Northern Australia Environmental Resources Hub
National Environmental Science Programme

Fish migration in Magela Creek and potential impacts of mining-related solutes

Final report

David Crook, Dion Wedd, Brendan Adair, Alison King, Tom Mooney, Andrew Harford and Chris Humphrey

CHARLES DARWIN UNIVERSITY AUSTRALIA

Australian Government
Department of Agriculture, Water and the Environment

This report should be cited as:

Crook D, Wedd D, Adair B, King A, Mooney T, Harford A and Humphrey C (2021). *Fish migration in Magela Creek and potential impacts of mining-related solutes*. Charles Darwin University, Darwin.

Cover photographs

Front cover: Magela Creek in the upper escarpment reaches during the 2019 wet season (photo Patch Clapp).

The Hub is supported through funding from the Australian Government’s National Environmental Science Program (NESP). The NESP NAER Hub is hosted by Charles Darwin University.

ISBN 8-1-922684-14-1

September, 2021

Printed by UniPrint

Contents

List of tables

List of figures

Acknowledgements

We pay our respects to all Traditional Owners of Kakadu National Park and the Darwin region where we conduct research and monitoring and acknowledge Elders past, present and emerging. The authors are grateful to the Djurrubu Rangers and Gundjeihmi Aboriginal Corporation for their assistance with project logistics and fieldwork and acknowledge Energy Resources of Australia Ltd for their cooperation and permissions for site access. We thank Northern Australia Helicopters for transporting the team and equipment safely to Bowerbird Billabong, and Dr John Morrongiello for conducting the generalised linear modelling analysis. Thanks also to staff at the NESP Northern Australia Environmental Resources Hub, particularly Jane Thomas, Clare Taylor and Patch Clapp, for their support over the life of the project. The Supervising Scientist Branch (SSB) of the Australian Department of Agriculture, Water and the Environment provided in-kind support for this project. We thank Andrew Jansen (SSB) for preparing Figure 3.11. This research was conducted under Charles Darwin University Animal Ethics Committee approval A18030, Northern Land Council permits 79102 and 82708, and NT Fisheries Act Special permit S17/3454.

Abbreviations and acronyms

EC	electrical conductivity
$MgSO_4$	magnesium sulfate
NERP	National Environmental Research Program
NESP	National Environmental Science Program
RUM	Ranger uranium mine
SSB	Supervising Scientist Branch

Executive summary

This project builds upon previous work by the Australian Department of Agriculture, Water and the Environment's Supervising Scientist Branch (SSB) to develop a comprehensive understanding of fish migration in Magela Creek. The results are used to assess the risks associated with the leaching of magnesium sulfate ($MgSO_4$), a mine-derived contaminant, into Magela Creek after the closure and rehabilitation of the Ranger uranium mine (RUM). The study combined early visual data (1980–90s) on wet-season movement of mainly small-bodied fish species with telemetry and sonar methods used to track movement of mid- and large-bodied species (2018–2020).

Fish movement and migration

Acoustic telemetry was used to examine spatial and temporal residency patterns of the adults of large- and moderate-sized fish species (Figure 1.1) in the Magela Creek sand channels from upstream (Bowerbird Billabong) and downstream (Mudginberri Billabong/Magela crossing) sources over two wet–dry cycles. High-resolution sonar was also used to quantify seasonal changes in fish assemblage composition and size structure in Bowerbird and Mudginberri billabongs, allowing for inference regarding the consequences of fish migration at the population and assemblage levels.

Of the adult large-bodied fish tagged in Bowerbird Billabong in the late dry season of 2018, ten (42%) saratoga, five (19%) sooty grunter and one (25%) sharp-nose grunter were detected in the RUM lease during the wet season, with the remaining fish detected only in Bowerbird Billabong. Given that only a very small proportion of the total population in Bowerbird Billabong was tagged, these observations suggest that large numbers of fish utilise habitats within the RUM lease each wet season.

Downstream movement into the RUM lease was initiated soon after the first wet-season flows. Fish that moved downstream used the mine lease area as habitat over periods of 3 to 5 months. Flows of >50 ML/d markedly increased the likelihood of saratoga and sooty grunter from Bowerbird Billabong being present in the mine lease area. Fish that had moved downstream into the mine lease in the early wet season generally moved back upstream into Bowerbird Billabong as flows receded between January and May.

Although most fish that entered the RUM lease were only detected in the main channel, four fish utilised backflow billabongs (Georgetown, Coonjimba) as habitat during the wet season. All of these fish made movements to the same backflow billabong in each year of the study. Concentrations of mine-derived $MgSO_4$ are moderately elevated in Georgetown Billabong, while concentrations of both $MgSO_4$ and manganese (Mn) may be highly elevated in Coonjimba Billabong. Dissolved oxygen can also reach very low levels at times in both billabongs.

Two saratoga (8%) and one sooty grunter (4%) were detected in Georgetown Billabong in both years of the study. In 2019, mean magnesium was 3.8 mg/L (maximum = 5.75 mg/L), mean manganese was 7.4 µg /L (maximum = 20.5 µg/L), and mean dissolved oxygen was 4.5 mg/L (minimum = 0.33 mg/L) during the period tagged fish were recorded. In 2020, mean magnesium was 2.4 mg/L (maximum = 3.7 mg/L), mean manganese was 7.0 µg /L (maximum = 13.8 µg/L), and mean dissolved oxygen was 3.8 mg/L (minimum = 2.5 mg/L) during the period tagged fish were recorded. One saratoga (4%) was very briefly detected in

Coonjimba Billabong (four detections over two minutes) in February 2019, with estimated magnesium at 8.3 mg/L, manganese at 20 µg/L and dissolved oxygen at 2.7 mg/L around that time. In late January to early March 2020, the same fish was detected in Coonjimba Billabong over a 35-day period, during which time mean magnesium was 9.3 mg/L (maximum = 11.20 mg/L), mean manganese was 41.4 µg/L (maximum = 107 µg/L), and mean dissolved oxygen was 2.7 mg/L (minimum = 0.76 mg/L).

These observations suggest that significant numbers of fish use the backflow billabongs as habitat during the wet season. However, further research would be required to determine whether fish actively avoid backflow billabongs during periods of poor water quality, including periods when mine contaminant concentrations are particularly elevated and when dissolved oxygen levels are very low.

Of the mid-bodied fish species tagged in the Mudginberri Billabong area in April and May 2019, one (11%) black catfish, one (13%) barred grunter, and no spangled perch were detected in the RUM lease during the recessional flow period. Upstream movement by these fish occurred at flows as low as 0.2 ML/d, and it appears likely that at least some fish moving under such conditions either take up residence in residual pools or become stranded in the drying sand channels as flow ceases. The remainder of the tagged mid-bodied fish remained resident in the Mudginberri Billabong area or were not detected in the array.

The seasonal sonar surveys in 2018 and 2019 showed that relative fish abundance during the dry season and build-up was much higher at Mudginberri Billabong than Bowerbird Billabong. Both billabongs contained large numbers of small-bodied fish (<10 cm) in these surveys but the relative abundance of large-bodied fish (barramundi, bony herring, forktail catfish, tarpon, saratoga) was much higher in Mudginberri Billabong. In the wet-season survey, fish numbers decreased dramatically in Mudginberri Billabong suggesting high levels of dispersal away from dry-season refuges onto inundated floodplains either nearby or downstream. The abundance of glassfish (Ambassidae) and rainbowfish (Melanotaenidae) increased dramatically in Mudginberri Billabong and Bowerbird Billabong in the dry-season survey, apparently reflecting an influx of upstream migrants that occurred during the wet season and at flow recession. These observations are consistent with historical (1985 to 1999) visual daily counts of large numbers of mainly small-bodied upstream migrating fish at a Magela Creek site near Ranger (MG001).

The combined results of the acoustic tracking and sonar surveys, together with those from earlier studies, demonstrate that the sand channel reaches of Magela Creek act as a critical migration pathway for fish by connecting the lowland reaches of the system to the escarpment refuge billabongs. The results also suggest that the sand channels and backflow billabongs are important feeding and nursery habitats for fish during the wet season. Based on these observations, we hypothesise that there are potential significant consequences for the health of fish assemblages in Magela Creek if contaminant concentrations and other water quality issues, such as low dissolved oxygen, reach levels that adversely affect connectivity or habitat quality in the sand channels or backflow billabongs.

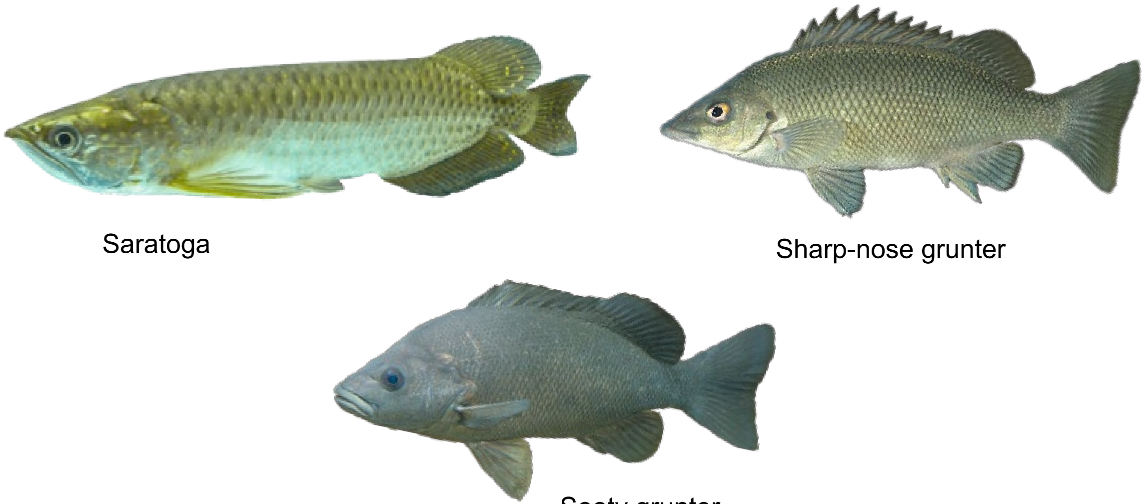
Fish behavioural responses to RP1 mine water

Field observations of fish conducted in March 2021 at creek site MG001 examined responses to mine discharge from Ranger retention pond 1 (RP1). No adverse behavioural responses to mine water discharge were observed at magnesium concentrations of 11 mg/L (almost four times the chronic exposure limit of 3 mg/L). While it is possible that there would be no adverse behavioural responses at higher magnesium concentrations (>11 mg/L), further observations of in situ fish behaviour would be needed to make inferences regarding higher concentrations. The relevance of these observations to fish migration through mine water egress of contaminant mixtures, including magnesium and manganese, would also require separate investigation.

Conclusions

Our results show that the key periods when fish species may be at risk from mine-derived solutes are: 1) during the wet season when fish are migrating and using the sand channels and backflow billabongs as habitat, and 2) the recessional flow period at the end of the wet season, when fish are moving mainly upstream through the sand channels to reach dry-season refuges. In the wet season, the adults of large-bodied species from the escarpment billabongs were only likely to be resident in the sand channels during periods when flows were >50 ML/d. Whether such flows have a significant dilution effect on mine-related contaminants, lowering the potential risks to fish using the main channel during the wet season, requires assessment once surface-water modelling results commissioned by ERA are available. Fish that use mine-site backflow billabongs during the wet season are potentially exposed to elevated magnesium, other co-contaminants, and low dissolved oxygen. Upstream migration of small- and mid-bodied fish occurs during the wet season, and on recessional flows at the end of the wet season, and may continue under very low flows. Any movement during the period of low, recessional flow poses risks for fish exposed to mine solutes in the main channel.

Based on our field observations of fish movement and behaviour, we conclude that the risk of adverse impacts of mine solute egress on fish in Magela Creek is low at magnesium concentrations of 11 mg/L or less. However, detailed solute modelling is required to identify the likely concentrations of future solute egress so that a more comprehensive assessment of the risk to fish can be conducted. Finally, our study emphasises the need for continued monitoring of water quality, including other contaminants of potential concern, and the condition of fish assemblages in Magela Creek to identify any negative mine legacy impacts and to facilitate mitigation if necessary.



Saratoga

Sharp-nose grunter

Sooty grunter

Figure 1.1. Saratoga, sharp-nose grunter and sooty grunter were among the large-bodied fish tagged.

1. Background

The importance of ecological connectivity in maintaining critical ecosystem processes has been increasingly recognised over recent years. For example, research conducted in Kakadu National Park under the National Environmental Research Program (NERP) and National Environmental Science Program (NESP) programs showed that fish migration during the wet season mediates the transport of large amounts of nutrients and energy from productive floodplains into riverine food webs (Jardine et al. 2012; Pettit et al. 2017; Crook et al. 2020). This process supports high-value ecological assets including crocodile and waterbird populations, barramundi, prawn and mud crab fisheries, and populations of threatened speartooth shark and sawfish. A wide range of human activities can adversely impact ecological connectivity in aquatic ecosystems, including climate change, dams and other barriers, habitat destruction, pollution and invasive species. However, despite the recent scientific focus on connectivity in aquatic ecosystems, the effects of mining activities on ecological connectivity in rivers remain poorly known globally.

In the Magela Creek region of the East Alligator catchment in the Northern Territory, Australia, surface and groundwater egress of contaminants from the waste rock cover of the Ranger uranium mine (RUM) final landform has been identified as a potentially important threat to ecological connectivity and the processes it supports (Bishop et al. 1995; Tomlinson and Metherall 2018). After the closure and rehabilitation of RUM in 2026, the rehabilitated landform is predicted to become a source of surface water run-off and exfiltrating groundwater with elevated electrical conductivity (EC) sourced from waste rock. The major component of the elevated EC is magnesium sulfate ($MgSO_4$). Solute egress modelling predicts that within 10 years of the mine closure, groundwater with a $MgSO_4$ concentration greater than the site-specific guideline value for surface waters (2.9 mg/L Mg) will reach the sand channels of Magela Creek, and that without mitigation, concentrations above this limit may remain for extensive periods of time (Sigda et al. 2013). Saline ($MgSO_4$) plumes associated with surface and groundwater egress to Magela Creek have the potential to impact fish migration in Magela Creek via direct toxicity and avoidance behaviour (Humphrey et al. 2016). The $MgSO_4$ concentrations that would lead to these adverse effects is unknown.

Detailed studies of the movements of fish in Magela Creek using visual observations and trapping were conducted by SSB in the 1980s and 1990s. Based on this research, Bishop et al. (1995) proposed that fish in Magela Creek take dry-season refuge in billabongs in the escarpment country upstream of RUM, and in floodplain and channel billabongs downstream of the mine. During the wet season fish migrate from these refugia to spawn and feed: downstream migration from below-escarpment billabongs to the sand channels and inundated floodplains, and lateral or upstream migrations from channel and floodplain billabongs to the sand channels and adjacent inundated floodplains. At the end of the wet season, large numbers of fish (peaking at >100,000 fish/hour) were observed migrating back upstream to refuge billabongs from or through the sand channels. These observations of fish migration suggest that future egress of saline surface water and groundwater from the rehabilitated RUM landform has the potential to reduce connectivity between upstream refugia and lowland floodplains, thus interrupting a key process that underpins the functioning and productivity of the river-floodplain ecosystem.

While the previous work on fish migration in Magela Creek was comprehensive, the reliance on visual observations and trapping data limits the inferences that can be made regarding ecological connectivity and the potential future impacts of waste rock contaminants in Magela Creek. For example, the extensive data on fish moving past specific locations (see Bishop et al. 1995) do not provide information on the distances travelled by fish or the significance of movement behaviour at the population level (i.e. do the majority of individuals move or just a small proportion?). This more detailed information on fish movement was identified by the SSB as critical to improving our understanding of the potential legacy impacts of the mine on aquatic biota and for the development of future monitoring programs.

The research described in this report builds upon the previous work by SSB to develop a comprehensive understanding of fish migration dynamics in the RUM/Magela Creek region. We employ acoustic telemetry to characterise individual-level patterns of spatial and temporal residency of different species in the Magela Creek sand channels from upstream (Bowerbird Billabong) and downstream (Mudginberri Billabong/Magela crossing) sources. High-resolution sonar is also used to quantify seasonal changes in fish assemblage composition, size class distribution, and relative abundance in Bowerbird and Mudginberri billabongs, thus allowing for inference regarding the consequences of fish migration at the population and assemblage levels. The data collected during the study are used to assess the risks to fish populations associated with mine-derived solute egress to Magela Creek after mine closure and rehabilitation of the RUM landform. Finally, we use learnings from the study to make recommendations regarding monitoring methods for ongoing assessment of fish populations in Magela Creek.

2. Methodology

2.1 Study site

The study was conducted between November 2018 and June 2020 in the mid-upper reaches of Magela Creek, a major tributary of the East Alligator River in the Northern Territory, approximately 260 km east of Darwin (Figure 2.1). The monsoonal climate of the region is characterised by periods of heavy and prolonged rainfall and high river discharge from December to May, and generally dry conditions for the remainder of the year (Figure 2.2). Magela Creek is a sand-bed stream which has its headwaters in Arnhem Land and flows through both the RUM lease area and Kakadu National Park. Wet-season rainfall at Jabiru Airport was well below the long-term average of 1,629 mm in both years of the study (2018/19 = 1,237 mm, 2019/20 = 1,073 mm). Stream discharge in Magela Creek over the study period is shown in Figure 2.2.

The surface waters of streams adjacent to RUM (including Magela Creek) have naturally low pH (~5.5–6.5), ionic strength (Na^+ < 2 mgL; Mg^{2+} < 1 mg/L, and SO_4 2– < 0.5 mg/L, ~5-20 µS/cm) and hardness (~5 mg/L as $CaCO_3$), and high water temperature (~30° C; Harford et al. 2015; Mooney et al. 2019). Given the low ionic strength of the natural surface waters in this region, resident biota can be highly susceptible to changes in the ionic environment (van Dam et al. 2010; Humphrey and Chandler 2018; Mooney et al. 2019).

