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Published in:
Journal of Environmental Management

DOI:
10.1016/j.jenvman.2021.113067

Published: 01/10/2021

Document Version
Peer reviewed version

Citation for published version (APA):
Espinoza, T., Burke, C. L., Carpenter-Bundhoo, L., Marshall, S. M., McDougall, A. J., Roberts, D. T., Campbell, H. A., & Kennard, M. J. (2021). Quantifying movement of multiple threatened species to inform adaptive management of environmental flows. *Journal of Environmental Management*, *295*, 1-12. Article 113067. https://doi.org/10.1016/j.jenvman.2021.113067

Quantifying movement of multiple threatened species to inform adaptive management of environmental flows.

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Abstract

There is a growing need for water managers to refine and optimise environmental flow strategies (e-flows) to balance water requirements for humans and nature. With increasing demands for freshwater and consequent declines in biodiversity, managers are faced with the problem of how to adaptively manage e-flows for multiple stakeholders and species whose flow requirements may overlap or vary. This study assessed the effectiveness of a regulated e-flow release strategy from a dam, aimed at providing movement opportunities and facilitating reproductive processes for multiple threatened species. Movements of 24 Mary River cod (*Maccullochella mariensis*), 20 Australian lungfish (*Neoceratodus forsteri*) and 13 Mary River turtle (*Elusor macrurus*) were quantified using acoustic telemetry over a three-year period. The influence of regulated e-flow releases, season, river depth, water temperature and rainfall on animal movements was assessed using Generalised linear mixed models (GLMMs). Models showed that hydraulic connectivity provided by both natural flows and regulated e-flow releases facilitated movement of all three species between habitats, throughout the year. Mary River turtles made extensive use of regulated e-flow releases when moving between habitats, whereas Mary River cod and Australian lungfish required additional natural rises in river height above the regulated e-flows to trigger movements. Significant movement activity was also recorded for cod and turtles during the dry season (winter and spring), broadly coinciding with breeding periods for these species. The effectiveness of, and potential improvements to, current e-flow strategies to sustain key life-history requirements of these species is discussed. Findings suggest a revised e-flow strategy with relatively minor increases in the magnitude of e-flow releases throughout winter and spring, would be effective in providing movement opportunities and supporting reproductive success for all three species. This study demonstrates that by quantifying movement behaviour in an e-flow context, ecological risk assessment frameworks can be used to assess and provide for critical life-history requirements of multiple species within the context of a highly regulated system under increasing water use demands.

Key words: environmental flows, adaptive management, threatened species, acoustic telemetry

1. Introduction

Human dependence on freshwater has impacted riverine ecosystems in many ways including impoundment, water extraction and flow regulation leading to the alteration, fragmentation and degradation of riverine habitats (Kingsford, 2000; Tharme, 2003). Dams and associated flow regime changes affect movement of aquatic species by altering key environmental factors such as connectivity, hydrologic and hydraulic cues, and habitat quality and quantity (Arthington et al., 2016; Crook et al., 2015). Understanding human impacts to flow regimes and habitats in relation to the spatial ecology of biota allows managers to assess and prioritise water requirements and provisions necessary to sustain aquatic ecosystems (Cooke et al., 2016). Furthermore, prioritising which spatiotemporal movements are critical to maintain population viability and species persistence, and what aspects of the flow regime are manageable considering human water security, are key to developing effective strategies for conservation management.

Movement is essential to the long-term viability of freshwater species such as fish and turtles supporting survival, dispersal, reproduction and genetic integrity over a range of spatio-temporal scales (Faulks et al., 2010; Jungwirth, 1998; Micheli-Campbell et al., 2017). The triggers, purpose and extent of movements are intimately tied to species life-history and physiology through the environmental conditions they encounter (Young et al., 2006). These movements can be broadly grouped into survival or reproductive strategies (Lucas and Baras, 2001; Northcote, 1998). Survival strategies are driven by resource requirements; water, food and habitat all play a role in stimulating movement for persistence, nutrition and refuge, respectively (Crook, 2004; Koehn and Nicol, 1996). These movements are generally opportunistic in time and space, driven by resource limitations, and support physiological condition (Koehn et al., 2009). Movements related to reproductive strategies are more specific in terms of timing, duration and habitat; driven by environmental triggers that initiate and facilitate the reproductive cycle (Humphries et al., 1999; Koehn and Nicol, 2016).

Flows of variable magnitudes, timing and duration provide differing ecosystem functions, with medium to high flows eliciting dramatic ecosystem responses (Arthington and Balcombe, 2011; Junk et al., 1989) including large-scale fish migrations (Crook et al., 2019; Reynolds, 1983). More recently, the importance of low flows in sustaining ecosystem processes including movement has also been shown (Marshall et al., 2016; Storer et al., 2021). However, not all animals move on all flows, and difficulties in quantifying movements of populations has resulted in limited quantitative evidence for ecologically significant movement events (Jønsson et al., 2016). This has led to a significant body of literature identifying what aspects of the flow regime trigger and facilitate movement of biota, and in turn, what movements are critical to sustain populations within freshwater environments subject to increasing pressure from water resource development (Dudgeon et al., 2006; Tickner et al., 2020).

Environmental flows (e-flows) are a key strategy for conservation management of freshwater ecosystems around the world. E-flows describe the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being (Acreman et al., 2014; Arthington et al., 2018). A key requirement for e-flow provision is identification and quantification of specific hydraulic habitat or discharges contributing to ecological outcomes focused on water quality, aquatic refugia and animal life-histories including movement. Implementation of e-flows however, can be difficult due to competition for water (Poff et al., 2003), scientific uncertainty in the movement and habitat requirements of species, particularly at early life stages contributing to recruitment (Gwinn et al., 2016; Koehn et al., 2020); and a general lack of research, monitoring and evaluation implemented within a risk-based framework (Davies et al., 2014; Mcgregor et al., 2018). Even in basins with comprehensive understanding of native fish ecology, delivery of prescribed e-flows have met with variable ecological responses across fish communities highlighting the need for more targeted quantification of flow-ecology relationships coupled with adaptive management frameworks (Cruz et al., 2020; King et al., 2010). Rare examples of targeted long-term research, monitoring and management programs have successfully demonstrated e-flows as an effective tool for mitigating impacts to threatened aquatic species (Koster et al., 2021, 2018, 2017, 2013).

The Mary River in south-east Queensland Australia supports several nationally-listed threatened species including the Mary River cod (*Maccullochella mariensis*), Australian lungfish (*Neoceratodus forsteri)* and Mary River turtle (*Elusor macrurus)* (Smith and Connell, 2018). Flow alteration and habitat fragmentation from water infrastructure (dams and weirs) and extraction are major threats to these species (Arthington, 2009; Clark et al., 2009; Kennard, 2003), highlighting the challenge for water managers in providing water for agriculture and rapidly growing urban and rural populations, whilst providing water for multiple threatened species with limited information and potentially competing requirements. As part of the Queensland Government water planning process for the Mary River catchment (NRM, 2003), an e-flow strategy was implemented for a dam on a major tributary (Obi Obi Creek) to mitigate potential impacts to the downstream environment. Due to limited ecologically relevant information, a precautionary e-flow strategy was introduced to address impacts to the low flow regime including reduced magnitudes and increased dry spells.

Mary River cod, Australian lungfish and Mary River turtle are riverine specialists with life history and habitat requirements that are critically-linked to key attributes of the flow regime (Department of Natural Resources, 2018). Current knowledge indicates that reproductive cycles for all three species are completed during the dry season (August – December) coinciding with low flows and rising water temperatures. These species also have specific flow-related habitat and movement requirements to support spawning and recruitment. Specifically, Mary River cod require connectivity for locating partners (ensuring genetic dispersal) and for accessing specific nesting habitat (complex instream structures) (DNRM, 2016; Simpson and Mapleston, 2002); in response to water temperatures that initiate the reproductive season (Espinoza et al., 2020). For Australian lungfish, variable low flows trigger spawning activity and facilitate movements to spawning habitat (dense beds of aquatic plants) (Espinoza et al., 2013; Kind, 2002). Mary River turtles require connectivity for locating mates (ensuring genetic dispersal) and for access to nesting habitat (sandy riverbanks) (Espinoza et al., 2018).

Although all three species' reproductive periods coincide with the dry season, the specific timing, magnitude and duration of flows that support reproduction for each species is poorly understood and requires further investigation (Brooks and Kind, 2002; Micheli-Campbell et al., 2017; Simpson and Mapleston, 2002). Quantification of flow-ecology relationships is essential to relate movement behaviour of these species to their environments and predict responses to potential management interventions. Acoustic telemetry allows researchers to passively measure and monitor animal movements and behaviour in aquatic environments, whilst also overcoming some of the constraints surrounding the study of threatened and cryptic species (Heupel and Webber, 2012; Hussey et al., 2015). This technology involves implanting animals with acoustic transmitters that are detected by hydrophones deployed across diverse habitats, over extended timeframes and has been used successfully in other e-flow studies on Australian species (Grothues, 2009; Harding et al., 2017; Koster et al., 2013).

This three-year study quantified the movements of Mary River cod, Australian lungfish and Mary River turtle, to assess the effectiveness of the current e-flow release strategy within Obi Obi Creek and identify potential refinements of these strategies to better support these threatened species. Movement patterns were evaluated in response to regulated e-flow releases, variations in river levels and water temperatures to assess how environmental conditions influenced connectivity and supported reproductive processes. We aimed to demonstrate that quantification of animal movement behaviour can inform ecological risk assessments to support adaptive management of e-flows. Results from this study can improve the sustainability of threatened species amidst increasing human water demands and inform water managers in other regulated rivers around the world.

