Appendix E: Fish Movement

1   Introduction

For many freshwater fish species, increases in river discharge are a strong behavioral cue that drive movement (Koster *et al.* 2018, Marshall *et al.* 2016). The majority of movements by fish are simply individuals relocating short distances to optimise their chances of growing and surviving (Schlosser 1998). However, fish also move or migrate across broader scales for a range of reasons that include: relocating between the habitats they require at different life-history stages (Schlosser 1998); to access refugia during extreme climatic events (Schaefer *et al.* 2003); to ensure gene flow within and between species' populations (Heggenes *et al.* 2006); and to colonize or recolonize unoccupied areas (Anderson and Quinn 2007). Variation in the magnitude of river discharge and the variable hydraulic conditions created, are key determinants in the nature, timing and extent of fish movement for both local range movements (Carpenter-Bundhoo *et al.* 2020b, Cocherell *et al.* 2011, Korman and Campana 2009) and long range movements (Koehn 2004, Reinfelds *et al.* 2013, Simpson and Mapleston 2002, Young *et al.* 2010).

Flow alteration as a result of human interventions is possibly the greatest threat to the persistence of riverine ecosystems (Bunn and Arthington 2002). However, whilst detrimental, the infrastructure used to entrain and divert water is essential to sustain urban, industrial and agricultural activities (Poff *et al.* 1997). As such, an impartial and efficient approach to management of water is required to ensure the ongoing health of rivers. Water releases for the environment are often used in regulated rivers, with the intention of benefitting native flora and fauna. However, the outcomes for biodiversity and the mechanisms that underpin changes due to these manipulations are poorly understood (Konrad *et al.* 2011, Murchie *et al.* 2008). Whilst the effectiveness of environmental flows in enhancing breeding and recruitment of fish has been demonstrated (King *et al.* 2010, Zampatti and Leigh 2013), most assessments have been carried out independently of any measurement of fish activity and their movement and relocation.

Bio-telemetry is used extensively by fisheries scientists across the globe to answer a range of questions, including many related to fish movement and their response to changes in river discharge. There are currently a number of acoustic bio-telemetry programs underway throughout the Murray-Darling Basin (MDB), answering among other questions, those relating to environmental flows and fish movement. Unlike these programs, the Gwydir River Selected Area (Gwydir Selected Area, Selected Area) LTIM/MER project utilised bio-telemetry to answer a range questions specific to the Gwydir system and more broadly, to the northern MDB. Here we report the findings of long-term broad-scale movements of Murray cod (*Maccullochella peelii*) and freshwater catfish (*Tandanus tandanus*) 2016-2020 across the Selected Area. We evaluated how fish movement varied between two broad-scale arrays deployed in two different rivers in response to changes in environmental conditions and how this varied between species. Specifically, we aimed to answer several questions posed in relation to the Fish Movement indicator:

- What did Commonwealth environmental water contribute to native fish dispersal?
- Did environmental water stimulate target species to exhibit movement consistent with breeding behaviour?
- Did environmental water facilitate target species to move/return to refuge habitat?
- What did Commonwealth environmental water contribute to native fish populations?

2 Methods

2.1 Study sites

The Gwydir and Mehi are semi-intermittent rivers located in the northern MDB, New South Wales (Figure 1). In the study area the Gwydir River channel typically does not exceed 25 m in width and 3 m in depth, whilst the Mehi River is considerably smaller, with most pools not exceeding 10 m width and 1-2 m in depth. Both rivers are highly regulated, with several instream structures ranging from 3 to 15 m in height. The rivers of the lower Gwydir are heavily exploited for irrigated-agriculture, with water also extracted for stock and domestic purposes throughout much of the catchment (Commonwealth of Australia 2017). The Gwydir system receives environmental releases from Copeton Dam (Figure 1, Figure 2) in most years, managed by the NSW Department Planning, Industry and Environment - Environment, Energy and Science, Office of Environment and Heritage (DPIE-EES) and the Commonwealth Environmental Water Office (CEWO).
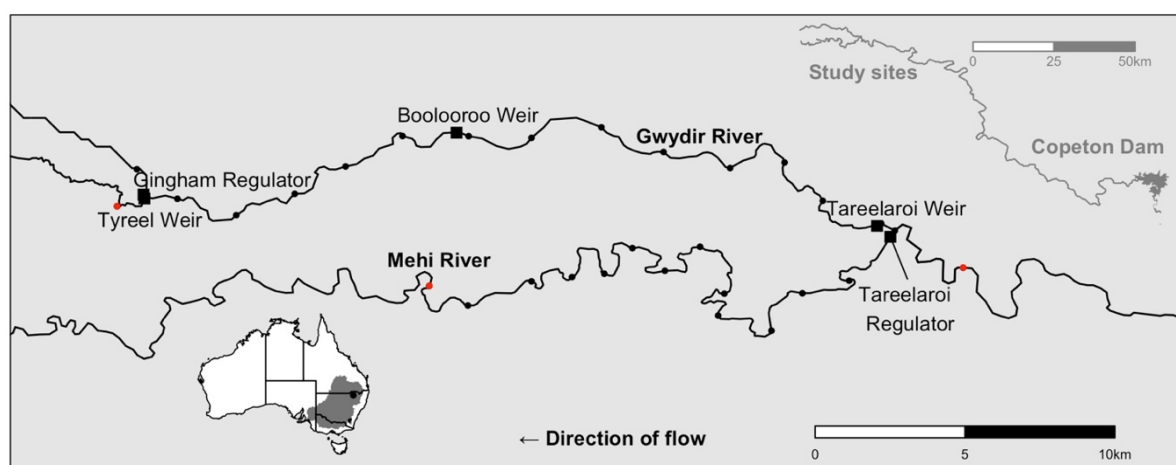

