Wheatstone Environmental Offsets -
Barriers to sawfish migrations

Murdoch UNIVERSITY

Freshwater Fish Group & Fish Health Unit

Centre for Fish & Fisheries Research

Centre for Fish and Fisheries Research

western australian marine science institution

Chevron

Wheatstone Project

Wheatstone Environmental Offsets -
Barriers to sawfish migrations

Murdoch University

Freshwater Fish Group & Fish Health Unit
Centre for Fish & Fisheries Research

Centre for Fish and Fisheries Research

western australian marine science institution

Chevron
Wheatstone Project

Suggested citation:
Morgan, D., Whitty, J., Allen, M., Ebner, B., Gleiss, A. & Beatty, S. (2016). Wheatstone Environmental Offsets - Barriers to sawfish migrations. A Freshwater Fish Group & Fish Health Unit (Centre for Fish & Fisheries Research, Murdoch University) report for Chevron Australia and the Western Australian Marine Science Institution.

Published by: Freshwater Fish Group & Fish Health Unit, Centre for Fish & Fisheries Research, Murdoch University
Design & Graphics: David Morgan and Jeff Whitty

Email: fish@murdoch.edu.au
http:/www.freshwaterfishgroup.com

Wheatstone Environmental Offests - Barriers to sawfish migrations

The most threatened family of the sharks and rays is the Pristidae (sawfishes), which is a unique family of batoid rays that are some of the largest chondrichthyans known. Western Australia has recently been identified as a global hotspot of sawfish diversity, with 4 of the world's 5 species found here. Most pristids have declined globally, and although the susceptibility of the rostrum (or saw) to entanglement in fishing nets is a major reason that all five species have declined and are listed as either *Critically Endangered* or *Endangered* by the International Union for the Conservation of Nature (IUCN), other threatening processes have also contributed to their range contractions and rarity. Among these processes are loss of nursery habitats, barriers to migration and reduction in habitat quality as a function of river regulation, targeted fisheries including for cultural purposes and taking of rostra as curios.

This project aimed to determine the impact of barriers to sawfish migration in Western Australia, and prioritise the barriers that are likely to have the highest impact in the region. It also summarises work in the Ashburton River and Fitzroy River, each of which offer globally significant habitat to sawfishes.

The project was led by Murdoch University's Freshwater Fish Group & Fish Health Unit with funding from Chevron Australia that was administered through the Western Australian Marine Science Institution (WAMSI). Project partners included the Nyikina-Mangala Rangers and Team Sawfish.

Large freshwater pools on the Fitzroy River are critical habitats to juvenile Freshwater Sawfish for their first few years of life.

Wheatstone Environmental Offsets - Barriers to sawfish migrations

A summary of the barriers to migration, critical habitats and threats to this group of endangered fishes.

A report for Chevron Australia and the Western Australian Marine Science Institution.

Project Proponents

Freshwater Fish Group & Fish Health Unit, Centre for Fish & Fisheries Research, Murdoch University, Murdoch, WA 6150, Australia.

Foreword

The north of Western Australia is a global hotspot of sawfish diversity. It is only very recently that we have begun to understand aspects of the distribution, nursery habitats and threats to these threatened species.

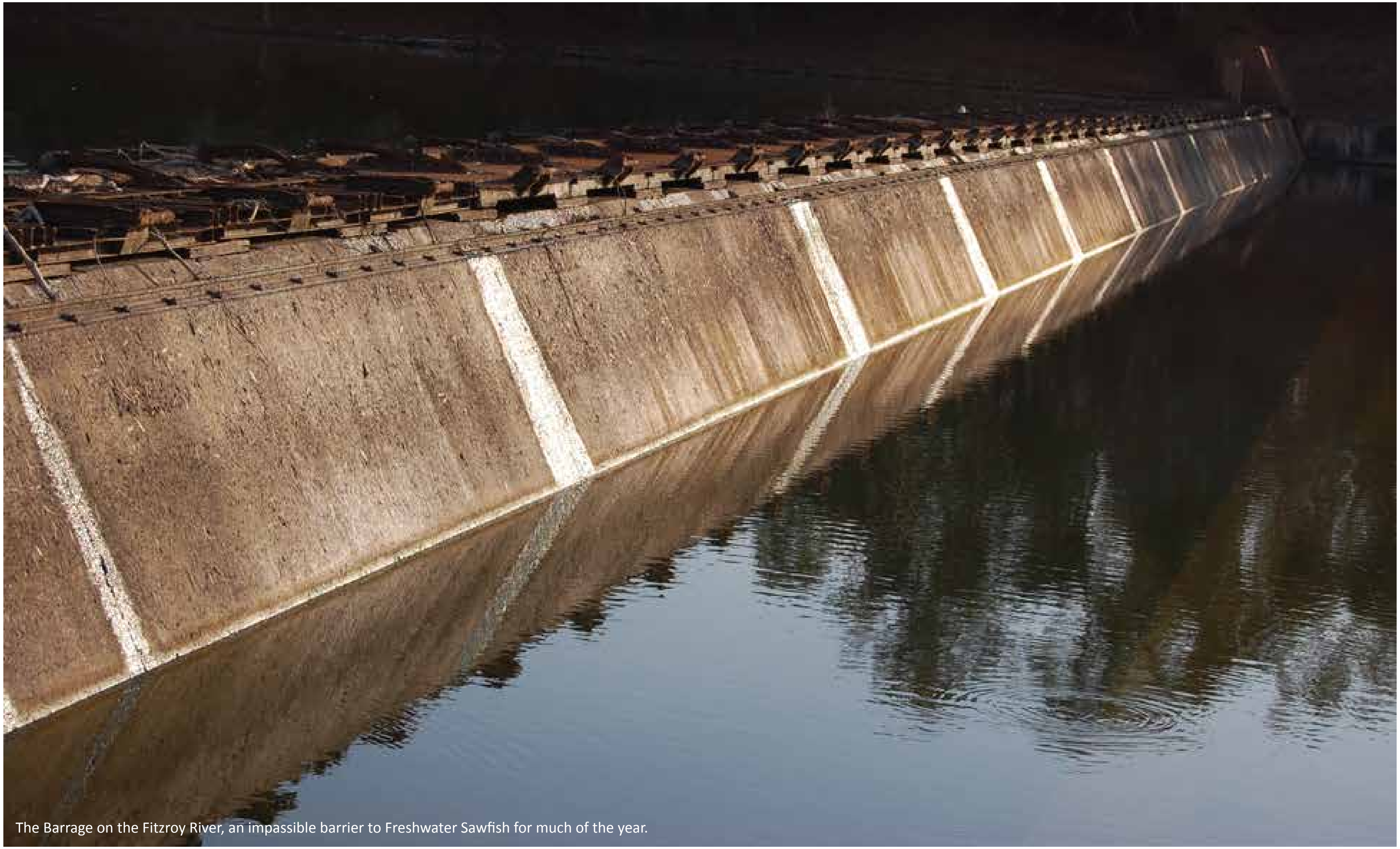
This project led to a substantial increase in our knowledge of many aspects of the ecology of this unique group of fishes. Specifically, the impact of estuarine and freshwater barriers in the north of the State to sawfishes is examined and reported. Furthermore, the Fitzroy River is arguably the most important nursery for Freshwater Sawfish (*Pristis pristis*) on the globe. Secondly, the Ashburton River estuary is currently the only identified pupping site and nursery for Green Sawfish (*Pristis zijsron*) in the world. The interannual variation in recruitment of Freshwater Sawfish appears to be directly related to freshwater discharge of the Fitzroy River, and recruitment over the duration of this study was extremely low; primarily as the river experienced several very poor wet seasons. We know little of the variables relating to the interannual variation in recruitment of Green Sawfish.

Priority barriers to Freshwate Sawfish migrations were identified within the Fitzroy River, Ord River and Ashburton River, however their degree of impact varies considerably, and is discussed within.

The north of Western Australia faces a number of future challenges, including climate and land use changes that can directly impact on river and mangrove ecosystems and their fauna. The compilation of knowledge presented here, provides new opportunities to manage and prepare for these challenges. It also highlights the value and need for continued monitoring, research and management of sawfish populations in this unique part of the globe. An increase in educational activity altering the public to the importance of these areas for the global conservation of sawfish is required.

Associate Professor David Morgan

Freshwater Fish Group & Fish Health Unit, Centre for Fish & Fisheries Research, Murdoch University


The Barrage on the Fitzroy River, an impassible barrier to Freshwater Sawfish for much of the year.

Freshwater Sawfish in the Fitzroy River

Language Names: Galwanyi (Bunuba and Gooniyandi), Wirridanyniny or Pial Pial (Nyikina), Wirrdani (Walmajarri)

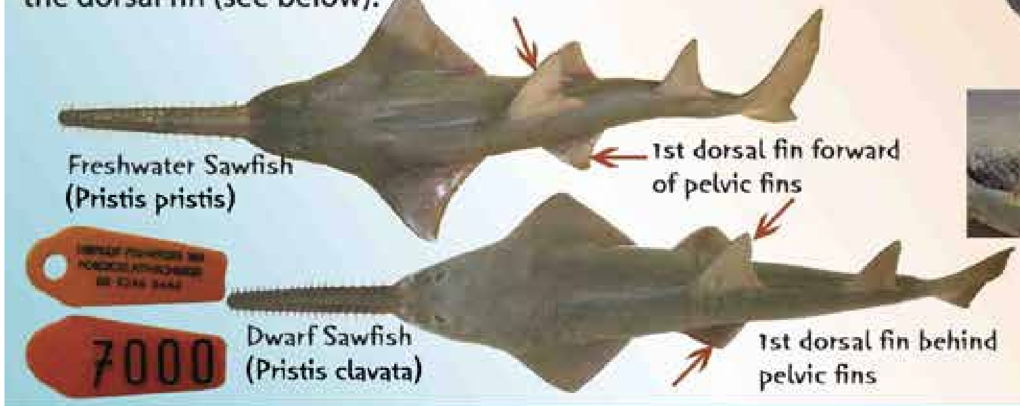
The Fitzroy River supports one of the last known substantial populations of the ENDANGERED Freshwater Sawfish in the world!

Numerous Sawfish have been tagged by Murdoch University.

If you catch one, you can help us learn more about these animals by recording the tag number, location, estimating the length and calling the CENTRE FOR FISH & FISHERIES RESEARCH on **(08) 9360 2813**

IDENTIFICATION

Two species of sawfish live in the Fitzroy River. The Dwarf Sawfish is usually found downstream of Telegraph Pool and the Freshwater Sawfish is found throughout the river. Both are also found in the ocean. You can recognise them by the position of the dorsal fin (see below).



Freshwater Sawfish
(Pristis pristis)

1st dorsal fin forward of pelvic fins

Dwarf Sawfish
(Pristis clavata)

1st dorsal fin behind pelvic fins

Chevron

Kimberley Language Resource Centre

Freshwater Fish Group & Fish Health Unit

Centre for Fish & Fisheries Research

western australian marine science institution

Yiriman Project

Kimberley Land Council

MURDOCH UNIVERSITY
PERTH, WESTERN AUSTRALIA

Project Participants

Project Leader

David Morgan (Murdoch University)

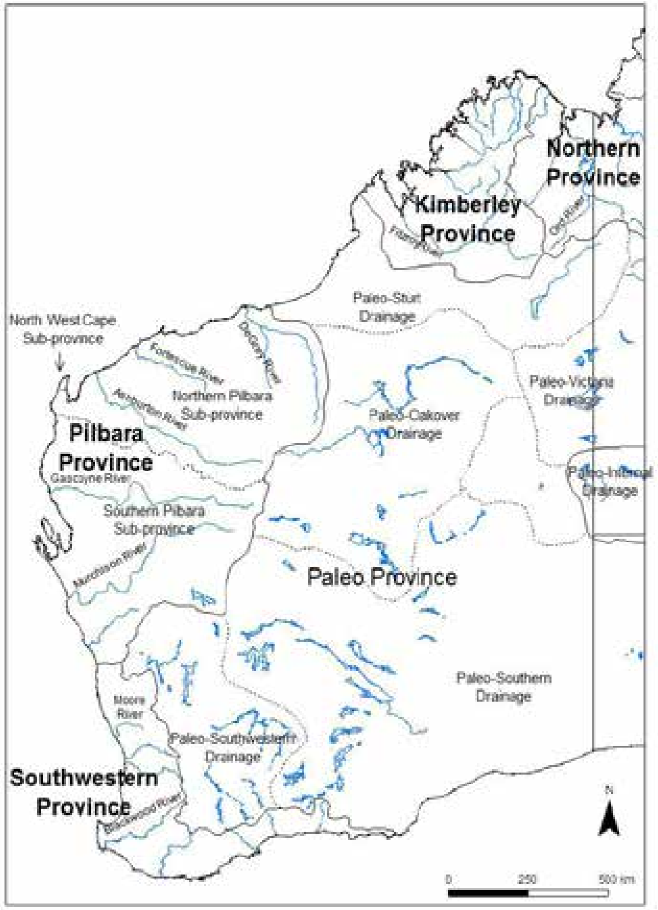
Project Staff

Jeff Whitty (Murdoch University)
Mark Allen (Murdoch University)
Brendan Ebner (JCU, CSIRO, Murdoch University)
James Keleher (Murdoch University)
Adrian Gleiss (Murdoch University)
Stephen Beatty (Murdoch University)

Project partners

Chevron Australia
Western Australian Marine Science Institution
Nyikina-Mangala Rangers
Team Sawfish

CONTENTS



The ichthyological provinces of Western Australia
(after Unmack 2013 and Morgan *et al*. 2014)

Summary and Recommendations

Sawfish populations have declined globally, yet little attention has been given to the impact of river regulation in the disruption of their migratory routes; a cause of global extirpations throughout much of their former range. During this study we identify the barriers to sawfish migrations in northern Western Australia. The identification of high impact barriers allows a prioritisation process to be implemented for future fishway construction or barrier removal.

An examination of barriers in Western Australia revealed that the highest impact barrier to Freshwater Sawfish migrations is the Camballin Barrage on the Fitzroy River, a barrier some 164 km upstream from the river mouth. This was followed by a second barrier on the Fitzroy River, Myroodah Crossing, a low level barrier some 30 km downstream of the Barrage. The prioritisation was largely based on the presence of a globally important nursery for Freshwater Sawfish in this river, as well as from the acoustic monitoring of sawfish movements at these barriers.

