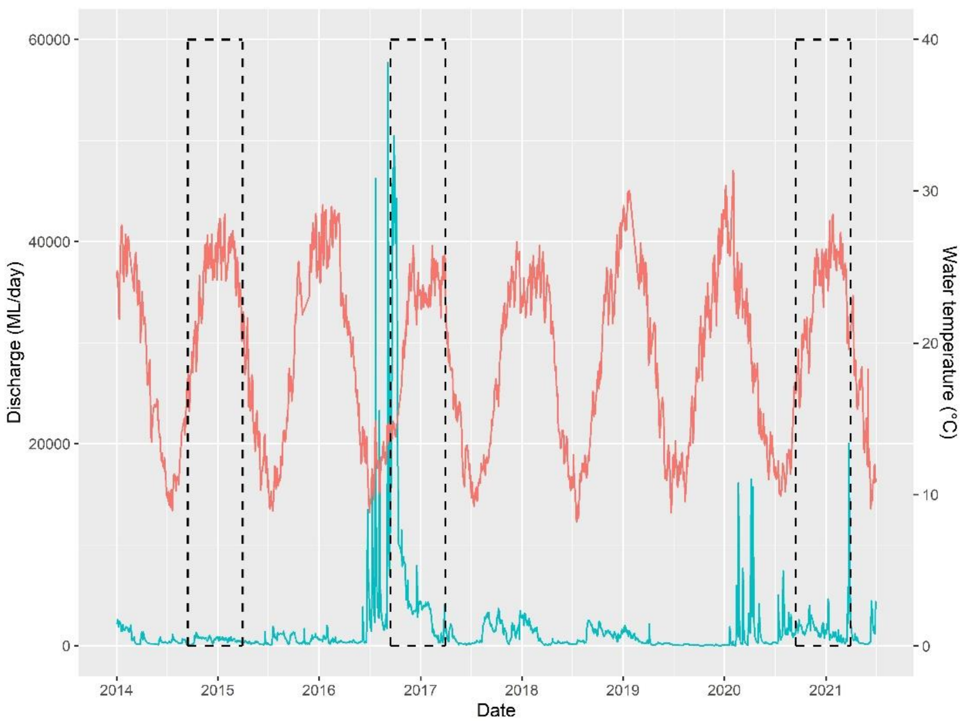


Figure 9. River discharge at Gin Gin gauging station (blue line) and water temperature at Baroona gauging station (red line) within the mid Macquarie River from January 2014 to June 2021. Dashed boxes indicate Murray cod breeding season when recruitment monitoring was conducted.