Figure 1 Acoustic telemetry array within the Gwydir and Mehi rivers. Receiver locations shown as black points, with terminal receivers highlighted as red points. The locations of weirs are also indicated. Upper right inset shows position of Copeton Dam in relation to the study area.
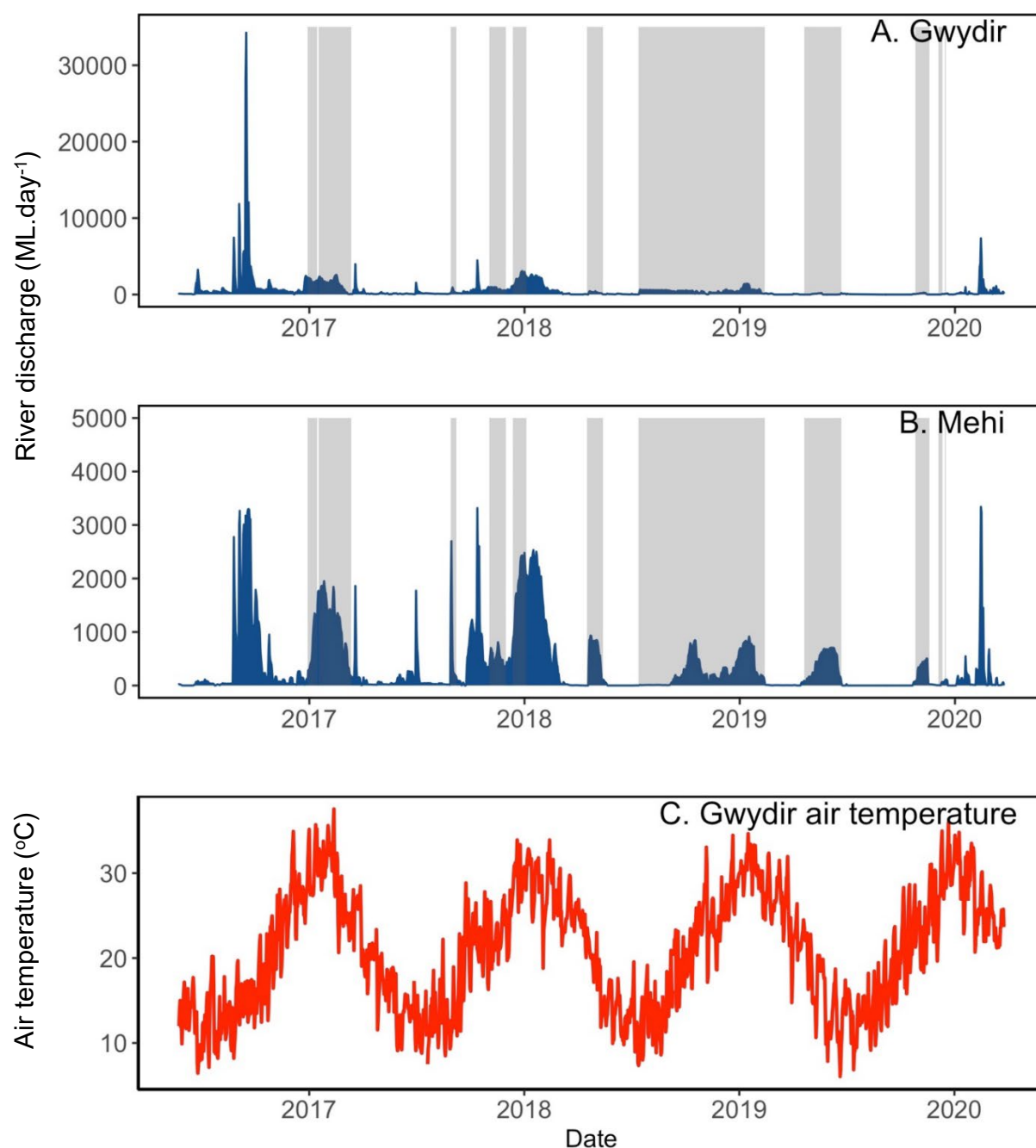
Figure 2 River discharge (A, B) and air temperatures (C) within the Gwydir and Mehi rivers from 25/5/16 to 25/3/20. Shaded areas in A and B indicate the timing of environmental flow delivery from Copeton Dam.