Other barrriers to sawfish migration exist on the Ashburton River in the Pilbara, and the Ord River in the east Kimberley, however, the records of Freshwater Sawfish near these barriers are on a much lower scale than for that of the Fitzroy River.

The habitats in the Ashburton River, while acting as a foraging habitat for sub-adult Freshwater Sawfish, appear to only be utilised by this species during high discharge events. The river however, acts as a pupping site and nursery for neonate and juvenile Green Sawfish. The tidal barriers on the Ashburton River do not however appear to impact Green Sawfish, as only two of almost 30 individuals that were acoustically tagged in this river, ventured >1 km upstream of the mouth of the river. However, the retrofitting of the barriers may provide an advantage to large sub-adult Freshwater Sawfish tagged in the river during their upstream migrations during periodic flood events.

Since the Ord river was dammed, the river morphology and flows have changed dramatically, particularly upstream of the Diversion Dam. Flows are lower in the wet season and higher in the dry season, and as a consequence the aquatic fauna is likely to have been altered. Although historic (pre-dam) sawfish records are low, occassional Freshwater Sawfish records indicate that fishways on the Ord's barrier may offer some benefit to this species.

The recommendations following the detailed examination of sawfish movements using acoustic telemetry and 'trap and haul' are:

1. Continue to examine the interannual variation in recruitment of Freshwater Sawfish in the Fitzroy River, as discharge is strongly linked to recruitment and recruitment has been poor in recent years.

2. Monitor the association of sub-adult Freshwater Sawfish and flows in the Ashburton River during high discharge events.

3. Examine the interannual variation in recruitment of Green Sawfish in the Ashburton River and link this to environmental variables in order to determine the importance and viability of this river as a long-term nursery habitat.

4. Develop a pathway for fishway construction on the Camballin Barrage and continue to explore 'trap and haul' as an alternative avenue for sawfish to negotiate this barrier until a fishway is constructed.

5. Develop a mechanism for sawfish to pass the Myroodah Crossing on the Fitzroy River by identifying ways to retrofit this barrier in the form of a culvert or a small fishway.

6. Explore sawfish abundances in the Ord system.

Wheatstone Project and Sawfish

The Wheatstone Project, near Onslow in Western Australia's Pilbara region, was given approval by the Australian Government in September 2011, subject to a series of environmental conditions. Conditions, from Australian Government (2011) "Approval - Construction and Operation of LNG and Domestic Gas Plant and Onshore and Offshore Facilities, State & Commonwealth Waters, Pilbara Coast, WA (EPBC 2008/4469)" made under sections 130(1) and 133 of the *Environmental Protection and Biodiversity Conservation Act 1999* relating to sawfish included:

MARINE FAUNA Coastal Processes Monitoring and Management Plan

Condition 32. *A Coastal Processes Monitoring and Management Plan (CPMMP), to protect habitat for listed species, including sawfish species, from changes to coastal processes. The program should include the following:*

a. An appropriate monitoring plan and sites to be used to collate baseline data and monitor changes to the functionality of the Ashburton River delta, including the chenier that impounds the coastal lagoon east of Entrance Point, Hooley Creek and other tidal creeks, which may be inhabited by sawfish, during and after construction.

b. Appropriate trigger levels and management actions to ensure no impacts to the functionality of sawfish habitat at the Ashburton River Delta, Hooley Creek, and other tidal creeks containing potential habitat for the sawfish.

BIODIVERSITY OFFSETS STRATEGY

Condition 66. *The person taking the action must submit for the Minister's approval a Biodiversity Offset Strategy within 12 months of the date of this approval, or as otherwise approved in writing by the Minister. The strategy must address the residual impacts to EPBC Act listed ......and sawfish from construction and production, including dredging and noise impacts and the increased recreation use of the area and its associated impacts to species. The offset commitments are to include the following:*

c. *Provide funding to a recognised research institution for research and development of sawfish-appropriate fishways to remove barriers to the movement of sawfish in riverine habitats.*

d. The design, fit or retrofitting of 5 sawfish-appropriate fishways or alternative measures to remove barriers to sawfish passage in riverine habitat in the Pilbara and/or Kimberley regions as identified through research referred to in 66 (c).

Aims of this study

This study was designed to assist in the conservation of sawfishes in Western Australia and implementing *Conditon 66 (c)*. This was achieved by gathering detailed ecological information on the current distribution, migration patterns, and habitats critical to the survival of the species. This information is crucial for prioritising, developing and implementing appropriate management arrangements to protect these rare species and their habitats. This project addresses the following key objectives:

- Assessing the locations of barriers to sawfish migrations in northern Western Australia.
- Prioritisation of existing barriers relative to their potential impact to the migration patterns of sawfish.
- Monitoring of sawfishes below specific barriers.
- Exploring the use of 'trap and haul' to assist sawfish negotiating potential barriers.

The Freshwater Sawfish (*Pristis pristis*).

Western Australia's sawfishes

Four of the world's five sawfish species are found within Western Australian waters, and the region is becoming known as a refuge of global significance for these species. It is only recently that information relating to their life history and distribution has been determined, but there is still much to learn.

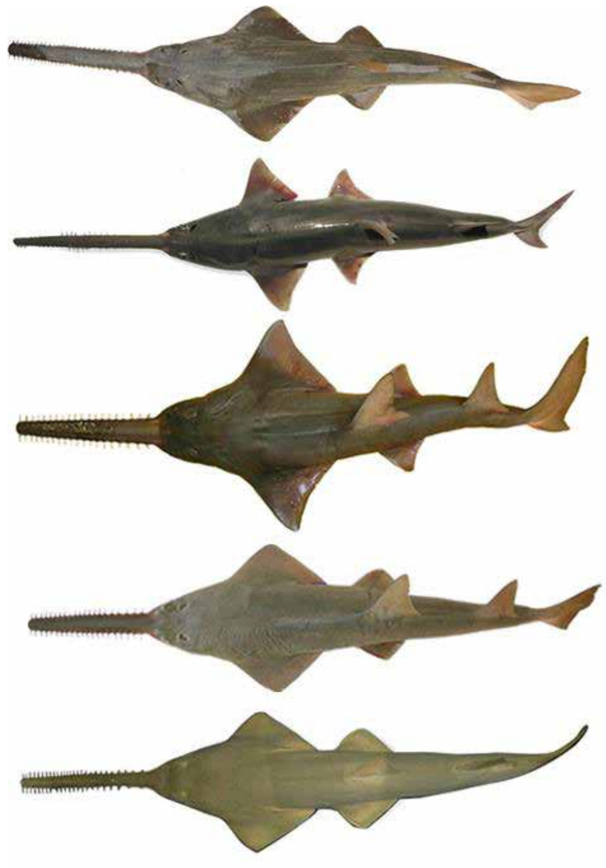
Of the chondrichthyan fishes (sharks and rays), those that are large-bodied and occur in shallow waters are at the greatest risk of extinction (Dulvy *et al*. 2014). The most threatened family of chondrichthyan is the Pristidae (sawfishes), which is a unique family of batoid rays that are some of the largest chondrichthyans known (Last & Stephens 2009, Dulvy *et al*. 2014, 2016).

Most pristids have declined globally (e.g. Simpfendorfer 2000, Fernandez-Carvalho *et al*. 2014, Leeney & Poncelet 2015, Moore 2015, Dulvy *et al*. 2016), and although the susceptibility of the rostrum to entanglement in fishing nets is a major reason that all five species have declined and are listed as either *Critically Endangered* or *Endangered* by the International Union for the Conservation of Nature (IUCN), other threatening processes have also contributed to their range contractions and rarity.

Among these processes are loss of nursery habitats (Simpfendorfer 2000), barriers to migration and reduction in habitat quality as a function of river regulation (Thorburn *et al*. 2007), targeted fisheries (Thorson 1982) including for cultural purposes (McDavitt 1996) and taking of rostra as curios (Seitz & Poulakis 2006; Morgan *et al*. 2011b, 2016). Pristid nurseries are located in relatively shallow coastal waters and specifically, freshwaters and estuaries in the case of Freshwater Sawfish (*Pristis pristis*) (Simpfendorfer 2000, Seitz & Poulakis 2002, Peverell 2005, Thorburn *et al*. 2007, 2008, Whitty *et al*. 2009, Morgan *et al.* 2011b). These habitats are often areas of high commercial and recreational fishing activity and are also often subjected to human development (Nagelkerken *et al*. 2015). Consequently, the effective conservation of pristids at the species and population level is likely to depend in part on the delineation and protection of nursery habitats (e.g. Whitty *et al*. 2009, Simpfendorfer *et al*. 2010, Morgan *et al*. 2015).

An understanding of the ontogenetic habitat partitioning within species, and the timing and form of emigration to and from nurseries, is also critical to sustainably managing relevant human activity along developed and developing coastlines. Specifically, the offshore emigration of late juvenile phase pristids and the return of philopatric females for pupping (e.g. Thorburn *et al*. 2007; Morgan *et al*. 2015, Phillps *et al*. 2016) are likely to be critical life history stages requiring science based management attention.

Within Western Australia, the knowledge of sawfish nursery habitats has recently been advanced for three species (Morgan *et al.* 2004, 2011b, 2015; Thorburn *et al.* 2007, 2008, Whitty *et al.* 2009), but known locations of pupping sites and nursery habitats is very narrow in range. For example, the Fitzroy River is arguably the most important nursery for Freshwater Sawfish (*Pristis pristis*) not only in Western Australia, but globally. During the current project, we discovered the only known pupping location for Green Sawfish (*Pristis zijsron*) in Western Australia, which is in the Ashburton River mouth, and neonate Dwarf Sawfish (*Pristis clavata*) are found within King Sound and the Fitzroy River estuary. This current study adds to the knowledge base that will greatly assist in the conservation of this unique group of fishes.



The world's sawfishes (from Sawfish Conservation Society) (Photographs: D. Thorburn and J. Stapley).

Phase I: Prioritisation and assessment of instream barriers in northern Western Australia

Northern Western Australia experiences distinct wet and dry seasons, with many of the rivers flowing only after cyclonic events. The climate changes from being tropical and arid in most of the Pilbara, to monsoonal in the Kimberley. River flow in the Pilbara can be periodic and short following summer cyclones, while river flow in the Kimberley is more predictable, but still highly seasonal following the monsoons. The strong seasonality and high discharge encountered within Kimberley rivers, such as the Fitzroy River, had led to a number diadromous (species that move between fresh and marine waters for breeding purposes) teleosts and euryhaline elasmobranchs utilising these predictable habitats as reliable nurseries. Examples include Barramundi (*Lates calcarifer*), Bull Sharks (*Carcharhinus leucas*) and Freshwater Sawfish. Catadromous fishes and euryhaline elasmobranchs are dependent upon the wet season flows to migrate upstream through the previously intermittent pools to access nursery areas, and to also leave such environments to mature and breed. However, unnatural (or constructed) barriers within these rivers can reduce or prevent species from moving upstream (or downstream) and can result in species bottlenecks and increased predation. The potential impact of a barrier on fish varies depending on many factors, including the location and size of the barrier, the period of which the barrier is inundated (and thus passable), and the timing of migration of the various species. The investigation of such variables is a crucial means to mitigate these impacts.

Potential barriers to migrating sawfish on the Ashburton River, near Old Onslow, Western Australia

Freshwater Sawfish

Our knowledge of the migration patterns and life history of Freshwater Sawfish is largely restricted to Kimberley Rivers, and in particular, to the Fitzroy River, where a long-term monitoring program by Murdoch University researchers and members of Team Sawfish has been ongoing since 2003. Freshwater Sawfish are pupped in the vicinity of the Fitzroy River mouth (King Sound, near Derby) during the wet season, and they then migrate upstream into freshwater pools during periods of high discharge, where they live for approximately four or five years before migrating to marine waters to mature and reproduce. Thus, all individuals within the river are immature, yet they grow to large lengths during their time in this nursery habitat (>2 m total length); such rapid growth a potential evolutionary response to outgrowing potential predators.

Large juveniles leave the river during periods of high discharge and enter King Sound where they migrate far and wide. Records of maturing/mature Freshwater Sawfish in Western Australia however are limited, with a handful of records stretching from Cape Naturaliste in the south-western corner of the State to the Kimberley coast, with two records in the Ashburton River estuary, and others near Port Hedland, 80 Mile Beach, Broome, One Arm Point and King Sound; although many of these records are based on the acquisition of severed rostra obtained from private collections (see Morgan *et al*. 2011b, Phillips *et al*. 2009, 2015, Whitty *et al*. 2014). The species is believed to be long-lived (>40 years), and attains approximately 7 m total length (TL); maturty not reached until lengths in excess of 3 m TL are achieved.

Phillips *et al*. (2011, 2015), using genetic data, demonstrated that Freshwater Sawfish are philopatric (mature females give birth near their natal nursery area), and found that most of the above records of adult Freshwater Sawfish had occupied the Fitzroy River as their nursery. This can have severe consequences if natal rivers are impacted by anthropogenic disturbances, such as reductions in water quality and stream flow; a factor behind the species extirpation from South Africa (see Everett *et al*. 2015), and possibly a further 28 countries within its range (Dulvy *et al*. 2016). The species has undergone a greater than 60% reduction in the Extent of Occurrence (Dulvy *et al*. 2016).

The reliance of Freshwater Sawfish on undisturbed freshwater riverine habitats during their nursery stage, lends them to be more susceptible to impacts in the form of instream barriers than species of sawfish that complete their life-cycle within marine and/or estuarine habitats.

The question is, which barriers in Western Australia pose the greatest impact to Freshwater Sawfish, and which ones are the highest priority barriers that should be considered to be either retrofitted with a fishway or removed if their original purpose is now

A sub-adult Freshwater Sawfish in the mouth of the Ashburton River fitted with an acoustic tag attached to the first dorsal fin, and a secondary identification tag attached to the second dorsal fin obsolete? This part of the study aimed to conduct a desktop analysis to identify all unnatural instream barriers in northern Western Australia (namely the Pilbara and Kimberley regions), and rank the barriers in accordance with their potential to impact Freshwater Sawfish migrations. Additionally, the study aimed to investigate the presence and behaviour of sawfish within the vicinity of priority barriers via field-based and historical surveys.