2. Methods

2.1 Study area

This study was undertaken between June 2013 and September 2016 within Obi Obi Creek, a tributary of the Mary River in southeast Queensland, Australia (Figure 1). This watercourse is approximately 57 kilometres long, drains a catchment area of approximately 202 km^2, and is within a rapidly developing urban region with increasing water demands (Bunn et al., 2010). Baroon Pocket Dam, a 61 000 ML storage intercepts flow at 26.4 km from the junction with the Mary River and provides potable and agricultural water for southeast Queensland region through an interconnected water grid. Below the dam wall, the creek passes through the pristine bedrock gorge and rock pools (Figure 2A) before emerging through a low-lying floodplain towards the Kenilworth township (Queensland Government, 2004). Catchment land use in this reach includes dairy/grazing, horticulture, rural-residential, urban and forestry (Brizga et al., 2005) which has had variable impacts on riparian habitat. Although some sections have very little riparian habitat (Figure 2B), other previously cleared areas have established riparian canopies of native and exotic species such as camphor laurel (*Cinnamomum camphora*) (Figure 2C). Obi Obi Creek has been recognised as an important wetland system in Australia (DIWA) (Miller and Deacon, 2005), and supports a key population of the endemic Mary River cod (Simpson and Jackson, 2000).

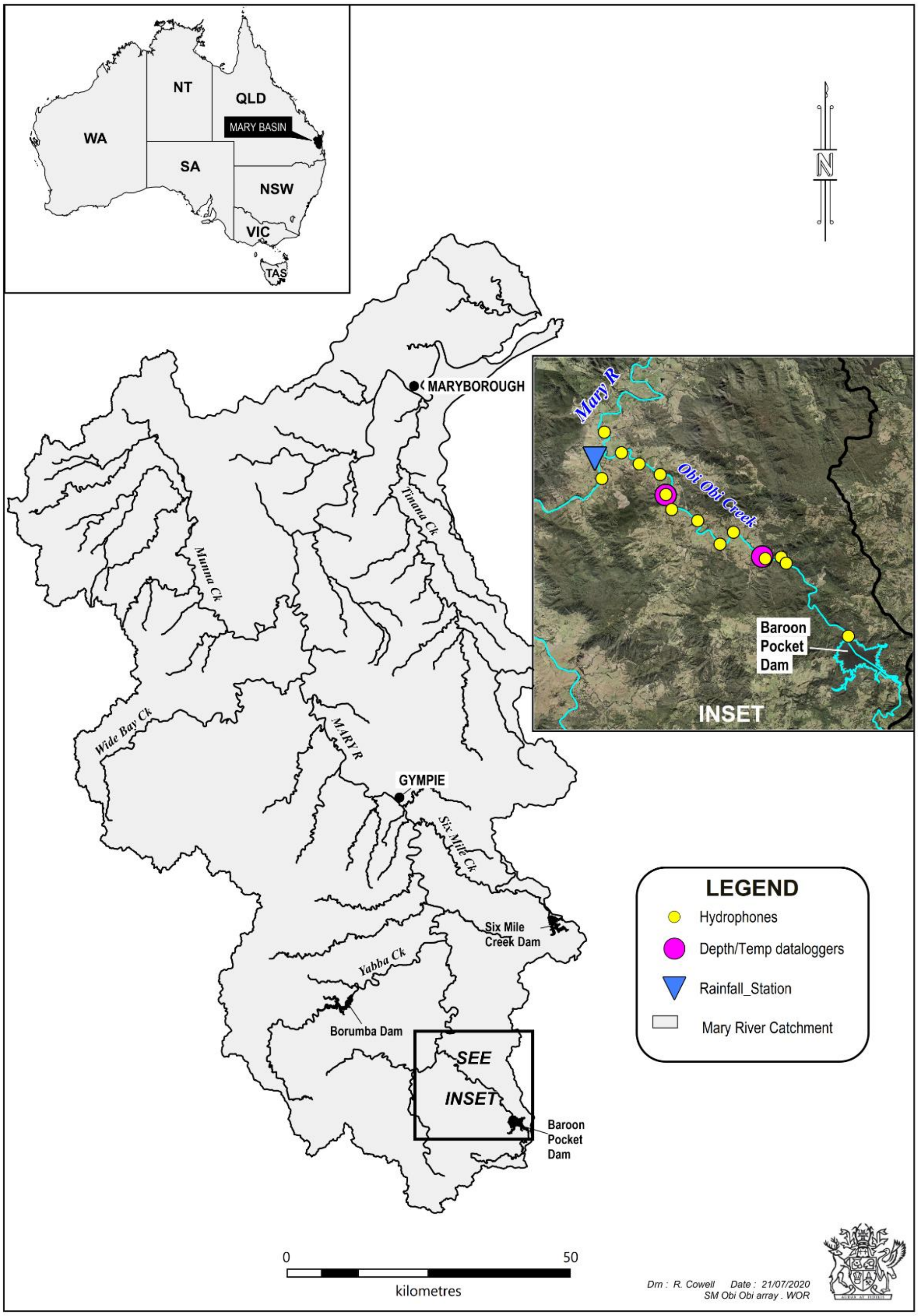

Figure 1: Study area showing locations of hydrophones, depth/temperature dataloggers and rainfall station

Obi Obi Creek has mean annual rainfall at its headwaters of ~2 000 mm providing Baroon Pocket Dam a mean annual inflow of ~70 000 ML (Queensland Government, 2004). A panel of scientific experts commissioned to advise development of the original Water Resource (Mary Basin) Plan 2006 (Government, 2006) highlighted significant impacts to the natural flow regime of Obi Obi Creek downstream of Baroon Pocket Dam, particularly reductions in low flows and increased dry spells (Queensland Government, 2004). These flow alterations were determined to likely affect movement and reproductive cues for key species such as Mary River cod, potentially affecting population viability, therefore a mitigation strategy was recommended. Currently, an e-flow strategy consisting of translucent releases (Growns and Reinfelds, 2014) is made from Baroon Pocket Dam to Obi Obi Creek for environmental purposes. This strategy aims to maintain water quality and support the requirements of Mary River cod, Australian lungfish and Mary River turtle. Releases are calculated based on gauged inflows to the dam with a proportion of inflows released up to a maximum of 15 ML.d^{-1}. Additionally, releases for downstream users and local rainfall runoff subsidise riverine flows in Obi Obi Creek (Government, 2011). Rainfall was considered average to below average during the study period, whilst mean temperatures were slightly above average (Figure 3) (Bureau of Meteorology, Commonwealth of Australia 2020).

Figure 2 Variable habitats of Obi Obi Creek in the (A) upper, (B) lower and (C) middle reaches.

2.2 Animal collection

Mary River cod and Australian lungfish were captured in June 2013 using a boat-mounted electrofisher unit (2.5 GPP; Smith Root, Inc., Vancouver, WA, USA), backpack electrofishing unit (LR-24 Smith-Root, Inc., Vancouver, WA, USA) or angling with lure. All fish were measured (Total Length – cm) using a wetted concave fish measuring board. In total, seven pools covering 13 km of Obi Obi Creek were electrofished in June 2013. Maximum depths of pools ranged from 3 - 4.5 m and were considered representative of the overall watercourse.

Mary River turtles were captured in September 2013 from six riffle habitats on Obi Obi Creek using double-winged fyke nets with 20 mm mesh, 10 m wings x 1.2 m drop, 4 round hoops with 0.9 m diameter. The cylindrical section of each net was 4 m in length with two internal funnels, each having a fixed opening of 0.4 m. Nets were set facing both upstream and downstream parallel to the riverbank, with a maximum set time of 12 hours per net. Wings and cod-end were secured using metal stakes, and polystyrene floats were inserted in the cod-end to allow air pockets for turtles and other animals. Standard Carapace Length (SCL) was measured for all turtles (cm) and mature specimens were sexed based on tail length with males having significantly longer and more robust tails.

2.3 Telemetry

Acoustic telemetry was used to track animal movement and location between 2013 and 2016. In total, 24 Mary River cod, 20 Australian lungfish and 13 Mary River turtles (8 males, 5 females) were tagged with Vemco™ V13 acoustic transmitters. Prior to surgery, fish were held in an aerated holding tank followed by an anaesthetic bath containing 50 mgL^{-1} of AQUI-S® (AQUI-S New Zealand Ltd). Once sedated, fish were placed in a V-shaped surgical cradle and measurements of total fish length and body depth were recorded. Transmitters were set to a 60-180 second roving ping rate and inserted into the gut cavity through a 15-20 mm incision behind the pectoral fin. Tag sizes ensured the weight ratio was kept under the recommended 2.25% of total fish body weight (Butler et al., 2009; Wagner et al., 2011). The incision was closed with absorbable sutures and tissue adhesive (Vetbond; Provet, Brisbane Qld, Australia). All fish were allowed to recover in aerated freshwater holding tanks until normal swimming behaviour was observed before release back into the creek at point of capture.

The procedure for transmitter attachment to turtles followed Micheli-Campbell et al. (2017). Two holes were drilled vertically through the posterior marginal scutes of the carapace and the transmitter was secured in place using a purpose-built cap, plastic saddle, and PVC nuts and bolts (1.5 mm). The nuts were secured with Loctite 243 (Henkel, Victoria, Australia), and the ends of the bolts were covered in a two-part epoxy putty (Kneadlt, Selleys, Padstow, Australia). Vemco™ V13 transmitters (36 mm L x 13 mm D) were set to a 60-180 s roving ping rate.

A longitudinal array of 12 hydrophones (Vemco VR2W-69 kHz) was deployed at regular intervals throughout Obi Obi Creek from the Mary River junction to Baroon Pocket Dam tailwater (Figure 1). Hydrophones were installed at ~2 km intervals except for a 6 km gorge section with limited access. One additional hydrophone was deployed in the main Mary River channel approximately 2 km downstream of the Obi Obi Creek junction to detect movement direction out of Obi Obi Creek. Hydrophones were secured to a concrete anchor and tethered to stable overhanging riparian vegetation using 5 mm stainless steel cable. No overlapping detection ranges occurred between adjacent hydrophones. A Vemco™ VR100 portable hydrophone was also used to manually locate and confirm animal positions at regular intervals (approx. 6 months) during the study period.

2.4 Environmental data

Regulated release data for Baroon Pocket Dam (e-flow) was obtained from Resource Operation Licence reporting data supplied quarterly to the Department of Regional Development, Manufacturing and Water (Figure 3). Data loggers (Diver, Schlumberger Ltd) recording water depth and temperature were also installed in Obi Obi Creek at two locations in Obi Obi Creek (Figure 1) for the entire study. Locations and heights of dataloggers were surveyed to cross-reference water levels to pool cease-to-flow points and the 90th percentile river level was also calculated from level data to separate baseflows provided by e-flows from natural flow events within the creek. Rainfall data was obtained from Climate Data Online (Bureau of Meteorology, Commonwealth of Australia 2020) for the Kenilworth Township rain gauge (site 040106, Figure 1).