The two sites selected to represent the key upper and mid-reach refuges were Bowerbird Billabong (12°46'17"S, 133°02'21"E, Figure 2.3) and Mudginberri Billabong (12°35'30", 132°52'34"E, Figure 2.4). Between these reaches there are no other permanent surface waters in the main sand channel, although near and downstream of RUM there are a series of shallow off-channel, backflow billabongs that generally retain some water throughout the dry season. Bowerbird Billabong is ~29 km upstream from Mudginberri Billabong and is an escarpment/rockpool billabong. Forming in the upper catchment and commencing below Djurrubu Falls, Bowerbird Billabong is part of a 10 km sand and rock pool–riffle sequence that extends from below the falls to the downstream end of Bowerbird Billabong, through sandstone escarpments and outcrops, until meeting the sand channels of Magela Creek (Figure 2.5). Bowerbird Billabong is relatively narrow (<40 m wide), has a sandstone bedrock-based substrate interspersed with sand patches (Walker and Tyler 1984). There is presently no vehicle access to Bowerbird Billabong, so all access to the field site was undertaken using helicopters (Figure 2.6).

Mudginberri Billabong is an enlarged section of the main channel of Magela Creek and is located at the sand channel terminus, also representing the upstream extent of the extensive Magela floodplain. Mudginberri Billabong has steep vegetated banks, a uniform coarse sandy substrate and is approximately 1 km long. It has a maximum width of ~90 m near the inflow and progressively narrows to a point approximately 3 m wide at the outflow.

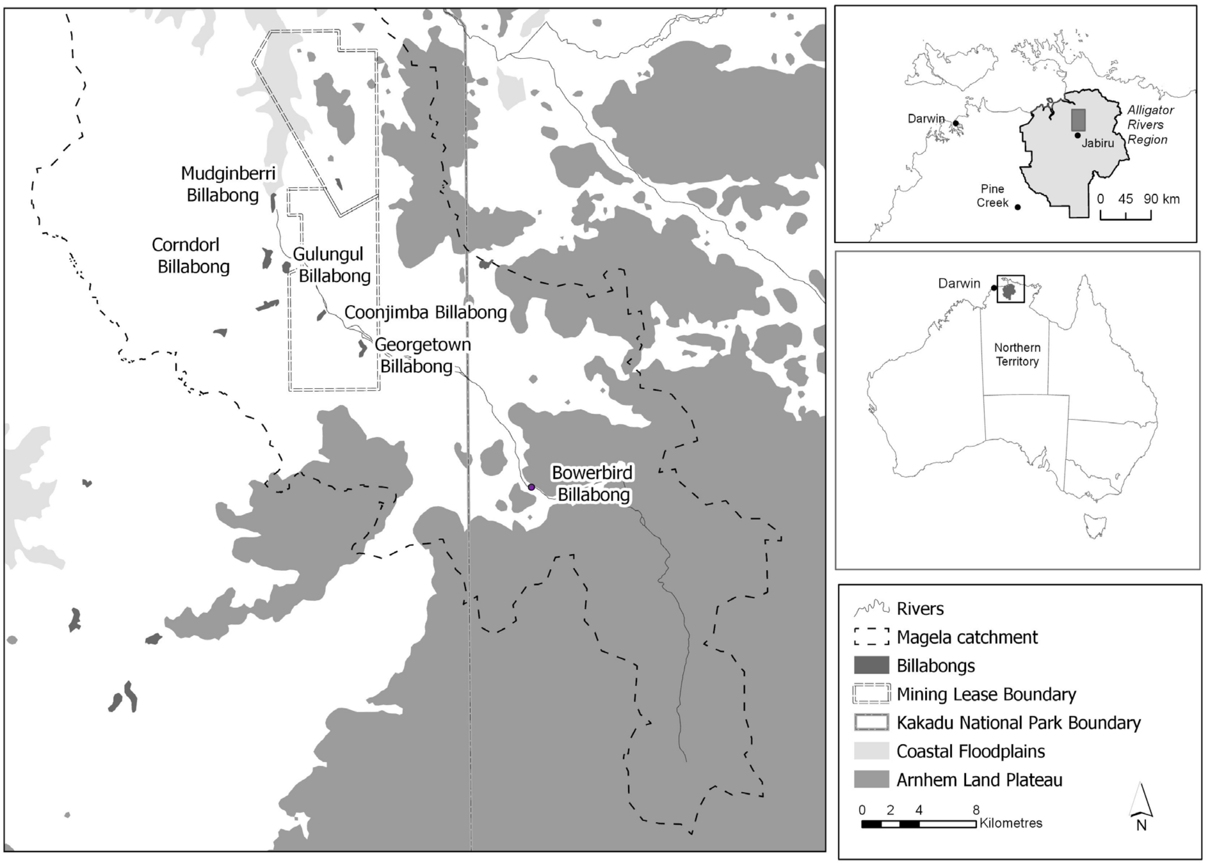


Figure 2.1. Map of the study area.

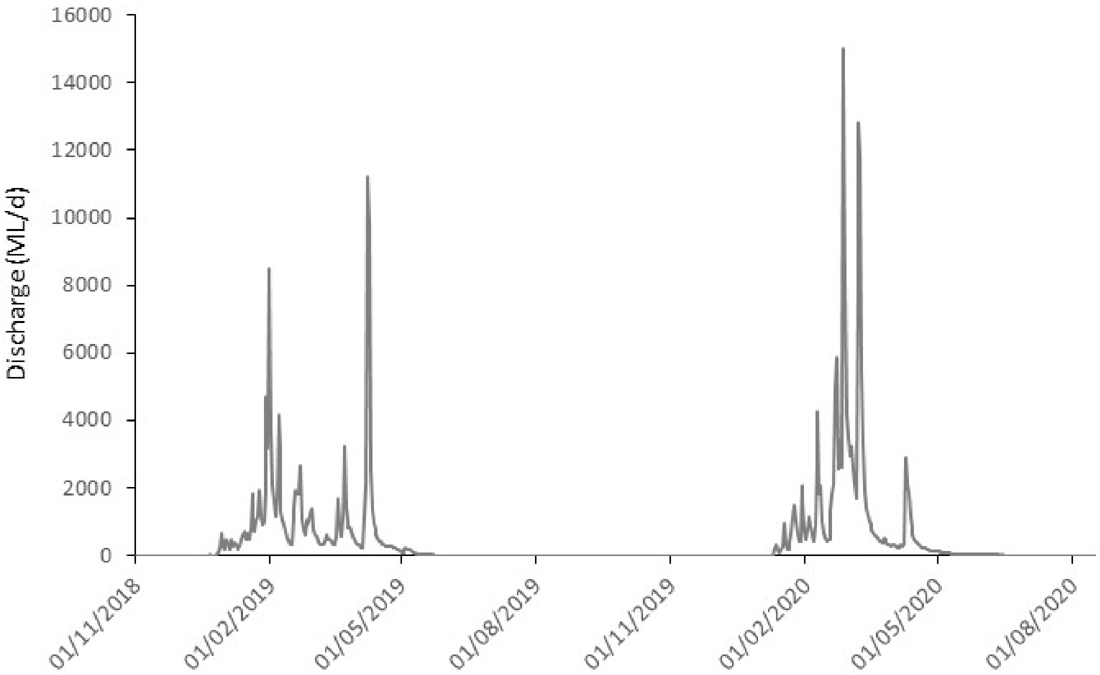


Figure 2.2. Magela Creek hydrology over the study period.

Figure 2.3. Bowerbird Billabong. Photo David Crook.

Figure 2.4. Mudginberri Billabong. Photo Sam Walker.

Figure 2.5. Sand channel region of Magela Creek between Bowerbird and Mudginberri billabong. Photo David Crook.

Figure 2.6. Access to Bowerbird Billabong was by helicopter. Photo Tom Mooney.

2.2 Acoustic telemetry

2.2.1 Fish collection and tagging

Acoustic telemetry was used to examine the movements of fish collected and tagged from Bowerbird Billabong and Mudginberri Billabong. Acoustic transmitters are electronic tags that transmit coded pulses of sound (known as 'pings') that can be decoded and recorded by acoustic receivers to track the movements of tagged fish over time. The first batch of fish tagged were large-bodied species (saratoga [*Scleropages jardinii*], sooty grunter [*Hephaestus fuliginosus*], sharp-nose grunter [*Syncomistes butleri*]) collected with the assistance of the Djurrubu Rangers from Bowerbird Billabong in November 2018 using hook-and-line fishing. Acoustic transmitters (V9-2x-180 kHz, Vemco, Nova Scotia) were surgically implanted into the peritoneal cavities of 24 saratoga, 26 sooty grunter and five sharp-nose grunter (Table 2.1). The V9 transmitters used for these fish had an estimated battery life of ~700 days, allowing the movements of tagged fish to be tracked throughout the array over two wet–dry season cycles (November 2018 to June 2020).

The second batch of fish tagged were smaller-bodied fish (spangled perch [*Leiopotherapon unicolor*], barred grunter [*Amniataba percoides*], black catfish [*Neosilurus ater*]) collected with the assistance of the Djurrubu Rangers in April and May 2019 using cast nets and hook-and-line fishing. These fish were collected from Magela Crossing ~100 m downstream of Mudginberri Billabong, from the upstream end of Mudginberri Billabong, and from the main channel of Magela Creek up to 4 km upstream of Mudginberri Billabong. The objective of this part of the study was to examine the upstream movement of smaller-bodied fish during the recessional flow period at the end of the wet season, as previously described by Bishop et al. (1995). Acoustic transmitters (V5-1x-180 kHz, Vemco, Nova Scotia) were surgically implanted into the peritoneal cavities of 17 spangled perch, 13 barred grunter and nine black catfish (Table 2.2). The V5 transmitters used for these fish had an estimated battery life of 91 days, allowing the movements of tagged fish to be tracked over a single recessional–flow period (April to August 2019).

Fish for tagging with acoustic transmitters were anaesthetised with Aqui-S (0.03 ml/L), weighed (g) and measured (total length and fork length to the nearest mm). Fish were then placed in a V-shaped foam holding cradle lined with wetted absorbent cloth (Figure 2.7). The transmitters were sterilised with Hibitane disinfectant (100 ml/L) and rinsed with sterile saline prior to implantation. Where necessary, several scales were removed from the ventral surface anterior to the anal vent and slightly offset from the midline, and the area swabbed with Betadine. An incision was made in an anterior–posterior orientation into the peritoneal cavity using a sterilised scalpel.

The transmitters were inserted into the peritoneal cavity through the incision and the incision was then closed with a single layer closure using 2–3 interrupted sutures placed into the musculature 3–4 mm beneath the skin (2.0 metric, absorbable monofilament, 26 mm swaged needle, Ethicon). Betadine spray was then applied to the area. The gills were irrigated with fresh river water throughout the procedure (2–4 min). After the procedure, fish were held in fresh river water until normal posture and gill movement had resumed and were then released at the site of collection.

Figure 2.7. Photo of acoustic transmitter being surgically implanted into a sooty grunter. Photo Dion Wedd.

2.2.2 Acoustic array

An array of 10 acoustic receivers (VR2W-180 kH, Vemco, Nova Scotia) was deployed from the downstream end of Mudginberri Billabong to the upper end of Bowerbird Billabong (Figure 2.8). Receivers were attached to riparian trees using plastic-coated wire. Each receiver was weighted down with heavy-gauge metal chain and a float was attached to ensure that the hydrophone remained in an upright position. Data were downloaded from the receivers in December 2018, March 2019, May 2019, August 2019, November 2019, September 2020 and November 2020. Acoustic data were downloaded and archived using the VUE software package (Vemco, Nova Scotia, Canada).

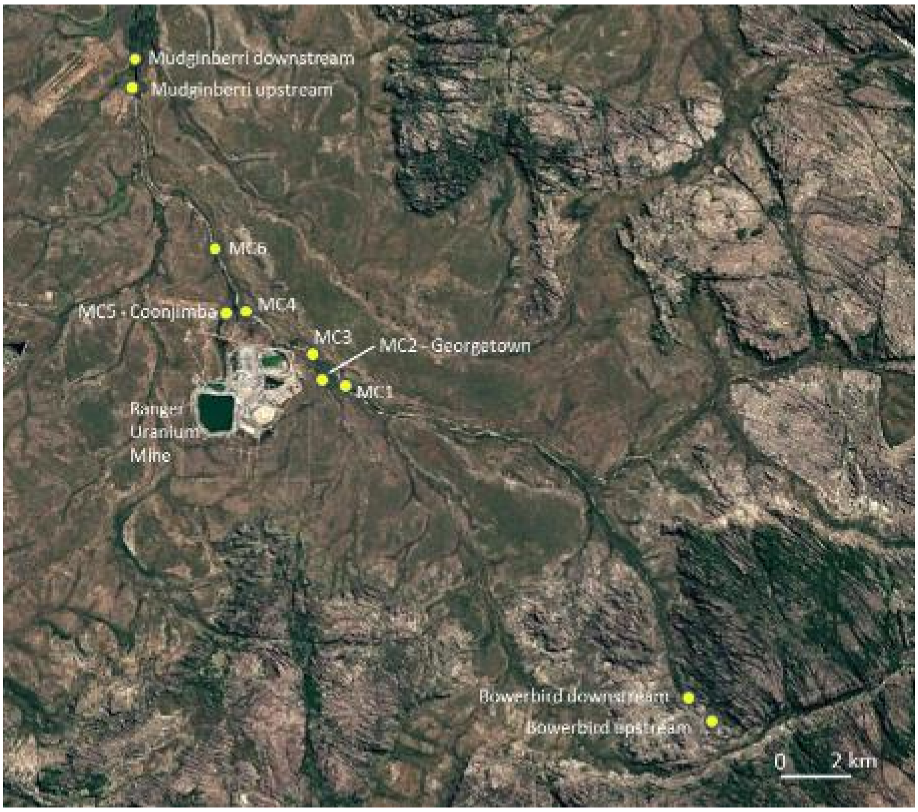


Figure 2.8. Locations of receivers in the passive acoustic array used to track tagged fish.

Table 2.1. Details of fish tracked during the study. SAR = saratoga, SGR = sooty grunter, SNG = sharp-nose grunter. Fish detected in the RUM lease during the study are shaded.

Tagging date	Species	Tag Code	TL (mm)	SL (mm)	Weight (g)	Detections	Final detection	Tracking duration (d)
14/11/2018	SAR	45789	555	485	1340	440,888	06/06/2020	570
14/11/2018	SAR	45791	375	320	315	16,817	16/04/2020	519
14/11/2018	SAR	45941	440	372	530	21,724	24/03/2020	496
14/11/2018	SAR	46049	350	295	300	12,649	17/01/2019	64
14/11/2018	SAR	46052	355	300	280	366,935	06/06/2020	570
14/11/2018	SAR	46106	355	300	285	220,765	06/06/2020	570
14/11/2018	SAR	46307	445	362	670	22,198	10/03/2020	482
14/11/2018	SAR	46335	455	390	665	275,477	19/11/2019	370
14/11/2018	SAR	46425	470	405	790	133,221	06/06/2020	570
14/11/2018	SAR	46433	400	340	415	30,630	18/01/2019	65
14/11/2018	SAR	46464	570	495	1275	116,370	06/06/2020	570
14/11/2018	SAR	46550	410	345	395	70,461	29/04/2019	166
14/11/2018	SAR	46552	440	385	610	405,989	08/04/2020	511
14/11/2018	SAR	46623	450	385	625	433,943	06/06/2020	570
15/11/2018	SAR	46646	365	310	315	12,221	14/04/2020	516
15/11/2018	SAR	46697	450	380	600	81,724	12/03/2020	483
15/11/2018	SAR	46751	495	425	860	24,061	18/02/2020	460
15/11/2018	SAR	46830	384	325	370	8,417	02/12/2018	17
15/11/2018	SAR	47021	450	347	430	17,057	12/03/2020	483
15/11/2018	SAR	47091	715	615	2915	593,803	06/06/2020	569
27/11/2018	SAR	46756	510	425	985	197	14/08/2019	260
27/11/2018	SAR	46776	590	495	1430	112	27/12/2018	30
27/11/2018	SAR	46780	475	400	750	45,238	12/04/2020	502
27/11/2018	SAR	47087	450	370	660	209,663	06/06/2020	557
14/11/2018	SGR	45831	295	255	475	14,894	21/03/2019	127
14/11/2018	SGR	45834	260	215	265	329,319	05/06/2020	569
14/11/2018	SGR	45850	225	180	170	17,568	06/03/2020	478
14/11/2018	SGR	45929	210	170	145	19,251	16/05/2020	549
14/11/2018	SGR	45995	240	200	200	9,327	05/03/2020	477
14/11/2018	SGR	46014	225	182	170	87,759	06/06/2020	570
14/11/2018	SGR	46043	290	240	355	42,739	22/01/2020	434
14/11/2018	SGR	46294	350	285	625	8,201	05/04/2020	508
14/11/2018	SGR	46317	302	250	425	27,891	27/05/2020	560
14/11/2018	SGR	46376	305	255	550	2,181	22/05/2020	555
14/11/2018	SGR	46379	292	242	465	2,011	16/02/2020	459
14/11/2018	SGR	46589	345	285	590	47,736	06/06/2020	570
15/11/2018	SGR	45804	230	196	225	15,220	18/12/2018	33
15/11/2018	SGR	46502	290	245	485	7,643	21/03/2019	126
15/11/2018	SGR	46509	335	280	555	57,520	27/01/2019	73
15/11/2018	SGR	46544	315	275	625	80,656	11/01/2020	422
15/11/2018	SGR	46549	305	257	465	22,382	16/04/2020	518
15/11/2018	SGR	46700	290	242	370	115,378	06/06/2020	569
15/11/2018	SGR	46732	264	235	390	407	24/11/2018	9
15/11/2018	SGR	46762	320	260	505	113,371	19/01/2020	430
15/11/2018	SGR	46790	325	282	630	374,831	14/04/2020	516
15/11/2018	SGR	46832	345	285	650	53,459	23/04/2020	525
15/11/2018	SGR	46873	305	255	500	301,472	15/04/2020	517
15/11/2018	SGR	47044	305	267	550	239,443	12/01/2020	423
27/11/2018	SGR	46740	245	210	270	462	09/01/2020	408
27/11/2018	SGR	46938	300	265	580	7,009	04/04/2019	128
14/11/2018	SNG	45906	190	155	100	10,553	16/12/2018	32
15/11/2018	SNG	46875	320	250	475	13,811	25/04/2020	527
27/11/2018	SNG	46662	290	235	355	40,368	01/06/2020	552
27/11/2018	SNG	47030	295	235	355	0	-	0
27/11/2018	SNG	46822	310	255	415	10,526	27/05/2020	547

Table 2.2. Details of fish tagged with V5 acoustic transmitters in Mudginberri Billabong region downstream of the mine lease. SPG = spangled perch; BGR = barred grunter; BCF = black catfish; MB = Mudginberri Billabong; MC = Magela Crossing below Mudginberri Billabong; USMB = Magela Creek 4 km upstream of Mudginberri Billabong. The single fish detected in the RUM lease during the study is shaded.