Methods

Location and prioritisation of barriers

The barrier assessment and prioritisation methods used in this study were adapted from those outlined in Beatty *et al.* (2013). This process consisted of a desktop review of the distributional data of the Freshwater Sawfish in fresh waters of Western Australia and a review of geospatial data on potential human-made barriers to their migration. The identification of barriers relied exclusively on a database maintained by the Department of Water, Government of Western Australia (DoW). This database includes information on infrastructure that disrupts longitudinal stream connectivity completely (e.g. dams, weirs) or partially (e.g. culverts, bridges, floodgates, levees, etc.) (Norton & Storer 2011). The DoW uses an automated process to assign a potential level of impact on fish movement for each listed barrier according to its structural characteristics and various criteria of the river in which it is located (e.g. major vs minor river, perennial vs ephemeral system). This process produces an impact code for each barrier that ranges from 1 (nil priority) to 6 (very high priority). However, much of the information used to assign these scores has not been validated in the field (Norton & Storer 2011).

All potential fish barriers in the target area (i.e. major coastal drainage systems of northern Western Australia, from the Ashburton River northwards, that lie within the Pilbara Province, Kimberley Province and Northern Province (see Unmack 2013, Morgan *et al*. 2014) were initially mapped using the ArcGIS 10.2 software package (Esri, California, USA) and categorised by impact code. The total number of barriers was extremely large (n = 62,013), but a visual assessment of the mapped data revealed that the vast majority of lower priority barriers (i.e. impact code ≤3) were located off the main channel of rivers and were thus unlikely to substantially inhibit sawfish migration. The majority of these data points were nil priority 'false positives'; an artefact of the automated process used to generate the fish barrier database, whereby any point of intersection between a road/railway and a river (including a floodplain boundary) is designated as a potential barrier (Fig. 1; see also Norton & Storer 2011). The lower priority barriers also included other structures unlikely to impede sawfish migration, such as bridges. Therefore, barriers with an impact code ≤3 were excluded from further assessment, as were any higher priority barriers (i.e. impact code >3) located in watersheds where sawfish have not been recorded historically or anecdotally (see Thorburn *et al*. 2004; Last & Stevens 2009; Morgan *et al.* 2004, 2011b, 2012).

Geospatial and structural data on the remaining barriers were then closely scrutinised in conjunction with a visual assessment of aerial imagery from Google Maps (2014; Google, California, USA) and Landgate (Landgate, Western Australia, Australia) to eliminate any erroneous or duplicate data points (see for example Fig. 2) and identify all barriers likely to have a significant impact on Freshwater Sawfish migration. A barrier was judged 'likely' if it met the following criteria: 1) located on the main channel of a known or probable sawfish migration route; and 2) with a head loss >0.2 m during periods of flow, when sawfish are known to migrate in rivers.

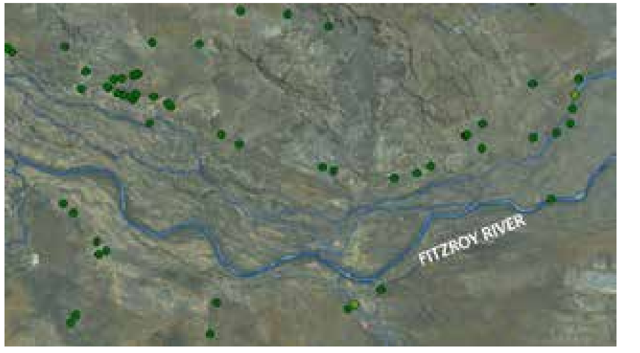


Figure 1. An example of the many nil priority 'false positive' barriers (green dots) in the DoW database. These data points are generated automatically wherever a road/ railway intersects a stream, floodplain boundary, or area of inundation. These barriers are unlikely to impact Freshwater Sawfish migration.

Figure 2. An example of data point duplication (red dots); an artefact of the automated process used to populate the DoW database for potential fish barriers.

Assessment of high priority barrier locations

This phase of the study was conducted in the Fitzroy and Ashburton rivers in Western Australia (Fig. 3) between 2013 and 2014, although data from previous years were included when applicable. A desktop study was conducted for the Ord River as the availability of literature on this system and its instream barriers made the need for an on-ground assessment unnecessary. The Fitzroy River is located in the Kimberley region of Western Australia and is a major tributary of the King Sound, a large and protected embayment that experiences >11 m tides. The Fitzroy River is relatively pristine but two road crossings (Myroodah Crossing and Fitzroy Old Crossing) and a small weir (the Camballin Barrage) are likely to impact fish movements to some degree (Morgan *et al*. 2005, 2011a; Fig. 3). Fitzroy 'Old' Crossing is a potential fish barrier, but due to its location in the upper reaches of the river and its minimal head loss, it is likely to have a negligible impact on sawfish migration and was therefore not examined further.

The Ashburton River is located in the subtropical to semi-arid environment of the southern Pilbara region of Western Australia, near the town of Onslow, and is one of the largest rivers in the region (Fig. 3). The Ashburton River Estuary is spatially constrained by the presence of a causeway and small weir located approximately 11.5 km from the river mouth (pictured page 16). These barriers limit the upstream penetration of tidal waters. The land immediately to the north of the lower reaches of the Ashburton River is currently undergoing substantial development for the Wheastone Project. This development includes construction of liquid natural gas processing infrastructure and extensive dredging in nearshore coastal environments.

The Ord River is located in the eastern Kimberley region of Western Australia and flows into the Cambridge Gulf (Fig. 3). The Ord River has been transformed by the installation of dams constructed for the Ord River Irrigation Scheme. The introduced dams have reduced annual variations in discharge of the river and seasonal flow regimes such that the river, which flowed seasonally prior to their construction, now flows year round. Installation of the two largest dams, the Lake Kununurra Diversion Dam (1963) and the Ord River Dam (1971), created the artificial impoundments of Lake Kununurra (~140 rkm) and Lake Argyle (~180 rkm), respectively (pictured page 18 and 20).

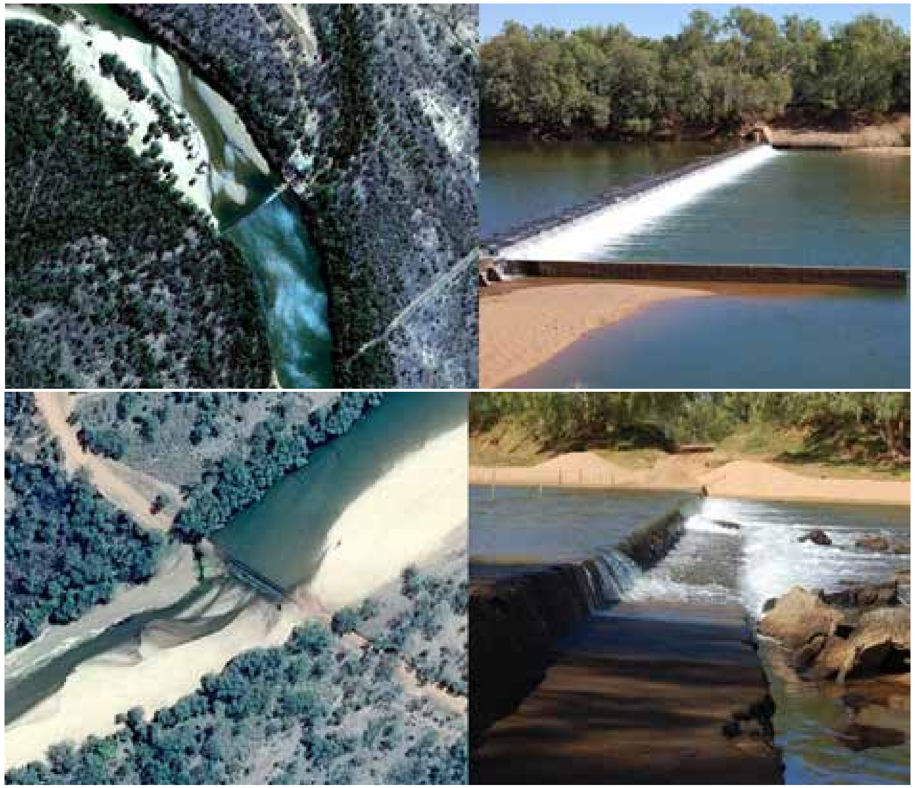
Habitat assessment

The environment, potential sawfish prey and sawfish predators were assessed within the rivers that contained high-priority barriers, in order to determine which habitats/rivers would be most favourable to Freshwater Sawfish. The hydraulic geometry, physicochemical parameters and vegetation of the rivers were analysed using a combination of aerial imagery (Google Earth, Landgate) and on-ground assessments between 2007 and 2014. In addition, water temperature and salinity were recorded during sampling efforts with the use of a YSI Professional Plus multiparameter meter (YSI, Yellow Springs, OH, USA). Water temperature and/or salinity were also continuously recorded by HOBO Water Temp Pro V2 Data Loggers (Onset Computer Corporation, Bourne, MA, USA) within the Fitzroy River. Water clarity was measured with a Secchi disk. For comparisons of water temperature between rivers, air temperature was used as a surrogate for water temperature, as water temperature in the shallows are often strongly correlated with air temperature, as observed in the Fitzroy River (Whitty 2011), and long-term water temperature data were not available for all rivers. Air temperature was obtained from the Bureau of Meteorology, Government of Western Australia (http://www.bom.gov.au/climate/averages/tables/cw_002056.shtml). Finally, river discharge and stage heights were obtained from the Department of Water, Government of Western Australia.

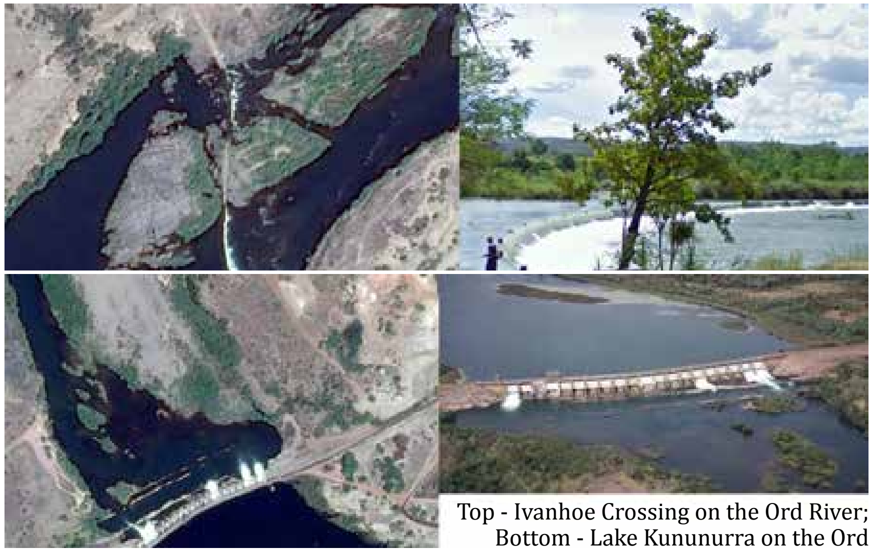
Figure 3. Top - Map of northern Western Australia indicating the rivers with high priority barriers to sawfish migration. Middle - location of barriers (red dots) and acoustic receivers (yellow dots) on the Fitzroy River. Bottom - barriers on the Ord River and Ashburton River.

Diversity and relative abundance of potential sawfish prey were measured in the Fitzroy River (Lower and Upper Myroodah Crossing Pools, Camballin Pool as well as Lower and Upper Barrage Pools) and the Ashburton River (Five Mile Pool), in order to determine if there was a marked difference among sites and between river systems, especially for known Freshwater Sawfish prey items including the Lesser Salmon Catfish (*Neoarius graeffei*) and the Bony Bream (*Nematalosa erebi*) (Thorburn 2006; Thorburn *et al*. 2014). Sampling of teleosts was conducted using a 26-m beach seine net, which consisted of two 8-m wings (6 mm mesh), a 10-m pocket (3 mm mesh) and fished to a maximum depth of ~1.5 m. In addition, a 35-m monofilament gill net (76 mm stretched mesh) and a 25-m monofilament gill net (127 mm stretched mesh) were deployed during 2014. Seine and gill nets were set for three replicates during day (~10:00 h) and night (~20:00 h) hours in July and October 2014 in the Fitzroy River, for a total of 12 seine and gill net sets per pool. Upper Myroodah Crossing Pool was sampled once in the early dry season 2014.

Relative abundances of sawfish predators, i.e. the Estuarine Crocodile (*Crocodylus porosus*) and the Freshwater Crocodile (*Crocodylus johnstoni*), as suggested from bite marks observed in this study and our previous records, and the Bull Shark (*Carcharhinus leucas*) (see Thorburn *et al*. 2014) were also measured in the Fitzroy River in July and October 2014. Relative abundance of Bull Sharks were estimated using CPUE (catch per unit effort) of sharks captured via gill net. Relative abundance of *Crocodylus* spp. was measured via spotlight surveys, which were conducted at night and followed methods that were similar to Messel (1981). Each pool was divided into 0.5-km transects, with the number of transects being dependent upon the length of the pool. A data recorder, two observers and a boat operator were involved in each survey. Two observers were involved to decrease the chance of missing an individual, with each observer responsible for counting the number of crocodiles on their respective side of the vessel. Vessel speed was constant throughout each survey. Counters employed high-output spotlights to observe the reflective eyes ('eye-shines') of crocodiles. Eye-shine counts only included those crocodiles on the surface of the water and land at the time of the count, and should be considered a conservative abundance estimate. In addition, this count does not discern species, but the number of



Top - The Camballin Barrage on the Fitzroy River; Bottom - Myroodah Crossing on the Fitzroy River).



Top - Ivanhoe Crossing on the Ord River; Bottom - Lake Kununurra on the Ord River).

A Freshwater Crocodile predating on a Freshwater Sawfish (image provide by Parks and Wildlife)

Myroodah Pool downstream of Myroodah Crossing on the Fitzroy River.