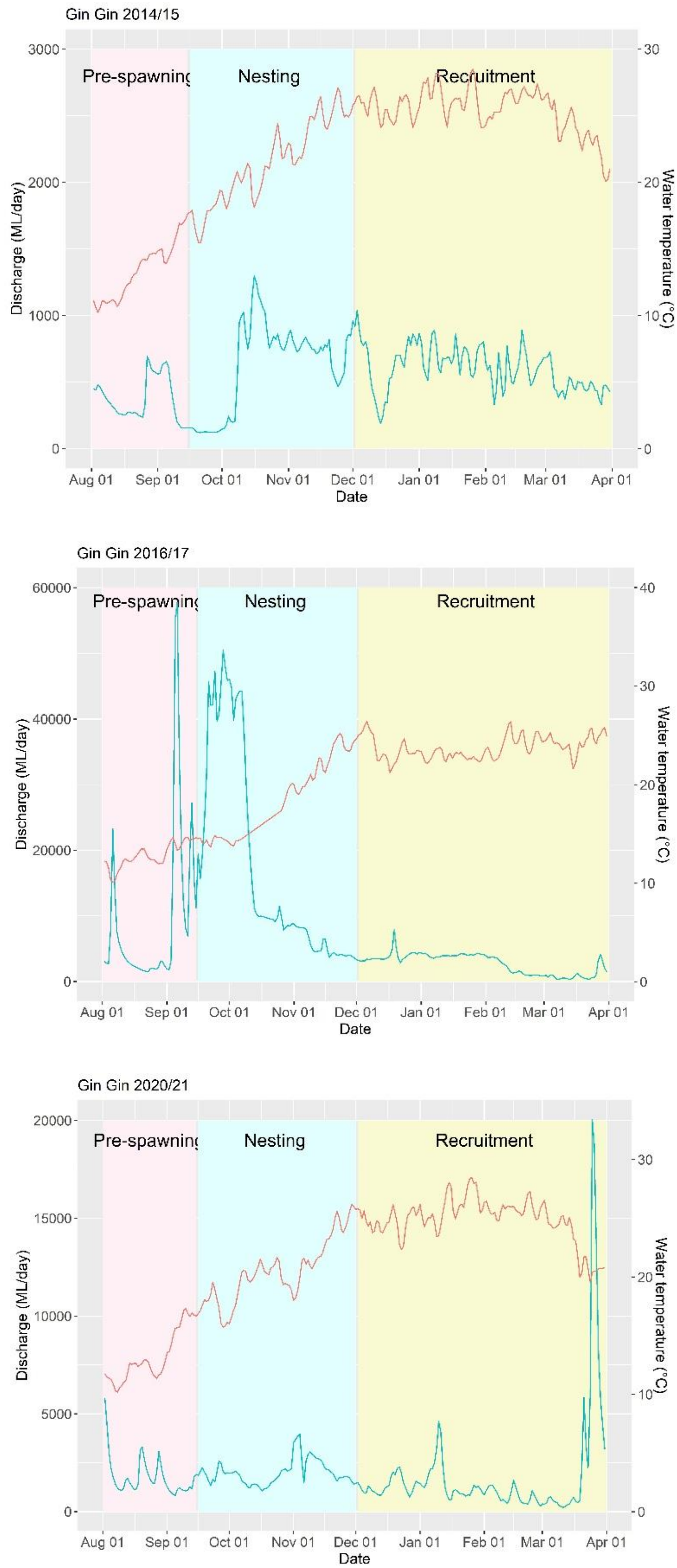


Figure 10. Hydrological conditions experienced throughout the three stages of Murray cod spawning and recruitment for years where juvenile recruitment data is available. Note the y-axis is of variable scale between years.

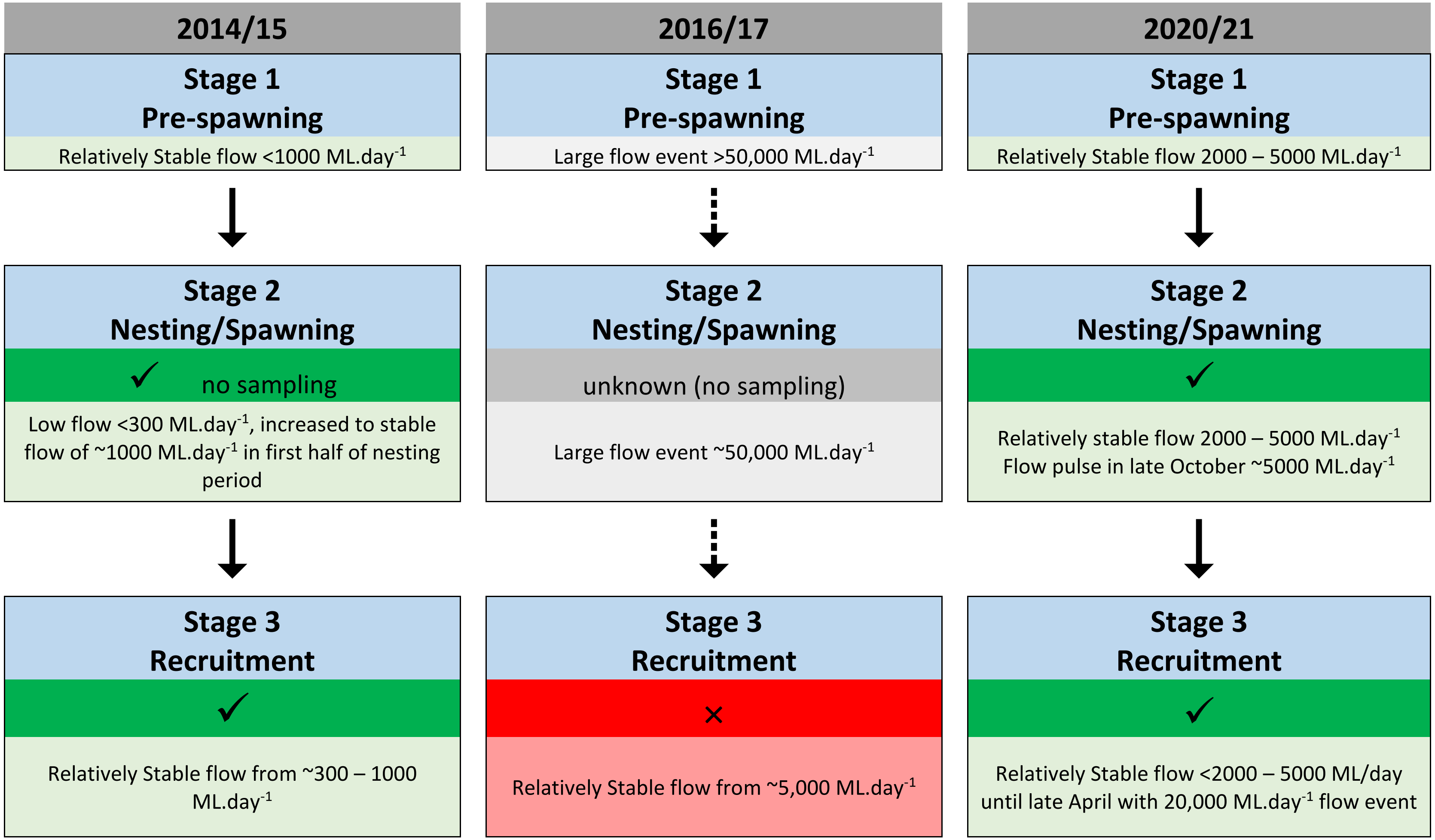


Figure 11. Stages of Murray cod recruitment and hydrological conditions of the mid-Macquarie River during each stage of development for the 2014/15, 2016/17 and 2020/21 Murray cod breeding seasons. Colours and tick/crosses indicate if fish monitoring detected successful spawning and/or recruitment during each breeding season. Solid arrows indicate the successful transition of young-of-year Murray cod between each stage of development; broken arrows indicate unknown or unsuccessful transition of young-of-year Murray cod between each stage of development.