Tagging date	Species	Tag Code	Tagging location	TL (mm)	SL (mm)	Weight (g)	Detections	Final detection	Tracking duration (d)
24/04/2019	SPG	45721	MC	98	119	30.1	0	-	-
24/04/2019	SPG	45731	MC	103	118	29.6	0	-	-
24/04/2019	SPG	45768	MC	100	121	31.5	0	-	-
24/04/2019	SPG	45760	USMB	130	155	75.6	0	-	-
25/04/2019	SPG	45713	MC	96	115	30	14	06/07/2019	72
25/04/2019	SPG	45745	MC	101	120	30.5	0	-	-
25/04/2019	SPG	45757	MC	102	123	30.2	0	-	-
25/04/2019	SPG	43754	USMB	95	114	30	0	-	-
25/04/2019	SPG	43757	USMB	102	124	35.8	0	-	-
25/04/2019	SPG	43960	USMB	98	115	30.1	0	-	-
25/04/2019	SPG	45177	USMB	111	130	40.5	0	-	-
25/04/2019	SPG	45232	USMB	107	124	38.4	0	-	-
25/04/2019	SPG	45632	USMB	94	112	30.1	0	-	-
25/04/2019	SPG	45636	USMB	132	155	74.1	0	-	-
25/04/2019	SPG	45661	USMB	100	122	30.3	0	-	-
25/04/2019	SPG	45696	USMB	122	141	50.8	0	-	-
25/04/2019	SPG	45752	USMB	108	130	42.1	0	-	-
24/04/2019	BGR	45770	MC	116	138	54	187,121	08/08/2019	106
25/04/2019	BGR	45623	MC	103	125	33	0	-	-
25/04/2019	BGR	45649	USMB	100	125	42.8	21	25/05/2019	30
26/04/2019	BGR	42713	MC	121	153	62	65,045	06/08/2019	102
26/04/2019	BGR	42717	MC	124	155	72.5	157	13/05/2019	17
08/05/2019	BGR	42740	MB	138	173	93.1	4,417	16/06/2019	39
08/05/2019	BGR	42757	MB	122	155	67.4	58,396	12/08/2019	96
08/05/2019	BGR	43269	MB	134	160	66	9,477	30/05/2019	22
08/05/2019	BGR	43274	MB	120	144	54.1	145	13/05/2019	5
08/05/2019	BGR	42649	MC	90	109	26	79,309	10/08/2019	94
08/05/2019	BGR	42884	MC	143	170	92.8	0	-	-
08/05/2019	BGR	43042	MC	134	164	79.5	14,217	06/06/2019	29
08/05/2019	BGR	43236	MC	94	116	29.1	0	-	-
26/04/2019	BCF	42615	MC	234	260	168	0	-	-
26/04/2019	BCF	42673	MC	302	318	322	143,193	12/08/2019	108
26/04/2019	BCF	42732	MC	245	274	188	13,409	30/06/2019	65
26/04/2019	BCF	43261	MC	242	271	174	5,284	31/05/2019	35
26/04/2019	BCF	43266	MC	260	293	202	29,837	29/07/2019	94
26/04/2019	BCF	45153	MC	243	279	174	3,051	08/05/2019	12
08/05/2019	BCF	42772	MC	252	294	214	48,897	11/08/2019	95
08/05/2019	BCF	43050	MC	238	267	139	5,127	18/08/2019	102
08/05/2019	BCF	43186	MC	285	315	274	29,573	14/06/2019	37

2.2.3 Data analysis

To examine the likelihood of tagged fish being present in the RUM lease under different stream discharge, each fish's daily location was assigned a zero (outside of mine lease) or one (inside of mine lease). We then used generalised additive mixed models fitted with a binomial distribution to model, for each species separately, the probability of individual saratoga or sooty grunter being within the mine lease as a function of river discharge. A random intercept was included for each fish to account for the repeated measures nature of the data and a cubic regression smoother was fitted to stream discharge. Zero discharge was recorded on 46.4% of days and the remaining discharges were heavily skewed. We therefore applied a 4th root transformation to discharge to improve model fit and aid model interpretation. Model comparison was conducted using Akaike information criterion.

2.3 Sonar surveys

2.3.1 Sonar imaging system

The imaging system used for this study was the ARIS (Adaptive Resolution Imaging Sonar) 1800 Explorer (Sound Metrics Corp, Bellevue, WA, USA). The ARIS 1800 unit produces video-like images using sound energy instead of light. High resolution sonar imaging systems are becoming increasingly popular for fisheries-related applications and have been used to assess fish behaviour, to count fish measure abundance and to identify fish (Becker et al. 2017; Lankowicz et al. 2020).

The ARIS 1800 Explorer produces 96 beams of sound energy at 1.1 or 1.8 MHz. Each beam has a 14° vertical view and a 0.3° horizonal view. This provides an overall coverage of 14° vertically and 28.8° horizontally. The images of fish and structure produced by the ARIS software are displayed as seen from above (i.e. plan view). At a frequency of 1.8 Mhz, objects as small as 3 mm can be detected up to 15 m away. At 1.1 Mhz, the useful range extends to 35 m although transmission loss is significant and image resolution is reduced. Based on the species likely to be encountered and their size ranges, we operated the unit at a frequency of 1.8 Mhz, with range settings varying from 10.3–10.8 m.

The ARIS transducer requires 36–42 VDC power to operate and is supplied with a 240VAC-42VDC transformer. If used in this configuration the transducer requires a 240 VAC power source, such as mains power or a portable generator. The use of a fuel-powered portable generator in an aluminium boat was likely to create excessive noise and vibration, potentially preventing fish from exhibiting normal behaviour (Becker et al. 2017). To address this issue, we developed a portable power solution consisting of a 36 V, 21 Ah, LNCM (lithium, nickel, cobalt and magnesium) battery built specifically for our purposes. The battery is housed permanently in a Pelican case and weighs less than 5 kg (Lithium Batteries Australia and Off Grid Power, www.lithbattoz.com.au). This battery can power the ARIS continuously for approximately 60 hours and can be fully charged in less than one hour. To mount the transducer, we designed and built an aluminium tripod with an adjustable horizontal mount that allowed pitch adjustments of +/-45° from horizontal.

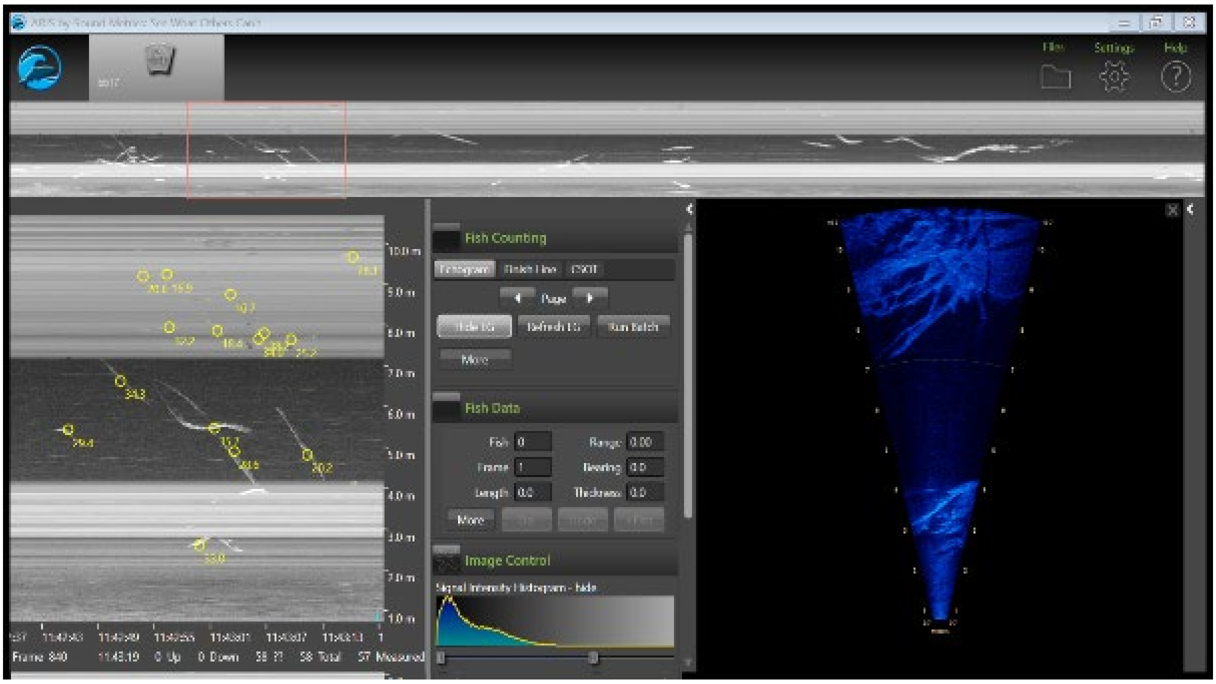
2.3.2 Sampling methodology

Sampling occurred in Mudginberri and Bowerbird Billabongs during daylight hours in December 2018 (‘build-up 1’), February/March 2019 (‘wet’), May 2019 (‘post-wet’), August 2019 (‘dry’) and November 2019 (‘build-up 2’). For each sampling period, up to 30 five-minute segments of sonar footage (‘shots’) were collected in each billabong. Sampling coverage was maximised by dividing each billabong into repeatable transects. Mudginberri Billabong was divided longitudinally into three transects, two ~15 m out and parallel to the east and west bank and one in the centre. Each transect was then divided into 10 repeatable sampling locations. The entire length of Mudginberri Billabong was accessible, and it was sampled in its entirety. The much narrower Bowerbird Billabong was divided longitudinally in half, creating one transect in the centre of the billabong. Fifteen sampling points were assigned from the centreline and two samples were recorded at each sampling point, one towards the southwest bank and the other towards the northeast bank. Rocky outcrops and shallow riffles prevented access upstream of Bowerbird Billabong, restricting sampling to 1.2 km of the complete 10 km pool–riffle sequence in which fish take year-round residence. The points chosen to sample along each transect included a variety of different habitat types to ensure representation of the available habitat. When sampling adjacent to a bank, the transducer was lowered into the water and aimed towards the bank. When sampling the middle transect of Mudginberri Billabong, the transducer was positioned parallel to the bank. Sonar pitch, relative to horizontal or 0°, varied according to the bottom topography. Once settled on the bottom, the live footage was closely examined to ensure effective coverage and correct angular orientation and any positional adjustments were carried out prior to recording. All recorded files were backed up on a hard drive for later analysis.

2.3.3 Data processing

Length-frequency data for each species was collected using the counting and measuring tools provided in the ARISFish software (Figure 2.9). Fish were identified to family level based on a descending hierarchy of physical characteristics including body shape, fin size and position, swimming pattern based on tail beats and body undulations over time (see Mueller et al. 2010), overall body size and, when present, the shape of the acoustic shadow (see Langkau et al. 2012). The characteristics identified as the most useful for each family were based on observer experience. Secondary verification was made by viewing footage captured simultaneously using a GoPro camera (Hero4, Black, Woodman Labs CA, USA) mounted on the tripod above the transducer, although in most instances water clarity prevented visual identification of targets beyond 1–1.5 m.

During image processing, background subtraction was applied to obtain an echogram of the five-minute shot period. Once the echogram loaded, background subtraction was removed from the footage and cross-talk reduction applied to remove artefacts. The footage was run for the five-minute duration and fish families were tentatively identified and their location on the echogram marked for final analysis during counting. Individual fish were measured using the ARISFish software. Discrepancies in measurement accuracy were considered (see Cook et al. 2019) and multiple measurements were taken and then averaged if the target's approach angle to the transducer prevented a full-length observation.



Fish 0
Range 0.00
Frame 1
Bearing 0.0
Length 0.0
Thickness 0.0

Frame 840 11:43:19 0 Up 0 Down 58 ?? 58 Total 57 Measured

Figure 2.9. Soundmetrics software interface used to convert sonar images into fish identifications and measurements.

2.3.4 Fish abundance estimation

The abundance of fish from each family in each billabong was estimated based on the number of fish counted in each five-minute shot. Since each shot was recorded from a stationary position, individual fish may have been recorded multiple times in each five-minute shot (see Ebner and Morgan 2013). To address this issue, we calculated MaxN, which is a widely used approach that limits duplicate counts of the same fish from video or hydroacoustic data (Becker et al. 2011). To calculate MaxN, we viewed the footage for each shot in its entirety and then selected time periods that displayed the maximum number of individuals within a taxonomic family group, and counted and measured those individuals. This was repeated for all family groups identified. The time period to record our $\text{MaxN}_{(\text{family})}$ counts depended on the time taken for individuals within that family group to enter and exit the field of view (see Watson et al. 2009).

2.4 Historical observations of fish movement (1985–1999)

Observations of fish movement in the Magela Creek channel were made daily through the months of February to April, spanning the period 1985 to 1999, with results to 1993 described in Bishop et al. (1995). The direct observation technique involved a stationary observer, located on the western bank of Magela Creek at ERA release point MG001, making counts of fish moving upstream or downstream across a line perpendicular to the water flow over a prescribed time (1 hr). Counts were standardised by the observer being in an elevated position (2–3 m) and using polarising glasses.

2.5 Fish behavioural responses to mine discharge in Magela Creek

A field-based examination of fish behaviour associated with an operational mine-water release from the MG001 discharge point on Magela Creek was undertaken in March 2021. The aim of this activity was to observe the behaviour of migrating fish interacting with a water release to determine whether there were contaminant concentration thresholds that could inhibit fish migration. Treated mine-waters are released into Magela Creek at ERA release point MG001. Releases occur by pumping mine-waters into a concrete bund adjacent to the creek, where they overflow through release ports, spilling down the bank and into the creek. Channels form as mine-waters travel down the bank and into the creek (Figure 2.10, Figure 2.11).

Figure 2.10. Retention pond 1 water being released into Magela Creek at MG001. Photo Tom Mooney.

Figure 2.11. Location where retention pond 1 water enters Magela Creek at MG001. Photo Tom Mooney.

2.5.1 Fish observations

Fish were observed migrating upstream past MG001 in Magela Creek on 3 March 2021. Observations were made from the bank and using underwater videography. Two cameras – one on the western bank and one on the eastern bank – were deployed in the creek to observe the interaction of fish with mine-waters entering Magela Creek. Cameras were mounted on a submersible stand and left to record for a minimum of 70 minutes. Mine-waters entered the creek on the western bank, along the preferential migration path for fish (Tom

Mooney pers. obs. supporting observations of Bishop et al. [1995]). Video processing time was standardised across videos at 60 minutes with five minutes settling time. Abundances were measured using MaxN, the maximum number of fish for a given species present in one frame for the 60-min analysis period following methods used by Ebner and Morgan (2013) and King et al. (2018). Videos were processed by trained SSB staff and identification was taken to species level for all fish.

2.5.2 Water quality parameters

Water-chemistry samples were collected prior to fish observations from inside the release bund, Magela Creek eastern bank and Magela Creek western bank where mine-waters mixed with Magela Creek water. Water samples and blank and procedural blank samples were filtered (0.45 µm) and analysed for a metal and major ion suite (Al, Co, Cr, Cu, Fe, Mn, Ni, Pb, U, Zn, Ar, Bo, Ba, Br, I, Li, Ca, K, Mg, Na, Cl, SO_4 [inferred from S]). Water-quality parameters (pH, DO, EC, turbidity and temperature) were measured in situ (EXO3 multiparameter sonde) at the same location that water chemistry samples were collected, as well as immediately upstream of the mine discharge. Additional water-chemistry data for Ranger on-site backflow billabongs, Coonjmba and Georgetown, were acquired from Energy Resources of Australia Ltd to match observations of tagged fish movement into the billabongs during the wet seasons.