2.2 Fish collection and tagging

For a detailed description of fish collection, transportation, tagging and release, refer to Commonwealth of Australia 2016. Total riverine fish tagged comprised 20 Murray cod in each river, three freshwater catfish in the Gwydir River and one freshwater catfish in the Mehi River. The low number of riverine freshwater catfish tagged reflects the scarcity of these fish within the two rivers. All riverine fish were caught, tagged and released at their respective capture location in each river. A further 56 freshwater

catfish were collected from Copeton Dam and translocated to the study rivers and tagged and released (Table 1, Figure 3).

Table 1 Source and numbers of catfish and Murray cod tagged and released in the Gwydir and Mehi rivers in May 2016 and November/December 2018.

	2016		2018	
	Gwydir	Mehi	Gwydir	Mehi
Murray cod	10	10	10	10
Freshwater catfish (Riverine)	3	1	0	0
Freshwater catfish (Lacustrine)	17	19	10	10

Figure 3 Anaesthetised freshwater catfish (Tandanus tandanus) in operation cradle during acoustic tag implantation adjacent to the Mehi River, December 2018.

2.3 Acoustic array

Fish movements were recorded using a linear acoustic telemetry array located within the Gwydir and Mehi rivers (Figure 1). The Gwydir array consisted of 17 Vemco VR2W 69 KHz receivers deployed over a 39 km reach, whilst the Mehi array consisted

of 13 receivers deployed over a 39 km reach below Tareelaroi Regulator. Receivers were deployed at intervals of approximately 3 km along each river. The array recorded a binary presence/absence for each tagged fish within the reception range (approximately 300 m) of a given receiver. A temperature logger (OneTemp, Sydney) was deployed at the most upstream and downstream receivers of each array. Data from each receiver was downloaded approximately every three to six months (25 May 2016 – 25 March 2020).

2.4   Data analysis

Data from all downloads were initially combined into one database, checked for correctness and the clean data extracted for analyses. Detections occurring within the first 24 hours for each fish were removed to discount any abnormal behaviour due to the tagging process (Carpenter-Bundhoo *et al.* 2020b). An iterative process was then used to establish the distance moved by each tagged fish. Initially the linear extent of each river reach was digitized into a spatial object using satellite imagery in ArcGIS 10.4 (ESRI, Redlands, CA, USA). The distance of each given receiver from the downstream-most receiver in its respective river array was then calculated. This was converted into a distance matrix in the V-Track package (Campbell *et al.* 2012) in R (R Development Core Team; www.r-project.org). A new database of fish movements was then created by pairing individual fish detections with the distance matrix. River distance between subsequent detections was then calculated for each individual fish. Total daily movement was calculated for each fish by summing individual movement distance values. These data were then matched with daily total river discharge, known breeding period, environmental flow period, average daily river temperature, moon phase data (calculated using *lunar* package in R (Lazaridis 2014) as well as fish sex and size (total length and weight).

After initially inspecting the data from the temperature loggers and the NSW Water gauge #418004 (Yarraman Bridge), it became apparent that it was not possible to produce a continuous recording of water temperature due to the dry periods experienced during the study. However, air temperature records downloaded from the Bureau of Meteorology (BOM) closely matched the water temperature records and were considered to be correct, these data were subsequently used in the analysis. Breeding period was assigned as a binary variable, falling within or outside of the fishes' respective breeding schedule. Freshwater catfish breeding period was assigned as beginning when average daily water temperatures reached 24°C and ending 70 days later (as described by Carpenter-Bundhoo *et al.* 2020b, Davis 1977). The breeding period for Murray cod was designated as beginning when temperatures reached 15°C and completed after 70 days (Humphries 2005, Koehn and Harrington 2006).

Broad-scale fish movement responses to the environmental variations were examined using hurdle linear mixed models in the *lme4* package (Bates *et al.* 2015). A generalized logistic regression (GLMM) was used to firstly predict movement/non-movement (a binary response) and then a standard linear mixed model (LMM) to predict movement distance (i.e. for the non-zero responses). River discharge, antecedent flow (sum of

previous 30 days), breeding period, environmental flow period, air temperature, moon phase and fish length were included as independent variables.