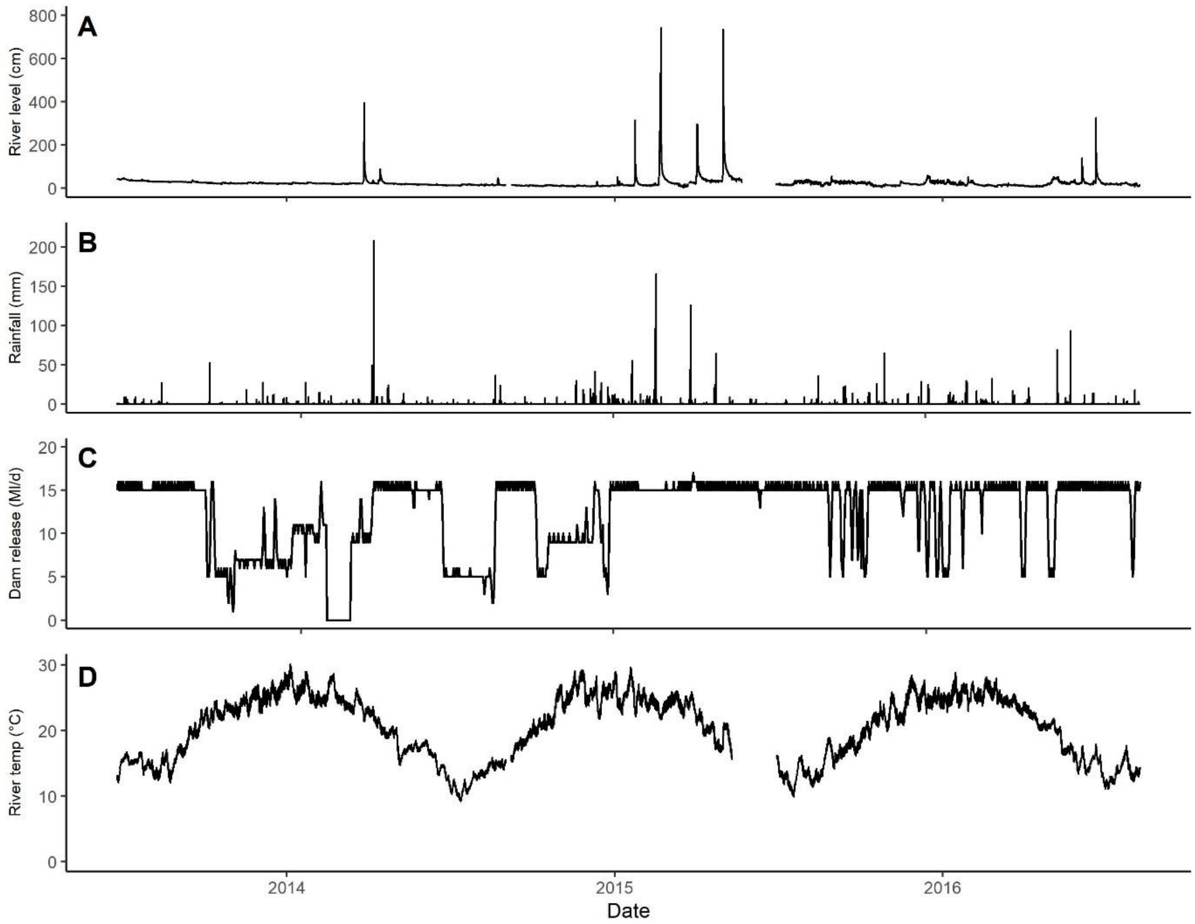

Figure 3 Summary of river level (A), rainfall (B), regulated e-flow release (C) and river temperature (D) for the study period.

2.5 Data analysis

Movement events were initially summarised and assessed against various environmental and biological variables of interest including reported breeding periods (Table 1), changes in river levels, rainfall, movement direction, hydrograph limb, dam releases and diel periods. Here, 'movement events' were defined as animal movements detected across multiple hydrophones within one week, i.e. if detection between two hydrophones took longer than one week, this was considered a separate 'movement event'. Results are presented as the percentage of movement events for each species in response to environmental variables.

Table 1 Documented key periods for each species in the study. Note, breeding involves mating, nesting and paternal care whereas spawning is oviposition only.

Species	Key period	Purpose	Reference
Mary River cod	Aug - Dec	Breeding	(Simpson and Jackson, 2000)
Australian lungfish	Aug - Dec	Spawning	(Brooks and Kind, 2002)
Mary River turtle	Oct - Dec	Nesting	(Micheli-Campbell et al., 2013)

The time lag of flow pulses between the upstream and downstream sections of the study reach was determined by assessing corresponding peaks in the hydrograph generated by spatially discrete river level loggers. This enabled projection of hydrographic conditions for each animal movement from each respective location, at the start of a movement event; and was summarised as a cumulative proportion plot of movement events versus river rise above baseflow, for all three species. Cumulative distance moved and total linear range were calculated for all individuals, where total linear range was the river distance between the most upstream and downstream detections for each fish for the total study period.

A spatial object was created by digitising the study reach from satellite imagery in ArcGIS 10.4 (ESRI, Redlands, CA, USA). From this, the distance between each receiver station and the most downstream station was calculated and the spatial object 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). Individual fish detections were then matched with the distance matrix and the distance between detections was calculated. Likelihood of movement was quantified as a distinct function of environmental and biological variables using a generalised linear mixed model (GLMM) in the *lme4* package in R (Bates et al., 2015), in which movement was treated as a binary variable (presence or absence of movement). We specified a logistic regression model for the binary response, with predictor variables considered including: total daily dam release, average daily river level, average daily river temperature, time of year (season), fish total length or turtle carapace length and sex (MRT only). Continuous independent variables were centred and scaled to ensure model convergence. Fish identity (ID) was included as a random intercept in the models. All possible models and interactions were examined, and the best model was selected using the Akaike information criterion (AIC). Following the protocol of Zuur et al. (2010), the data was checked for statistical outliers and collinearity among predictor variables was assessed using variance inflation factors (VIF). Model fit was assessed by comparing model binned residuals and fitted values.

3. Results

Of the 24 Mary River cod, 20 Australian lungfish and 13 Mary River turtles tagged, greater than 70% of individuals across all species were recorded within the study area for at least 100 days. Only four cod and one lungfish were not detected on any receiver throughout the study. One Mary River cod tag was discovered (by manual tracking) in a shallow open section of a pool and had been expelled by the fish soon after tagging. Manual tracking revealed tagged turtles and fish residing permanently in habitats between hydrophones, and amongst complex habitats (undercut banks, hollow logs and log jams) that prevented reliable detection of those individuals by the hydrophone array. Although some tags ceased to be recorded without being detected at terminal hydrophones of the array (which would signal movement out of the creek), no specific evidence for predation effects or human interference was found for any tagged animal.

Mary River turtle were found to move greater cumulative distances compared to the two fish species, although Australian lungfish undertook the largest linear movements (Table 2). Mary River cod were the most sedentary species demonstrated through highest rates of detection, and smallest linear and cumulative distance moved within the hydrophone array.

Table 2 Summary statistics for Mary River cod, Australian Lungfish and Mary River turtle for the study period including mean (± SE) and range of values. Number of tags missing out of array or lost from animal from start of study in parentheses.

	Cod (n = 24)[5]	**Lungfish (n = 20)[1]**	**Turtles (n = 13)[0]**

Metric	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range
Total Length (mm)	558 ± 34	(335 - 850)	955 ± 21	(780 - 1100)	350* ± 1	(260 - 410)
No. of detections	102321 ± 19375	(0 - 321691)	60592 ± 17490	(0 - 279773)	41773 ± 17678	(0 - 230158)
Days detected in array	421 ± 69	(0 - 1116)	194 ± 41	(0 - 542)	222 ± 50	(0 - 680)
No. of movements	1 ± 0	(0 - 8)	3 ± 1	(0 - 8)	14 ± 3	(0 - 36)
Cumulative dist. moved (km)	1 ± 1	(0 - 17)	6 ± 1	(0 - 23)	21 ± 5	(0 - 53)
Linear range (km)	1 ± 0	(0 - 6)	5 ± 1	(0 - 19)	5 ± 1	(0 - 10)

* carapace length

3.1 General movement patterns

Male Mary River turtles moved frequently between pools with a preference for nocturnal movements during river rises, particularly regulated e-flow releases, followed by return movements back to home pools (Table 3). Female Mary River turtles also made extensive use of regulated e-flow releases during nocturnal periods, with a greater proportion of movements during the reported breeding season. Although Mary River cod generally resided within a single 'home' pool, movements generally coincided with all flow-related environmental variables (i.e. river rise, regulated e-flow release and rainfall), with a high relative proportion of movements during the reported breeding season (August to December). Mary River cod also preferred nocturnal movements between pools and tended to utilise hydraulic conditions provided by the rising limb of the hydrograph. Australian lungfish also generally resided within home pools throughout the study period although movements coincided with all flow-related variables, particularly natural flow events with a rising and falling limbs (i.e. not regulated e-flow releases). Movements during the reported breeding season were not observed for Australian lungfish.

Table 3 Summary of animal movements over the study period. Results presented as percentage of animal movements in response to environmental variables.