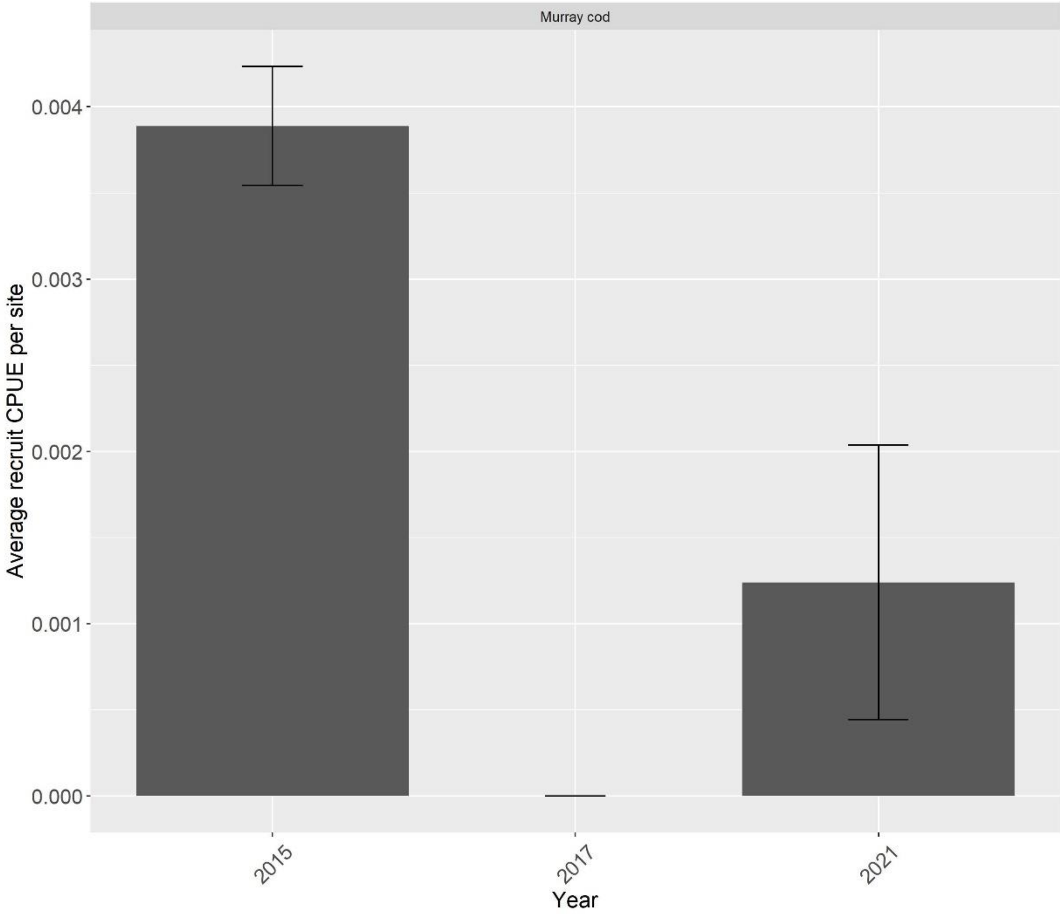


Figure 12. Mean catch per unit effort of young-of-year Murray cod (<120mm TL) captured in March recruitment sampling during 2015, 2017 and 2021 within the Macquarie River between Narromine and Warren.

Fish Community

During the January 2021 fish community sampling, Murray cod were the most abundant species captured, followed by carp gudgeon species complex and common carp (Figure 13). No Murray cod greater than the legal slot limit were captured during the January 2021 sampling and only two of the 82 Murray cod captured were within the legal slot limit of 550 – 750mm (Figure 13). A small number of Murray cod greater than the legal slot limit were captured in 2015 and 2017 (Figure 14).

The mean abundance of each species captured per site was compared against previous years sampling conducted in January within the mid-Macquarie River (Stocks et al., 2015, Stocks et al., 2021), (Figure 15). A significant interaction was observed between sampling year and species ($F_{42,240}$=2.94; P<0.001). Pairwise comparisons within a species indicated significant reductions in the abundance of Australian smelt and freshwater prawn between 2015 and 2021 (P<0.05). All other comparisons within a species between years were non-significant (P>0.05).