Fish identity (ID) and year were included as random intercepts in the models. All possible models and interactions were checked, and the best model was selected with backwards stepwise model selection, using the LMERConvenienceFuntions package (Tremblay and Ransijn 2013) for the binary component, and the LMERTest package (Kuznetsova *et al.* 2017) for the non-zero component. Following the protocol of Zuur *et al.* (2010), we checked for statistical outliers and collinearity among predictor variables was assessed using variance inflation factors (VIF) in R. Model residuals were checked for normality and model fit was assessed by comparing model residuals and fitted values.

3   Results

3.1   Fish detection and movement summary

Thirty-six Murray cod and 56 freshwater catfish were detected over the study period (Table 2). One undetected riverine freshwater catfish (ID 53543) was confirmed to be alive, inhabiting an area between the detection range of two receivers for the life of its tag (Carpenter-Bundhoo et al. 2020b). The remaining four Murray cod and three freshwater catfish were not detected on any receiver. Average (± SE) number of days detected for Murray cod was 120 ± 21 and for freshwater catfish 62 ± 13 (Table 2). One Murray cod tagged in 2016 (ID 53599) was detected until the culmination of the study in 2020 (586 days).

Examination of temporal variation in longitudinal movement behaviour revealed idiosyncratic patterns among individuals of both species in each river. It was evident that weirs posed significant barriers to upstream but not downstream movement of both species in both rivers (Figure 4). There were only eight instances of individual fish successfully passing Tarreelaroi Regulator in the Mehi River, and these upstream movements only occurred on relatively large flow events. Several fish of both species moved from the Mehi River into the Gwydir River, but not vice versa.

The total individual cumulative distance moved was lower on average for Murray cod than freshwater catfish, 33 ± 7 km versus 38 ± 7 km, respectively (Table 2). The largest cumulative distance moved was by a freshwater catfish, moving a combined distance of 290 km both upstream and downstream between the first and last time it was detected. The largest single day movement by a Murray cod was 20 km, whilst a freshwater catfish moved 31 km in one day. A number of Murray cod showed pronounced increases in activity in the August/September/October breeding period (Figure 4). Some of these individuals did not return to their previous ranges whilst others did (Figure 4).

Table 2 Summary statistics Murray cod and freshwater catfish movement and morphology, showing minimum, maximum and mean (± SE) values for length, weight, number of detections in array, number of days detected in array, number of movements and cumulative movement for the study period.

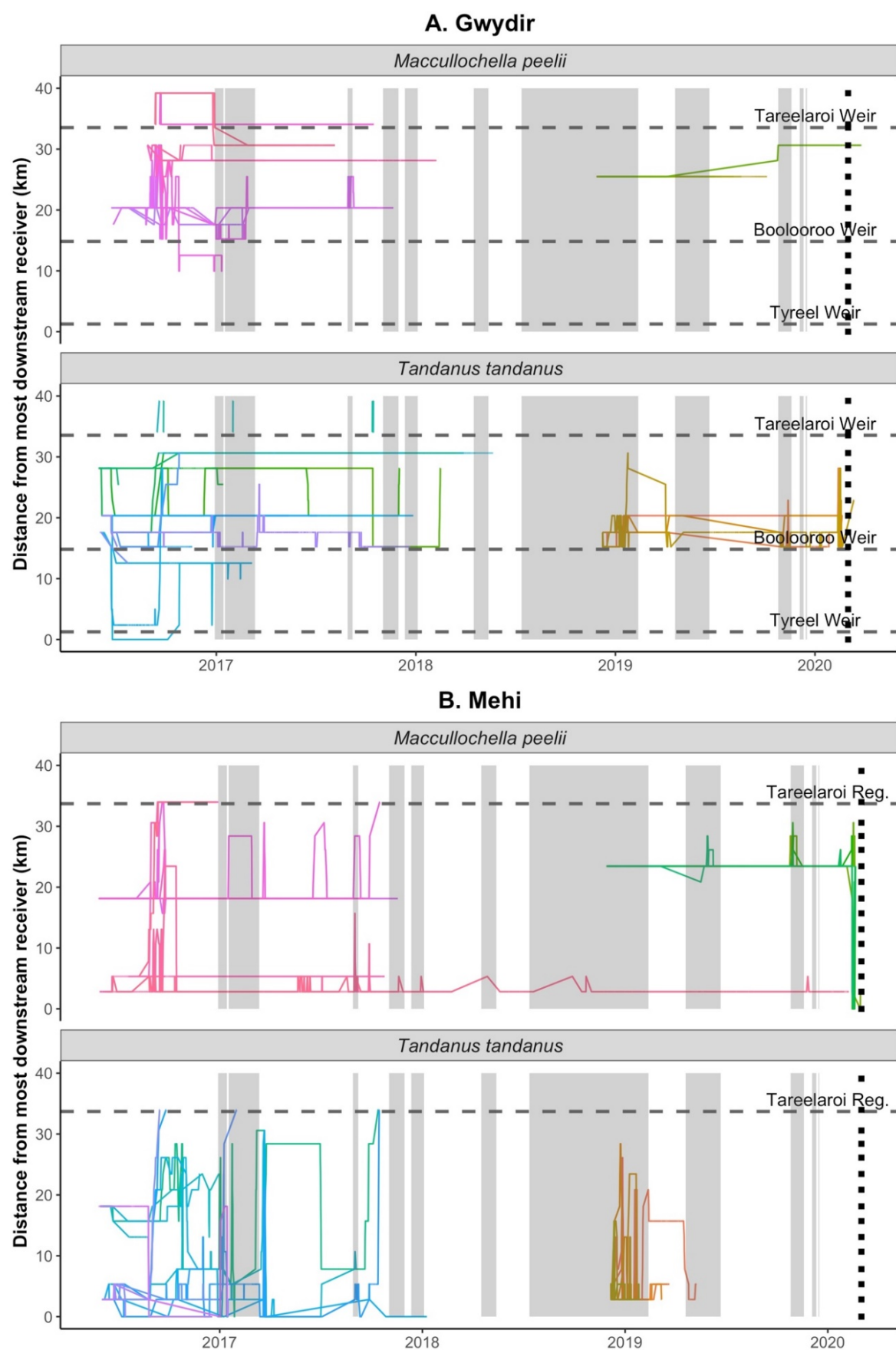|	Murray cod					
	Length (mm)	Weight (g)	No. of detections	Days detected in array	No. of movements	Cumulative distance moved
N	40	40	40	40	36	36
Min	380	601	0	0	0	0
Mean	568 ± 24	2,760 ± 435	31,070 ± 8,774	120 ± 21	8 ± 2	33 ± 7
Max	955	12,400	273,636	586	40	169
	Freshwater catfish					
N	60	60	60	60	56	56
Min	405	639	0	0	0	0
Mean	523 ± 6	1,633 ± 56	16,506 ± 5,984	62 ± 13	8 ± 1	38 ± 7
Max	590	2,545	310,261	552	46	288