Species	Sex	Period	River rise	Rain	Direction	Return	Hydrograph	E-flow release	Nocturnal
Mary River turtle	Male (n=8)	Overall	45% yes	60% yes	53% downstream	45% yes	13% rising 25% falling 62% steady	100% yes	70% yes
		Breeding season (3%)	100% yes	100% yes	100% upstream	0% yes	100% rising 0% falling 0% steady	100% yes	0% yes
	Female (n=5)	Overall	32% yes	77% yes	55% downstream	9% yes	14% rising 14% falling 72% steady	100% yes	82% yes
		Breeding season (60%)	15% yes	69% yes	54% upstream	8% yes	0% rising 8% falling 92% steady	100% yes	85% yes
Mary River cod		Overall	100% yes	100% yes	62% upstream	25% yes	81% rising or peak 19% falling 0% steady	100% yes	88% yes

	Breeding season (50%)	100% yes	100% yes	50% upstream	25% yes	87% rising or peak 13% falling 0% steady	100% yes	88% yes
Australian lungfish	Overall	96% yes	92% yes	56% downstream	20% yes	56% rising or peak 40% falling 4% steady	100% yes	52% yes
	Breeding season (0%)	0% yes	0% yes	n/a	n/a	n/a	0% yes	0% yes

Movement plots for all three species were plotted as distance from river mouth to provide a comparable reference point for all species and identified distinct patterns across the study period (Figure 4). Male Mary River turtles frequently undertook short distance movements within defined home ranges throughout Obi Obi Creek, although longer distance movements were recorded on large natural flow events (Figure 3). A significant overlap in habitat use was observed within a 5 km reach of Obi Obi Creek between AMTD 5 km and 10 km for both males and females (Figure 4). Female Mary River turtles generally remained within home pools except during the reported nesting season, where repeated movements during spring to habitats in the vicinity of the junction with the Mary River, followed by return movements to home ranges, were recorded. In addition, one female Mary River turtle moved a cumulative distance of over 52 km during the study period. A majority of Mary River cod tagged in this study stayed within resident pools for the entire study period however, repeated return movements to and from home pools were observed during the late winter - early spring period for some individuals. Although largely sedentary, Australian lungfish movements were characterised by long distance movements during high flow events, often without return to previous home ranges. Synchronised movements in both upstream and downstream directions were detected, including three Australian lungfish with significant downstream movements on the same flood of which two lungfish exited Obi Obi Creek without return (Figure 4).

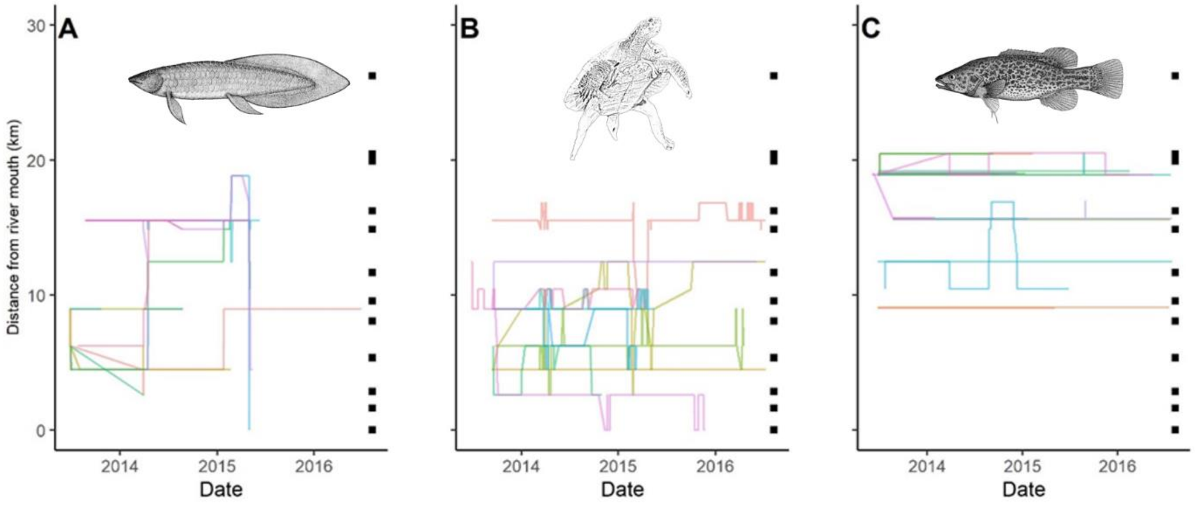

Figure 4 Distance from the river mouth (km) of individual Australian lungfish (A), Mary River turtle (B) and Mary River cod (C) throughout the study array, presented as unique colours. Blocks on the right denote the hydrophone positions along Obi Obi Creek. Cod have been jittered 0.02 to reduce visual overlap. Fish drawings by Pusey et al. (2004), turtle photograph by John Cann and converted to drawing (all images used with permission).

Assessment of cumulative movements for all three species in relation to river rises above regulated e-flow releases also revealed important relationships (Figure 5). More than 50% of Mary River turtle movements occurred solely on regulated e-flow releases from Baroon Pocket Dam, with 80% of movements accounted for by a further 15 cm river rise above regulated releases. In contrast, for Mary River cod and Australian lungfish, a low proportion (< 15%) of movements coincided with regulated e-flow releases alone. Small river rises of less than 30 cm during rainfall-driven flow events however, facilitated a significant proportion of movements for Mary River cod and Australian lungfish.

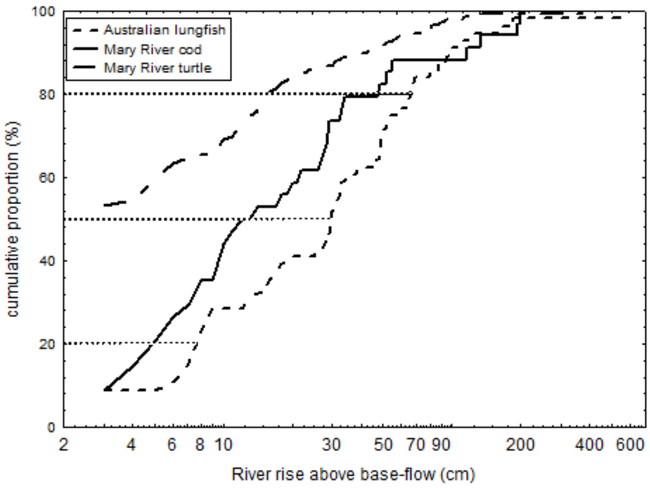

Figure 5 Cumulative proportion of movements for river rises above base-flow (regulated e-flow releases). Horizontal dashed lines indicate 20%, 50% and 80% of cumulative movements.

3.2 Seasonal movement patterns

Monthly summary plots of movements across the study period identified important seasonal patterns for each species in relation to documented reproductive periods (Figure 6 and Table 1). All three species moved frequently during large natural flow events in late summer and early autumn (February – May; Figure 3). Male Mary River turtles and Australian lungfish were particularly active during these periods, although one female Mary River turtle and one Mary River cod also made relatively long-distance movements during this time. Mary River turtles were active during the winter – spring period with males predominantly moving in winter, females predominantly in spring, and movements for both males and females overlapping in September. Mary River cod were relatively active during the late winter and spring period with July and August noted for movements across multiple individuals. Australian lungfish movements coincided with all wet season months covering summer and early autumn for multiple individuals.

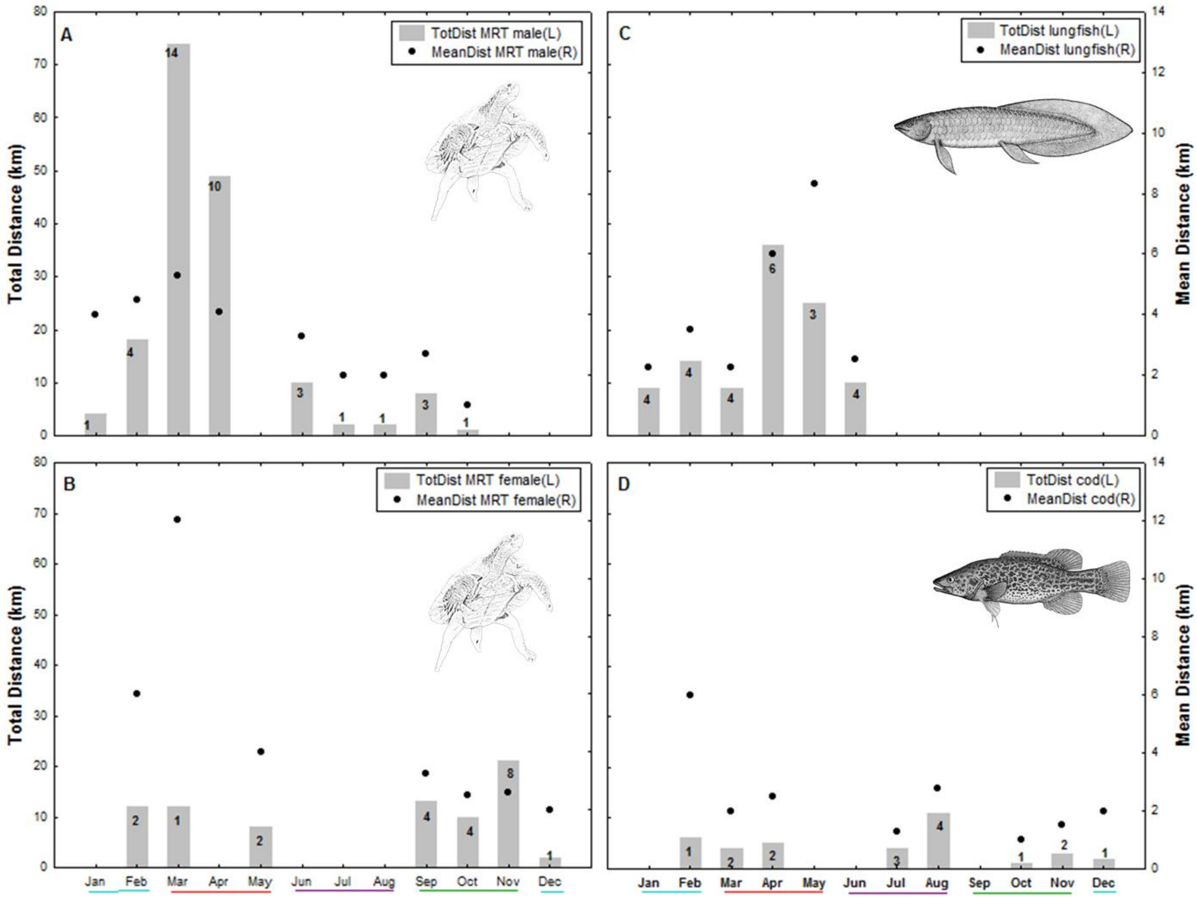

Figure 6 Monthly movement summaries for total distance (grey bars), mean distance (black dots) and number of individuals contributing to monthly movements. Mary River turtle (male – A, female – B), Australian lungfish (C) and Mary River cod (D). Summer (light blue), Autumn (orange), winter (purple) and spring (green) also shown on x axis.