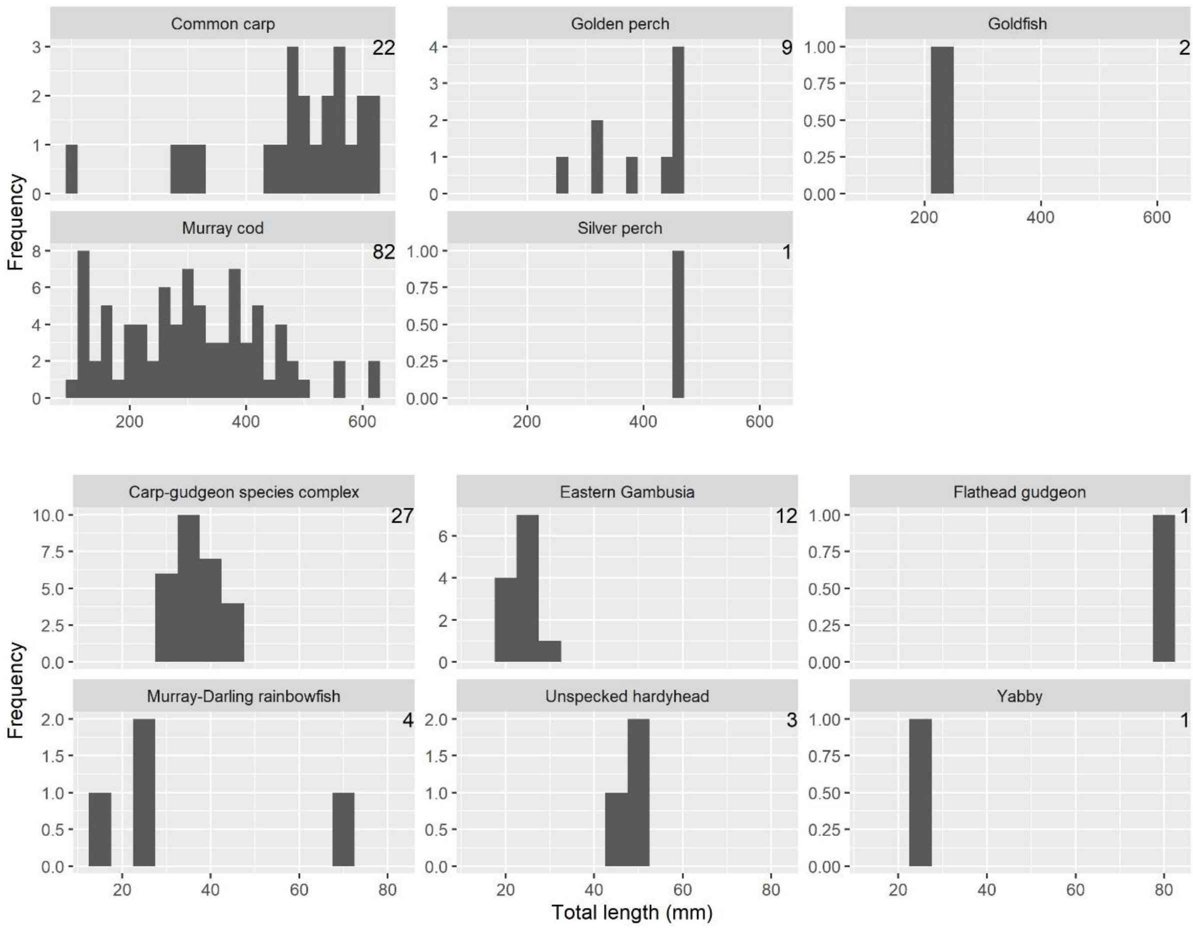


Figure 13. Length frequency distributions and abundances of fish captured during January 2021 standardised fish community sampling at five sites within the mid-Macquarie River.