Figure 4 Linear distance travelled and orientation over time for each species shown for the Gwydir (A) and Mehi (B) River arrays. Each colour represents a different fish. Black points denote receiver locations along

the array, dashed lines denote weir or regulator position and shading denotes periods of environmental water delivery.

3.2   Effects of environmental flow deliveries and other environmental variations of fish movement

Regression modelling revealed that the probability and distance of movement in both fish species was related to several environmental and biological characteristics (Table 3, Table 4). For Murray cod, important explanatory variables related to the magnitude of river discharge, environmental flow periods, river inhabited, temperature, fish sex and breeding period, as well various interactions between these variables. For freshwater catfish important explanatory variables related to river discharge, river inhabited, temperature, breeding period, as well as interactions between these variables. Environmental flow period and fish sex only had effects on freshwater catfish movement through interactions, i.e. only under certain conditions. For both species, more variables related to probability of movements than to the distance of movement.

Murray cod were most likely to move during an environmental flow event (estimate ± SE= 0.7 ± 0.24, p=0.004). Overall, Murray cod was also more likely to move (0.91 ± 0.15, p<0.001), and would move further (0.12 ± 0.02, p<0.001) on all higher river discharges. The likelihood of movement was higher in the Mehi River (0.62 ± 0.13, p<0.001, Figure 5), and lower during the breeding season (-0.85 ± 0.15, p<0.001, Figure 5). The model also suggested Murray cod were likely to move further on increased river discharge at warmer temperatures (0.07 ± 0.02, p=0.002).

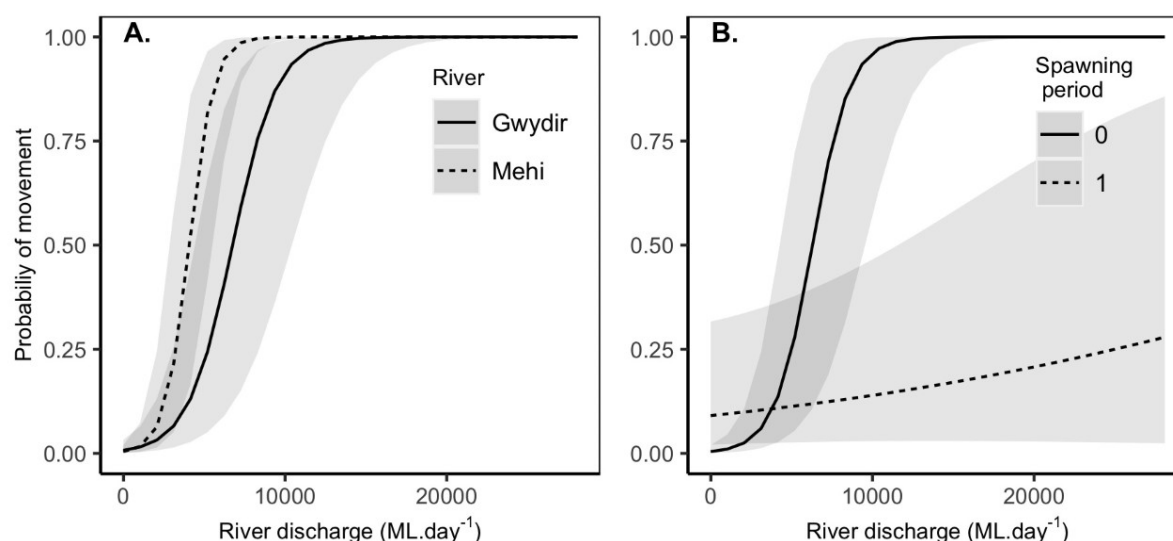*Figure 5 Predicted probability of Murray cod movement as a function of river discharge (+/− 95% CI) between (A) the Mehi and Gwydir Rivers and (B) during and outside of the breeding season. Probabilities were generated from the binomial model and all other covariates held at their mean values.*