3.3 Effects of environmental variations on probability of movement

Generalised Linear Mixed Modelling (GLMM) of animal movements in relation to environmental variability further highlighted contrasting relationships across all three species (Table 4; Figure 7). The probability of Mary River turtle movement increased significantly with increases in dam release magnitudes and river level. Winter, summer and spring were also associated with increased probabilities of movement; however, increases in regulated e-flow releases during spring did not increase the probability of movement for turtles. In addition, although higher river temperatures were also associated with increased probabilities of movement, the cooler periods in spring and summer were preferred. Finally, male Mary River turtle were significantly less likely to move in spring compared to females.

Table 4 Parameter estimates (± SE) and significance levels from binomial GLMM relating to environmental variables and morphology, and animal movements for three species. Continuous predictor variables are scaled. Also shown are attributes of the random effects from each model, including number of IDs and years of release, among-ID and release year standard deviation and number of observations.

	Mary River turtle		Mary River cod		Australian lungfish	
Fixed effect	**Est. ± SE**	***P***	**Est. ± SE**	***P***	**Est. ± SE**	***P***
River level (cm)	0.2 ± 0.07	**<0.001**	0.35 ± 0.12	**<0.001**	0.62 ± 0.09	**<0.001**

Regulated release (ML day^{-1})	1.43 ± 0.6	**0.02**	1.51 ± 0.71	**0.03**	1.29 ± 0.52	**0.01**
River temperature (°C)	1.29 ± 0.25	**<0.001**			1.27 ± 0.49	**0.01**
Spring	1.81 ± 0.68	**0.01**	1.94 ± 1.1	0.08	-17.63 ± 6388	0.99
Summer	1.88 ± 0.85	**0.03**	-16.53 ± 191.21	0.93	2.8 ± 0.93	**<0.001**
Winter	2.92 ± 0.87	**<0.001**	1.62 ± 0.91	0.08	-8.89 ± 2.85	**<0.001**
River level : Spring			2.45 ± 1.14	**0.03**	-0.73 ± 15150	0.99
River level : Summer			-0.65 ± 389.2	0.99	-0.34 ± 0.16	**0.03**
River level : Winter			2.68 ± 0.6	**<0.001**	2.17 ± 0.8	**0.01**
Reg release : Spring	-1.84 ± 0.68	**0.01**				
Reg release : Summer	-0.91 ± 0.65	0.16				
Reg release : Winter	-0.51 ± 0.77	0.51				
River temperature : Spring	-1.83 ± 0.53	**<0.001**			-1.14 ± 8150	0.99
River temperature : Summer	-2.86 ± 0.71	**<0.001**			-6.16 ± 1.87	**<0.001**
River temperature : Winter	0.49 ± 0.61	0.43			-6.1 ± 1.41	**<0.001**
Autumn : Male	1.13 ± 0.96	0.24				
Spring : Male	-4.52 ± 1.38	**<0.001**				
Summer : Male	0.86 ± 0.98	0.38				
Winter : Male	-1.26 ± 1.03	0.22				
Random effect	**ID**	**Year**	**ID**		**ID**	
N	11	4	17		19	
Std. Dev.	1.3797	0.1539	2.172		1.624	
Observations	2708	2708	9362		3791	

Probability of movement of Mary River cod increased in response to increases in river level, particularly during winter and spring (Figure 7B) however, regulated e-flow releases alone did not increase the probability of movement for this species (Table 4; and Figure 7C). Probability of movement of Australian lungfish increased significantly with increases in river level, river temperature and regulated e-flow releases (Table 4). Australian lungfish were also most likely to move in summer (Figure 7D) at cooler river temperatures; and much less likely to move in spring or winter. Increased river levels in winter however, increased probability of movement.

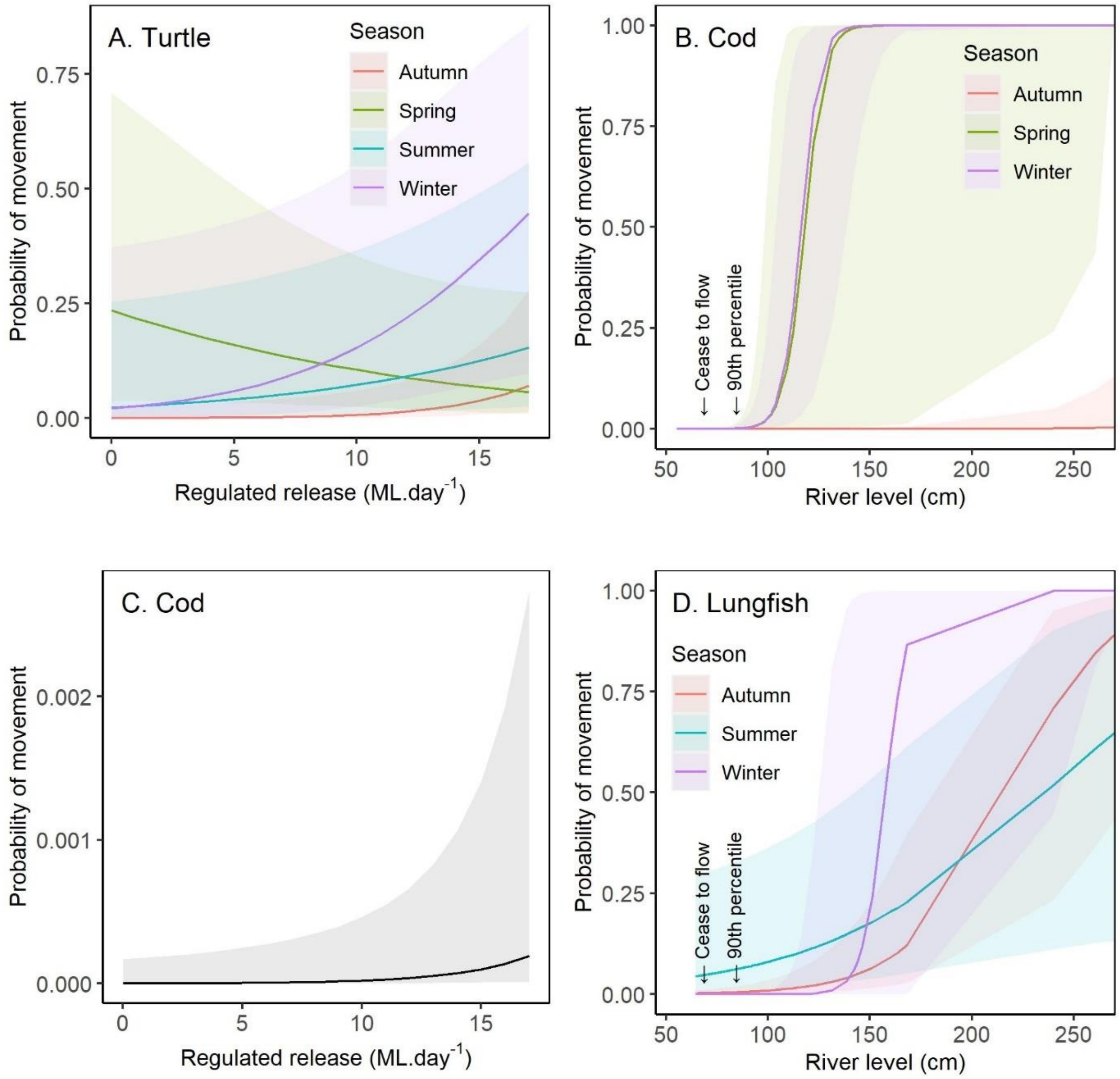

Figure 7 Predicted probability of movement for (A) Mary River turtle, (B, C) Mary River cod and (D) Australian lungfish as a function of dam release and river level (+/− 95% CI) across season. Probabilities were generated from the binomial model and all other covariates held at their mean values.

Discussion

This study quantified movements of multiple individuals of three threatened species in relation to environmental conditions, and an existing e-flow strategy, demonstrating that targeted monitoring of e-flows provides an improved understanding of flow-ecology relationships in regulated rivers (Davies et al. 2014; King et al. 2010; Scheele et al. 2018). We found increased probability of movements for three threatened species in response to both natural flows and regulated e-flow releases, coupled with seasonal changes in environmental conditions. By understanding the specific timing, minimum discharges and environmental conditions correlated to movements of all three species; risks from changes in the flow regime can be better quantified through ecological risk assessments that consider not only the frequency and timing of these flows for each species, but also the corresponding consequences for the life-history for each species (Mcgregor et al. 2018). Assessment of e-flows within an adaptive management framework not only helps identify key aspects of the flow regime required to support the requirements of target species (Crook et al., 2015; Robinson et al., 2018), but also provides an opportunity to refine and improve the current e-flow strategy within the socio-economic constraints of regulated river systems (Webb et al., 2017, 2010).

For Mary River cod and Australian lungfish, correlations between movement and discharge have been recorded in response to natural flow events in unregulated watercourses (Brooks and Kind, 2002; Simpson and Mapleston, 2002); whereas although Mary River turtles have shown a high propensity to move (Micheli-Campbell et al., 2017), this is the first record of movements in response to flow. Extensive Mary River turtle movements in response to regulated e-flow releases, and preference of Mary River cod and Australian lungfish for river rises above these discharges, demonstrate the importance of specific hydraulic cues and habitat for these species. Mary River turtles do not traverse dry habitats between waterholes (M. Connell pers. comm.) and although no-flow periods were rare during this study, our results support the requirement for hydraulic connectivity to facilitate Mary River turtle movements. In contrast, the lack of Mary River cod and Australian lungfish movement observed on regulated e-flow releases alone, even though suitable water depths were recorded (i.e. greater than maximum depth of fish), suggests other environmental variables or hydraulic cues associated with natural flow events trigger these species to move. Changes in water level (flow variability) and water quality (water temperature and water chemistry) have been previously shown to elicit movement responses for many Australian fish species (Amtstaetter et al., 2021; Harding et al., 2017; Thiem et al., 2018).