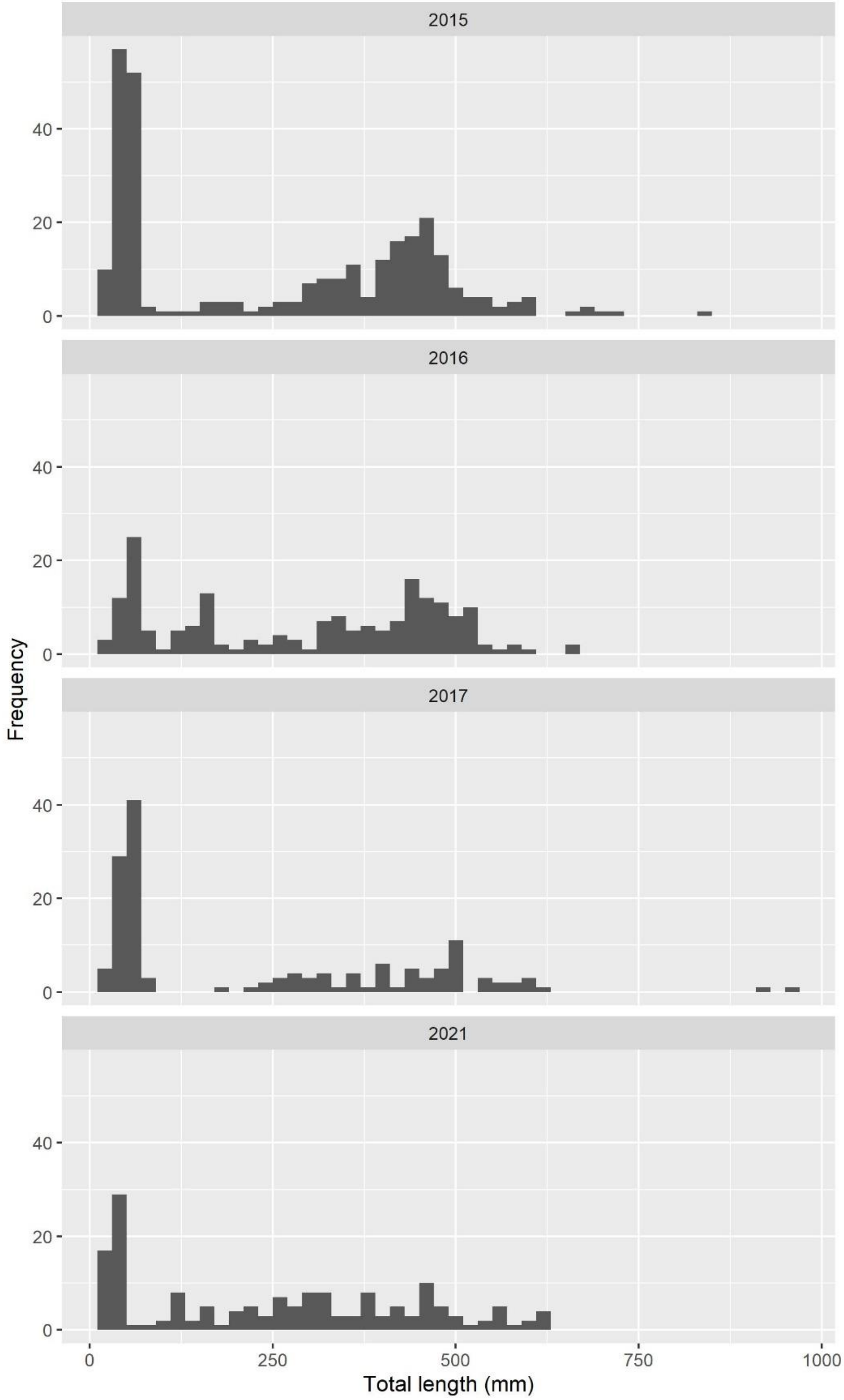


Figure 14. Length frequency distribution of Murray cod by sampling year from the mid-Macquarie River between Narromine and Warren. Sampling was conducted in Summer each year.

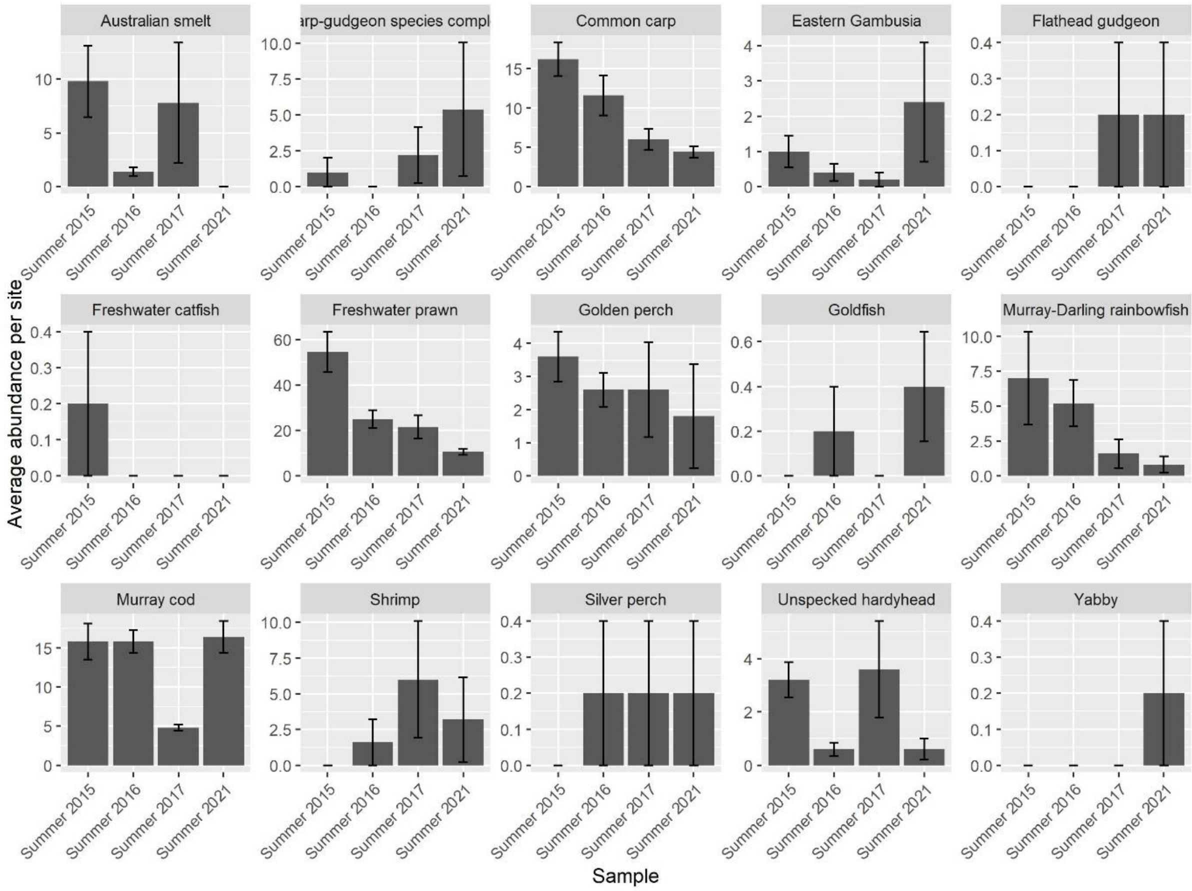


Figure 15. Mean abundance per site of all species captured during standardised sampling between 2015 and 2021.

Discussion

Successful spawning and juvenile recruitment of Murray cod was observed during the 2020/21 watering year within the mid-Macquarie River. This can likely be attributed to spring environmental water deliveries specifically targeted to promote Murray cod spawning and recruitment. Murray cod larvae accounted for 88% of the total larval catch from October 2020 into early November 2020. Sampling conducted in early 2021 indicated that these larvae successfully recruited to the juvenile life-stage; suggesting that flow conditions post the spawning period were conducive to support recruitment. Flow characteristics for each stage of the Murray cod recruitment process were examined in relation to recruitment strength for the three years of available data. Stable flows during the nesting and spawning period appear to be the predominant drivers of Murray cod recruitment strength based on the limited data set.