3. Results

3.1 Acoustic telemetry

3.1.1 Downstream movement into the RUM lease – Bowerbird Billabong

Fifty-four of the 55 fish tagged in Bowerbird Billabong were detected during the study, with a single sharp-nose grunter not detected after tagging (Table 2.1). The average tracking duration of detected fish was 415 days (n = 24, range: 17–570 days) for saratoga, 406 days (n = 26, range: 9–570 days) for sooty grunter and 415 days (n = 4, range: 32–552 days) for sharp-nose grunter. More than 5.6 million detections were recorded during the study, with 42 fish detected more than 10,000 times and 16 fish detected more than 100,000 times (Table 2.1). Ten (42%) saratoga, five (19%) sooty grunter and one (25%) sharp-nose grunter were detected in the RUM lease during the study (Figure 3.1, Figure 3.2), with the remaining fish detected only on the listening stations deployed near the tagging site at Bowerbird Billabong. Downstream movement into the RUM lease for all three species was initiated soon after the first wet-season flows. Results of the generalised linear modelling showed that downstream movement into the lease was strongly related to the amount of flow in the creek, with the likelihood of tagged saratoga and sooty grunter being present in the RUM lease increasing substantially at flows greater than ~50 ML/d (Figure 3.3). There was insufficient data to run similar analyses for sharp-nose grunter.

Three of the five sooty grunter that moved into the RUM lease reached the Ranger discharge point, but none of these were detected further downstream in either year of the study (Figure 3.2). Of the 10 saratoga that moved into the RUM lease, seven reached the discharge point and six of these subsequently moved further downstream. One of these six fish moved downstream beyond the RUM lease to Mudginberri Billabong (~33 km downstream of Bowerbird Billabong), where it was detected on the most downstream listening station on 6 February 2019 and again on 24 March 2019. It appears likely that this fish had moved further downstream into the lower floodplain reaches of the Magela Creek system during this time, before moving back upstream to Bowerbird Billabong by 5 April 2019. The single sharp-nose grunter that moved into the RUM lease reached the discharge point in the first year. In the second year, this fish moved through the lease and was last detected in Mudginberri Billabong, having presumably moved further downstream from Mudginberri Billabong into the lowland, floodplain reaches of Magela Creek.

Homing behaviour

A striking feature of the data for all species was the accurate upstream homing behaviour exhibited towards the end of the wet season. All five of the sooty grunter that moved into the RUM lease made return movements back to the same ~1 km reach of Bowerbird Billabong in the first year of the study, with three fish also exhibiting similar behaviour the following year (the transmitters on the other two fish ceased being detected during the second year). Most sooty grunter made multiple (up to five) return movements between Bowerbird Billabong and the lease in the same year. Six saratoga (including the fish that reached Mudginberri Billabong) also timed their return to Bowerbird Billabong as wet-season flows decreased in the first year (Figure 3.1), with one fish undertaking two return movements in the first year. Another two saratoga were detected in the upstream region of the lease as flows receded in the first year but not in Bowerbird Billabong in the 2019 dry season, suggesting that these fish may have moved into permanent water just downstream of the billabong listening stations prior to the 2019 dry season (Figure 3.1f, g). Two saratoga completed return movements in the second year, while one that had moved downstream the previous year was not detected in the lease in the second year. Transmitters for the remaining saratoga that moved into the lease in the first year ceased being detected at various stages during the second year. The single sharp-nose grunter that entered the RUM lease made three return movements in the first year before moving downstream out of the study area during high flows in the second year (Figure 3.2f).

Use of backflow billabongs

Three saratoga and one sooty grunter were detected in Ranger on-site backflow billabongs during the study (Figure 3.1, Figure 3.2). Their movements are described below.

Saratoga 46780 (Figure 3.1c) moved downstream from Bowerbird Billabong into the RUM lease on 27 January 2019 before moving into Georgetown Billabong 11 hours later. It was detected in Georgetown Billabong until early April and made two excursions back to the main channel during this time, including one return movement to Bowerbird Billabong. It was detected in Georgetown Billabong on 11 April 2019 and then returned to Bowerbird Billabong where it spent the 2019 dry season. The maximum residence time spent in Georgetown Billabong was 75 days. The following wet season, this fish moved back downstream to Georgetown Billabong where it was detected from 27 January until its final detection there on 12 April 2020, that is, a potential maximum residence time of 77 days.

Saratoga 46646 (Figure 3.1g) moved downstream from Bowerbird Billabong and was detected in Georgetown Billabong from 29 January to 8 April 2019, a 70-day period. It was detected on multiple occasions moving within the main channel (MC1 to MC6) during this time. After moving upstream of the RUM lease over the 2019 dry season (but not detected at Bowerbird Billabong), this fish was detected back in Georgetown Billabong from 24 January to 8 February 2020, a 16-day period. It then moved back into the main channel where it was last detected at MC6 on 14 April 2020.

The single sooty grunter (46762, Figure 3.2c) that used a backflow billabong moved downstream from Bowerbird Billabong into the lease on 3 January 2019 before moving into Georgetown Billabong on 13 January. It was detected in Georgetown Billabong until 26 March 2019, making one excursion to the main channel during this time. It then moved back upstream to Bowerbird Billabong where it spent the 2019 dry season. The maximum residence time spent in Georgetown Billabong in 2019 is 73 days. This fish returned to the RUM lease the following wet season on 10 January 2020 and was last detected in the main channel on 19 January 2020.

Water-quality sampling over the periods in which tagged fish were present in Georgetown Billabong in 2019 showed a mean magnesium of 3.8 mg/L (maximum = 5.75 mg/L), mean manganese of 7.4 µg /L (maximum = 20.5 µg/L), and mean dissolved oxygen of 4.5 mg/L (minimum = 0.33 mg/L). In 2020, mean magnesium was 2.4 mg/L (maximum = 3.7 mg/L), mean manganese was 7.0 µg /L (maximum = 13.8 µg/L), and mean dissolved oxygen was 3.8 mg/L (minimum = 2.5 mg/L).

The only fish that was detected in Coonjimba Billabong during the study was a saratoga (46307, Figure 3.1e) that entered the RUM lease and moved into Coonjimba Billabong on 20 February 2019, where it was detected four times over a 2-minute period before returning to the main channel. Around the time of this brief visit, magnesium was estimated to be 8.3 mg/L, manganese 20 µg/L and dissolved oxygen 2.7 mg/L (measured 18 February 2019). This fish returned to the main channel, where it was infrequently detected until 9 April, before moving upstream to Bowerbird Billabong by 15 May 2019 where it spent the 2019 dry season. The following wet season, this fish was once again detected in Coonjimba Billabong (628 detections from 31 January to 3 March 2020, a 33-day period), before leaving Coonjimba Billabong and moving back into the main channel. During the extended period of residency by this fish in Coonjimba Billabong in 2020, mean magnesium was 9.3 mg/L (maximum = 11.20 mg/L), mean manganese was 41.4 µg/L (maximum = 107 µg/L), and mean dissolved oxygen was 2.7 mg/L (minimum = 0.76 mg/L).

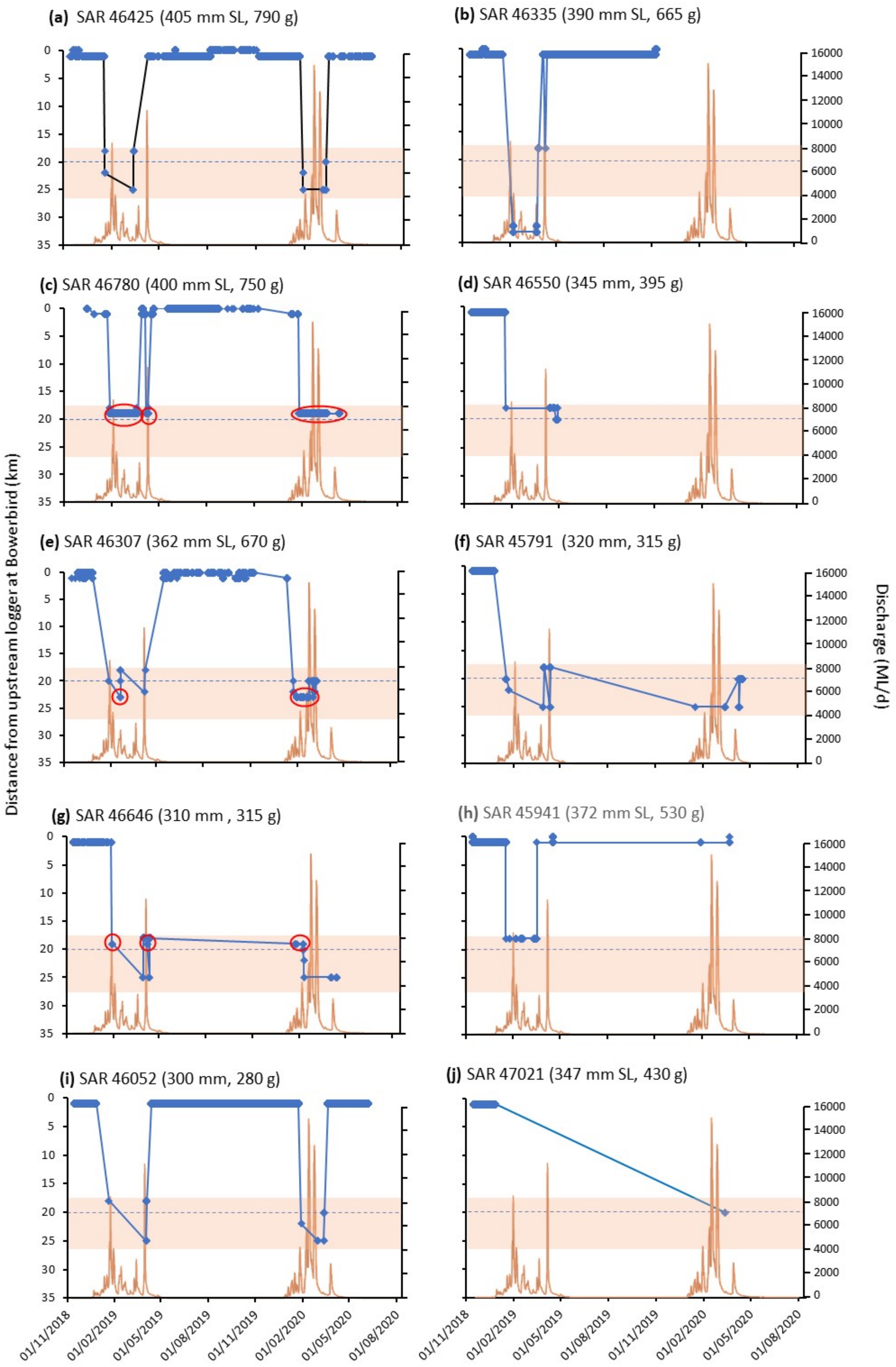


Figure 3.1. Movements of the ten saratoga (SAR) that entered the RUM lease during the study. Blue symbols represent tag detections and a blue line connects consecutive detections. Red ellipses show time spent in backflow billabongs. The orange shaded area shows the approximate locations of the RUM lease and the broken line shows the discharge location (MG001). The orange line shows creek discharge. Tag codes, standard lengths and weights are shown for each fish.

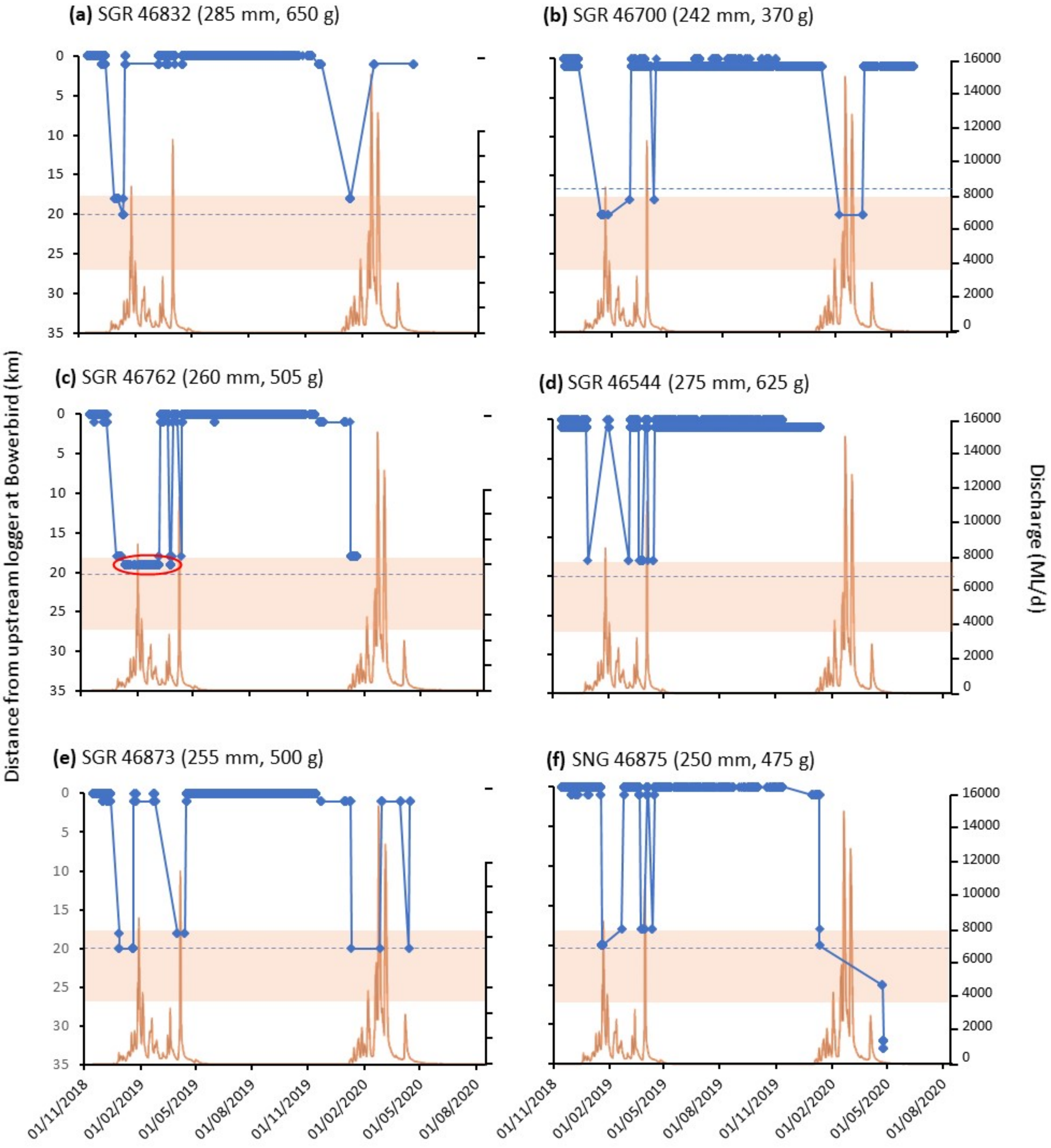


Figure 3.2. Movements of the five sooty grunter (SGR) and one sharp-nose grunter (SNG) that entered the RUM lease during the study. Blue symbols represent tag detections and a blue line connects consecutive detections. Red ellipses show time spent in backflow billabongs. The orange shaded area shows the approximate locations of the RUM lease and the broken line shows the discharge location (MG001). The orange line shows creek discharge. Tag codes, standard lengths and weights are shown for each fish.

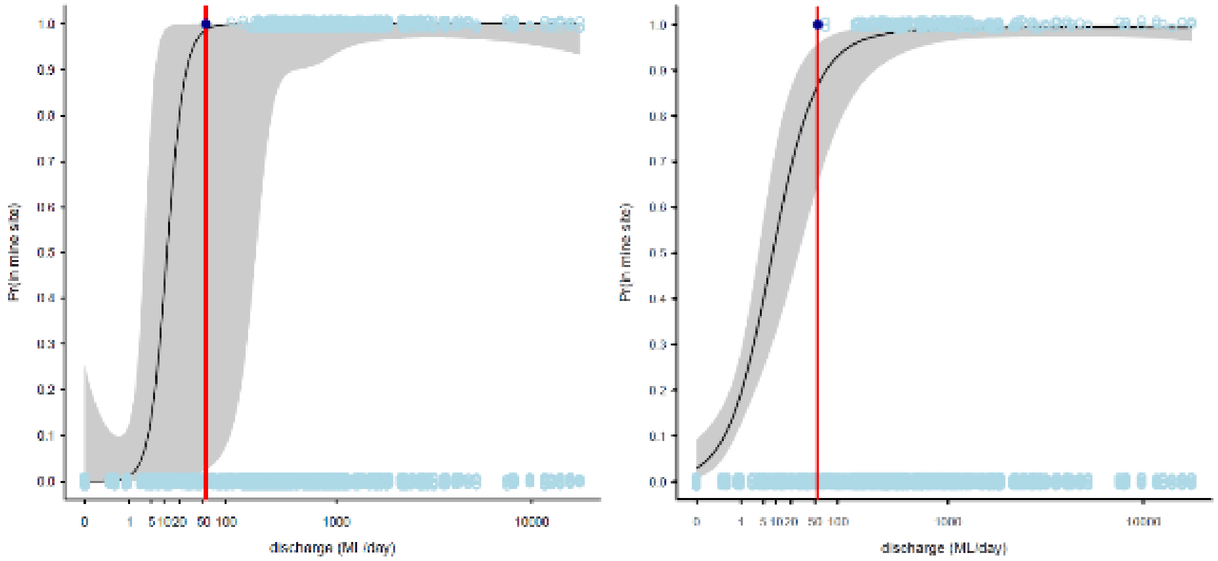


Figure 3.3. Results of mixed effects generalised linear modelling showing the likelihood (Pr) of saratoga (left) and sooty grunter (right) occurring in the RUM lease relative to creek discharge. The red line shows the minimum flow when fish were detected in the lease.

Movement in Bowerbird Billabong region

Fish that were detected only in Bowerbird Billabong (i.e. upstream of the RUM lease) were recorded very frequently during the dry season but had much lower detection rates during wet-season flow events, suggesting a wider range of movement in the reaches above the mine lease during this period for the three species (Figure 3.4).