Movements related to reproduction have been previously observed in spring (September-November) for all three species in this study (Kind, 2002; Micheli-Campbell et al., 2017; Simpson and Mapleston, 2002). Flows that facilitate reproductive processes of aquatic species are often targeted as measurable indicators for long-term viability through links to animal condition, spawning, recruitment and movement (King et al., 2009; Koehn et al., 2014; Mcgregor et al., 2018). In this study, female Mary River turtle and Mary River cod were more likely to move when connectivity was provided during spring, with repeated and return movements recorded across individuals and breeding seasons. Both of these species are also known to seek suitable nesting habitat during this period (Micheli-Campbell et al., 2013; Simpson and Jackson, 2000) with flows facilitating this impetus. No movements were recorded for Australian lungfish during spring, in contrast to previous studies which recorded targeted movements during this period, particularly upstream movements from impounded to riverine habitats (Kind, 2002). This is an unexpected result for Australian lungfish and we speculate this may be due to flood-related loss of food resources (scouring of macrophytes and associated benthic fauna) in Obi Obi Creek prior to our study period which potentially affected lungfish condition, breeding potential and availability of preferred spawning habitat.

Outside of the spring period, increased movement was recorded for Australian lungfish and male Mary River turtle during high flow events which is common for many Australian freshwater species (Ocock et al., 2018; Pusey et al., 2004; Roe and Georges, 2008). Movement during winter for all three species, however, is a novel finding of this study. Probability of movement for Mary River turtle increased significantly during winter, and monthly movement summaries highlighted this to be driven primarily by males. Mary River cod and Australian lungfish were also more likely to move during winter on natural flow events. Mary River cod have also recently been shown to increase movement activity prior to breeding (Espinoza et al., 2020). Whether these movements are related to pre-conditioning in anticipation of breeding (Arthington et al., 2014; Rolls et al., 2013), or representative of actual reproductive activity (Mary River cod – nest location, Australian lungfish – spawning, and Mary River turtle - mating) is unknown, however, the provision of low flows in winter is a key finding in the development of effective e-flow strategies for all three species.

Outside of movements during seasonal flow events, we found all three species to demonstrate an affinity for home pools, rather than a propensity to move. Quantitative evidence for ecologically significant movement events across populations is not common (Jønsson et al., 2016), and although advances in tagging technologies have addressed issues of low sample sizes and cost-effective monitoring of more individuals over larger spatial scales; this does not necessarily apply to endangered species due to restricted distributions and increased ethical limitations for research (Cooke et al., 2012). Regardless, quantitative movement data from even small proportions of populations has important implications for population viability through dispersal, range shifts, climate change adaptability and genetic mixing (Cooke et al., 2016; Faulks et al., 2010; Reside et al., 2017). Two factors that may have affected movement activity during our study include the relatively optimal instream and riparian habitat that occurs within Obi Obi Creek compared to the rest of the catchment (T. Espinoza pers. observations); and record floods prior to our study period (early 2011 and 2013) which caused extensive geomorphic changes and removal of aquatic plants within the watercourse. Increased habitat availability and environmental predictability learned by animals over various spatial scales has been shown to limit movement across species and habitats (Riotte-Lambert and Matthiopoulos, 2020).

Management Implications

Key lessons for water management from this study include: (1) hydraulic connectivity provided by either natural flows or regulated releases facilitate movement of Mary River cod, Australian lungfish and Mary River turtle throughout the year; (2) current regulated e-flow releases from Baroon Pocket Dam provide baseflows that are particularly important for Mary River turtle; (3) small river rises above these regulated baseflows significantly increase the probability of movement of Mary River cod and Australian lungfish; and, (4) e-flow strategies that include flow provision during winter (in addition to spring) months will be most effective for all three species in this study.

Winter and spring (May – December), however, represent the Queensland dry season (Klingaman, 2012), which coincides with increased water demands and increased potential conflict between environmental and human water use. For example, although flows found to facilitate movement have the potential to be delivered from existing infrastructure due to small magnitudes, the current maximum e-flow release is restricted by the need to maintain reliability of water for human use. With better understanding of the hydrologic requirements of Mary River turtle, Mary River cod and Australian lungfish provided by this study, ecological risk assessments can be used to ensure the long-term viability of these species through improved opportunities for movement within reproductive periods throughout the Mary water plan area (Mcgregor et al., 2018).

Conclusions

The current e-flow strategy within Obi Obi Creek is providing opportunities for movement for key threatened species including Mary River cod, Australian lungfish and Mary River turtle. E-flow releases alone are used extensively by Mary River turtles, and also by Mary River cod and Australian lungfish when small additional river rises are provided by natural flow events. Refinement of the current e-flow strategy to target winter and spring with increased flow variability and small increases in discharges, will improve its effectiveness. This study will inform future ecological risk assessments to review the efficacy of e-flow releases within Obi Obi Creek and develop suitable e-flow strategies for these threatened species in the broader Mary River catchment.

Acknowledgements

The authors would like to thank Marilyn Connell, Dr Mariana Micheli-Campbell, Dr Ross Dwyer, Doug Harding, Tess Mullins and Sean Gibson for assistance with surgery and fish collection. We would also like to thank Tom & Ali Ryan, Tonia Murtagh-Skoupy, John & Lynn Cutmore, Mal & Mandy McIntyre, Darryl & Paula Gillis, Wes Lowecke, Sara Bucher and Gyan Duffy for their hospitality and access to key sites. This work was authorized under General Fisheries Permit 163172 and conducted in accordance with the requirements of the University of Queensland Animal Ethics Committee (approval number SBS/302/12/URG).

References

Acreman, M., Arthington, A.H., Colloff, M.J., Couch, C., Crossman, N.D., Dyer, F., Overton, I., Pollino, C.A., Stewardson, M.J., Young, W., 2014. Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world. Front. Ecol. Environ. 12, 466–473.

Amtstaetter, F., Yen, J.D.L., Hale, R., Koster, W., O'Connor, J., Stuart, I., Tonkin, Z., 2021. Elevated river discharge enhances the immigration of juvenile catadromous and amphidromous fishes into temperate coastal rivers. J. Fish Biol. https://doi.org/10.1111/jfb.14699

Arthington, A.H., 2009. Australian lungfish, Neoceratodus forsteri, threatened by a new dam. Environ. Biol. Fishes 84, 211–221.

Arthington, A.H., Balcombe, S.R., 2011. Extreme flow variability and the "boom and bust" ecology of fish in arid-zone floodplain rivers: A case history with implications for environmental flows, conservation and management. Ecohydrology 4, 708–720. https://doi.org/10.1002/eco.221

Arthington, A.H., Bhaduri, A., Bunn, S.E., Jackson, S.E., Tharme, R.E., Tickner, D., Young, B., Acreman, M., Baker, N., Capon, S., Horne, A.C., Kendy, E., McClain, M.E., Poff, N.L., Richter, B.D., Ward, S., 2018. The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018). Front. Environ. Sci. 6, 45. https://doi.org/10.3389/fenvs.2018.00045

Arthington, A.H., Dulvy, N.K., Gladstone, W., Winfield, I.J., 2016. Fish conservation in freshwater and marine realms: status, threats and management. Aquat. Conserv. Mar. Freshw. Ecosyst. https://doi.org/10.1002/aqc.2712

Arthington, A.H., Rolls, R.J., Sternberg, D., Mackay, S.J., James, C.S., 2014. Fish assemblages in subtropical rivers: low-flow hydrology dominates hydro-ecological relationships. Hydrol. Sci. J. https://doi.org/10.1080/02626667.2013.844345

Bates, D., Mächler, M., Bolker, B.M., Walker, S.C., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67. https://doi.org/10.18637/jss.v067.i01

Brizga, S., Arthington, A., Balcombe, S., Condina, P., Connell, M., Connolly, N., Craigie, N., Kennard, M., Kenyon, R., Mackay, S., Schlacher, T., 2005. Mary Basin draft water resource plan : environmental flow assessment framework and scenario implications. Queensland Government, Dept. of Natural Resources and MInes, Brisbane.

Brooks, S.G., Kind, P.K., 2002. Ecology and demography of the Queensland lungfish (Neoceratodus fosteri) in the Burnett River, Queensland with reference to the impacts of Walla Weir and future water infrastructure development : final report, Project report (Queensland. Dept. of Primary Industries) ; QO02004; Project report]. Dept. of Primary Industries, Queensland Agency for Food and Fibre Sciences, Brisbane.

Bunn, S.E., Abal, E.G., Smith, M.J., Choy, S.C., Fellows, C.S., Harch, B.D., Kennard, M.J., Sheldon, F., 2010. Integration of science and monitoring of river ecosystem health to guide investments in catchment protection and rehabilitation. Freshw. Biol. https://doi.org/10.1111/j.1365-2427.2009.02375.x

Butler, G.L., Mackay, B., Rowland, S.J., Pease, B.C., 2009. Retention of intra-peritoneal transmitters and post-operative recovery of four Australian native fish species. Mar. Freshw. Res. 60, 361–370.

Campbell, H.A., Watts, M.E., Dwyer, R.G., Franklin, C.E., 2012. V-Track: Software for analysing and visualising animal movement from acoustic telemetry detections. Mar. Freshw. Res. 63, 815–820. https://doi.org/10.1071/MF12194

Clark, N.J., Gordos, M.A., Franklin, C.E., 2009. Implications of river damming: The influence of aquatic hypoxia on the diving physiology and behaviour of the endangered Mary River turtle. Anim. Conserv. 12, 147–154.

Cooke, S., Paukert, C., Hogan, Z., 2012. Endangered river fish: factors hindering conservation and restoration. Endanger. Species Res. 17, 179–191. https://doi.org/10.3354/esr00426

Cooke, S.J., Martins, E.G., Struthers, D.P., Gutowsky, L.F.G., Power, M., Doka, S.E., Dettmers, J.M., Crook, D.A., Lucas, M.C., Holbrook, C.M., Krueger, C.C., 2016. A moving target—incorporating knowledge of the spatial ecology of fish into the assessment and management of freshwater fish populations. Environ. Monit. Assess. https://doi.org/10.1007/s10661-016-5228-0

Crook, D.A., 2004. Is the home range concept compatible with the movements of two species of lowland river fish? J. Anim. Ecol. 73, 353–366.