Overall, Murray cod in the Mehi River moved further than those in the Gwydir River (0.16 ± 0.07, p=0.036). Murray cod were less likely to move (-0.67 ± 0.11, p<0.001) and moved shorter distances (-0.14 ± 0.05, p=0.008) during higher temperatures. Those in the Mehi moved further on higher temperature than those in the Gwydir River

(0.24 ± 0.06, p<0.001). Murray cod were more likely to move during the breeding period (2.68 ± 0.29, p<0.001), however, this was less likely for males (-1.92 ± 0.36, p<0.001) compared to females.

Table 3 Parameter estimates (± SE) and significance levels from hurdle regression models relating Murray cod movements (probability of movement and distance of movement) to environmental variables, breeding season and morphology. Also shown are attributes of the random effects from each G/LMM, including number of fish IDs/years in each model, among-fish ID/year standard deviation and number of observations.

Fixed effect	Binomial		Non-zero (*log*)	
	Est. ± SE Err.	p	Est. ± S.E.	p
Environmental flow	0.7 ± 0.24	0.004		
River discharge	0.91 ± 0.15	<0.001	0.12 ± 0.02	<0.001
Air temperature	-0.67 ± 0.11	<0.001	-0.14 ± 0.05	0.008
River (Mehi)			0.16 ± 0.07	0.036
Breeding	2.68 ± 0.29	<0.001		
Sex (M)	1.78 ± 0.71	0.012		
River discharge: River (Mehi)	0.62 ± 0.13	<0.001		
River discharge: Breeding	-0.85 ± 0.15	<0.001		
River discharge: Air temperature			0.07 ± 0.02	0.002
Air temperature: River (Mehi)			0.24 ± 0.06	<0.001
Breeding: Sex (M)	-1.92 ± 0.36	<0.001		
Random effect	ID	Year	ID	
Observations	4796	4796	279	
N (groups)	36	5	25	
Std. dev.	1.77	1.34	0.135	

While environmental flows did not have a pronounced effect on either the likelihood or distance of freshwater catfish movements, there was a lower likelihood of movement in relation to environmental flow releases if there had been higher antecedent flow (-1.91 ± 0.47, p<0.001, Figure 6). Freshwater catfish were more likely to move during higher river discharge (0.32 ± 0.08, p<0.001) and like Murray cod, this was more evident in the Mehi River (1.09 ± 0.23, p<0.001, Figure 6) compared to the Gwydir River. Freshwater catfish were also more likely to move further during the breeding period at elevated discharge levels (0.41 ± 0.1).
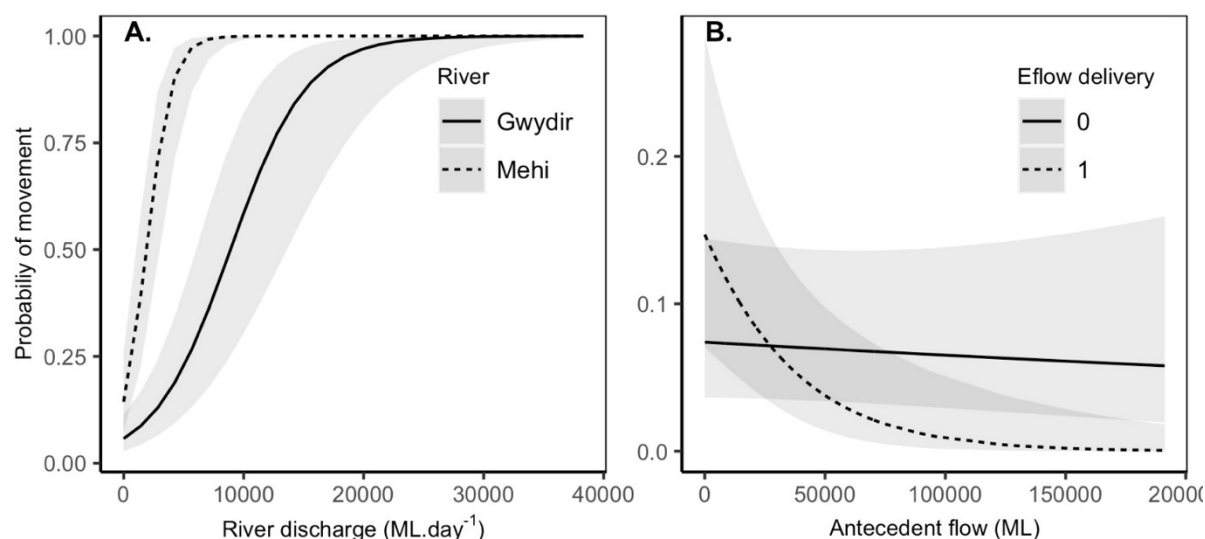
Figure 6 Predicted probability of freshwater catfish movement as a function of (A) river discharge (+/− 95% CI) between the Mehi and Gwydir Rivers and (B) antecedent flow (sum of previous 30 days) during and outside environmental flow deliveries. Probabilities were generated from the binomial model and all other covariates held at their mean values.