Recruitment strength

Annual recruitment strength of Murray cod for 2020/21 was compared to the 2014/15 and 2016/17 watering years. Murray cod recruitment was greatest during the 2014/15 watering year when CEWO and NSW environmental watering targeted Murray cod recruitment. Although water was limited and drought conditions were experienced during the 2014/15 watering year, Murray cod recruitment strength was the highest. Low recruitment strength was not unexpected for the 2016/17 watering year due to a large flow event (>50,000 ML.day^{-1}) during the spawning period that likely disrupted nesting. The higher recruitment strength in 2014/15, compared to 2020/21, may be attributed to: 1) the higher abundances of sexually mature fish present within the population during 2014/15 compared to 2020/21, increasing the populations' reproductive potential; 2) Reduced electrofishing efficiency due to increased water turbidity during the 2021 recruitment sampling; 3) a true response in recruitment strength to the varied hydrological conditions experienced between the sampling years.

Life-history history and conceptual flow models

A recent publication by Stocks et al. (2021) conducted in the mid-Macquarie River used back-calculated hatch dates of YOY juvenile Murray cod to examine the abiotic driver of spawning and successful recruitment. The study found Murray cod had periodic recruitment during the spring and summer months. Larval hatch dates coincided with low to moderate stable discharges (<1500 ML.d^{-1}) during a relatively narrow thermal window as water temperatures were increasing. A peak in hatch dates occurred at approximately 19˚C water temperature and hatch date frequencies were highest when there were no flood days (>20th percentile flow duration) in the preceding 2 weeks before hatching. These results were based on a limited dataset of 3 years; long-term monitoring that incorporates a range of hydrological regimes is needed to further understand the conditions that will optimise Murray cod recruitment within the mid-Macquarie River.

A study by Butler et al. (unpublished) detailed the timing and nesting behaviour of Murray cod in the northern Murray-Darling Basin. Male Murray cod select a nesting site in pools with little or no flow at <1m depth and vigorously clean the site of debris. After cleaning, spawning generally occurred within 2 – 4 weeks. Following spawning, eggs hatch after 5 – 13 days and nests are tended by the male for a period of 2 – 3 weeks until the larvae disperse. As such, to ensure nesting success, stable moderate flows need to be maintained from the time of nest selection through to larval dispersal. Given the anecdotal evidence of shallow nest site selection (<1m) small fluctuations in river height may result in nest abandonment or desiccation. Stuart et al. (2019) recommended a maximum total reduction in water level of <0.3m during the nesting period. It is also thought that hydrological stressor such as increased water velocity over the nest may be detrimental to egg and larvae retention (G. Butler pers. Comm. 27/7/2021).

Studies by Tonkin et al. (2020) and Stuart et al. (2019) examined the link between flow attributes and Murray cod recruitment, each providing a conceptual hydrograph specifically designed to promote Murray cod recruitment (Figure 16). Each study emphasised the importance of accounting for flows that influence each of the key life stages during the recruitment process. Key components of the hydrograph provided in Tonkin et al. (2020) included spring bank-full flows and flooding to enhance productivity and availability of spawning habitat, primarily through movement opportunities; and minimal flow variability during the core spawning period that disturbs nesting and egg and larvae retention. Associations between recruitment strength and summer discharge differed between systems. Tonkin et al. (2020) found a negative association between recruitment strength and river discharge in four of the five river systems examined. However, the idiosyncratic links between summer flow and recruitment strength among rivers highlights the need for waterway specific studies (Tonkin et al., 2009). The conceptual hydrograph by Stuart et al. (2019) was designed to restore Murray cod populations in Gunbower Creek, an anabranch of the mid-Murray River in north-central Victoria that was previously managed wholly for irrigation efficiency. Key components of the conceptual hydrograph provided by Stuart et al. (2019) included: 1) an annual spring spawning flow with no rapid water level drops; 2) an annual base winter connection flow to maintain lotic ecology and food webs for YOY and juveniles, and; 3) maintenance of flowing habitats that are longitudinally continuous and hydrodynamically complex.

Although there are differences between the two conceptual hydrographs presented by Stuart et al. (2019) and Tonkin et al. (2020), each highlight the importance of minimal flow variability during the core breeding season. Tonkin et al. (2020) recommended spring bank-full flows or flooding to enhance primary productivity and provide movement opportunities to find suitable nesting sites. After the recession of this pre-nesting flow, minimal flow variability was recommended during the core spawning season to prevent nest disturbance (Figure 16a). Conversely, Stuart et al. (2019) recommend an in channel rise to bank-full or near-bank full prior to nesting and the maintenance of the bank-full flow until the end of the spawning season (Figure 16b). The maintenance of this flow provides additional nesting habitat through inundation and prevents nest abandonment as a result of water level reduction. This breeding season flow is then followed by a slow recession of flows through autumn to a permanent winter base flow (Figure 16b). Each of these seasonal flow attributes that promote Murray cod recruitment align with the natural flow regime that has been severely modified by river regulation (Poff et al., 1997, Tonkin et al., 2020). Specifically, river regulation has reduced the magnitude and frequency of winter and spring flows and flooding and increased flows in summer and autumn. Therefore, the role of water for the environment in facilitating native fish recruitment is pertinent to the recovery of native fish stocks.