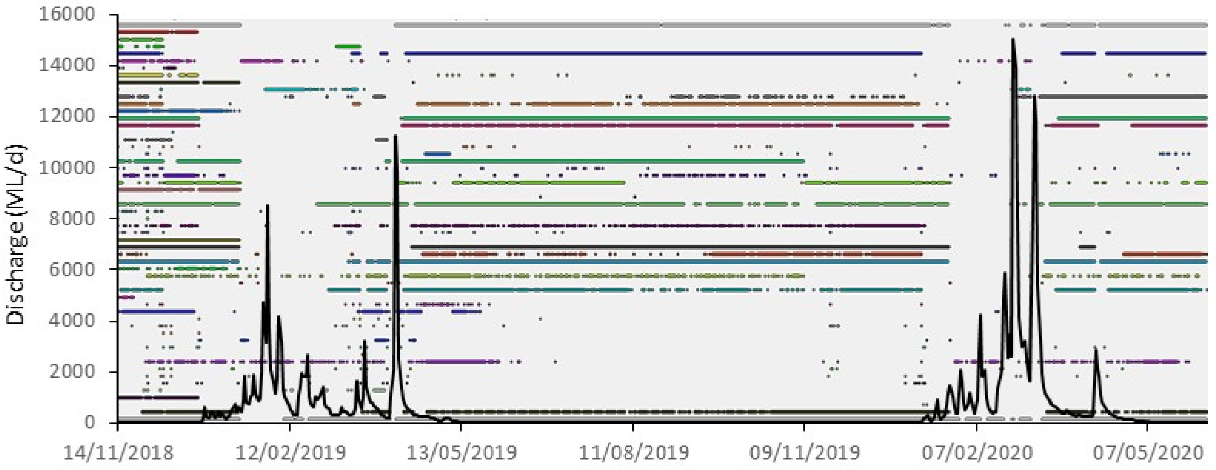


Figure 3.4. Plot showing detections of tagged fish at the downstream Bowerbird Billabong acoustic receiver over the study period. Each row of data points shows the detections for an individual fish and the solid line shows creek discharge (gauge G8210009). This figure demonstrates the reduction in detections in Bowerbird Billabong during periods of high flow, which is attributed to migration into the RUM lease and localised movements upstream of the lease.

3.1.2 Upstream movement of mid-sized fish species from Magela Creek and Mudginberri Billabong

Of the nine black catfish tagged at Magela Crossing in late April and early May 2019, eight were subsequently detected in Mudginberri Billabong for between 12 and 108 days after tagging (Table 2.1). One of these fish (tagged on 26 April 2019) was detected on 7 May 2019 within the RUM lease ~8 km upstream of Mudginberri Billabong (MC6) and on 8 May 2019 (MC1) (Figure 3.5a). Flows during this upstream movement ranged from ~150–250 ML/d (Figure 3.5a). This fish was not detected on the main channel receivers between MC1 and MC6 (MC3, MC4). Although fish tagged at Bowerbird Billabong were detected at MC3 and MC4 on high flows during the wet season, it appears that receivers MC3 and MC4 were not placed within the channel(s) that were used by the two upstream migrating fish on recessional flows.

Of the eight barred grunter tagged at Magela Crossing, five were subsequently detected in Mudginberri Billabong for 17–106 days after tagging (Table 2.1). The four fish tagged at the upstream end of Mudginberri Billabong were all subsequently detected in Mudginberri Billabong for 5–96 days after tagging. None of these fish were detected upstream of Mudginberri Billabong. The single barred grunter tagged upstream (4 km) of Mudginberri Billabong was detected three times on 14 May 2019 in the RUM lease at MC6 and 18 times on 25 May 2019 at MC1 (Figure 3.5b). Flow in Magela Creek was 29 ML/d when this fish was detected at MC6 and 0.2 ML/d when the fish reached MC1 at the upstream end of the RUM lease (Figure 3.5b). Similar to the black catfish that moved upstream, this fish was not detected on the main-channel receivers between MC1 and MC6 (MC3, MC4). This failure to detect upstream migrating fish on receivers MC3 and MC4 is likely due to the braided nature of the Magela Creek channel in the RUM lease area, which provides fish with multiple channels in which to migrate.

Of the six spangled perch tagged at Magela Crossing, only one was detected in Mudginberri Billabong (Table 2.1). Assuming no tagging mortality, the remaining fish presumably spent the recessional flow and subsequent dry season in permanent pools downstream of Mudginberri Billabong. The single spangled perch that moved into the main body of Mudginberri Billabong was detected 14 times on 6 July 2019 on the downstream receiver, 72 days after it was tagged. Of the 11 spangled perch tagged up to 4 km upstream of Mudginberri Billabong, none were detected in the acoustic array.

In summary, these results suggest that the majority of spangled grunter, barred grunter and black catfish still resident in the Mudginberri Billabong region during recessional flows in April to May did not move further upstream into the RUM lease or to the escarpment refuge habitats. This finding, in combination with the sonar survey data (see below), suggests that most movement by mid-bodied fish species through the RUM lease occurs earlier in the wet season than the late stages of the recessional flow period. Nonetheless, a small proportion of tagged fish moved through the RUM lease area during recessional flows and were detected moving in the sand channels under very low flows. Given that these migrating fish were not subsequently detected at Bowerbird Billabong, it appears likely that a proportion of late-migrating fish either take up residence in residual pools or become stranded in the drying sand channels as flow ceases. Residency of fish in residual pools of Magela Creek over the dry season has previously been demonstrated by Woodland and Ward (1992).

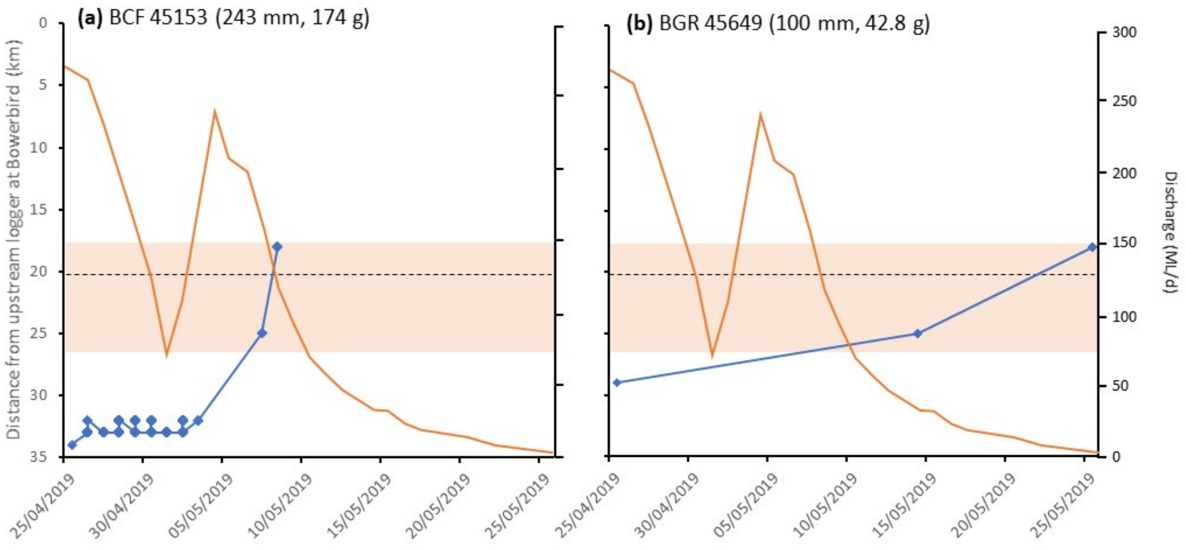
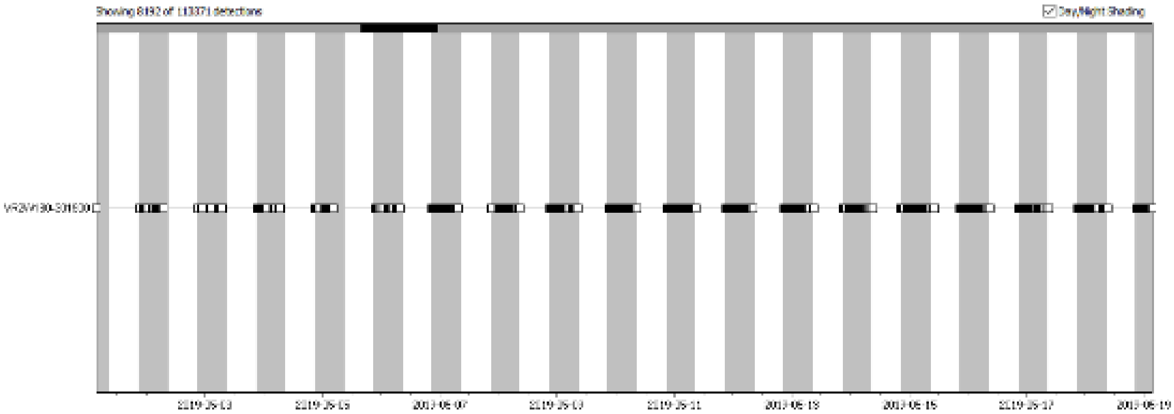


Figure 3.5. Movements of the one black catfish (BCF) and one barred grunter (BGR) that moved upstream into the RUM lease on recessional flows at the end of the wet season. Blue symbols represent tag detections and a blue line connects consecutive detections. The orange shaded area shows the approximate locations of the RUM lease and the broken line shows the discharge location (MG001). The orange line shows creek discharge. Tag codes, standard lengths and weights are shown for each fish.

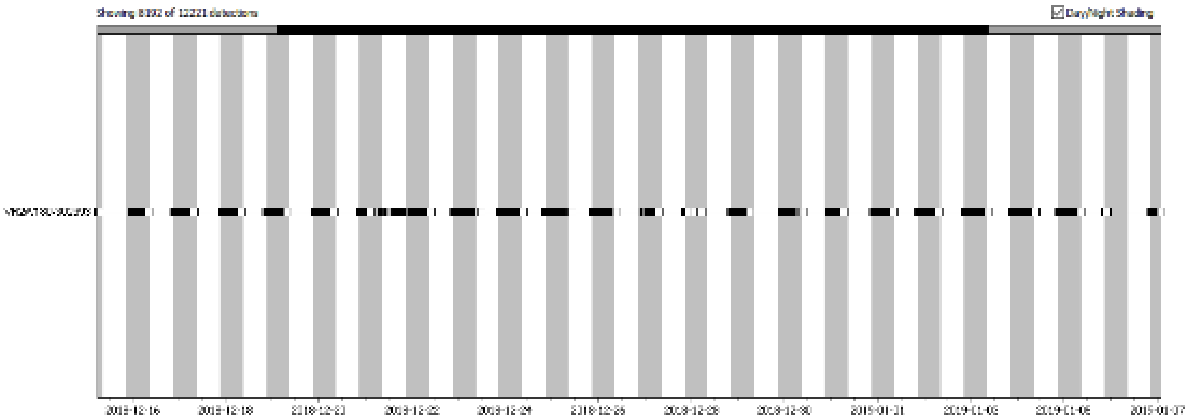
3.1.3 Diel patterns of activity

Although the focus of the current study was on the broad-scale movements of fish in Magela Creek, the acoustic telemetry data also revealed periods of strong diel activity by some the tagged fish. During the dry season in Bowerbird Billabong, several saratoga and most sooty grunter showed periods of strong diurnal (daytime) activity, while sharp-nose grunter exhibited periods of strong nocturnal (night-time) activity (Figure 3.6). In Mudginberri Billabong, black catfish and barred grunter both exhibited periods of strong diurnal activity (Figure 3.6; Figure 3.7). We did not collect sufficient data on spangled perch to make any inferences on diel activity for this species. Although the timing of diel activity was generally very strong and consistent for periods of up to several weeks, consistent diel patterns did not occur throughout the entire dry season for most fish.

(a) SGR 46762



(b) SAR 46646



(c) SNG 46822

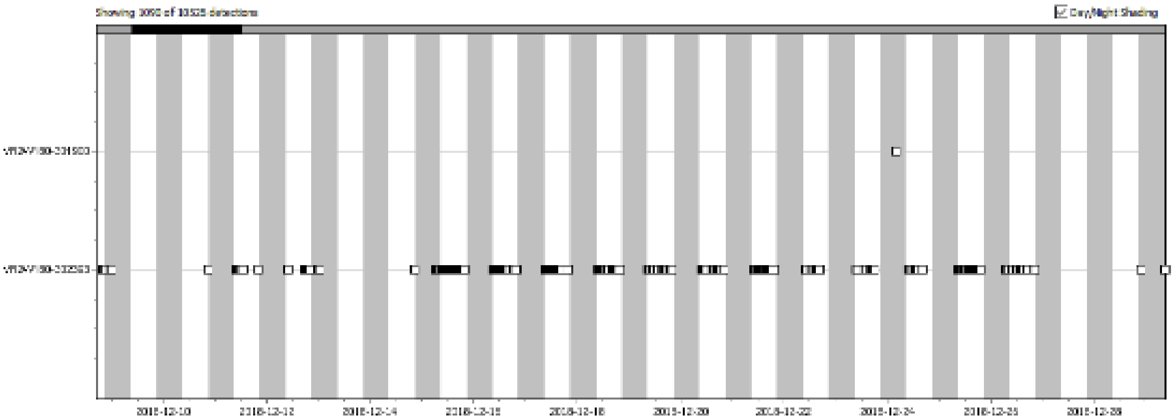
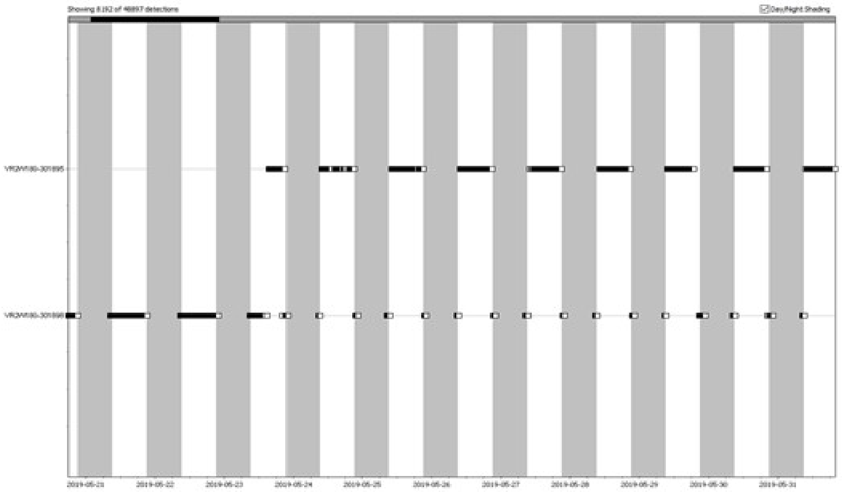


Figure 3.6. Screen shots of VUE acoustic tracking software showing examples of increased daytime detections (square symbols) of (a) sooty grunter 46762 and (b) saratoga 46646, and night-time detections of (c) sharp-nose grunter 46822 in Bowerbird Billabong during the dry season. Shaded bars represent daytime.

(a) BCF 42772



(b) BGR 42713

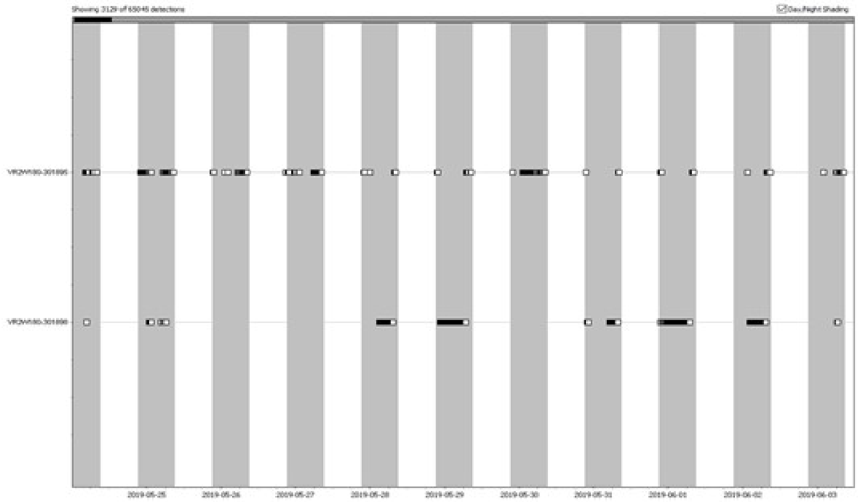


Figure 3.7. Screen shots of VUE acoustic tracking software showing examples of increased daytime detections (square symbols) of (a) black catfish 42772 and (b) barred grunter 42713 in Mudginberri Billabong during the dry season. Shaded bars represent daytime.

3.2 Sonar surveys

Deployment of the ARIS sonar in Mudginberri Billabong and Bowerbird Billabong allowed us to obtain sonar video of sufficient quality to identify fish to the family level and to measure the total lengths of individual fish (Figure 3.8). The number of fish in Bowerbird Billabong ranged from 8.0 to 19.5 fish per five-minute shot and was generally much lower than Mudginberri Billabong which ranged from 6.5 to 59.2 fish per shot. The only time that relative total fish numbers were higher in Bowerbird Billabong than Mudginberri Billabong was during the wet season (Table 3.1). Total fish numbers peaked in Bowerbird Billabong during the dry season, whereas fish density peaked in Mudginberri Billabong during the build-up surveys.