Overall, the likelihood of freshwater catfish moving increased as temperatures warmed (0.92 ± 0.17, p<0.001). However, this was less likely for males (-1.06 ± 0.2, p<0.001) compared to females. Freshwater catfish in the Mehi River were also more likely to move further during periods of warmer temperatures (0.24 ± 0.05, p<0.001). Overall, freshwater catfish in the Mehi River had a higher likelihood of movement (1.59 ± 0.54, p=0.003). Males were more likely than females to move during the breeding period in both rivers (0.89 ± 0.27, p=0.003).

Table 4 Parameter estimates (± SE) and significance levels from hurdle regression models relating freshwater catfish movements (probability of movement and distance of movement) to environmental variables, breeding season and morphology. Also shown are attributes of the random effects from each G/LMM, including number of fish IDs/years in each model, among-fish ID/year standard deviation and number of observations.

Fixed effect	Binomial		Non-zero (*log*)	
	Est. ± SE Err.	p	Est. ± SE	p
Environmental flow	0.01 ± 0.22	0.967		
River discharge	0.43 ± 0.07	<0.001	0.01 ± 0.01	0.927
Air temperature	0.88 ± 0.13	<0.001	-0.01 ± 0.04	0.716
Breeding			-0.06 ± 0.05	0.293
River (Mehi)	1.51 ± 0.49	0.002	0.09 ± 0.06	0.169
Environmental flow: Antecedent flow	-1.17 ± 0.39	0.003		
River discharge: River (Mehi)	0.89 ± 0.22	<0.001		
River discharge: Breeding			0.41 ± 0.1	<0.001
Air temperature: River (Mehi)			0.24 ± 0.05	<0.001
Air temperature: Sex (M)	-1.04 ± 0.17	<0.001		
Sex (F): Breeding	-0.28 ± 0.24	0.239		
Sex (M): Breeding	0.88 ± 0.26	0.001		
Random effect	ID	Year	ID	
Observations	3681	3681	454	
N (groups)	54	5	47	
Std. dev.	1.61	0.22	0.12	

4   Discussion

4.1 Murray cod (*Maccullochella peelii*)

The movement patterns of Murray cod in the current study were consistent with that reported previously but in some ways also locally distinct. Overall, Murray cod were found to be more likely to move during periods of increased flow, including during environmental flow deliveries. These results suggests that environmental flows, which are delivered based on the biological schedules of a range of taxa not just fish, are beneficial to Murray cod, both enabling as well as most likely stimulating movement and relocations to new home-sites. There was also a marked increase in probability of movement during the breeding season for Murray cod. Whilst individual Murray cod have previously been reported to make large movements during their breeding season

(Koehn *et al.* 2009, Thiem *et al.* 2018), in most cases the majority have been shown to have restricted home-ranges during this period (Koehn *et al.* 2009). Given Murray cod have been observed reproducing without moving from their pre-breeding home-site (G Butler *pers. comm.*), it seems likely that some individuals in intermittent rivers are opportunistically moving to breed, facilitated by increased connectivity which is directly linked to increases in discharge.

Whilst, Murray cod were more likely to move during the breeding period, there was a lesser relationship with river discharge during this period compared to other times of the year. Additionally, male Murray cod were found to be less likely to move than females during the breeding period. This is best explained by the nesting behaviour of the species, where males remain at or near nests for up to four weeks after the initial selection of sites (Rowland 1998). In contrast, females are more likely to have to move to find males that have established nesting sites outside of their normal home-range (G. Butler *pers. comm.*).