Crook, D.A., Buckle, D.J., Morrongiello, J.R., Allsop, Q.A., Baldwin, W., Saunders, T.M., Douglas, M.M., 2019. Tracking the resource pulse: Movement responses of fish to dynamic floodplain habitat in a tropical river. J. Anim. Ecol. 1365-2656.13146. https://doi.org/10.1111/1365-2656.13146

Crook, D.A., Lowe, W.H., Allendorf, F.W., Eros, T., Finn, D.S., Gillanders, B.M., Hadwen, W.L., Harrod, C., Hermoso, V., Jennings, S., Kilada, R.W., Nagelkerken, I., Hansen, M.M., Page, T.J., Riginos, C., Fry, B., Hughes, J.M., 2015. Human effects on ecological connectivity in aquatic ecosystems: Integrating scientific approaches to support management and mitigation. Sci. Total Environ. 534, 52–64. https://doi.org/10.1016/j.scitotenv.2015.04.034

Cruz, D.O., Kingsford, R.T., Suthers, I.M., Rayner, T.S., Smith, J.A., Arthington, A.H., 2020. Connectivity but not recruitment: Response of the fish community to a large-scale flood on a heavily regulated floodplain. Ecohydrology 13. https://doi.org/10.1002/eco.2194

Davies, P M, Naiman, R.J., Warfe, D.M., Pettit, N.E., Arthington, A.H., Bunn, S.E., 2014. Flow-ecology relationships: Closing the loop on effective environmental flows. Mar. Freshw. Res. 65, 133–141.

Davies, Peter M., Naiman, R.J., Warfe, D.M., Pettit, N.E., Arthington, A.H., Bunn, S.E., 2014. Flow-ecology relationships: Closing the loop on effective environmental flows. Mar. Freshw. Res. https://doi.org/10.1071/MF13110

Department of Natural Resources, M. and E., 2018. Review of Water Plan (Mary Basin) 2006 and Resource Operations Plan: Summary of Ecological Monitoring. Brisbane.

DNRM, 2016. Mary River cod – Maccullochella mariensis: An update on demography, habitat, movement, ageing and genetics to inform management. Department of Natural Resources and Mines, Brisbane. Queensland Government, Brisbane.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.-I., Knowler, D.J., Lévêque, C., Naiman, R.J., Prieur-Richard, A.-H., Soto, D., Stiassny, M.L.J., Sullivan, C.A., 2006. Freshwater biodiversity: Importance, threats, status and conservation challenges. Biol. Rev. Camb. Philos. Soc. 81, 163–182.

Espinoza, T., Burke, C.L., Carpenter-Bundhoo, L., Marshall, S., Roberts, D., Kennard, M.J., 2020. Fine-scale acoustic telemetry in a riverine environment: Movement and habitat use of the endangered mary river cod maccullochella mariensis. Endanger. Species Res. 42, 125–131. https://doi.org/10.3354/ESR01046

Espinoza, T., Connell, M., Marshall, S., Beukeboom, R., McDougall, A., 2018. Nesting behaviour of the endangered Mary River turtle: Monitoring and modelling to inform e-flow strategies. Aust. J. Zool. https://doi.org/10.1071/ZO17044

Espinoza, T., Marshall, S.M., McDougall, A.J., 2013. Spawning of the endangered Australian lungfish (Neoceratodus forsteri) in a heavily regulated river: A pulse for life. River Res. Appl. Volume 29, 1215–1225. https://doi.org/10.1002/rra.2607

Faulks, L.K., Gilligan, D.M., Beheregaray, L.B., 2010. Islands of water in a sea of dry land: Hydrological regime predicts genetic diversity and dispersal in a widespread fish from Australias arid zone, the golden perch (Macquaria ambigua). Mol. Ecol. 19, 4723–4737. https://doi.org/10.1111/j.1365-294X.2010.04848.x

Government, Q., 2011. Mary Basin Resource Operations Plan - September 2011.

Government, Q., 2006. Water Resource (Mary Basin) Plan 2006.

Grothues, T.M., 2009. A Review of Acoustic Telemetry Technology and a Perspective on its Diversification Relative to Coastal Tracking Arrays. https://doi.org/10.1007/978-1-4020-9640-2_5

Growns, I., Reinfelds, I., 2014. Environmental flow management using transparency and translucency rules. Mar. Freshw. Res. 65, 667–673.

Gwinn, D.C., Beesley, L.S., Close, P., Gawne, B., Davies, P.M., 2016. Imperfect detection and the determination of environmental flows for fish: challenges, implications and solutions. Freshw. Biol. 61, 172–180. https://doi.org/10.1111/fwb.12684

Harding, D.J., Dwyer, R.G., Mullins, T.M., Kennard, M.J., Pillans, R.D., Roberts, D.T., 2017. Migration patterns and estuarine aggregations of a catadromous fish, Australian bass (Percalates novemaculeata) in a regulated river system. Mar. Freshw. Res. https://doi.org/10.1071/MF16125

Heupel, M.R., Webber, D.M., 2012. Trends in acoustic tracking: where are the fish going and how will we follow them? Am. Fish. Soc. Symp. 76, 219–231.

Humphries, P., King, A.J., Koehn, J.D., 1999. Fish, flows and flood plains: Links between freshwater fishes and their environment in the Murray-Darling River system, Australia. Environ. Biol. Fishes 56, 129–151.

Hussey, N.E., Kessel, S.T., Aarestrup, K., Cooke, S.J., Cowley, P.D., Fisk, A.T., Harcourt, R.G., Holland, K.N., Iverson, S.J., Kocik, J.F., Flemming, J.E.M., Whoriskey, F.G., 2015. Aquatic animal telemetry: A panoramic window into the underwater world. Science (80-.). 348, 1255642. https://doi.org/10.1126/science.1255642

Jønsson, K.A., Tøttrup, A.P., Borregaard, M.K., Keith, S.A., Rahbek, C., Thorup, K., 2016. Tracking Animal Dispersal: From Individual Movement to Community Assembly and Global Range Dynamics. Trends Ecol. Evol. https://doi.org/10.1016/j.tree.2016.01.003

Jungwirth, M., 1998. River Continuum and Fish Migration - Going Beyond the Longitudinal River Corridor in Understanding Ecological Integrity, in: Jungwirth, M., Schmutz, S., Weiss, S. (Eds.), Fish Migration and Fish Bypasses. Fishing News Books, Oxford, pp. 19–32.

Junk, W.J., Bayley, P.B., Sparks, R.E., 1989. The Flood Pulse Concept in River-Floodplain Systems. Proc. Int. Large River Symp. 106, 110–127.

Kennard, M.J., 2003. Mary Basin Water Resource Plan, Environmental Conditions Report, Appendix H Freshwater Fish. Griffith University.

Kind, P.K., 2002. Movement patterns and habitat use in the Queensland lungfish Neoceratodus forsteri (Krefft 1870). Department of Zoology and Entomology, University of Queensland.

King, A.J., Tonkin, Z., Mahoney, J., 2009. Environmental flow enhances native fish spawning and recruitment in the Murray River, Australia. River Res. Appl. 25, 1205–1218. https://doi.org/10.1002/rra.1209

King, A. J., Ward, K.A., O'Connor, P., Green, D., Tonkin, Z., Mahoney, J., 2010. Adaptive management of an environmental watering event to enhance native fish spawning and recruitment. Freshw. Biol. 55, 17–31. https://doi.org/10.1111/j.1365-2427.2009.02178.x

King, A J, Ward, K.A., O'Connor, P., Green, D., Tonkin, Z., Mahoney, J., 2010. Adaptive management of an environmental wateringevent to enhance native fish spawning and recruitment. Freshw. Biol. 55, 17–31.

Kingsford, R.T., 2000. Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. Austral Ecol 25, 109–127.

Klingaman, N.P., 2012. Rainfall in Queensland Part 1: A literature survey of key rainfall drivers in Queensland, Australia: Rainfall variability and change.

Koehn, J., Nicol, S., 1996. Habitat and movement requirements of fish. Riverine Environ. Forum 770, 1–6.

Koehn, J.D., King, A.J., Beesley, L., Copeland, C., Zampatti, B.P., Mallen-Cooper, M., 2014. Flows for native fish in the Murray-Darling Basin: lessons and considerations for future management. Ecol. Manag. Restor. 15, 40–50. https://doi.org/10.1111/emr.12091

Koehn, J.D., McKenzie, J.A., O'Mahony, D.J., Nicol, S.J., O'Connor, J.P., O'Connor, W.G., 2009. Movements of Murray cod (Maccullochella peelii peelii) in a large Australian lowland river. Ecol. Freshw. Fish 18, 594–602.

Koehn, J.D., Nicol, S.J., 2016. Comparative movements of four large fish species in a lowland river. J. Fish Biol. 88, 1350–1368. https://doi.org/10.1111/jfb.12884

Koehn, J.D., Raymond, S.M., Stuart, I., Todd, C.R., Balcombe, S.R., Zampatti, B.P., Bamford, H., Ingram, B.A., Bice, C.M., Burndred, K., Butler, G., Baumgartner, L., Clunie, P., Ellis, I., Forbes, J.P., Hutchison, M., Koster, W.M., Lintermans, M., Lyon, J.P., Mallen-Cooper, M., McLellan, M., Pearce, L., Ryall, J., Sharpe, C., Stoessel, D.J., Thiem, J.D., Tonkin, Z., Townsend, A., Ye, Q., 2020. A compendium of ecological knowledge for restoration of freshwater fishes in Australia. Mar. Freshw. Res. https://doi.org/10.1071/MF20127

Koster, W.M., Amtstaetter, F., Dawson, D., Coleman, R.A., Hale, R., 2021. Environmental influences on the juvenile migration of the threatened amphidromous Australian grayling (Prototroctes maraena). Mar. Freshw. Res. 72, 411–417. https://doi.org/10.1071/MF20039

Koster, W.M., Amtstaetter, F., Dawson, D.R., Reich, P., Morrongiello, J.R., 2017. Provision of environmental flows promotes spawning of a nationally threatened diadromous fish. Mar. Freshw. Res. 68, 159–166. https://doi.org/10.1071/MF15398

Koster, W.M., Crook, D.A., Dawson, D.R., Gaskill, S., Morrongiello, J.R., 2018. Predicting the Influence of Streamflow on Migration and Spawning of a Threatened Diadromous Fish, the Australian Grayling Prototroctes Maraena. Environ. Manage. 61, 443–453. https://doi.org/10.1007/s00267-017-0853-0

Koster, W.M., Dawson, D.R., Crook, D.A., 2013. Downstream spawning migration by the amphidromous Australian grayling (Prototroctes maraena) in a coastal river in south-eastern Australia. Mar. Freshw. Res. 64, 31–41.