The length-frequency plots (Figure 3.9) show a large influx of fish of 20–30 cm length in Bowerbird Billabong in the post-wet survey, but these fish declined in abundance in subsequent surveys. In contrast, very few fish of <10 cm were observed in the post-wet survey, but there was a sharp increase in the abundance of small fish in the dry-season survey. Mudginberri Billabong had higher relative numbers of large-bodied fish (>40 cm) than

Bowerbird Billabong, including large numbers of forktail catfish (*Neoarius* sp.), saratoga, tarpon (*Megalops cyprinoides*), bony herring (*Nematalosa erebi*), and barramundi (*Lates calcarifer*) up to 127 cm length. Small-bodied fish <10 cm were extremely abundant in Mudginberri Billabong in all surveys except for the wet-season surveys where numbers of all size classes were drastically reduced. Small-bodied fish were particularly abundant in Mudginberri Billabong during the two surveys conducted during the build-up season.

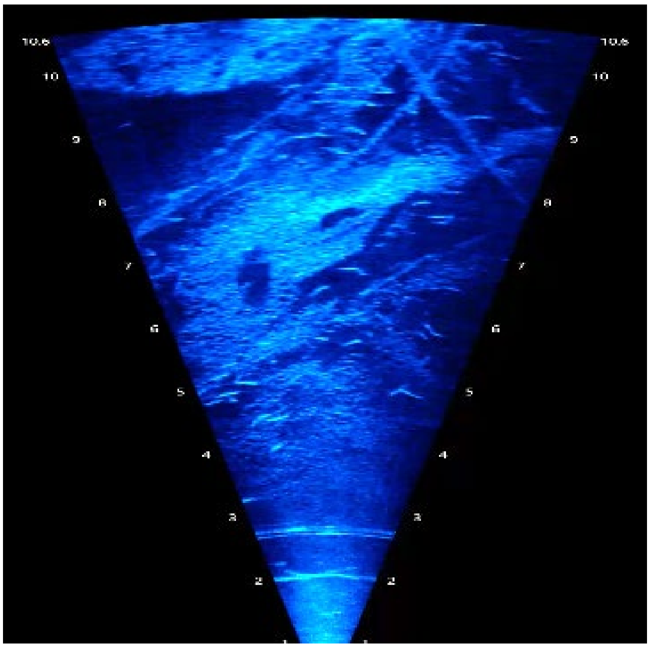


Figure 3.8. Example of plan-view sonar image used to estimate fish abundance and biomass. This image shows a school of eel-tail catfish swimming above woody structure on the riverbed. The numbers at the side of the image show the distance in metres from the sonar camera.

The most consistently abundant families recorded in the sonar surveys were bony herring (Clupeidae), rainbowfish (Melanotaenidae), eel-tailed catfish (Plotosidae) and grunters (Terapontidae) (Figure 3.10). The abundances of each taxonomic group were highly variable among the surveys. For example, the abundance of bony herring varied by two orders of magnitude in both Bowerbird and Mudginberri billabongs across the five survey periods, with highest abundances in the build-up periods and lowest abundance in the dry season.

Table 3.1. Summary of fish observations from ARIS sonar surveys (all fish taxa pooled).

Site	Survey	Shots	Number of fish	Fish per shot
Bowerbird	Build-up 1	26	209	8.0
	Wet	30	305	10.2
	Post-wet	26	486	18.7
	Dry	21	410	19.5
	Build-up 2	30	337	11.2
Mudginberri	Build-up 1	30	1,374	45.8
	Wet	30	196	6.5
	Post-wet	23	619	26.9
	Dry	30	938	31.3
	Build-up 2	30	1,775	59.2

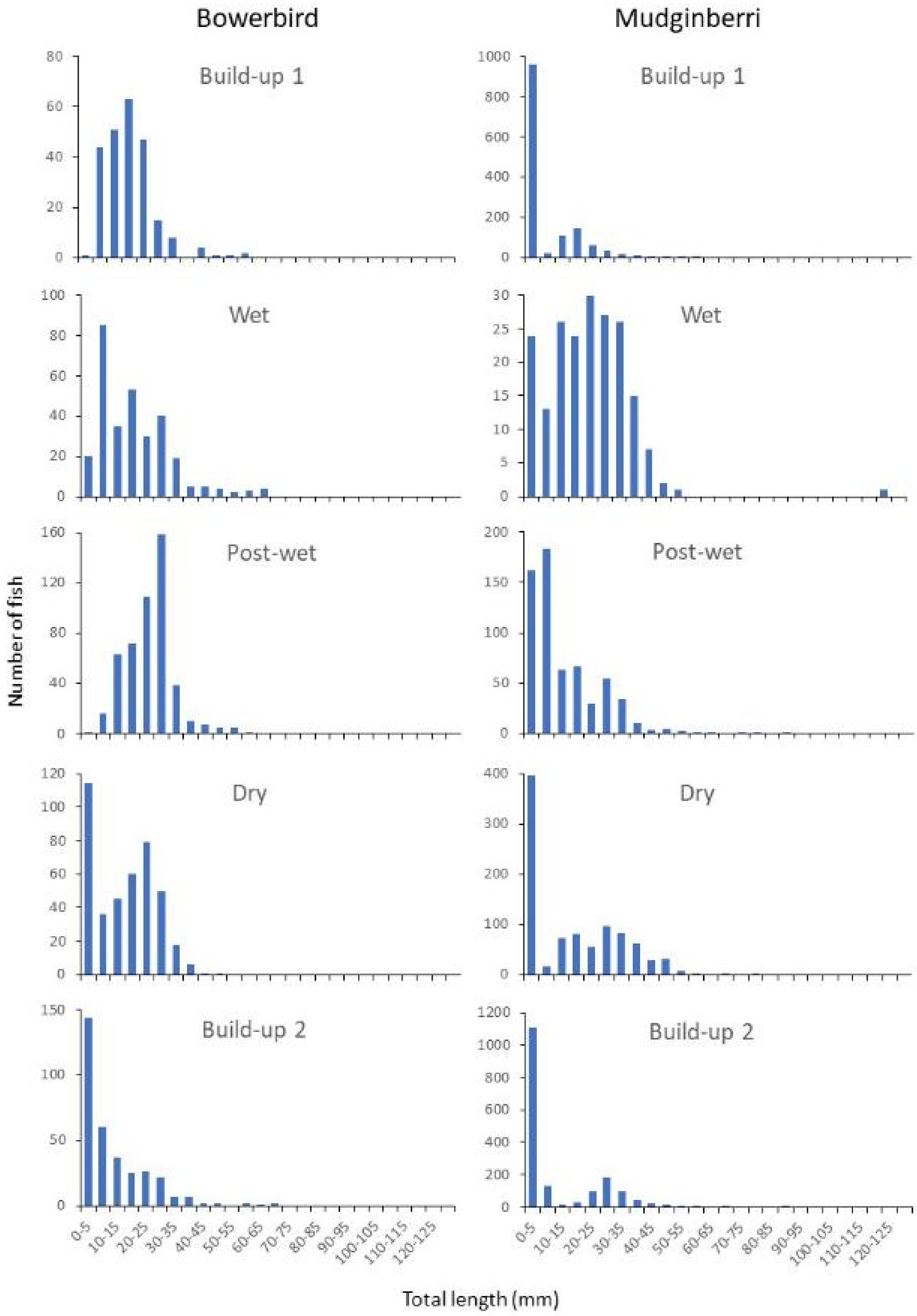


Figure 3.9. Length-frequency histograms showing the size distributions across all fish species for each season and location. Note that the x-axis scale is different for each graph.

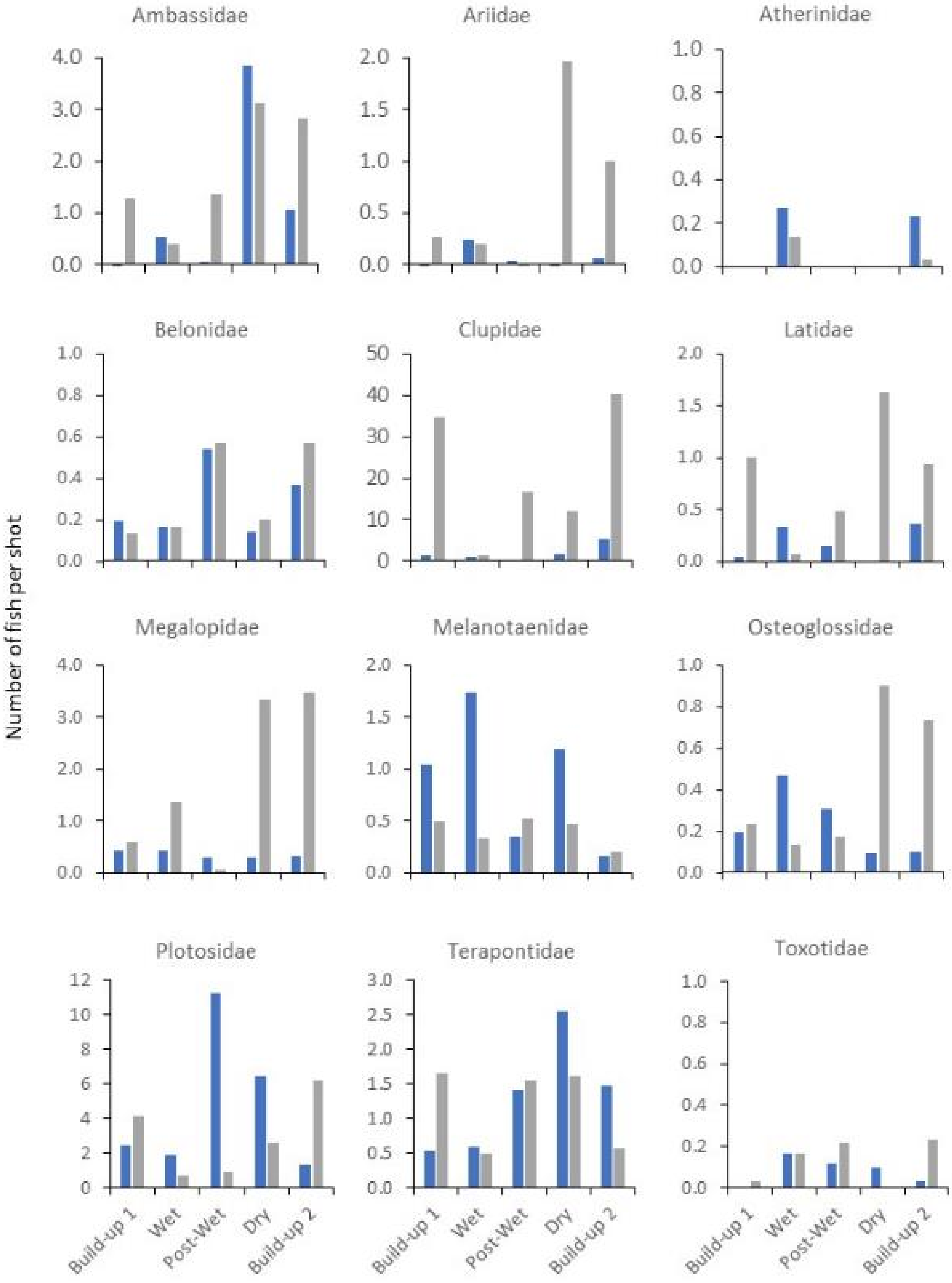


Figure 3.10. Mean number of fish from each taxonomic group per five-minute sonar 'shot' across the five seasonal sonar surveys. Blue bars = Bowerbird Billabong; grey bars = Mudginberri Billabong.

3.3 Historical observations of fish movement (1985–1999)

The collated fish observation data from 1985 to 1999 showed that 30 different species were observed at the survey site in the sand channel region of Magela Creek, with 29 species observed February to March and 26 species observed April to May (Table 3.2). Very few large-bodied fish were observed during the historical counts with the vast majority of fish represented by small or mid-sized species, or juveniles of large-bodied species such as sooty grunter and sharp-nose grunter.

Small-bodied species dominated the data set, with chequered rainbowfish (*Melanotaenia splendida inornata*) and glassfish (*Ambassis* sp.) by far the most abundant species migrating past MG001. Chequered rainbowfish contributed 59% of the net upstream migration February to March and 28.6% April to May. Glassfish contributed 33.6% of the net upstream migration February to March and 68.7% April to May. With the exception of Rendahl's catfish (*Porochilus rendahli*), which was observed in very low abundance, all species exhibited net upstream migration. It should be noted, however, that many species (including the large-bodied barramundi, tarpon and saratoga) were observed in very low numbers (<1 fish/hour) during the surveys. There was strong variation in the abundance of migrating fish among months (February, March, April) and among years. On average, smaller fish species (*Ambassis* sp., *Melanotaenia splendida inornata*) had a propensity to migrate upstream earlier in the wet season (February, March) versus late wet season (April), whereas migrations of the mid-sized fish species (e.g. barred grunter) and juveniles of the larger fish species (e.g. sooty grunter, Midgley's grunter [*Pingalla midgleyi*]) occurred during the late wet season/early recession (Figure 3.11).

While daily fish migration observations between 1985 and 1999 spanned additional months to those reported in Table 3.2 and Figure 3.11 (i.e. January and June), movement in January, May and June was much reduced over that recorded for the February to April period. Mean daily flow in Magela Creek near RUM for the months of January, February, March, April and May for the 1985–1999 period was 1,235, 2,652, 1,728, 665 and 53 ML/d respectively. Given that very little fish movement was observed in the May period, this provides support that the same flow constraints limiting residence of adults of large-bodied species tagged in this study to the sand channels and billabongs near RUM (>50 ML/d, Section 3.1.1) also limit residence of the larger suite of species observed historically, that is, upstream migration back to the escarpment billabongs had largely ceased at flows <50 ML/d.

Table 3.2. Midday fish movement (mean number/hour) in Magela Creek at RUM during late wet season from 1985 to 1999. n = number of separate observations in sample.

Scientific name	**Feb–Mar (n=542)**			**Apr–May (n=377)**			**Total (n=919)**		
	US	DS	Net	US	DS	Net	US	DS	Net
Ambassis	1030.2	19.6	1010.5	3155.6	113.3	3042.3	1902.1	58.0	1844.0
Amniataba percoides	40.8	1.4	39.4	79.9	7.5	72.4	56.8	3.9	52.9
Arius leptaspis	0.002	0.000	0.002	0.000	0.000	0.000	0.001	0.000	0.001
C. stercusmuscarum	18.8	2.1	16.7	14.6	5.5	9.1	17.1	3.5	13.6
Craterocephalus marianae	5.1	1.4	3.7	25.6	7.7	17.8	13.5	4.0	9.5
Denariusa bandata	0.5	0.2	0.3	0.8	0.0	0.8	0.6	0.1	0.5
Glossamia aprion	1.0	0.0	0.9	1.5	0.1	1.4	1.2	0.1	1.1
Glossogobius giuris	0.009	0.007	0.002	0.000	0.000	0.000	0.005	0.004	0.001
Hephaestus fuliginosus	1.4	0.1	1.3	3.1	0.3	2.9	2.1	0.2	1.9
Hypseleotris compressa	0.018	0.000	0.018	0.005	0.003	0.003	0.013	0.001	0.012
Lates calcarifer	0.006	0.000	0.006	0.008	0.008	0.000	0.007	0.003	0.003
Leiopotherapon unicolor	89.1	6.7	82.4	127.1	160.7	-33.6	104.7	69.9	34.8
Megalops cyprinoides	0.018	0.011	0.007	0.011	0.000	0.011	0.015	0.007	0.009
Melanotaenia nigrans	23.7	2.2	21.5	16.9	1.6	15.3	20.9	2.0	19.0
Melanotaenia splendida inornata	1884.3	104.6	1779.7	1540.5	275.3	1265.1	1743.3	174.6	1568.6
Mogurnda mogurnda	0.083	0.002	0.081	0.942	0.435	0.507	0.435	0.180	0.256
Nematalosa erebi	4.0	2.6	1.4	6.2	2.0	4.1	4.9	2.4	2.6
Neosiluris hyrtlii	9.7	0.1	9.6	3.7	0.2	2.7	7.3	0.1	6.8
Neosilurus ater	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1
Ophisternon gutturale	0.002	0.000	0.002	0.000	0.000	0.000	0.001	0.000	0.001
Oxyeleotris lineolata	0.090	0.006	0.085	0.032	0.005	0.027	0.066	0.005	0.061
Oxyeleotris nullipora	0.061	0.007	0.054	0.003	0.000	0.003	0.037	0.004	0.033
Pingalla midgleyi	9.9	0.5	9.4	15.6	1.0	14.6	12.2	0.7	11.5
Porochilus rendahli	0.000	0.000	0.000	0.127	0.515	-0.387	0.052	0.211	-0.159
Pseudomugil gertrudae	0.004	0.000	0.004	0.000	0.000	0.000	0.002	0.000	0.002
Pseudomugil tenellus	0.358	0.004	0.354	0.817	0.019	0.798	0.546	0.010	0.536
Scleropages jardini	0.072	0.007	0.065	0.090	0.005	0.085	0.079	0.007	0.073
Strongylura kreffti	2.6	0.6	2.0	2.2	1.3	0.9	2.4	0.9	1.5
Syncomistes butleri	0.234	0.004	0.231	0.257	0.029	0.228	0.244	0.014	0.230
Toxotes chatareus	11.7	0.3	11.4	6.4	1.4	5.0	9.5	0.8	8.8
Total	3157	146	3011	5006	580	4426	3916	324	3591
Number of species		29			26			30	