Murray cod were significantly more likely to move in the Mehi River in comparison to those in the Gwydir River. This likely relates to the difference in the relative size of the two rivers, with Murray cod in the smaller Mehi River needing to shift more often, than those is the larger Gwydir River, to access resources. The increased probability of movement during higher river discharges was also found to be more likely in the Mehi River compared to the Gwydir River. Given the differences in the relative size of the two rivers, an equal quantity of water delivered to both systems would result in proportionally higher water velocity, connectivity, and the inundation of benches (Brierley and Fryirs 2000) in the Mehi compared to the Gwydir. As such, future release of water for the environment in any system should not only consider the amounts and timing of releases but also the general morphology of the system receiving the water.

4.2   Freshwater catfish (*Tandanus tandanus*)

Whilst freshwater catfish were not found to significantly increase their activity during environmental flow deliveries, they were more likely to move during an environmental flow following a period of low antecedent flow. This behaviour suggests that environmental flows delivered proceeding low or no-flow conditions will not only provide an opportunity for freshwater catfish to undertake more exploratory behaviour as connectivity increases but may also stimulate movement. Overall, despite no apparent direct relationship to environmental releases specifically, river discharge was a main driver of freshwater catfish movement, including during the breeding period. For many riverine fish species, flow is considered a key behavioural cue in stimulating breeding-related movements (Amtstaetter *et al.* 2016, Reinfelds *et al.* 2013, Walsh *et al.* 2013). Although the recognised life-history of freshwater catfish does not include a breeding migration as such, relationships between increased activity and the breeding period were apparent in the current study. As freshwater catfish are known to be sedentary nesters (Carpenter-Bundhoo *et al.* 2020a, Davis 1977) and have even been known to reproduce in ponds (Lake 1967), these findings likely reflect that the increased distance moved when discharge increased during the breeding season, and the increased likelihood of males moving in particular, relates to non-migratory exploratory

movements associated with nest site selection. Freshwater catfish require access to areas of shallow, cobble beds to build nests (Davis 1977, Lake 1967, Merrick and Midgley 1981) and elevated river discharge increases inundation of and connectivity between such habitat patches in an intermittent river like those across the lower Gwydir valley. As such, whilst other environmental factors such as water temperature are thought to cue as well as ensure breeding success (Carpenter-Bundhoo *et al.* 2020a, Davis 1977), river discharge must also be considered a primary contributor as it facilitates movement to and also creates nesting areas.

As discussed previously, over the life of the study as a whole, male freshwater catfish were more likely to move than females during their breeding season. However, in previous years (2016-2018 data) it was reported that males appeared to move less than females during the breeding season (Commonwealth of Australia 2019). One likely explanation is that the translocation and restocking of adult freshwater catfish as part of the current study has led to increased intraspecific competition, meaning smaller or less aggressive individuals are having to move greater distances to find suitable nesting habitat. There was also an increased probability of movement by freshwater catfish during increased river discharges in the Mehi River compared to the Gwydir River. As with Murray cod in the current study, this likely relates to differences in the morphology of the two rivers, with the same flows down each system resulting in different hydraulics as well as differences in the levels of connectivity.

4.3   Conclusions

Given that the delivery of environmental water to the lower Gwydir system is often associated with other deliveries of consumptive water, our results can at best be used to comment on the overall timing and on the effect of the total combined river discharge during these periods, rather than specifically regarding environmental water alone. We suspect a number of factors contribute to the effectiveness of environmental flows across the channels of the lower Gwydir, however, based on our findings, river discharge, river morphology, and species life-history are the main factors to be considered when managing environmental flow releases.

One consideration for water managers is that environmental flow deliveries need to be tailored to specific species' needs, rather than attempting to take a whole of ecosystem approach when setting targets. However, this approach is not without its challenges given the multitude of objectives around environmental water releases, particularly in relation to the diversity of taxa that includes not only fish but waterbirds, vegetation, invertebrates and amphibians. Given this complexity and based on the findings of the current study, we suggest that not all species of fish need targeted flow releases to stimulate breeding events, but that these species generally only require a supplemented base-flow to provide better connectivity and bench inundation during what could be considered as critical periods rather than across the entire year. Additionally, whilst larger pulses will help maintain the genetic integrity of both species over the long-term by promoting larger-scale movements, they may be better used to align with the breeding schedules of flow cued species such as golden perch (*Macquaria*

ambigua) and silver perch (*Bidyanus bidyanus*). Ongoing flow releases and monitoring, coupled with hydrological modelling, will help to refine our understanding of the outcomes of different environmental water strategies for different species, resulting in more efficient deliveries in the future.

5   References

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