Table 1. Sampling effort (20-m net $1h^{-1}$) in the respective pools within the Fitzroy and Ashburton rivers in the early (April-August) and late (September-November) dry seasons in 2013 and 2014. ED, early dry; LD, late dry

		2013		2014	
River	Pool	ED	LD	ED	LD
Fitzroy	Estuary	-	4.3	8.5	-
Fitzroy	Pandanus Pool	-	-	9.3	-
Fitzroy	Udialla Pools	-	-	-	-
Fitzroy	Lower Myroodah	-	48.9	62.9	55.4
Fitzroy	Upper Myroodah	-	-	8.1	-
Fitzroy	Camballin Pl	75.8	-	55.35	14.5
Fitzroy	Lower Barrage	-	22.8	31.1	8.9
Fitzroy	Upper Barrage	-	12.3	-	4.7
Ashburton	Estuary	-	-	3	20.7
Ashburton	Five Mile Pool	-	-	20.2	31.2

Estuarine Crocodiles in the freshwater pools was usually negligible (n = 0 to 1). Daylight observations, the presence of 'slides' and local knowledge from the Nyikina-Mangala Rangers were used to determine the species likely to be present during night counts.

Sawfish presence

Sampling for sawfish in the Fitzroy River consisted of over 164 h of 20-m gill net sets (152 mm stretched mesh) in August and October 2013, and over 258 h of 20-m gill net sets (152 mm stretched mesh) in July and October 2014 (Table 1). Sampled pools included Telegraph Pool (13 rkm), Pandanus Pool (35 rkm), Udialla Pools (60 rkm), Lower and Upper Myroodah Crossing Pools (126 and 129 rkm), Camballin Pool (160 rkm) as well as Lower and Upper Barrage Pools (164 and 165 rkm) (Fig. 3). Additional fishing effort, including hook and line methods were employed during gill net sampling.

Sampling of the Ashburton River consisted of over 75 h of 20-m gill net sets (152 mm stretched mesh) in the Ashburton River Estuary (0 rkm) and Five Mile Pool (16.5 rkm) in April and November 2014 (Table 1, Fig. 3). Five Mile Pool is the first pool upstream of the Lower Ashburton River Crossing and Weir (Fig. 3). Additional fishing efforts including hook and line were employed during gill net sampling.

Data analysis

A Student's paired t-test was used to compare mean annual discharges of the Fitzroy and Ashburton rivers, as well as the Fitzroy and Ord rivers. Additionally, a Student's paired t-test was employed to compare mean annual air temperature of the Fitzroy River area (i.e. Derby) and the Ashburton River area (i.e. Onslow), as well as the Fitzroy River area and the Ord River area (i.e. Kununurra). The Fitzroy River was used as a baseline indicator for these variables as it is a known and well established nursery for Freshwater Sawfish.

Relative abundance, in the form of catch per unit effort (CPUE), was calculated for teleosts, Freshwater Sawfish and Bull Sharks captured in gill nets with the standard unit of effort equalling 1 h of 20 m net sets, as the typical net panel deployed was 20 m in length. However, a conversion factor was employed when multiple panels were joined. Catch per unit effort was also calculated for fishes captured by seine net, with the unit of effort equalling one net set. A chi-square goodness of fit test was run to determine if the numbers of teleosts captured by seine net within the sampled pools were equal. In this test all teleosts and size classes were pooled. Comparisons of the relative abundance of prey species captured by gill net were qualitatively assessed, due to the small number of captured fishes in most pools. Species specific comparisons of gill net captured fishes included *N. graeffei* and *N. erebi* (i.e. known prey items of Freshwater Sawfish).

Relative abundance of crocodiles was calculated using transect length (i.e. 0.5 km) as the unit of effort. A mean estimate was calculated for each pool by calculating the mean of all 0.5-km transects within each respective pool. A chi-square goodness of fit test was run to determine if the mean number of crocodiles 0.5 km^{-1} was equal between pools.

Results and Discussion

Barrier prioritisation

A total of 62,013 potential fish barriers in the Pilbara and Kimberley regions of Western Australia were identified in the DoW database and assessed in this desktop review. The vast majority of data points were categorised as low to nil priority barriers (i.e. impact code ≤3). Less than 2% were categorised as medium, high or very high priority (i.e. impact code >3). Of this 2%, only six barriers were considered likely to have a significant impact on the migration of Freshwater Sawfish (Table 2).

Table 2. Details of shortlisted barriers in the Pilbara and Kimberley regions of Western Australia located in catchments housing Freshwater Sawfish. (FID, site identification number)

FID	Catchment	Lat.	Long.	Site name	Barrier type
61639	Ashburton	-21.7568	114.949	Lower Ashburton Crossing and Weir	Causeway and weir
61890	Fitzroy	-18.1867	124.492	Camballin Barrage	Minor Dam (3 m crest)
61951	Fitzroy	-18.0798	124.223	Myroodah Crossing	Causeway
59004	Ord	-15.6895	128.689	Ivanhoe Crossing	Causeway
61894	Ord	-15.7917	128.696	Lake Kununurra Diversion Dam	Major Dam (20 m crest)
61892	Ord	-16.1218	128.739	Lake Argyle Dam	Major Dam (68 m crest)

Ashburton River

This site contains two concrete barriers located within a 200 m section of the lower Ashburton River (12 rkm). Whilst these barriers are relatively minor (i.e. crest height < 3 m), the stochastic flow regime of the Ashburton River and the close proximity of the barriers to the river mouth renders them a potentially large impediment to sawfish migration.

Fitzroy River

Myroodah Crossing is a concrete causeway, located at 128 rkm, which has similar structural characteristics as the Ashburton River causeway (e.g. a relatively minor crest height of <3 m). Myroodah Crossing is an effective barrier, mostly to upstream fish migration (due to the greater head loss on the downstream side of the causeway), as flows subside during the annual dry season. Installation of a fishway, or modification of the causeway to include a bridge or large box culvert would allow fish to bypass this barrier during the shoulder flow period in the late wet/early dry season each year, opening up access to an additional 36 km of the river (i.e. up to the Camballin Barrage).

The Camballin Barrage is a small concrete dam (crest height 2.6 m) across the Fitzroy River main channel located at 164 rkm, about 36 km upstream of Myroodah Crossing. The dam was installed in the 1950s as part of a now defunct irrigation scheme. Currently it is leased and is used to divert water through Uralla Creek (or Snake Creek), a constructed off-take channel, for the purpose of growing feed for livestock. Morgan *et al.* (2005) discussed the impacts of the barrage on fish and suggested it to be an effective barrier for at least nine months of the year to migratory species such as sawfish, barramundi and cherabin.

Myroodah Crossing, Fitzroy River

A tagged juvenile Freshwater Sawfish (bottom of frame), blocked by the Camballin Barrage, Fitzroy River

Ord River

Several barriers are found in the Ord River. The Ivanhoe Crossing is a small relief concrete causeway located approximately 130 rkm upstream. This barrier is likely to be passable during times of high flows, but would be a barrier to sawfish in the late wet and dry seasons. This causeway was constructed with numerous pipe culverts along its length that may allow smaller fish to bypass the barrier. However, the small diameter of the pipe culverts is likely to prevent large-bodied sawfish from doing the same. Modification of the causeway to include a bridge or large box culvert section may provide sawfish with an extended temporal window to move beyond this barrier during the shoulder flow period (i.e. late wet/early dry) each year.

The Lake Kununurra Diversion Dam is a major dam (crest height 20 m) across the Ord River, near the town of Kununurra. The dam was completed in 1963 as part of the Ord River Irrigation Scheme. Construction of this dam and the upstream Lake Argyle Dam has resulted in decreased wet season flow and flooding, higher dry season flows, increased siltation, reduced water depth, and a hydrological regime shift from intermittent to permanent flow (Wolanski *et al.* 2001). The impoundment formed upstream of the dam not only provides irrigation water for horticulture/agriculture, but is also used recreationally for boating and fishing and is an important tourist drawcard. The impoundment supports a diverse array of wildlife including over 20 freshwater fish species and is a Ramsar listed wetland of global significance for migratory bird species.

Similar to the Ivanhoe Crossing, the benefit of providing sawfish access to habitats above this barrier may be limited without the installation of a fishway or other mitigation plan at the much larger Lake Argyle dam located 50+ km further upstream. There have been a number of studies that have investigated the benefits of a fishway at Lake Kununurra (e.g. Doupé *et al.* 2005).

Lake Argyle Dam is unlikely to be a major barrier to sawfish migration due to the combined impediment to migration of the two downstream barriers (i.e. Ivanhoe Crossing and Lake Kununurra Diversion Dam). However, if any decisions are taken in the future to mitigate the impacts of the downstream barriers, Lake Argyle would undoubtedly become a significant impediment to sawfish movement.

Providing a fish passage facility for sawfish over this 68 m high rockfill dam looms as a major logistical challenge; however, a potential pathway for sawfish to bypass the Lake Argyle Dam already exists in the form of Spillway Creek. This narrow channel drains from the northernmost extension of the impoundment (north-northeast of the dam wall) and stretches *ca* 15 km before re-connecting with the Ord River main channel downstream of the dam. Some modifications (e.g. channel widening/dredging of the bypass creek and flow supplementation via pumping from the reservoir) would likely be required in order to attract migrating sawfish towards the bypass and to allow them to traverse the bypass channel into the impoundment. Anecdotal evidence discussed in Thorburn *et al.* (2004) suggests that Freshwater Sawfish have been captured in Spillway Creek, and can potentially enter Lake Kununurra during flooding and connectivity with the Dunham River.

Assessment of high priority barrier locations

Fitzroy River (habitats)

The Fitzroy River flows for over 600 km through the Kimberley region in northern Western Australia.

Telegraph Pool, where flows from the Fitzroy River meet the macro-tides of King Sound, is an important dry season refuge for Freshwater Sawfish and Dwarf Sawfish, and supports a relative high degree of recreational fishing.

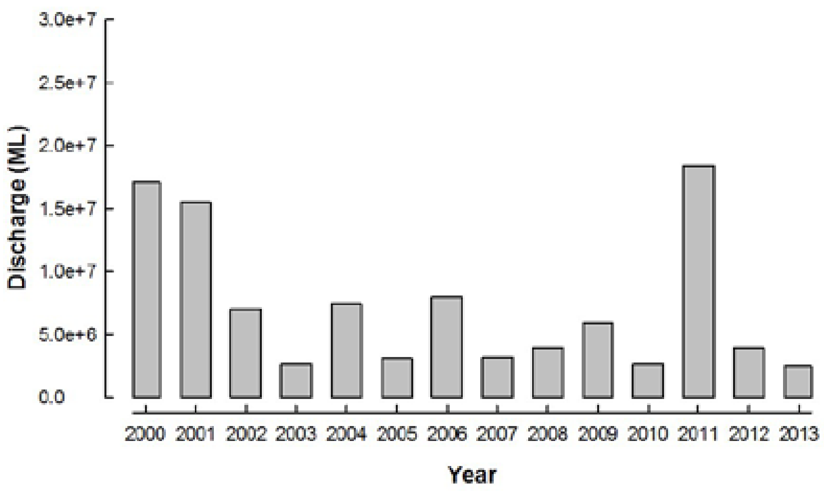
While the lower 17 km of the river is estuarine and inundated by large tides, the majority of the river is fresh (salinity <1.0 ppt). Maximum dry season pool depth varies with the time of year, and increases with distance from the river mouth, varying between <2 m at the river mouth to >3 m in the freshwater pools. Isolated pockets along the meanders of pools can reach over 6 m in depth. Below the Camballin Barrage exists 84 km of deep water pools i.e. potential sawfish habitat (pictured opposite, Morgan *et al.* 2011a). Above the Camballin Barrage exists 179 km of deep water pools, typically with characteristics (e.g. depth, vegetated cover, river shape, etc.) similar to those found below the barrier. Between Myroodah Crossing and the Camballin Barrage there are seven deep water pools that vary in length between 1.5 and 6 km, and which span approximately 36 km of the river. As such, sawfish are likely to benefit from an increase in the availability of deep water pool habitat if fishways (or other barrier mitigation strategies) were to be implemented at both Myroodah Crossing and Camballin Barrage. In other words, accessibility to an additional two-thirds of the available deep water pool habitats within the river would temporarily increase through the introduction of a fishway or alternate means that allows fish to bypass the Camballin Barrage (prior to pools naturally becoming isolated during the dry season).

River discharge and the duration of the wet season change annually on the Fitzroy River. On average, the wet season in this region occurs between December and April, but can extend from November until May. Annual wet season discharge ranged from 0.9e+6 to 2.8e+7 ML (mean = 9.9e+6 ML ± 2.2) between 2000 and 2013.

Mean air and water temperatures near the lower Fitzroy River, ranged between 14.7 (July) and 38.1 ºC (November) and between 15 and 38 ºC, respectively during the sampled years. Water temperature was observed to vary by as much as 8.5 ºC within a 24 h period, with the greatest fluctuations occurring in the estuarine pools during the late dry season. Salinity also varied substantially in the estuarine pools throughout the year, ranging between 0.2 ppt in the early dry season and 38.4 ppt in the late dry season, but remains <1.0 ppt year round in the non-tidal freshwater pools. Visibility in the freshwater pools was observed to range between 1.1 to >3.6 m, and between 0.2 and 0.8 m in the estuarine pools during sampling trips, but is likely to drop to 0 m during periods of high flow (e.g. the wet season, incoming tides) in both the freshwater and estuarine pools.

Riparian vegetation abounds along the majority of the river and comprises woodlands of *Eucalyptus* spp., *Ficus* spp. and *Acacia* spp. (Storey *et al*. 2001). Riparian vegetation in the lower estuarine region becomes sparser and comprises *Melaleuca* spp. and a few *Eucalyptus* spp. (Storey *et al.* 2001). The river is populated with large woody debris (classified as wood-based debris with a diameter of ≥10 cm, e.g. fallen branches, snags, stumps). Overhangs in the form of eroded banks and large trees are also present throughout the majority of the river.