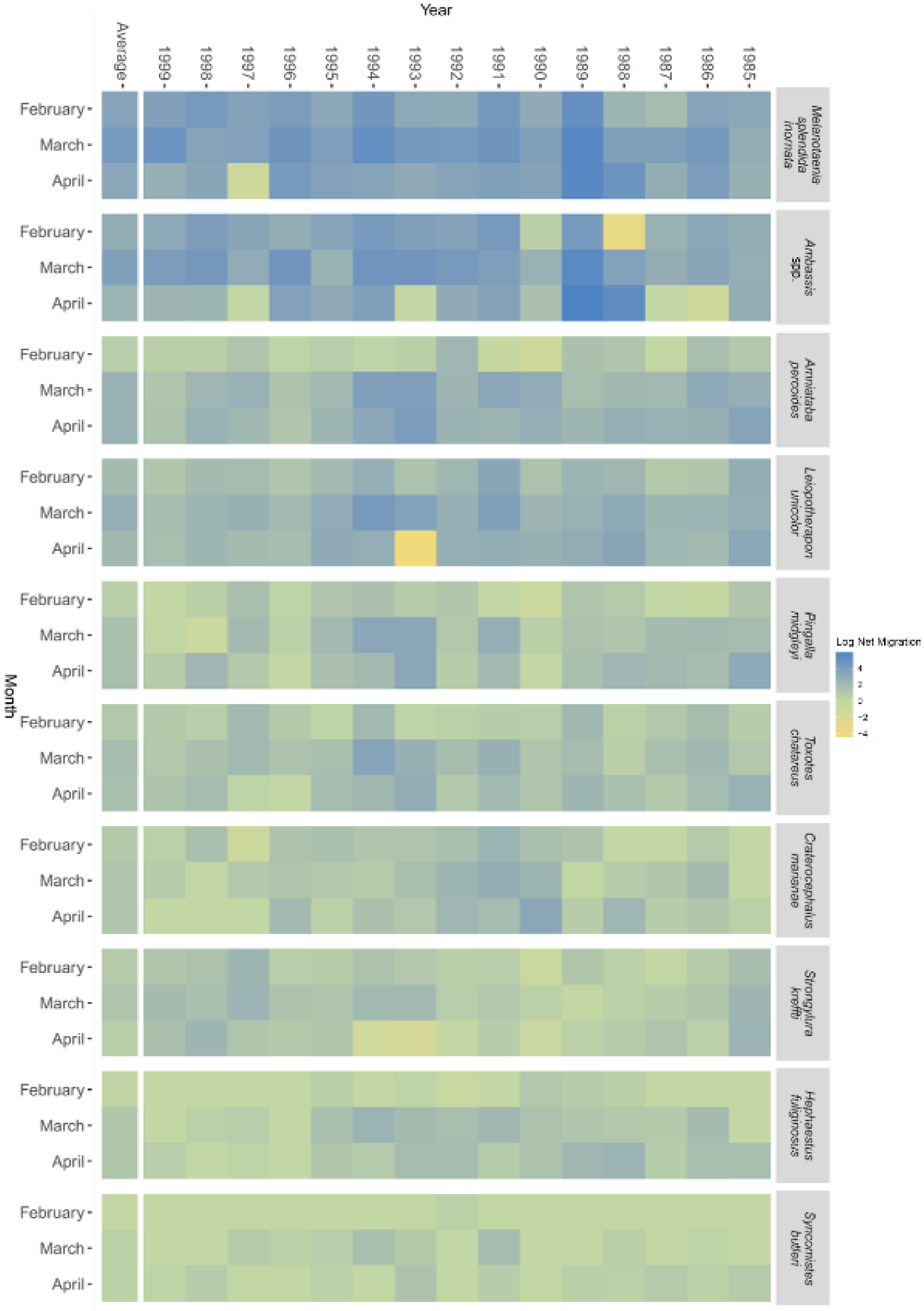


Figure 3.11. Patterns of net migration (mean number/hour) in Magela Creek during late wet season from 1985 to 1999.

3.4 Responses to mine discharge

During the surveys of fish at the mine discharge site, schools of chequered rainbowfish (*Melanotaenia splendida inornata*) were observed swimming through mine-water plumes and preferentially swimming up mine-water channels to the base on the bund wall. Rainbowfish were also observed inside the bund which contained 100% retention pond 1 (RP1) water. The western bank position was near the main mine-water and creek-water mixing location. The camera on the western bank was placed near the main discharge and mixing channel. At this location the camera recorded a constant migration of fish swimming upstream past the camera. Twelve species of fish were recorded at this location and the MaxN for each species was determined (Table 3.3). The most abundant fish species observed were chequered rainbowfish, glassfish (*Ambassis agrammus*), and hardyhead (*Craterocephalus stercusmuscarum*). The camera on the eastern bank observed five species and MaxN abundances were less than those recorded for the western bank (Table 3.3). Schools of fish migrating upstream along the eastern bank were more intermittent compared to the western bank.

Table 3.3. The species and abundance (MaxN) of fish observed using underwater videography. MaxN = the maximum number of fish observed in a single frame of video.

Species	Eastern Bank (MaxN)	Western bank mine discharge channel (MaxN)
Ambassis agrammus	0	15
Amniataba percoides	1	3
Craterocephalus stercusmuscarum	2	13
Hephaestus fuliginosus	0	1
Lates calcarifer	0	1
Leiopotherapon unicolor	1	1
Melanotaenia splendida inornata	16	25
Melanotaenia nigrans	0	1
Pingalla midgleyi	0	1
Scleropages jardini	0	5
Strongylura kreffti	0	1
Toxotes chatareus	1	7

Magela Creek has naturally low electrical conductivity (EC) as represented by the Magela Creek upstream and eastern bank EC measurements (Table 3.4). Water contained within the release bund had an EC of 130 µS/cm. The release water had elevated concentrations of Mn, U, Mg, Na, K and Ca when compared to the concentrations in Magela Creek. When mixed with Magela Creek water, mine-waters were diluted, reducing the EC and concentrations of mining-related contaminants (Table 3.4, Table 3.5).

Table 3.4. Water-quality parameters of mine waters and Magela Creek water.

Location	pH	Electrical conductivity (µS/cm)	Dissolved oxygen (%)	Turbidity (NTU)	Temperature (°C)
Release bund	6.3	130	6.5	4.17	29.9
Eastern bank	5.8	11.7	95.7	1.56	30.0
Western bank discharge channel	6.3	85	75	2.9	30.3
Upstream of discharge	6.1	14.7	92	2.2	30.4

Table 3.5. Water chemistry for each sampling and observation location.

Location	Al (µg/L)	Co (µg/L)	Cr (µg/L)	Cu (µg/L)	Fe (µg/L)	Mn (µg/L)	Ni (µg/L)	Pd (µg/L)	U (µg/L)	Zn (µg/L)
Release bund	52	0.18	0.2	0.24	280	88	1.2	0.07	2.1	0.4
Eastern bank	74	0.13	0.2	0.27	170	4.7	0.15	0.05	0.066	10
Western bank	76	0.12	0.2	4	240	14	0.68	0.26	0.36	8.6

Location	Ar (µg/L)	Bo (µg/L)	Ba (µg/L)	Br (µg/L)	I (µg/L)	Li (µg/L)	Mg (mg/L)	Ca (mg/L)	Na (mg/L)	K (mg/L)
Release bund	0.2	20	8	31	13	0.3	11	2.5	3.4	1.9
Eastern bank	0.06	10	2	14	4	0.3	0.5	0.3	1.2	0.2
Western bank	0.07	20	4	17	4	0.4	2	0.7	1.7	0.4

4. Discussion

4.1 Fish movement and assemblage structure in Magela Creek

A primary objective of this study was to identify the sources of colonisation and patterns of spatial and temporal residency by fish in the Magela sand channels and backflow billabongs. The acoustic tracking component of the study provides important new information on the migration and residency patterns of fish, including the first detailed data on the movements of saratoga and sharp-nose grunter. A key finding of the study was the large-scale movements undertaken during the wet season by the saratoga, sharp-nose grunter and sooty grunter tagged at Bowerbird Billabong. Although the majority of tagged fish were detected only on the listening stations deployed near the tagging site at Bowerbird Billabong, 10 (42%) saratoga, five (19%) sooty grunter and one (25%) sharp-nose grunter were detected in the RUM lease during the wet season.

Downstream movement by these fish was usually initiated on a rising hydrograph during high-flow events. Analysis of fish residency in relation to stream discharge showed that there was a very high probability of large-bodied fish from Bowerbird Billabong being present in the mine lease area once flows exceeded 50 ML/d. Many of the fish that took up residence in the sand channels or backflow billabongs during the wet season returned to Bowerbird Billabong at the end of the wet season, and several of these fish repeated the same pattern of movement in the second year of the study. These findings are similar to a previous acoustic and radio-tracking study of barramundi and forktail catfish in the South Alligator River (Crook et al. 2016, 2020), which found that both species undertook large-scale migrations onto the inundated floodplain during the wet season before accurately homing to their previous locations (refuge billabongs) as the floodwaters receded.

Four of the fish that entered the mine lease took up temporary residence in backflow billabongs (Georgetown, Coonjimba) during the wet season, but none of these appeared to use the backflow billabongs as dry-season refuges. Given that only a small proportion of the Bowerbird Billabong fish population was tagged, these observations suggest that significant numbers of fish use the backflow billabongs as habitat during the wet season.

The two saratoga and one sooty grunter detected in Georgetown Billabong appear to have been exposed to magnesium concentrations of up to 5.75 mg/L in 2019 and 3.73 mg/L in 2020. The single saratoga that occupied Coonjimba Billabong was exposed to magnesium concentrations of up to 8.7 mg/L in 2019 and 11.2 mg/L in 2020. These levels are below or approximately equal to the magnesium concentration of 11 mg/L to which fish showed no behavioural response in the field observations (see Section 3.4). From ERA field notes and EC records in Coonjimba Billabong, connectivity of Coonjimba Billabong to the main Magela Creek in the early wet season of 2019 was established between 21 and 29 January – the period when large-bodied fish species from Magela Creek could potentially enter Coonjimba Billabong. Both the ~3-week delay between billabong inundation and detection of the saratoga in the billabong (i.e. 20 February), and lack of any ensuing residence of this fish in the billabong, could suggest unfavourable conditions for fish residence between late January and 20 February. In this period, mean magnesium in the billabong was 8.1 mg/L (maximum = 8.7 mg/L), mean manganese was 28 µg/L (maximum = 40 µg/L), and mean dissolved oxygen was 2.4 mg/L (minimum = 1.9 mg/L). While metal concentrations (magnesium and manganese) in this January–February 2019 period in Coonjimba were no greater than exposure concentrations supporting tagged fish residence in the billabong in 2020 and in Georgetown Billabong in 2019 and 2020, dissolved oxygen concentrations were notably lower than periods supporting fish residence at other times and locations. Thus low dissolved oxygen may have inhibited fish residence in Coonjimba Billabong in 2019. Further research would be required to determine the extent to which fish actively avoid backflow billabongs during periods of elevated magnesium and co-contaminants, and/or when dissolved oxygen levels are low.

With the exception of one eel-tailed catfish and one barred grunter, the mid-bodied species tagged in the Mudginberri Billabong area failed to move upstream into the mine lease. Observations made while in the field suggested that there were very low numbers of upstream migrating fish on recessional flows in the 2018–19 wet season compared to previous years with higher rainfall and stream discharge (Table 3.2). The low numbers of fish and rapidly falling stream discharge in the post-wet period in 2019 made it very challenging to collect fish on recessional flows. While the observations of two upstream migrants demonstrate that some migration occurred through the RUM lease on recessional flows as low as 0.2 ML/d, it is possible that the low flows in the late wet season resulted in a lack of rheotactic response to stimulate the mass upstream migration by fish in Magela Creek.

Nonetheless, examination of the historical observations of fish movement in the sand channels towards the end of the wet season provides strong evidence of extensive upstream migration at the end of the wet season and supports the conclusions of Bishop et al. (1995) that the lowland regions of Magela Creek are an important source of colonisation of the sand channels by fish. The visual observations made from 1985 to 1999 demonstrate that a wide range of species undertake upstream migrations in the sand channels, although rainbowfish and glassfish were by far the numerically dominant species observed migrating upstream during, and at the end of, the wet season. Although migration for most species was in a predominantly upstream direction, the abundance of upstream migrators into the mine lease was temporally variable and, as previously mentioned, likely to be strongly linked to stream discharge.

Another interesting finding of the study was the diel patterns of activity of tagged fish during the dry season, with saratoga, sooty grunter, barred grunter and black catfish showing periods of strong diurnal activity and sharp-nose grunter exhibiting periods of nocturnal activity. Similar patterns of diurnal activity by acoustically tagged sooty grunter were observed in the Daly River as part of a separate NESP-funded project (Crook et al. unpubl. data). These observations of diel activity are consistent with the observations of Bishop et al. (1995) who reported peaks in upstream migration during daylight hours for sooty grunter and barred grunter. As discussed by Bishop et al. (1995), understanding of diel activity is important for any future monitoring of fish assemblages in Magela Creek, as observations may be biased if diel activity is not appropriately accounted for.

The seasonal ARIS sonar surveys provide important information on the assemblage-level implications of migration of fish in Magela Creek. Relative fish abundance (i.e. fish per shot) was generally much higher at Mudginberri Billabong than Bowerbird Billabong. Both billabongs contained large numbers of small-bodied fish (<10 cm) in most surveys; however, the relative abundance of large-bodied fish (barramundi, bony herring, forktail catfish, tarpon, saratoga) was much higher in Mudginberri Billabong, showing that this habitat supports a much greater density of fish than the escarpment refuge habitat at Bowerbird Billabong. An interesting exception to this pattern was during the wet-season survey, where fish numbers decreased dramatically in Mudginberri Billabong. This observation is consistent with the reduction in transmitter detections we observed during the wet season and with previous work on the South Alligator River which demonstrated high levels of dispersal away from dry-season refuge billabongs onto the inundated floodplain during the wet season (Crook et al. 2020). Fish abundance remained more constant in Bowerbird Billabong during the wet season, despite a similar reduction in detections of tagged fish. Reasons for this observation are unclear, but it is possible there was an influx of fish from downstream and/or that resident fish ranged more widely across the 6 km extent of available habitat upstream of the Bowerbird Billabong system and were more often out of range of the receivers during the wet season.

The abundance of glassfish and rainbowfish increased dramatically in Mudginberri Billabong and Bowerbird Billabong in the dry-season survey. The increased abundance of these species in Bowerbird Billabong could either reflect local recruitment or large-scale upstream migration from downstream sources into the escarpment refuges at the end of the wet season, as suggested by Bishop et al. (1995). Recent studies of larval occurrence suggest that glassfish spawn predominantly during the wet season and that rainbowfish have aseasonal reproduction (King et al. 2019), so it is likely that juveniles of both species were present in the lower reaches of Magela Creek at the end of the wet season. While it is possible that recruitment within Bowerbird Billabong explains the increased abundance of glassfish and rainbowfish in the dry season, the timing of spawning and the fact that both taxa have previously been observed migrating upstream in large numbers (Bishop et al. 1995; this report) suggest that the sonar surveys detected an influx of upstream migrants that occurred at the end of the wet season. Given that the 2018–19 wet season was one of the driest in recent history, we would expect an even larger increase in small-bodied fish in Bowerbird Billabong in wet seasons with higher rainfall and stream discharge.

4.2 Fish avoidance of mine-waters

Our direct observations of fish behaviour at the MG001 discharge site in March 2021 aimed to address the issue of whether a contaminant plume in the sand channels might act as a barrier that inhibits fish migration and connectivity in Magela Creek. To put these observations into an appropriate context, we have summarised historical observations on avoidance behaviours of fish during releases of water from Ranger retention pond 4 (RP4) discharged into Magela Creek in the 1984–85, 1985–86 and 1988–89 wet seasons (see text box below).

Observations of fish interactions with mine-waters released into Magela Creek in the current study did not find evidence that fish were deterred or avoided RP1 water released at MG001. In fact, chequered rainbowfish were observed preferentially swimming up discharge channels and were not deterred by EC of up to 130 µS/cm and magnesium concentrations of 11 mg/L. These observations conflict with historical observations of fish avoidance of RP4 water in the field and laboratory.

A comparison of the metal and major ion concentrations in these two waters, historical RP4 and contemporary RP1, does not explain the difference in fish behaviour when exposed to mine waters (Table 3.5, Table 4.1). Additional studies conducted on RP4 water during the 1980s and early 1990s indicate that RP4 water had a higher toxicity than expected based on its metal and major ion concentrations. In 1984–85, it was observed that the digestive glands of mussels resident in RP4 or exposed to RP4 water were coloured dark red. Mussel reproduction upstream and downstream of the RP4 water discharge point in Magela Creek was measured over this same period. A decrease in female mussels bearing embryos and larvae, and a decrease in the quantity of larvae present in marsupia of female mussels was detected up to 120 m downstream of the RP4 water release point (Annual Research Summary 1985). Ecotoxicological testing was conducted on RP4 water using the freshwater Cladocera *Moinodaphnia macleayi*. Toxicity of RP4 water was detected at dilutions of 0.3% RP4 water in Magela Creek water. These field and laboratory responses suggest the presence of an unknown toxicant in RP4 water (Annual Research Summary 1991).

Solvent extraction experiments conducted on the early RP4 water indicated that the unknown toxicant was not extractable in freon or dichloromethane, but it was soluble in methanol, providing evidence of the presence of an unknown polar organic substance (Annual Research Summary 1991). Hence, it is likely that the fish avoidance behaviour observed during the 1980s to early 1990s was in response to this unknown polar organic substance present in RP4 water at the time. There is no recent evidence to suggest such a toxicant is present in current Ranger mine-waters. Based on the lack of avoidance behaviour in fish exposed to RP1 water, we conclude that concentrations of magnesium up to 11 mg/L are unlikely to inhibit the migration of fish in Magela Creek. Further evidence of a lack of avoidance response at these concentrations is provided by the observation of a saratoga that inhabited Coonjimba Billabong over a 35-day period with average magnesium of 9.3 mg/L (maximum = 11.20 mg/L). As previously discussed, however, other aspects of water quality, such as elevated manganese and particularly low dissolved oxygen, may act as deterrents and influence the suitability of habitat for fish in the mine lease area.