Lucas, M.C., Baras, E., 2001. Migration of freshwater fishes. Oxford: Blackwell Science Ltd.

Marshall, J.C., Menke, N., Crook, D.A., Lobegeiger, J.S., Balcombe, S.R., Huey, J.A., Fawcett, J.H., Bond, N.R., Starkey, A.H., Sternberg, D., Linke, S., Arthington, A.H., 2016. Go with the flow: the movement behaviour of fish from isolated waterhole refugia during connecting flow events in an intermittent dryland river. Freshw. Biol. https://doi.org/10.1111/fwb.12707

Mcgregor, G.B., Marshall, J.C., Lobegeiger, J.S., Holloway, D., Menke, N., Coysh, J., 2018. A Risk-Based Ecohydrological Approach to Assessing Environmental Flow Regimes. Environ. Manage. https://doi.org/10.1007/s00267-017-0850-3

Micheli-Campbell, M.A., Baumgartl, T., Booth, D.T., Campbell, H.A., Connell, M., Franklin, C.E., 2013. Selectivity and repeated use of nesting sites in a freshwater turtle. Herpetologica 69, 383–396. https://doi.org/10.1655/HERPETOLOGICA-D-12-00057

Micheli-Campbell, M.A., Connell, M.J., Dwyer, R.G., Franklin, C.E., Fry, B., Kennard, M.J., Tao, J., Campbell, H.A., 2017a. Identifying critical habitat for freshwater turtles: integrating long-term monitoring tools to enhance conservation and management. Biodivers. Conserv. 26, 1675–1688. https://doi.org/10.1007/s10531-017-1325-9

Micheli-Campbell, M.A., Connell, M.J., Dwyer, R.G., Franklin, C.E., Fry, B., Kennard, M.J., Tao, J., Campbell, H.A., 2017b. Identifying critical habitat for freshwater turtles: integrating long-term monitoring tools to enhance conservation and management. Biodivers. Conserv. https://doi.org/10.1007/s10531-017-1325-9

Miller, G.J., Deacon, G., 2005. A review and update of Queensland site accounts in “A Directory of Important Wetlands in Australia”. Unpublished report (updated September 2005). Department of Environment and Heritage, Canberra.

Northcote, T.G., 1998. Migratory Behaviour of Fish and its Significance to Movement through Riverine Fish Passage Facilities, in: Jungwirth, M., Schmutz, S., Weiss, S. (Eds.), Fish Migration and Fish Bypasses. Fishing News Books, Oxford, pp. 3–18.

NRM, 2003. Mary Basin Draft Water Resource Plan. South East Regional Water Planning Group, Department of Natural Resources and Mines., Brisbane.

Ocock, J.F., Bino, G., Wassens, S., Spencer, J., Thomas, R.F., Kingsford, R.T., 2018. Identifying Critical Habitat for Australian Freshwater Turtles in a Large Regulated Floodplain: Implications for Environmental Water Management. Environ. Manage. https://doi.org/10.1007/s00267-017-0837-0

Poff, N.L., Allan, J.D., Palmer, M.A., Hart, D.D., Richter, B.D., Arthington, A.H., Rogers, K.H., Meyer, J.L., Stanford, J.A., 2003. River flows and water wars: emerging science for environmental decision making. Front. Ecol. Environ. 1, 298–306.

Pusey, B.J., Kennard, M., Arthington, A., 2004. Freshwater fishes of North-eastern Australia. CSIRO Publishing, Collingwood., Centre for Riverine Landscapes, Griffith University.

Queensland Government, D. of N.R. and M. prepared by M.B.T.A.P., 2004. Mary Basin draft water resource plan : environmental conditions report (includes Mary River, Burrum River and Beelbi Creek catchments) : final report (volume 1). Dept. Natural Resources and Mines.

Reside, A.E., VanDerWal, J., Moilanen, A., Graham, E.M., 2017. Examining current or future trade-offs for biodiversity conservation in north-eastern Australia. PLoS One 12, e0172230. https://doi.org/10.1371/journal.pone.0172230

Reynolds, L.F., 1983. Migration patterns of five fish species in the Murray-Darling River system. Aust. J. Mar. Freshw. Res. 34, 857–871.

Riotte-Lambert, L., Matthiopoulos, J., 2020. Environmental Predictability as a Cause and Consequence of Animal Movement. Trends Ecol. Evol. https://doi.org/10.1016/j.tree.2019.09.009

Robinson, N.M., Scheele, B.C., Legge, S., Southwell, D.M., Carter, O., Lintermans, M., Radford, J.Q., Skroblin, A., Dickman, C.R., Koleck, J., Wayne, A.F., Kanowski, J., Gillespie, G.R., Lindenmayer, D.B., 2018. How to ensure threatened species monitoring leads to threatened species conservation. Ecol. Manag. Restor. https://doi.org/10.1111/emr.12335

ROE, J.H., GEORGES, A., 2008. Terrestrial activity, movements and spatial ecology of an Australian freshwater turtle, Chelodina longicollis, in a temporally dynamic wetland system. Austral Ecol. 33, 1045–1056. https://doi.org/10.1111/j.1442-9993.2008.01877.x

Rolls, R.J., Growns, I.O., Khan, T.A., Wilson, G.G., Ellison, T.L., Prior, A., Waring, C.C., 2013. Fish recruitment in rivers with modified discharge depends on the interacting effects of flow and thermal regimes. Freshw. Biol. 58, 1804–1819. https://doi.org/10.1111/fwb.12169

Scheele, B.C., Legge, S., Armstrong, D.P., Copley, P., Robinson, N., Southwell, D., Westgate, M.J., Lindenmayer, D.B., 2018. How to improve threatened species management: An Australian perspective. J. Environ. Manage. 223, 668–675. https://doi.org/10.1016/J.JENVMAN.2018.06.084

Simpson, B., Jackson, P., 2000. The Mary River Cod research and recovery plan. Department of Primary Industries-Fisheries Group.

Simpson, R., Mapleston, A., 2002. Movement and habitat use by the endangered Australian freshwater Mary River Cod, Maccullochella peelii mariensis. Environ. Biol. Fish. 65, 401-410 pp.

Simpson, R.R., Mapleston, A.J., 2002. Movements and habitat use by the endangered Australian freshwater Mary River cod, Maccullochella peelii mariensis. Environ. Biol. Fishes. https://doi.org/10.1023/A:1021129021451

Smith, T., Connell, M., 2018. Mary's Famous Five: a story of connection, commitment and community in the recovery of threatened aquatic species in the Mary River catchment, Queensland., in: Garnett, S., Latch, P., Lindenmayer, D., Woinarski, J. (Eds.), Recovering Australian Threatened Species-a Book of Hope. CSIRO Publishing, pp. 33–42.

Storer, T., Bannister, J., Bennett, K., Byrnes, E., Crook, D.A., Morgan, D.L., Gleiss, A., Beatty, S.J., 2021. Influence of discharge regime on the movement and refuge use of a freshwater fish in a drying temperate region. Ecohydrology 14, e2253. https://doi.org/10.1002/eco.2253

Tharme, R.E., 2003. A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers. River Res. Appl. 19, 397–441.

Thiem, J.D., Wooden, I.J., Baumgartner, L.J., Butler, G.L., Forbes, J., Taylor, M.D., Watts, R.J., 2018. Abiotic drivers of activity in a large, free-ranging, freshwater teleost, Murray cod (Maccullochella peelii). PLoS One 13, e0198972. https://doi.org/10.1371/journal.pone.0198972

Tickner, D., Opperman, J.J., Abell, R., Acreman, M., Arthington, A.H., Bunn, S.E., Cooke, S.J., Dalton, J., Darwall, W., Edwards, G., Harrison, I., Hughes, K., Jones, T., Leclère, D., Lynch, A.J., Leonard, P., Mcclain, M.E., Olden, J.D., Ormerod, S.J., Robinson, J., Tharme, R.E., Thieme, M., Tockner, K., Wright, M., Young, L., 2020. Bending the Curve of Global Freshwater Biodiversity Loss: An Emergency Recovery Plan. Bioscience 330. https://doi.org/10.1093/biosci/biaa002

Wagner, G.N., Cooke, S.J., Brown, R.S., Deters, K.A., 2011. Surgical implantation techniques for electronic tags in fish. Rev. Fish Biol. Fish. 21, 71–81. https://doi.org/10.1007/s11160-010-

9191-5

Webb, J.A., Stewardson, M.J., Chee, Y.E., Schreiber, E.S.G., Sharpe, A.K., Jensz, M.C., 2010. Negotiating the turbulent boundary: The challenges of building a sciencemanagement collaboration for landscape-scale monitoring of environmental flows. Mar. Freshw. Res. 61, 798–807.

Webb, J.A., Watts, R.J., Allan, C., Warner, A.T., 2017. Principles for Monitoring, Evaluation, and Adaptive Management of Environmental Water Regimes, in: Water for the Environment: From Policy and Science to Implementation and Management. Elsevier Inc., pp. 599–623. https://doi.org/10.1016/B978-0-12-803907-6.00025-5

Young, J.L., Bornik, Z.B., Marcotte, M.L., Charlie, K.N., Wagner, G.N., Hinch, S.G., Cooke, S.J., 2006. Integrating physiology and life history to improve fisheries management and conservation. FISH Fish. 7, 262–283.

Zuur, A.F., Ieno, E.N., Elphick, C.S., 2010. A protocol for data exploration to avoid common statistical problems. Methods Ecol. Evol. 1, 3–14. https://doi.org/10.1111/j.2041-210x.2009.00001.x