Results of targeted environmental assessments of pools below and above Myroodah Crossing and the Camballin Barrage showed that these pools varied in their length, and to some extent depth and habitat quality. The greatest difference between upstream and downstream pools was observed at the Camballin Barrage. While Upper Barrage Pool ranged from 3 to 7 km in length (the pool was divided in half by a sandbar during the late dry season of years with less precipitation), the pool length of Lower Barrage Pool was ~0.06 km in length, a 50-fold reduction compared to its upstream counterpart. Movement of fish from Lower to Upper Barrage Pool could reasonably be assumed to decrease intraspecific competition for habitat. In addition, there is a substantial difference in habitat complexity between the pools below and above the Camballin Barrage. Lower Barrage Pool completely lacks overhanging vegetation and woody debris, whereas Upper Barrage Pool has an abundance of these habitat features throughout the pool. Active and passive acoustic monitoring of Freshwater Sawfish have demonstrated Freshwater Sawfish uses such overhangs and woody



Total wet season discharge (ML) at the Camballin Barrage, Fitzroy River between 2000 and 2013. Sourced from the Department of Water, Government of Western Australia debris during daylight hours, potentially as a form of cover or sanctuary (see Phase II). Increased movement of sawfish above the Upper Barrage Pool from Lower Barrage Pool via a fishway or by trap and haul efforts would thus increase the amount and quality of habitat immediately available to these fish.

The differences between Lower and Upper Myroodah Crossing pools were less extreme. Lower Myroodah Crossing Pool was 3 km in length. Upper Myroodah Crossing Pool measured 1.9 km in length. Both of these pools consisted of shallow (<1 m) and deep (>3 m) areas, however shallow regions dominated in Upper Myroodah Crossing, comprising >50 % of the pool. Overhanging vegetation and woody debris was observed throughout both pools and appeared typical of surrounding freshwater pools. Movement of sawfish into the Upper Myroodah Crossing Pool is not likely to greatly increase the amount or quality of habitat available to them, but would enable fish to access seven pools located between Myroodah Crossing and the Camballin Barrage, prior to these pools becoming naturally isolated. Alternatively, movement of sawfish downstream of Myroodah Crossing would allow these individuals to move into the river mouth area, a behaviour exhibited by several size classes of Freshwater Sawfish during the wet season (see Phase II).

Fitzroy River (predators)

Bull Sharks, Estuarine Crocodiles and Freshwater Crocodiles were observed in the estuarine and freshwater pools of the Fitzroy River. These species were observed upstream at least as far as the Camballin Barrage, although the concentration of Estuarine Crocodiles is far lower in the freshwater pools than within the estuarine reaches. Estuarine Crocodiles have not often been reported from above the Camballin Barrage, unlike Freshwater Crocodiles, which have been found beyond Geikie Gorge (>385 rkm). Bull Sharks have also been recorded as far

Aerial image of the Fitzroy River catchment showing the extent of the deep-water pool habitat mapping (blue lines indicate pools). Image courtesy of Google Maps (maps.google.com.au).

Table 3 Summary of deep-water pool characteristics in the Fitzroy River catchment located between Langi Crossing and Dimond Gorge.

	ABOVE BARRAGE	BELOW BARRAGE	TOTAL
Total number of pools	104	67	171
Total pool length (km)	178.9	83.7	262.6
River channel length (km)	285.4	148.8	434.2
% pool habitat	62.70%	56.24%	60.48%
Mean pool length (km)	1.72	1.25	1.54
Median pool length (km)	1.02	0.94	0.96
Maximum pool length (km)	14.10	7.18	14.10
Minimum pool length (km)	0.15	0.10	0.10

upstream as Geikie Gorge, and although captures of these sharks were believed to be uncommon in this area (Thorburn & Rowland 2008); during this study we found nine Bull Sharks within Geikie Gorge (each deceased due to a depletion in DO), including two that we had tagged previously below the Barrage.

Relative abundances of crocodiles in pools above and below the assessed barriers were not significantly different ($p = 0.31$) (excludes Pandanus Pool, which is not located in close proximity to a barrier). In July 2014, nearly all sampled pools (i.e. Lower and Upper Myroodah Pool, Camballin Pool and Upper Barrage Pool; 126 to 170 rkm) had a minimum CPUE of between 19.5 and 21.4. Only in Pandanus Pool (35 rkm) was there a marked difference in relative abundance, with a CPUE of 9.1. In October 2014, relative abundance of crocodiles was greater than in July, with a CPUE of 32.2 and 27.2 in Upper Barrage Pool and Lower Myroodah Crossing, respectively. Crocodile counts were also conducted in Lower Barrage Pool in October 2014, with only three individuals observed in the 0.06 km pool. This would equate to a CPUE of 25 in a 0.5 km pool, but this estimate should be treated with caution. Overall, the number of crocodiles (most of which were presumably Freshwater Crocodiles) appeared to be relatively uniform in the sampled freshwater pools (e.g. the Myroodah Crossing, Camballin and Barrage pools). It is therefore unlikely that risk of sawfish predation by Freshwater Crocodiles would be increased if access beyond instream barriers was improved via construction of a fishway or by trap and haul efforts. However, it is reasonable to assume that predation may be relatively high in at least Lower Barrage Pool, as the sawfish are more constrained within this pool and because of the lack of overhanging vegetation and large woody debris where sawfish can potentially seek refuge.

Relative abundances of Bull Sharks below the assessed barriers in the early dry season 2014, was greater than in all other sampled pools, with a mean CPUE of 0.32 (± 0.124) in Lower Barrage Pool and 0.10 (± 0.058) in Lower Myroodah Pool. Bull Sharks were not captured immediately above these barriers. However, a lack of capture does not preclude the presence of the animal. On two occasions tagged Bull Sharks were known to be present within Lower Myroodah Crossing (previously attached acoustic transmitter was detected) and Upper Barrage Pool (released into pool during trap and haul efforts) during sampling, but were never captured. Acoustic monitoring data suggested that these sharks had moved away from the areas where and when nets were deployed. Although numbers of Bull Sharks may be greater below barriers, Thorburn & Rowland (2008) demonstrated that Bull Sharks do occur above the Camballin Barrage, and we also found a number in December 2015 around 300 rkm upstream. As such, movement upstream of the Camballin Barrage may benefit Freshwater Sawfish with a decreased risk of being predated on by Bull Sharks; our previous work demonstrating that predation by Bull Sharks is high at these sites (Thorburn *et al*. 2014). However, upstream movement of predators like Bull Sharks may also be facilitated by the introduction of an indiscriminate fishway, which should be considered. Targeted 'active' strategies such as trap and haul would reduce the likelihood of an increase in Bull Sharks numbers above the Camballin Barrage, that a 'passive' strategy, such as a fishway, may cause.

Fitzroy River (prey)

Fishes captured in the 76 mm mesh gill net consisted primarily of *N. graeffei* (71.8% of the captured fish; 126-435 mm TL) and *N. erebi* (23.4% of the captured fish; 140-292 mm TL), with both species captured in all sampled pools. Thorburn (2006) and Thorburn *et al*. (2014) demonstrated that these species comprised two of the three most common prey items of Freshwater Sawfish in the Fitzroy River. The relatively high abundance of these species in the Fitzroy River helps explain why these species dominate the diet of Freshwater Sawfish. Other species that were captured by gill net included the Barramundi (*Lates calcarifer*) (323-437 mm TL), Black Catfish (*Neoarius ater*) (248-380 mm TL), Ox-eye Herring (*Megalops cyprinoides*) (472 mm TL) and Diamond Mullet (*Liza alata*) (298 mm TL) (Table 4). The number of species captured did not vary greatly between pools, with four species observed in Upper Barrage Pool and Upper Myroodah Crossing, and three species observed in the other sampled pools. Relative abundance of fishes caught via gill net in the early dry season was similar or slightly higher in pools directly above barriers in comparison to those directly below. Mean CPUE of *N. graeffei* and *N. erebi* in the early dry season in the freshwater pools ranged between 0 (± 0) and 10.06 (± 0.39), and between 0 (± 0) and 5.59 (± 1.53), respectively.

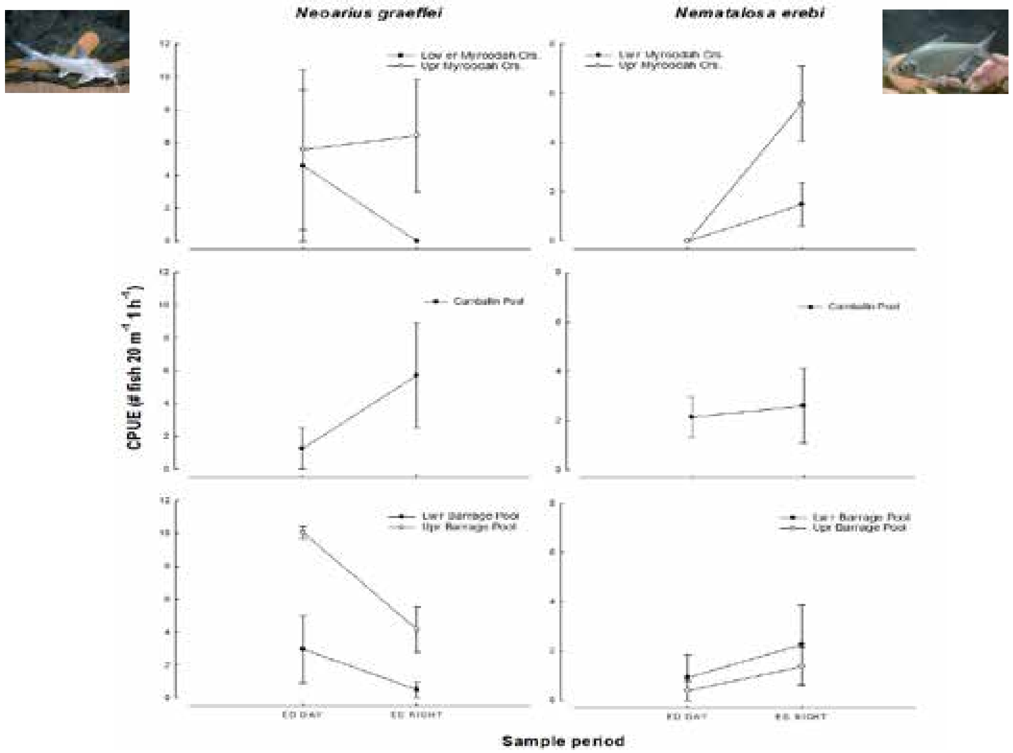
Between 8 and 14 fish species were captured with seine nets in the sampled pools. Lower Myroodah Crossing Pool, Lower Barrage Pool and Upper Barrage Pool had 14, 14 and 13 species, respectively. Only eight and nine species were captured with a seine net in Upper Myroodah Crossing Pool and Camballin Pool, respectively, although Upper Myroodah Crossing Pool was only sampled in the early dry season. The only three species to be captured in Lower Myroodah Crossing Pool (the last pool to occur before the barriers) but not in Upper Barrage Pool (the first pool to occur after the barriers) were Striped Scat (*Selenotoca multifasciata*), Diamond Mullet (*Liza alata*) and the Whipfin Silver Biddy (*Gerres filamentosus*). All three of these species are marine migrants and spawn in estuarine/marine environments (Morgan *et al*. 2014). This suggests that these barriers not only block the movement of sawfish, but also teleosts that are potential sawfish prey, as suggested by Morgan *et al.* (2005).

Relative abundance of fishes captured with a seine net varied between pools in the late dry season when species and size classes were pooled ($p < 0.001$). Mean relative abundance and the total number of fishes caught were both greater in Upper Barrage Pool than in pools downstream of the Camballin Barrage i.e. Lower Barrage Pool and Camballin Pool. However, this difference was due to a greater number of fish <50 mm TL. In the late

Table 4. Freshwater fishes (excluding elasmobranchs) in the Ashburton, Fitzroy and Ord rivers. Catch data was supplemented with data from Storey (2003), Morgan *et al.* (2004, 2011c), Gill *et al.* (2006) and Buckle *et al.* (2010).