Designing Murray cod flows for the Mid-Macquarie River

There is a need to consider an adjustment to the timing of conceptual model flows based upon latitudinal variation in the timing of the Murray cod spawning season. Within the Ovens River and Murray River of the southern Murray-Darling Basin, Koehn and Harrington (2006) caught larval Murray cod between 9 November and 18 January; larvae in the current study were captured at least 1 month prior to this date. Spawning has been shown to commence earlier in the northern Murray-Darling Basin (Butler et al. unpublished). Within the mid-Macquarie River Murray cod larvae of each age class, from 1 to 16+ days old, were captured during each of the 5 weeks of sampling between October 12th and November 12th, 2020. Abundances of larval Murray cod were greatest during the first week of sampling (October 12th – 14th 2020). This indicates that the Murray cod breeding season began prior to October 12th and likely continued beyond November 12th. It is unknown if drifting larvae abundances were higher preceding this date. Larval monitoring was continued through a collaborative project within the mid-Macquarie River at a subset of the sample sites until March 2021. Murray cod larvae continued to be captured in larval drift nets until December 1st, 2020 (Bretzel, J. pers. Comm. 10/4/21). Future larval monitoring within the mid-Macquarie River should commence in early September to identify the timing that spawning commences within the mid-latitudes of the Murray-Darling Basin.

Future hydrographs designed to promote Murray cod recruitment within the mid-Macquarie should include a bank-full flow pulse in August/early September to facilitate pre-spawning Murray cod movement and to increase lower trophic level productivity, an important food resource for juvenile Murray cod (Tonkin et al., 2020). Stuart et al. (2019) recommend this bank-full flow be maintained throughout the entirety of the nesting period (Figure 16b). The conceptual model adopted for the mid-Macquarie will therefore depend on water availability and impacts to water users. Recruitment strength should be monitored under each flow scenario to determine which conceptual model best applies to the mid-Macquarie River.

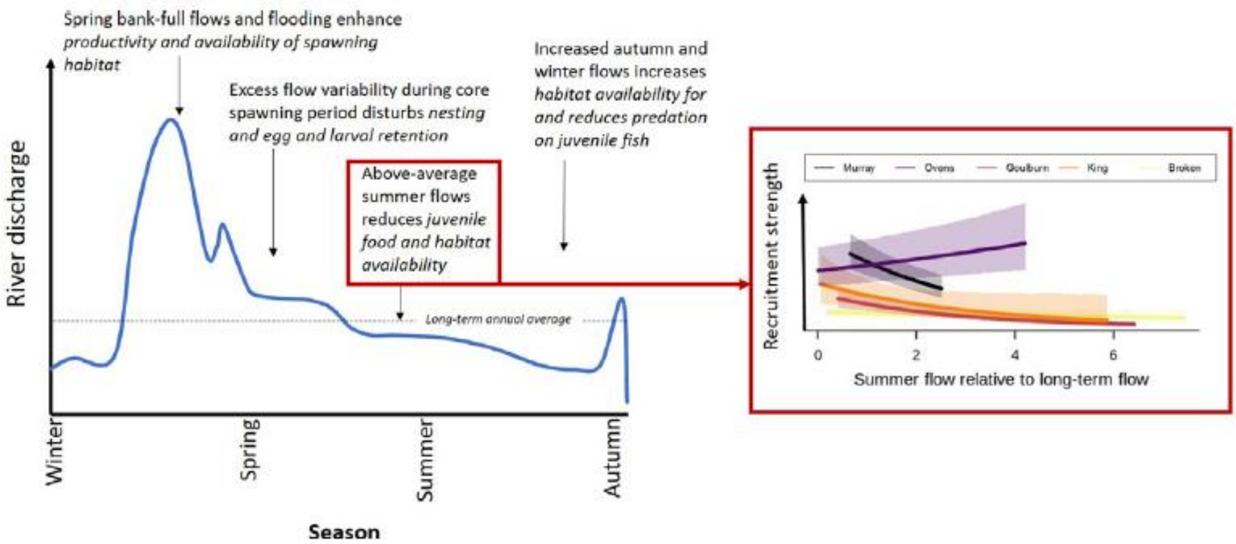
Under the Tonkin et al. (2020) conceptual model the pre-spawning bank-full flow pulse should be followed by a stable moderate flow during the nesting period. A flow of 1000 $ML.day^{-1}$ at Gin Gin Gauging Station from mid-September to late November/early December is recommended to cover the majority of the Murray cod nesting period. The suggested flow of 1000 $ML.day^{-1}$ is based on the flows experienced in the 2014/15 breeding season that resulted in the highest recruitment. However, this protracted period of stable moderate flows may compromise other environmental watering outcomes, so consideration of water priorities will be required. Similarly, Koehn and Harrington (2006) recorded drifting larval Murray cod over a protracted period of 70 days within the southern Murray-Darling Basin. At a minimum, the critical period to maintain a stable moderate flow is during the peak in Murray cod nesting. Within the mid-Macquarie River, the majority of larvae were caught during the first week of sampling (October 12 – 15th 2020) and were estimated to be <16 days old, resulting in back-calculated hatch dates of the last week of September/first week of October. Based on this data the peak of this critical period is believed to occur between mid-September to late October in the mid-Macquarie River. During this period water level stability should be maintained, water level reduction should not exceed 0.3m (Stuart et al., 2019) and increases in water level should be minimised.