Text box 1. Annual research summaries for fish movement observations associated with discharge of water from retention pond 4 (RP4) into Magela Creek from 1984 to 1989.

Annual research summary 1984–85

- Twenty-two fish species were observed moving over the duration of this study. The five most abundant species were analysed to determine their response to RP4 water. Two species showed a response to RP4 water mixed with Magela Creek water at a ratio of 1:12. Chequered rainbowfish were observed moving laterally across the plume of RP4 water during periods of discharge. This increased the net migration rate of fish on the eastern bank of the creek channel. However, net upstream migration remained unaffected. Long toms, *Strongylura krefftii*, were attracted to RP4 water and their net upstream movement increased during discharge periods.
- Laboratory avoidance testing of chequered rainbowfish was conducted with RP4 to validate field observations. Rainbowfish demonstrated a statistically significant ($p<0.01$) avoidance of RP4 water.

Annual research summary 1985–86

- Due to lower water levels and slower flow rate, a greater number of fish were using the eastern bank of the channel for migration, which limited the ability to detect the lateral avoidance of fish migrating upstream to mine-water plumes.

Annual research summary 1988–89

- The response of migrating fish in Magela Creek to February–March 1986 discharges of RP4 waters through Djalkmara Billabong were examined. Emigrations of rainbowfish from Djalkmara Billabong were observed during morning mine-water releases. Two factors may have influenced this observation:
    - Emigrations were generally preceded by large immigrations. An accumulation of fish in the billabong system may have led to overcrowding and increased competition, resulting in the observed outflow of fish.
    - As emigration generally occurred in the morning, unfavourable water quality may have developed overnight resulting in anoxic conditions in the heavily vegetated areas, inducing an avoidance response.
- Laboratory-based avoidance testing using different dilutions of RP4 water mixed with Magela Creek water indicated that fish avoided 100% RP4 water and a mixture of 37% RP4 water. A mixture with 10% RP4 water saw a net increase of fish, similar to the controls of 100% Magela Creek water.

Contaminant concentrations in RP4 water for the three wet seasons are summarised in Table 4.1.

Table 4.1. Physicochemical properties of RP4 water over three wet seasons.

	EC (µS/cm)	Turb (NTU)	pH	Alk (mg/L)	Na (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4 (mg/L)	Cu (µg/L)	Pb (µg/L)	Mn (µg/L)	Zn (µg/L)	U (µg/L)	Ra-226 (mBq/L)
Oct 1984 to Mar 1985																
Max	260	67	9	99	6.4	2	34	3.1	7.6	42	2	<1	28	4	68	210
Min	150	8	7.8	52	3.1	1.1	18	1.8	4	24	1	<1	11	<1	24	140
Mean	210[a]	19[a]	8.4[a]	73[a]	4.6[b]	1.5[b]	26[b]	2.4[b]	6.2[c]	33[c]	1[b]	<1[b]	19[b]	2[b]	40[b]	180[b]
Apr 1985 to Mar 1986																
Max	380	78	8.9	130	10	2.3	47	4.1	9.9	64	3	<1	120	3	110	280
Min	150	4	7.3	50	2.5	1	19	1.6	3.6	25	<1	<1	26	<1	28	160
Mean	250[c]	14[d]	8.0[d]	77[d]	5.4[e]	1.5[e]	28[e]	2.6[e]	5.8[e]	47[e]	2[f]	<1[f]	65[f]	1[f]	62[f]	210[f]
Apr 1988 to Mar 1989																
Max	790	21	8.4	200	15	4.9	110	7.4	17	270	1	1	290	3	420	600
Min	390	2	7.2	50	5.9	2.1	49	3.8	4.9	170	<1	<1	51	<1	25	130
Mean	590[g]	5[g]	7.8[g]	110[g]	9.5[h]	3.4[h]	81[h]	5.6[h]	10[h]	230[h]	1[i]	1[i]	120[i]	1[i]	140[i]	260[i]

Future monitoring considerations

Given the predicted increase in $MgSO_4$ in Magela Creek from surface and groundwater egress of contaminants from the waste rock cover of the final RUM landform, there is a need for ongoing monitoring to ensure that fish populations are not negatively impacted by the legacy effects of the mine in the future. Prior to developing a monitoring program it is important to clearly define the program's objectives and identify appropriate response variables to monitor. Once a monitoring design has been developed it should be placed within an adaptive framework with appropriate feedback of information; for example, a monitoring, evaluation, reporting and improvement (MERI) framework (e.g. Butcher and Schreiber 2020).

In Magela Creek, monitoring of the condition of fish assemblages in refuge and backflow billabongs will provide an indication of any chronic or acute effects of contaminant egress on fish at the assemblage level over time. Response variables that could be used to assess assemblage health include:

- *species composition:* provides information on whether any species (e.g. sensitive species) are lost from particular habitats
- *abundance:* provides information on whether there are declines of particular species
- *biomass:* provides a measure of changes in habitat carrying capacity
- *size structure:* provides information on annual recruitment strength (presence of young-of-year fish) and recruitment variability over time (via length at age relationships).

Methods to collect assemblage condition data need to take into consideration safety, logistics and costs, as well as the quality of data that can be attained from different approaches. Due to the logistical difficulties of accessing refuge sites on Magela Creek, the presence of estuarine crocodiles and the very low water conductivity, we do not recommend physical sampling techniques such electrofishing or netting (e.g. fyke, pop-nets, gill nets) for future monitoring of fish assemblage condition.

The use of videography by SSB to monitor fish assemblages in the Magela Creek system has been highly successful and, with recent advances in automation of video-footage analysis, provides an appropriate method for collecting assemblage condition data for future monitoring. Underwater cameras are suitable for collecting data on species composition, relative abundance using MaxN and size-structure (if stereo-videography is used).

The high-resolution sonar video system used in the current study also presents opportunities for future monitoring of fish assemblage condition. Compared to cameras which rely on light, this system provides the advantage of much greater range of image collection (up to 30 m) and the potential to be used at night or in turbid water. The ARIS software also allows for accurate measurement of individual fish lengths, which can be readily converted to a biomass estimate using species-specific length–weight relationships and habitat area estimates. Another advantage of the sonar system is that it samples a defined area, so it is possible to calculate the ensonified volume for each shot. This can then be used to calculate absolute density (fish/m^3) and biomass (grams of fish/m^3). Estimates of absolute density and biomass provide a much more tractable measure of assemblage condition than relative measures based on catch-per-unit effort or MaxN.

In the current study, we used a static approach to the ARIS sampling where up to 30 five-minute shots were conducted in each survey. The data were then analysed using a MaxN approach in a similar way to camera data. While this approach provided data on relative abundance and size frequency for each species, the MaxN approach cannot be used for absolute density and biomass estimates due to the bias introduced by measuring the maximum number of fish observed over the five-minute shot. If the objective of the monitoring is to collect absolute density and biomass estimates, we would recommend a moving transect approach where a large number of discrete snippets of video footage are analysed.

It should also be noted that high-resolution sonar has several disadvantages compared to light-based cameras. Firstly, the images collected are not in colour and are less clear than light-based video. This limited the identification of different taxa in Bowerbird and Mudginberri billabongs to the family level. Identification of fish using the sonar video also requires considerable expertise based on a hierarchy of physical characteristics including body shape, fin size and position, swimming pattern based on tail beats and body undulations, overall body size and the shape of the acoustic shadow. Unlike analysis of light-based video footage, which can now be automated, analysis of the sonar video footage collected in our study was a laborious process, taking several months to complete. Although it has great potential as a monitoring tool, the use of ARIS sonar for fish assemblage monitoring is in its infancy and requires further development (especially automated analysis of footage) before it could be readily incorporated into a standardised monitoring program.

5. Conclusions

A primary objective of the current project was to assess the potential risks of mine contaminant egress on fish movement and migration in Magela Creek. Consistent with previous studies, our acoustic tracking and sonar surveys demonstrate that the sand-channel reaches of Magela Creek within the mine lease act as a critical migration pathway for fish by connecting the lowland reaches of the system to the escarpment refuge billabongs. We also show that the sand channels and backflow billabongs are important temporary habitats for fish in the region, with a considerable proportion of tagged fish taking up extended residency in these habitats during the wet season. Examination of previous observational data demonstrates the biodiversity value of the sand channels and backflow billabongs within the mine lease area, with >30 species of native fish recorded from the sand channels. Based on these observations we hypothesise that there are potential significant consequences to the health of the diverse fish assemblages of Magela Creek if contaminant concentrations reach levels that adversely affect connectivity or habitat quality. The threshold concentration for magnesium that would impact connectivity could not be determined in the current study, although we did determine that it is above the concentrations of 11 mg/L in the water released by the mine in March 2021.

Our findings suggest that the key periods when fish migration may be at risk from mine-derived solutes are during the wet season, when fish are actively using the sand channels and backflow billabongs as habitat, and the recessional flow period at the end of the wet season, when fish are actively migrating through the sand channels to reach dry-season refuges. In the wet season, we found that large-bodied fish from the escarpment billabongs were likely to be resident in the sand channels at flows >50 ML/d. Such flows are likely to have a significant dilution effect on mine-related contaminants, which lowers the potential risks during higher-flow periods. Evidence from the current and previous studies shows that most upstream migration of small-bodied fish (e.g. glassfish, rainbowfish) and mid-bodied fish (black catfish, barred grunter) occurs during the wet season and on recessional flows at the end of the wet season and, for a very small proportion of fish, may continue under very low flows. The period of low, recessional flow poses the highest risk for fish exposed to mine solutes.

At the outset of the project we had intended to use the outputs of solute modelling commissioned by the mine operator as a basis for assessing the risks of future contaminant egress from the final RUM landform for fish. Unfortunately, results from this modelling were not available at the time of writing. Nonetheless, our field observations of fish responses to mine discharge from RP1 and residency in backflow billabongs can be used to make some conclusions regarding the risks of exposure to elevated solute levels. These observations found no evidence of adverse behavioural responses by fish to mine-water discharge containing magnesium concentrations up to 11 mg/L and showed that fish inhabited backflow billabongs at magnesium concentrations of up to 11.2 mg/L. This is almost four times the site-specific water-quality guideline value of 2.9 mg/L (Supervising Scientist 2021) that is applied to the off-site environment. Based on these observations, and the transitory nature of exposure to mine solute egress during the recessional flow period, we conclude that the risk of adverse impacts of mine solute egress on fish are low at magnesium concentrations of 11 mg/L or less. However, we strongly recommend that detailed solute modelling be used to identify the likely concentrations of future magnesium egress so that a more comprehensive assessment of risk can be conducted. We also emphasise the need for continued monitoring of water quality, including other contaminants of potential concern, and the condition of fish assemblages in Magela Creek to identify any negative mine legacy impacts and to facilitate mitigation if necessary.

References

Becker, A., Whitfield, A.K., Cowley, P.D., and Cole, V.J. (2017). Does water depth influence size composition of estuary-associated fish? Distributions revealed using mobile acoustic-camera transects along the channel of a small shallow estuary. *Marine and Freshwater Research* 68, 2163-2169.

Becker, A., Whitfield, A.K., Cowley, P.D., Jarnegren, J., and Naesje, T.F. (2011). An assessment of the size structure, distribution and behaviour of fish populations within a temporarily closed estuary using duel-frequency identification sonar (DIDSON). *Journal of Fish Biology* 79, 761-775.

Bishop, K.A., Pidgeon, R.W.J. and Walden, D.J. (1995). Studies on fish movement dynamics in a tropical floodplain river: prerequisites for a procedure to monitor the impacts of mining. Australian Journal of Ecology, 20(1), pp.81-107.

Butcher, R. and Schreiber, E.S.G. (2020). Evaluation Strategy for the Long Term Intervention Monitoring and Murray-Darling Basin Environmental Water Knowledge and Research Projects. *Report to the Commonwealth Environmental Water Office, Water's Edge Consulting.*

Cook, D., Middlemiss, K., Jaksons, P., Davison, W., and Jerrett, A. (2019). Validation of fish length estimations from a high frequency multi-beam sonar (ARIS) and its utilisation as a field-based measurement technique. *Fisheries Research* 218, 59-68.

Crook, D.A., Buckle, D.J., Allsop, Q., Baldwin, W., Saunders, T.M., Kyne, P.M., Woodhead, J.D., Maas, R., Roberts, B. and Douglas, M.M. (2016). Use of otolith chemistry and acoustic telemetry to elucidate migratory contingents in barramundi *Lates calcarifer*. *Marine and Freshwater Research*, 68, 1554-1566.

Crook, D.A., Buckle, D.J., Morrongiello, J.R., Allsop, Q.A., Baldwin, W., Saunders, T.M. and Douglas, M.M. (2020). Tracking the resource pulse: Movement responses of fish to dynamic floodplain habitat in a tropical river. *Journal of Animal Ecology* 89, 795-807.

Ebner, B.C. and Morgan, D.L. (2013). Using remote underwater video to estimate freshwater fish species richness. *Journal of Fish Biology* 82, 1592-1612.

Harford, A., Mooney, T., Trenfield, M., and van Dam, R. (2015). Manganese toxicity to tropical freshwater species in low hardness water. *Environmental Toxicology and Chemistry* 34, 2856-2863.

Humphrey, C.L., Bishop, K.A. and Dostine, P.L. (2016). Vulnerability of fish and macroinvertebrates to key threats in streams of the Kakadu region, northern Australia: assemblage dynamics, existing assessments and knowledge needs. *Marine and Freshwater Research* 69, 1092-1109.

Humphrey, C.L., and Chandler L. (2018). Use of field-effects information to inform surface water guideline values for magnesium sulfate in Magela Creek. Supervising Scientist Report 213 Supervising Scientist, Darwin NT.

Jardine, T.D., Pusey, B.J., Hamilton, S.K., Pettit, N.E., Davies, P.M., Douglas, M.M., Sinnamon, V., Halliday, I.A. and Bunn, S.E. (2012). Fish mediate high food web connectivity in the lower reaches of a tropical floodplain river. *Oecologia* 168, 829-838.

King, A.J., Doidge, C., Buckle, D., and Tyler, K.J. (2019). Preliminary evidence of spawning phenologies of freshwater fish in a wet–dry tropical river: the importance of both wet and dry seasons. *Marine and Freshwater Research* 71, 202-212.

King, A.J., George, A., Buckle, D.J., Novak, P.A., and Fulton, C.J. (2018). Efficacy of remote underwater video cameras for monitoring tropical wetland fishes. *Hydrobiologia*, 807, 145-164.

Langkau, M.C., Balk, H., Schmidt, M.B., and Borcherding, J. (2012). Can acoustic shadows identify fish species? A novel application of imaging sonar data. *Fisheries Management and Ecology* 19, 313-322.

Lankowicz, K.M., Bi, H., Liang, D., and Fan, C. (2020). Sonar Imaging surveys fill data gaps in forage fish populations in shallow estuarine tributaries. *Fisheries Research* 226, 105520.

Mooney, T.J., Pease, C.J., Hogan, A.C., Trenfield, M., Kleinhenz, L.S., Humphrey, C., van Dam, R.A., and Harford, A.J. (2019). Freshwater chronic ammonia toxicity: A tropical-to-temperate comparison. *Environmental Toxicology and Chemistry* 38, 177-189.https://doi.org/10.1016/jfishres.2020.105520

Mueller, A.M., Burwen, D.L., Boswell, K.M., and Mulligan, T. (2010). Tail-beat patterns in Dual-frequency Identification Sonar echograms and their potential use for species identification and bioenergetic studies. *Transactions of the American Fisheries Society* 139, 900-910.

Pettit, N.E., Naiman, R.J., Warfe, D.M., Jardine, T.D., Douglas, M.M., Bunn, S.E. and Davies, P.M., (2017). Productivity and connectivity in tropical riverscapes of northern Australia: ecological insights for management. *Ecosystems* 20, 492-514.

Sigda, J., Arthur, R., and Pickens, J. (2013). Pit 3 Solute Egress Mitigation Modelling: assessing potential impacts to Magela Creek from Pit 3 closure, Presentation to Alligator Rivers Region Technical Committee, Darwin, November 2013.

Supervising Scientist 2021. Magnesium in Surface Water — Rehabilitation Standard for the Ranger uranium mine (version 2). Supervising Scientist Branch, Darwin, NT. http://www.environment.gov.au/science/supervising-scientist/publications/ss-rehabilitation-standards.

Tomlinson, M. and Metherall, N. (2018). Review of the potential effects of increased solute egress from mine tailings and waste rock on ecological connectivity in Magela Creek. Unpubl. report Supervising Scientist Branch, Darwin, NT.

van Dam, R.A., Hogan, A.C., McCullough, C.D., Houston, M.A., Humphrey, C.L., and Harford, A.J. (2010). Aquatic toxicity of magnesium sulfate, and the influence of calcium, in very low ionic concentration water. *Environmental Toxicology and Chemistry* 29, 410–421.

Walker, T., & Tyler, P. (1984). Tropical Australia, a dynamic limnological environment. *Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen* 22, 1727-1734.

Watson, D.L., Anderson, M.J., Kendrick, G.A., Nardi, K., and Harvey, E.S. (2009). Effects of protection from fishing on the lengths of targeted and non-targeted fish species at the Houtman Abrolhos Islands, Western Australia. *Marine Ecology Progress Series* 384, 241-249.

Woodland, D.J., and Ward, P.J. (1992). Fish communities in sandy pools of Magela Creek, Alligator Rivers Region. Australian Government Publishing Service, Canberra.