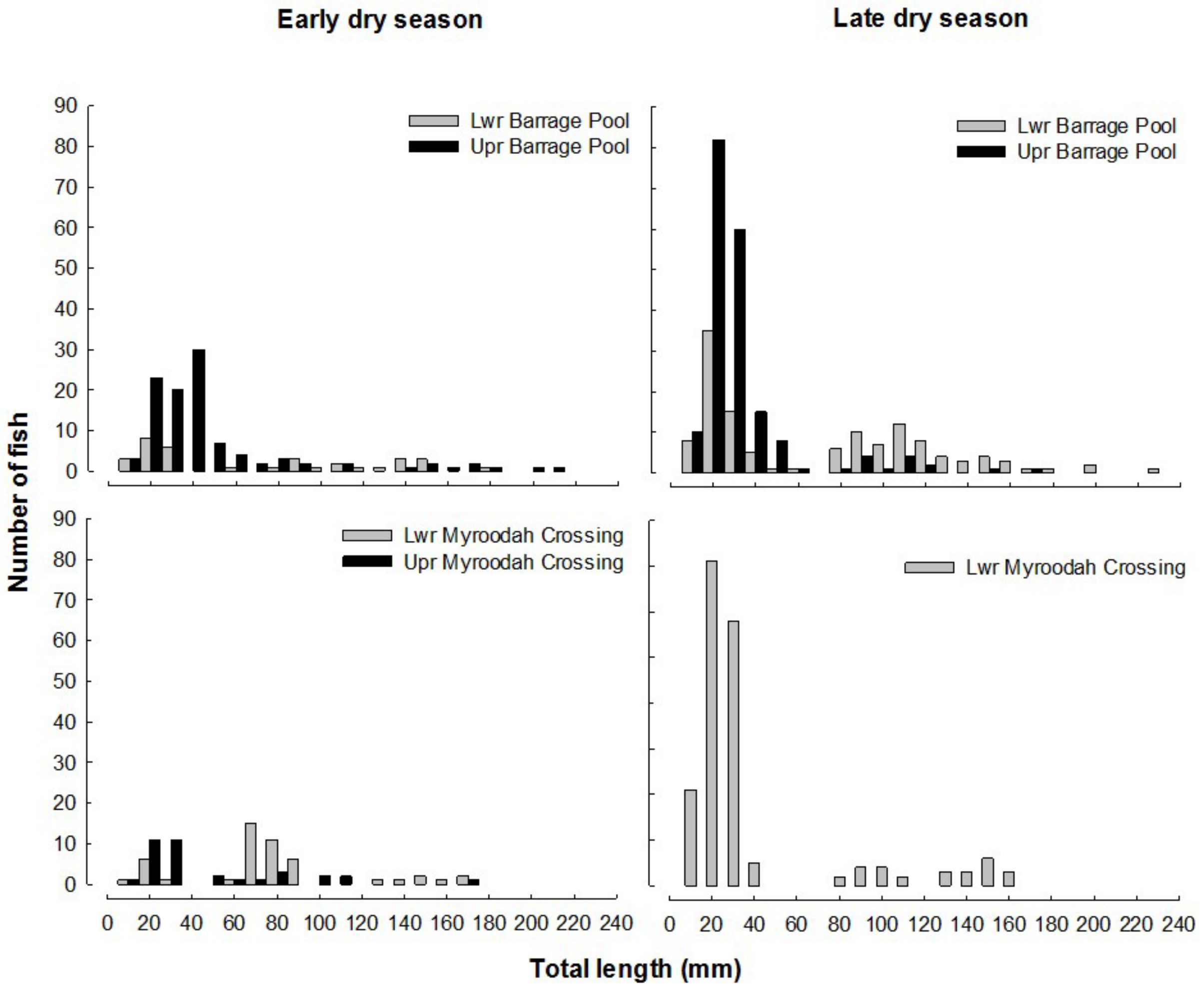
Species Name	Common Name	Ashburton	Fitzroy	Ord
Acanthopagrus latus	Western Yellowfin Bream	x		
Ambassis spp.	Glassfish		x	x
Amniataba percoides	Barred Grunter	x	x	x
Anguilla bicolor	Indian Short-finned Eel		x	x
Anodontiglanis dahli	Toothless Catfish		x	
Arramphus sclerolepis	Garfish			x
Aseraggodes klunzingeri	Tailed Sole			x
Chanos chanos	Milkfish	x		
Craterocephalus lentiginosus	Prince Regent Hardyhead		x	
Craterocephalus stercusmuscarum	Fly-specked Hardyhead			x
Craterocephalus stramineus	Strawman			x
Elops hawaiensis	Giant Herring		x	x
Gerres filamentosus	Whipfin Silver Biddy		x	
Gerres subfasciatus	Roach	x	x	
Glossamia aprion	Mouth Almighty		x	x
Glossogobius giuris	Flathead Goby	x	x	x
Hannia greenwayi	Greenway's Grunter		x	
Hephaestus jenkinsi	Jenkin's Grunter		x	x
Hypseleotris compressa	Empire Gudgeon			x
Hypseleotris kimberleyensis	Barnett River Gudgeon		x	
Lates calcarifer	Barramundi	x	x	x
Leiognathus equulus	Ponyfish			x
Leiopotherapon aheneus	Fortescue Grunter	x		
Leiopotherapon unicolor	Spangled Perch		x	x
Liza alata	Diamond Mullet		x	x
Liza subvirdis	Greenback Mullet		x	
Lutjanus argentimaculatus	Mangrove Jack	x	x	
Marilyna meraukensis	Merauke Toadfish		x	x
Megalops cyprinoides	Ox-eye Herring		x	x
Melanotaenia australis	Western Rainbowfish	x	x	x
Mogurnda mogurnda	Northern Trout Gudgeon			x
Mogurnda oligolepis	Kimberley Mogurnda		x	
Mugil cephalus	Sea Mullet	x		
Nematalosa spp.	Bony Bream	x	x	x
Neoarius graeffei	Lesser Salmon Catfish	x	x	x
Neoarius leptaspis	Triangular Shield Catfish			x
Neoarius midgleyi	Shovel-nosed Catfish			x
Neosilurus ater	Black Catfish		x	x
Neosilurus hyrtlii	Hyrtl's Tandan	x	x	x
Neosilurus pseudospinosus	False-spine Catfish		x	x
Netuma thalassina	Giant Catfish	x		
Nibea squamosa	Scaly Croaker		x	x
Oxyeleotris lineolatus	Sleepy Cod			x
Oxyeleotris selheimi	Giant Gudgeon		x	
Parambassis gulliveri	Giant Glassfish			x
Porochilus rendahli	Rendahl's Catfish		x	x
Scatophagus argus	Spotted Scat		x	x
Selenotoca multifasciata	Striped Scat		x	
Strongylura krefftii	Freshwater Longtom		x	x
Syncomistes butleri	Butler's Grunter			x
Syncomistes rastellus	Drysdale Grunter			x
Syncomistes trigonicus	Long-nosed Grunter			x
Thryssa sp.	Anchovie sp.			x
Toxotes chatereus	Seven-spot Archerfish			x
Toxotes kimberleyensis	Kimberley Archerfish		x	
Total		**14**	**34**	**38**

dry season, the number of seine net captured fish >80 mm TL was greater in Lower Barrage Pool than in Upper Barrage Pool. No marked differences in the mean relative abundance or total number of fishes captured via seine net was observed between Lower and Upper Myroodah Crossing in the early dry season (Upper Myroodah was not sampled in the late dry season), when all fishes and size classes were pooled. However, when separating size classes, fishes >70 mm TL were found to be more abundant below rather than above Myroodah Crossing, and those <40 mm TL were more abundant above the Crossing, Barrage Pool and Upper Myroodah Crossing, and three species observed in the other sampled pools. Relative abundance of fishes caught via gill net in the early dry season was similar or slightly higher in pools directly above barriers in comparison to those directly below. Mean CPUE of *N. graeffei* and *N. erebi* in the early dry season in the freshwater pools ranged between 0 (± 0) and 10.06 (± 0.39), and between 0 (± 0) and 5.59 (± 1.53), respectively.



Relative abundance of *Neoarius graeffei* and *Nematalosa erebi*, captured via gill net, in respective pools in the Fitzroy River, Western Australia in the early dry season 2014.

From this data it would appear that, in general, prey abundance is not greater below the barriers on the Fitzroy River than in the pools above the barriers. Some discrepancy is apparent in regards to the relative abundance of larger sized prey items between data derived from sampling using gill nets versus seine nets. However, results from the gill net sampling are supported by results from Morgan *et al.* (2005), which observed various sizes of *N. erebi* (including those >70 mm TL) to be more abundant above Camballin Barrage than below. It had previously been suggested that an increased abundance of prey below barriers may have resulted in an increased number of predators below the barriers on the Fitzroy River, and/or have resulted in Freshwater Sawfish returning to, or remaining in, such pools during or after the wet season (Whitty 2011). However, the results from this study suggest that this is not the case. Rather, it may simply be that the movements of these predatory fishes are being obstructed. Entrapment of predators below barriers is likely to result in increased predation and therefore lower abundances of prey species.



Number of fishes (at each respective total length) captured in seine nets within Upper and Lower Barrage pools as well as Upper and Lower Myroodah Crossing pools on the Fitzroy River in the early and late dry season 2014.

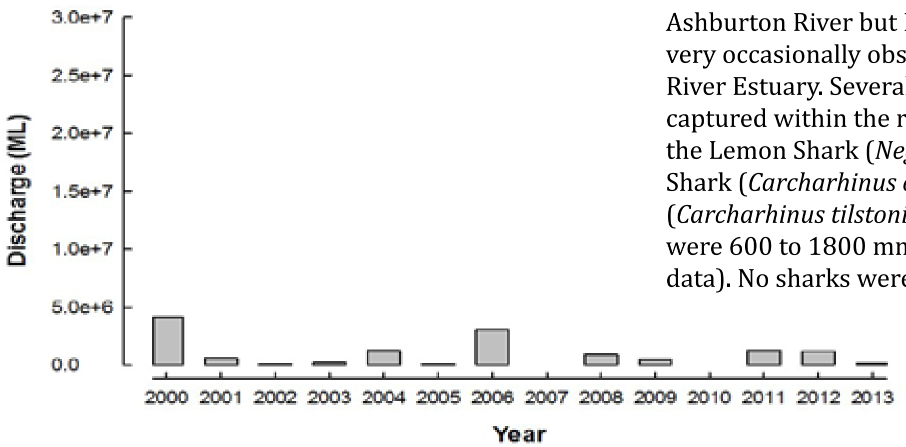
Ashburton River (habitat)

The main channel of the Ashburton River runs for approximately 680 km through the southern Pilbara region in Western Australia (Fig. 3). The major tributaries become confluent with the main stem of the river at approximately 180 rkm. While the lower 11 km of the river is estuarine, the majority of the river is fresh (salinity <1.0 ppt). Deep water pools >0.5 km in length are more prevalent in frequency and size in the lower 145 km of the river. Between the assessed barriers on the Ashburton River (i.e. 11 rkm) and 145 rkm, deep water pools >0.5 km in length comprise approximately 41% of the river (~55 km in total), and occur on average every 4 km. Conversely, the pools located between 145 rkm and 469 rkm (location of the last pool >0.5 km in length), comprise approximately 18% (~58 km in total) of this stretch of river, and occur on average every 9 km. Thus, while deep water pools that may be appropriate for Freshwater Sawfish occur up to 469 rkm in the Ashburton River, only the lower 145 km contains a high concentration of this habitat and is more likely to allow for increased inter-pool movements.

The southern Pilbara Region is arid and receives considerably less rainfall than the Kimberley. On average, the wet season occurs between December and July, is relatively contracted and peaks in April to May. Annual wet season discharge on the Ashburton River ranged between 0 and 4.1e+6 ML (mean = 1e+6 ML ± 3.3) between 2000 and 2013. Mean discharge in the Ashburton River between 2000 and 2013, was significantly less ($p < 0.001$) than in the Fitzroy River (9.9e+6 ML ± 2.2). Thus the duration of time that inter-pool movement is possible in the Ashburton River is likely to be more retracted than in the Fitzroy River.

Five Mile Pool is immediately above the human-made instream barriers in the Ashburton River. This pool is 13.4 km in length and is the largest freshwater pool in the river. However, this pool becomes divided by a sandbar in the late dry season. The pool is generally shallow, but can reach depths of 2-3 m during the dry season. Mean air temperature near the lower Ashburton River ranged between 12.9 (July) and 36.5 ºC (January). Mean maximum and minimum annual air temperatures on the Ashburton River were observed to be significantly lower than that on the Fitzroy River ($p < 0.01$). Mean surface water salinity and water temperature within Five Mile Pool was 0.24 ppt (± 0.000) and 27.0 ºC (± 0.067), respectively, in November 2014. Mean visibility within Five Mile Pool was 323 mm (± 6.7) in the late dry season.

Vegetation along Five Mile Pool consists mostly of isolated groves of *Eucalyptus* spp. trees, occasional *Melaleuca* spp. and few *Acacia* spp. Reeds and grasses occur closer to the water, along the banks of the river. Overhanging trees and large woody debris are limited in Five Mile Pool.



Total annual (December to November) discharge (ML) at Nanutarra, Ashburton River between 2000 and 2013. Sourced from the Department of Water, Government of Western Australia.

While the Ashburton River has similar hydraulic geometry to the Fitzroy River, it varies significantly in terms of both discharge and air temperature. Sawfish have been shown to be sensitive to both of these variables. For example, fish kills of the Smalltooth Sawfish (*Pristis pectinata*) have been observed after cold snaps in Florida, USA, when water temperatures dropped below 8 ºC, remained below 12 ºC for three days and below 15 ºC for 12 days (mean air temperature for this area is between 15 and 27 ºC) (Poulakis *et al*. 2011)). The prevailing conditions in the Ashburton River, particularly winter temperatures, may be unsuitable for sawfish as they can be sensitive to cold temperatures, although the thermal tolerance of Freshwater Sawfish specifically is unknown. In addition, the relative abundance of Freshwater Sawfish has been demonstrated to be positively correlated with discharge in the Fitzroy River (Whitty 2011). The significantly lower mean annual discharge of the Ashburton River may prevent Freshwater Sawfish from accessing this river for the majority of the year and could reflect a low abundance of sawfish within this system.

Ashburton River (predators)

Freshwater Crocodiles do not occur within the Ashburton River but Estuarine Crocodiles are very occasionally observed within the Ashburton River Estuary. Several species of shark have been captured within the river mouth area, including the Lemon Shark (*Negaprion acutidens*), Nervous Shark (*Carcharhinus cautus*) and Blacktip Shark (*Carcharhinus tilstoni*). Size ranges of these sharks were 600 to 1800 mm TL (authors unpublished data). No sharks were captured in the freshwater pools of the river. While predation of sawfish is likely to occur within the river mouth area, as was observed with a Green Sawfish (*Pristis zijsron*) during this study, movement of sawfish into the freshwater pools would substantially decrease and potentially prevent risk of predation.

Ashburton River (prey)

The number of fishes captured in the 127 mm mesh gill net was small (n = 9) and consisted of *N. graeffei* (267-488 mm TL), the Giant Catfish (*Netuma thalassina*; 389-438 mm TL) and the Sea Mullet (*Mugil cephalus*; 435-485 mm TL). Catch per unit effort of *N. graeffei* and *N. thalassina*, when pooled together (similar sized and shaped fishes), was 3.47 (± 2.08) during day sets and 0.48 (± 0.48) during night sets. These values were generally greater than those observed in the Fitzroy River during the same period ($CPUE_{day}$: 0 to 0.3; $CPUE_{night}$: 0 to 1.89). Other fishes captured in the Ashburton River (n = 64) consisted primarily of *L. calcarifer* (580-738 mm TL), Giant Threadfin (*Polydactylus macrochir*) (615-854 mm TL; only observed in the river mouth) and *N. erebi* (313-397 mm TL). Less common species captured using gill nets were the Mangrove Jack (*Lutjanus argentimaculatus* (415-436 mm TL) and Milkfish (*Chanos chanos*; 635-672 mm TL). Queenfish (*Scomberoides commersonnianus*; 470-792 mm TL) and a flathead (470 mm TL) were also captured, but only in the river mouth area.