Within the mid-Macquarie River during the 2020 watering year a flow pulse was delivered in late October/early November following the peak in Murray cod spawning. Although this flow was not specifically targeted for Murray cod recruitment and not a flow component of the conceptual hydrographs presented by Stuart et al. (2019) and Tonkin et al. (2020), it was thought this flow would increase larval dispersal over the 5 – 7 day larval drift phase (Koehn and Harrington, 2006); helping deliver larvae to the 2019/20 drought and fish kill impacted reach downstream of Warren.

Recommendations and future research

- Future hydrographs designed to promote Murray cod recruitment in the Macquarie should include a flow pulse (large fresh or preferably bank-full) in August/early September to facilitate pre-spawning Murray cod movement and to increase lower trophic level productivity. Ideally, this should be followed by a stable moderate flow of approximately 1000 $ML.day^{-1}$ at Gin Gin gauging station from mid-September to late November/early December to cover the majority of the Murray cod nesting period. Stable moderate flows should be maintained from the time of nest selection through to larval dispersal. During this period water level reduction should not exceed 0.3m (Stuart et al., 2019) and increases in water level should be minimised. In the Macquarie River the peak of this period is between mid-September to late October. A post spawning flow pulse is not a required component of the conceptual Murray cod hydrograph.
- Monitoring of Murray cod spawning and recruitment should be continued over multiple breeding seasons and across a range of hydrological regimes. This will provide important data that can be used to compare recruitment strength and refine the hydrograph to most efficiently use environmental water to promote Murray cod spawning and recruitment.
- Future larval monitoring should commence in early September to more accurately identify the timing that Murray cod spawning commences within the mid-Macquarie River.
- The use of acoustic telemetry is recommended to examine the movement patterns and nesting behaviour of native fish species in response to hydrological conditions within the Macquarie River.
- Mesocosm trials are recommended to provide further information on the impact of hydrological stressors (water level fluctuations and change in water velocity) on nest abandonment and recruitment failure of Murray cod.
- Further research is required to examine the role of environmental flows in the dispersal of early life stage bivalves, post glochidia stage.

a)



b)

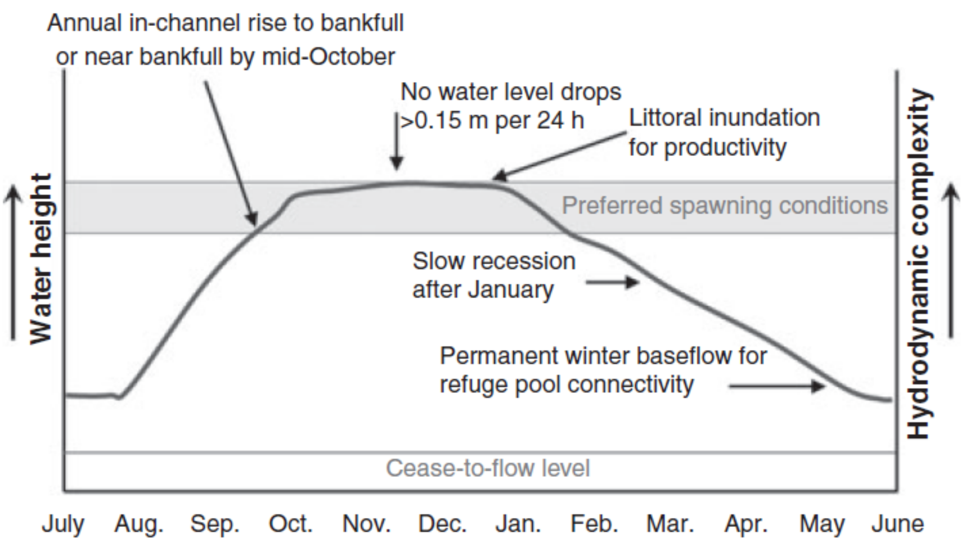


Figure 16. Conceptual hydrograph designed to support Murray cod recruitment from. a) Tonkin et al. (2020), and; b) Stuart et al. (2019). Note: The timing of conceptual flows should account for latitudinal variation in the Murray cod breeding season.

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Appendix 1. Plates

Plate 1. Larval Murray cod collected from larval drift nets within the mid-Macquarie River from October-November 2020.

Plate 2. Species collected from larval drift nets within the mid-Macquarie River from October-November 2020. From top to bottom: Yabby, Murray cod, freshwater catfish and common carp.

Plate 3. Yabby (top) and bivalve sp. (bottom) collected from larval drift nets within the mid-Macquarie River from October-November 2020.

Plate 4. Example of a light trap containing glow stick used for the collection of larval fish.

Plate 5. Fisheries technician retrieving a larval drift net.

Plate 6. Gin Gin Bridge Reserve sampling site.

Plate 7. Juvenile Murray cod and golden perch captured from the Macquarie River near Gin Gin during recruitment monitoring in March 2021.

Plate 8. Juvenile Murray cod and a golden perch captured from the Macquarie River near Gin Gin during recruitment monitoring in March 2021.

Plate 9. Spangled perch captured from the Macquarie River near Gin Gin during monitoring in March 2021.