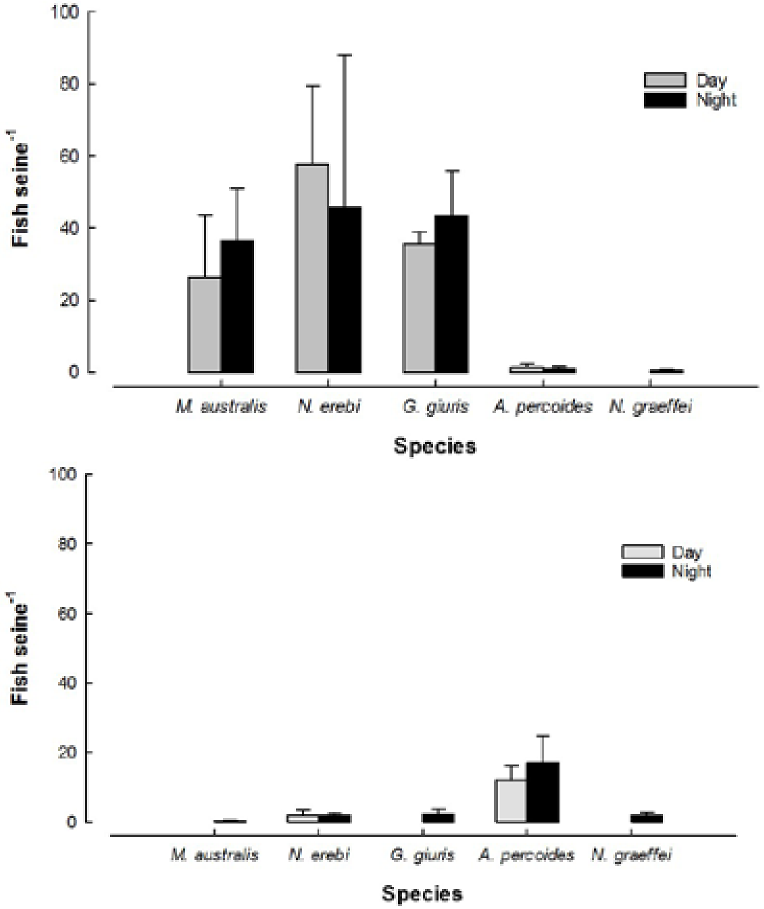
Only five species of fish (*M. australis*, 5-68 mm TL; *N. erebi*, 5-112 mm TL; *G. giuris*, 4-116 mm TL; *N. graeffei*, 325 mm TL; *A. percoides*, 21-90 mm TL) were captured with a seine net in Five Mile Pool. This is markedly less than the 8 to 14 species captured via seine net in the Fitzroy River. However, the relative abundance of *M. australis*, *N. erebi* and *G. giuris* was greater than observed in the Fitzroy River. The majority of these fishes ranged in size between 10 and 90 mm TL.


A Freshwater Crocodile waiting for prey below the Myroodah Crossing

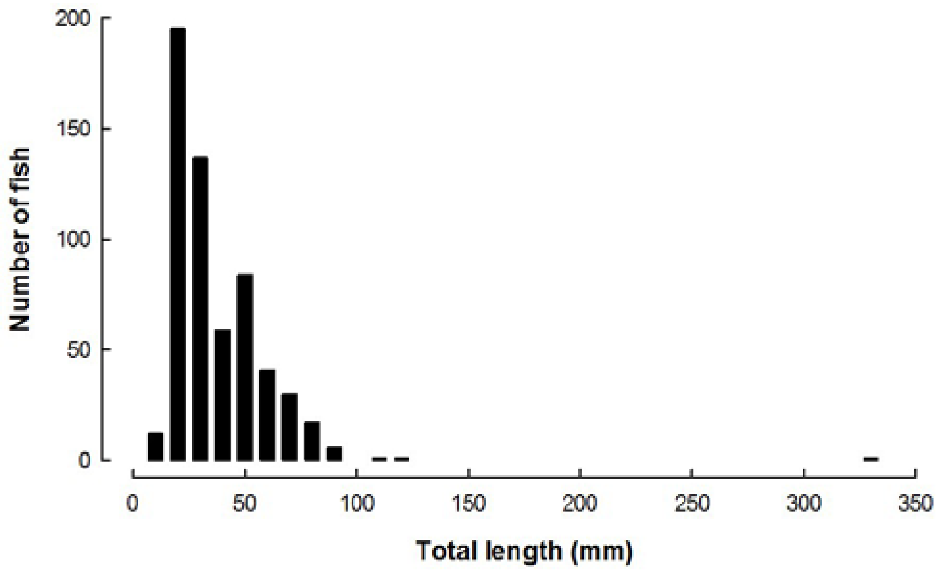
Together, these findings demonstrate that the Ashburton River has a low diversity of fishes compared with both the Fitzroy and Ord Rivers, with only 12 species (14 in literature; see Table 3) of fish being observed above the Ashburton River barriers (six species with estuarine origins) (Table 3). However, these species do include known sawfish prey. Additionally, the relative abundance of these species appears to be equal or greater than that observed in the Fitzroy River. These results suggest that the lower Ashburton River may contain an adequate prey source for Freshwater Sawfish.

Ord River (habitat)

The Ord River runs for 650 km through the east Kimberley region in Western Australia (Fig. 3). Damming of the river has resulted in the formation of Lake Argyle upstream of the Lake Argyle Dam, which is located at approximately 180 rkm, and Lake Kununurra, an artificial impoundment located at approximately 140 rkm, upstream of the Lake Kununurra Diversion Dam. Installation of these flow regulating dams transformed the downstream region from a seasonally to a perennially flowing river. Having the lower reaches of the river



Mean number of fishes (those captured in both the Fitzroy and Ashburton rivers) captured in day and night seines in the (top) Ashburton River and (bottom) Fitzroy River in the late dry season 2014.

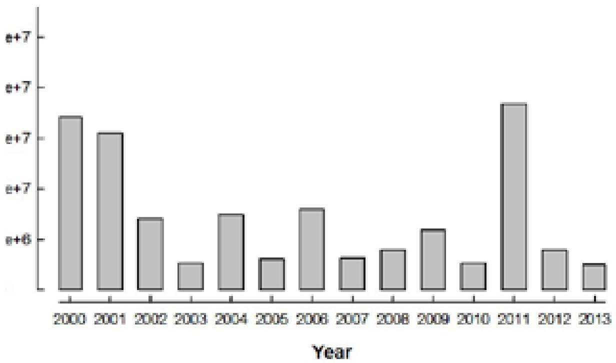


Number of fishes (at each respective total length), which were captured using seine nets (all species pooled) within Five Mile Pool, Ashburton River in the late dry season 2014.

connected year round may benefit sawfish with increased access to habitat (up to at least the barriers). However, it also allows large bodied euryhaline predators with year round access throughout the lower Ord River (i.e. below the Lake Kununurra Diversion Dam) (Water and Rivers Commission 2003).

The wet season in this region typically occurs between November and March. However as the river flow is regulated, discharge levels below the dams are determined by both seasonal precipitation and flow released from Lake Argyle. Between 2000 and 2013, annual river discharge at Tarrara Bar (located downstream of Lake Kununurra) ranged between 2.5e+6 and 1.8e+7 ML (mean = 7.2e+6 ML ± 1.5) (Fig. 18), with peaks in flow between February and March. Mean discharge in the lower Ord River between 2000 and 2013, was significantly less ($p < 0.001$) than the Fitzroy River (9.9 e+6 ML ± 2.2e+6); however, discharge was higher in the Ord in comparison to the Fitzroy in 2005, 2010 and 2013, when precipitation was relatively low.

Mean air temperature in the lower Ord River ranged between 15.1 (July) and 38.1 ºC (November). Mean maximum annual air temperature on the Ord River was observed to be significantly lower than that on the Fitzroy River ($p = 0.02$), but no significant difference was observed between mean minimum annual air temperature ($p = 0.17$). Mean water temperature, salinity and turbidity were reported to be 29 ºC, 0.46 ppt and 177.9 mm, respectively, in pools downstream of the Lake Kununurra Diversion Dam after a release of water from the dam in October 2002 (Wetland Research and Management 2002). These variables may differ from those typically observed because of the release of water, which may have increased turbidity and decreased visibility within the pools. Although the reported visibility is low, Freshwater Sawfish experience lower levels of visibility in the estuarine and freshwater (during the wet season) pools of the Fitzroy River. Along with visibility, water temperature and salinity appear to be suitable for the habitation of Freshwater Sawfish in the Ord River.



Total annual (December to November) discharge (ML) at Tarrara Bar, Ord River between 2000 and 2013. Sourced from the Department of Water, Government of Western Australia.

Riparian vegetation cover along the Ord River is patchy and varies from barren ground to diverse woodlands. The composition of species also varies among regions located downstream of Lake Argyle in the Ord River, including grass dominated, vine dominated and tree dominated lands (Water and Rivers Commission 2003). Areas that are tree dominated may be of greater benefit to sawfish as the trees create overhangs and are a source of woody debris that sawfish can use as cover. The vegetation in the regulated regions of the Ord River differs from surrounding rivers and has a greater abundance and diversity of exotic species, but fewer native species (Water and Rivers Commission 2003). Similar to that found along the Fitzroy River, the native riparian vegetation on the lower Ord River includes, but is not limited to *Ficus* sp., *Melaleuca* spp., *Eucalyptus* spp. and *Pandanus spiralis* (Start and Handasyde 2002; Water and Rivers Commission 2003). Abundance and diversity of aquatic vegetation has also been altered by flow regulation, and has increased over the years (Start & Handasyde 2002). Aquatic vegetation is largely lacking in the Fitzroy River. Whether aquatic vegetation is beneficial (used as cover) or detrimental (cause entanglement or reduced manoeuvrability) to sawfish is yet to be determined. Above Lake Argyle, the vegetation is largely composed of grasses, legumes and trees, with *Eucalyptus camaldulensis* and *Melaleuca leucadendra* dominating the overstorey (Pettit *et al.* 2001).

Ord River (predators)

The Ord River and tributaries of the Cambridge Gulf contain a high abundance of Freshwater Crocodiles (Web and Manolis 2010) and Estuarine Crocodiles. While Estuarine Crocodiles are abundant in the lower Ord River, downstream of the Kununurra Diversion Dam (Yoshikane *et al*. 2006), Freshwater Crocodiles occur throughout the entire river (Yoshikane *et al*. 2006; Web & Manolis 2010). Bull Sharks have been observed in the lower Ord River (Water and Rivers Commission 2003, Thorburn & Rowland 2008, Gehrke 2009), but like sawfish, are likely to be unable to migrate beyond the Lake Kununurra Diversion Dam. Installation of a fishway to allow sawfish upstream may also increase the presence of Bull Sharks and Estuarine Crocodiles, depending upon the design of such a structure.

Ord River (prey)

The lower Ord River houses 25 freshwater fish species and 13 marine or estuarine opportunists (Table 3; Storey 2003, Morgan *et al*. 2011c, Storey & Creagh 2014). The composition of these fishes varies slightly from that observed in the Fitzroy River, although both rivers contain known prey species of Freshwater Sawfish, including *N. erebi* and *N. graeffei* (Table 3). Slightly fewer species are known from Lake Kununurra (n = 22), but *N. erebi* is one of the three most abundant fishes in the lake, and *N. graeffei*, *A. percoides* and the Silver Cobbler (*Neoarius midgleyi*) are also present (Gill *et al*.

2006). Storey (2003) reported *L. alata* and *N. graeffei* to be the two most abundant species in the pools of the lower Ord River (i.e. below the Lake Kununurra Diversion Dam) during late dry season sampling, comprising 49 and 25.6% of the fishes captured by multi-panel gill nets, respectively. The most abundant species in these regions during the late wet season was *N. graeffei*, which comprised 42.7% of the captured fishes (Storey 2003). Although, it was not possible to compare the abundances of the fishes between the Ord and Fitzroy River, it is evident that the known prey items of Freshwater Sawfishs are present and relatively abundant in the Ord River system.

Sawfish presence near priority barriers

Fitzroy River

Twenty-six juvenile Freshwater Sawfish were captured during Fitzroy River sampling efforts for Phase I and II of this study (Table 5). An additional seven Freshwater Sawfish were recaptured. Two of these recaptures were reported by recreational fishers (M1118: tagged June 2011, recaptured June 2013; M413: tagged August 2012, recaptured September 2014). All sawfish ranged in length between 1011 and 2510 mm TL (males: 1011 to 2510 mm TL; females: 1860 to 2345 mm TL). Captured Freshwater Sawfish were estimated to be between 0+ and 3+ years of age (following Thorburn *et al.* 2007; Peverell 2008), with the majority belonging to the 2011 year class (2+ years of age). The lack of captured 0+ Freshwater Sawfish in 2013 was potentially due to the lower than average river discharge during the wet season of 2012-2013, as the CPUE of 0+ Freshwater Sawfish in the freshwater pools is positively correlated with river discharge (Whitty 2011). Capture of only two 0+ Freshwater Sawfish in 2014, was unexpected as discharge during the 2013-2014 wet season appeared to be of adequate level to have allowed for increased survival and movement upstream of 0+ Freshwater Sawfish. Capture of the 0+ Freshwater Sawfish occurred at only 8 and 35.5 rkm. The lack of 0+ Freshwater Sawfish in the freshwater pools may be a result of a

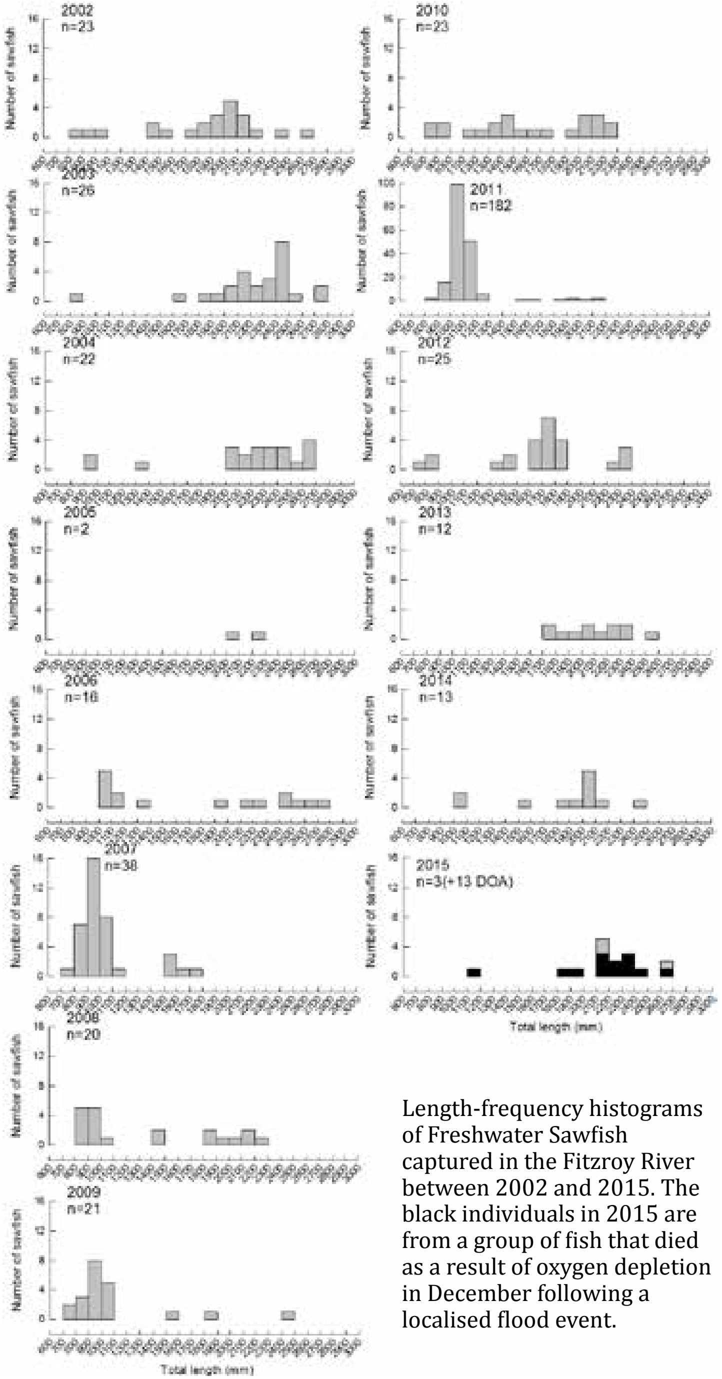
Table 5. Catch data of Freshwater Sawfish (*Pristis pristis*) captured in the Fitzroy River in 2013 and 2014.

Date	Location	Rototag #	Acoustic ID #	Sex	TL (mm)
10-Aug-12	Camballin Pool	PPMN0812	1143402	F	820
11-Aug-12	Camballin Pool	M414	1143410	F	1870
3-Jun-13	Telegraph Pool	M1118 R*	-	F	-
18-Aug-13	Camballin Pool	M332	1167478	M	1885
18-Aug-13	Camballin Pool	PPMN0813	1167477	F	2280
20-Aug-13	Camballin Pool	M418	1167484	F	2063
20-Aug-13	Lwr Myroodah Crs.	M432	1167487	F	2310
21-Aug-13	Telegraph Pool	M318	1167474	F	2345
22-Aug-13	Telegraph Pool	M294	1167479	F	2247
22-Aug-13	Telegraph Pool	M423	1167485	M	1925
22-Aug-13	Telegraph Pool	M433	1167486	M	2093
22-Aug-13	Telegraph Pool	M322	-	M	1701
22-Aug-13	Telegraph Pool	M365	-	F	2190
30-Oct-13	Camballin Pool	M366	1167481	M	2510
30-Oct-13	Camballin Pool	M1101	1167482	M	1780
23-Jul-14	Lwr Barrage Pool	M446	11830000	M	2030
24-Jul-14	Lwr Barrage Pool	M375	1183004	F	2020
25-Jul-14	Camballin Pool	M372	1183003/1194190	F	2093
25-Jul-14	Camballin Pool	M380	1183004	M	1835
26-Jul-14	Camballin Pool	M372 R*	1183003/1194190*	F	2093
26-Jul-14	Camballin Pool	M385	1183005	F	2145
29-Jul-14	Snag Pool	M384	1183006	M	1023
30-Jul-14	Pandanus Pool	M383	1194191	M	1011
30-Jul-14	Pandanus Pool	M390	1194193	M	1594
30-Jul-14	Pandanus Pool	M395	-	M	1940
1-Aug-14	Lwr Myroodah Crs.	M438	-	M	-
1-Aug-14	Lwr Myroodah Crs.	M448	-	M	2058
2-Aug-14	Lwr Myroodah Crs.	M1188 R*	1183008/1194192	M	2062
3-Aug-14	Lwr Myroodah Crs.	M438 R*	1167483	M	-
21-Sep-14	Cuttings	M413 R*	-	M	2140
5-Oct-14	Upr Barrage Pool	M339	1200103	F	1860
6-Oct-14	Camballin Pool	M380 R*	1183004*	M	1835
9-Oct-14	Telegraph Pool	M324	1167476	F	2238
9-Oct-14	Telegraph Pool	M441	1167480	M	1978
10-Oct-14	Lwr Myroodah Crs.	M1188 R*	1183008/1194192*	M	2111
11-Oct-14	Lwr Myroodah Crs.	M438 R*	1167483*	M	2116
12-Oct-14	Lwr Myroodah Crs.	M1188 R*	1183008*	M	2111
12-Oct-14	Lwr Myroodah Crs.	M448 R*	1200100	M	2105

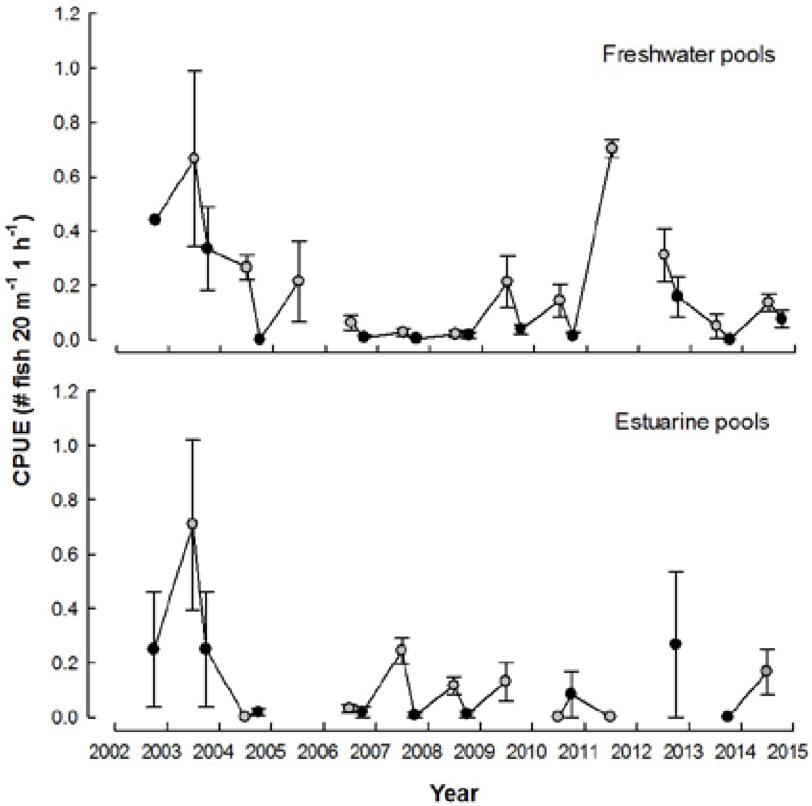
* Recapture

relatively early wet season, with peak river flows and stage height occurring from December through March. The paucity of 0+ Freshwater Sawfish captures since 2012 was likely to have driven the relatively low CPUE observed in 2014 (see Fig. left).

Sampling for sawfish above and below the Camballin Barrage in 2014, resulted in the capture of a single Freshwater Sawfish above this barrier and two below. Sampling for sawfish above and below Myroodah Crossing in 2014, resulted in no captures of Freshwater Sawfish above and three below the barrier. Sampling below these barriers was exhaustive (a total of 162+ h of 20 m net set in Lower Myroodah Crossing and 62+ h of 20 m net sets in Lower Barrage Pool in 2013 and 2014), allowing for some certainty in that all sawfish in these pools were captured at least once (as suggested by the number of recaptures). However, the fishing effort above the barriers was less intensive (a total of 8.1 h of 20 m net sets in Upper Myroodah Crossing and 17 h of 20 m net sets in Upper Barrage Pool in 2013 and 2014), and it is possible that not all sawfish were captured in these pools. One acoustically tagged Freshwater Sawfish was known to inhabit Upper Barrage Pool, as it was detected by acoustic receivers but was not captured during sampling efforts.



Length-frequency histograms of Freshwater Sawfish captured in the Fitzroy River between 2002 and 2015. The black individuals in 2015 are from a group of fish that died as a result of oxygen depletion in December following a localised flood event.



Mean (± S.E.) CPUE of Freshwater Sawfish in the freshwater (126 to 160 rkm) and estuarine sampled pools in the early (grey dot) and late (black dot) dry seasons between 2002 and 2014.

Green Sawfish (*Pristis zijsron*) captured in the Ashburton River mouth during sampling in November 2014

Ashburton River

Sampling for sawfish in the Ashburton River occurred in April and November 2014. No sawfish were captured in the Ashburton River during the April sampling. In November, five Green Sawfish (*Pristis zijsron*) were captured within the river mouth, but no Freshwater Sawfish were observed. Previous sampling has shown large juvenile Freshwater Sawfish to occur within at least the river mouth area up to the instream road crossings (Morgan *et al.* 2012). It is possible that the Ashburton River may experience interannual as well as seasonal shifts in the abundance of Freshwater Sawfish within the various regions of the river, as is typical of the Fitzroy River. Thus, it cannot be concluded with certainty whether the Ashburton River is a nursery for Freshwater Sawfish. However, a lack of reports of any sawfish captures from the freshwater reaches of the river suggests that it is not a nursery or that it maintains a small population. Genetic examination of the Freshwater Sawfish in the Ashburton River estuary may elucidate the location of their nursey (e.g. Fitzroy River (see Phillips *et al*. 2011)).

Ord River

Freshwater Sawfish have been observed in recent years in the Ord River, although only in low numbers (Storey 2003; Water and Rivers Commission 2003; discussed by Thorburn *et al.* 2004; Last & Stevens 2009). In addition, anecdotal evidence discussed in Thorburn *et al.* (2004) suggested that Freshwater Sawfish have been captured in Spillway Creek, an anabranch of the Ord River that connects Lake Argyle with the river proper. Anecdotal information from fishers also suggests Freshwater Sawfish does occasionally move into Lake Argyle and its tributary, Emu Creek (Thorburn *et al.* 2004). However, this is likely to be a rare event as research surveys have not recorded this species above the Lake Kununurra Diversion Dam (Thorburn *et al.* 2004; Gill *et al.* 2006), and reports from fishers of sawfish from this area are infrequent. From this evidence, it is not possible to determine if the Ord River is currently a nursery for the species, however it is evident that like the Ashburton River, Freshwater Sawfish does utilise this river. The change from an intermittent river, to a perennially flowing system through flow regulation and irrigation may have led to the Ord River now being unsuitable for Freshwater Sawfish. Additionally, the high numbers of large Estuarine Crocodiles presumably will exhibit a high level of predation on sawfish, compared to the Fitzroy River.

CONCLUSIONS

These results demonstrate that there are six barriers in Western Australia that are likely to influence the migration of Freshwater Sawfish to some degree. However, the level of the effect on the overall Western Australian population/s is likely to be dependent upon the habitat quality of the river and presence of sawfish. The Fitzroy River is a well-established nursery for the species and arguably has one of the largest populations of Freshwater Sawfish in the world. As such, barriers within this river are likely to have a large influence on sawfish migration.

The Ashburton River appears to have a less optimal environment for Freshwater Sawfish, due to the reduced wet season and river stage height and colder temperatures. In conjunction with discovering no Freshwater Sawfish within the freshwater reaches, nor having observed any anecdotal reports of their presence in the river, the barriers on this river are likely to only have a relatively minor impact on the species. This impact would most likely affect sub-adults that inhabit the river mouth area, potentially migrants from neighbouring nurseries, as it would prevent their at least temporary movement into freshwater pools.

The Ord River is less straightforward in terms of the impacts of dams on sawfish. Although the habitat appears similar to the Fitzroy, and suitable for juvenile Freshwater Sawfish, reports of Freshwater Sawfish within this system have been sporadic and anecdotal. The presence of Freshwater Sawfish within the system prior to installation of the three high-priority barriers is not well documented, and thus it cannot be determined, although it is likely that damming of the river decreased the numbers of sawfish, as they are naturally found in adjacent rivers, and that flows and habitats would have been similar to the Fitzroy River prior to regulation. The perennial flows in the Ord River, from historically being an intermittent river, may have impacted the suitability of this river as a sawfish nursery.

In concluding this study, the high-impact dams were further prioritised amongst themselves and it was concluded that the Camballin Barrier on the Fitzroy River likely has the greatest impact on sawfish, and second was Myroodah Crossing. The Ord River barriers should be considered together, as the degree of impact of one barrier is dependent upon whether an animal can bypass the other upstream and/or downstream barriers. A similar case can be made for Myroodah Crossing and the Camballin Barrage, which is discussed later in this document. The barriers on the Ashburton River may impact larger juvenile/sub-adult Freshwater Sawfish that are more nomadic, but the river does not appear to be a nursery for the species, rather an opportunistic feeding ground during flood events.

Phase II: Monitoring sawfish near instream barriers and exploration of 'trap and haul'

Neonate and juvenile elasmobranchs will often use rivers, estuaries and/or near-shore habitats as nursery areas, as these environments often provide increased prey and/or decreased predation (Castro 1993, Beck *et al.* 2001, Heupel *et al.* 2007). It is important to maintain the access to and conditions of these nurseries to aid in the recruitment of the juveniles into the adult population. However, these near-shore environments are at high risk from habitat modification due to urban development, runoff, mining and dams. Restricting access to or modification of these nursery areas can lead to a decrease in the carrying capacity of the nursery area, decrease the fitness of the animals reliant on the nursery area and/or force the animals into other unfavourable environments with lower prey availability or increased risk of predation (Simpfendorfer *et al.* 2005; Jennings *et al.* 2008, Carlisle and Starr 2009).

The Freshwater Sawfish is listed as *Critically Endangered* by the International Union for the Conservation of Nature (IUCN), and as *Vulnerable* on Australia's Environment Protection and Biodiversity Conservation Act 1999 (EPBC). Sawfish numbers and ranges have decreased substantially due to fishing (captured as bycatch) and habitat modification. Pupped within, or near to, river mouths during the wet season, the Freshwater Sawfish moves upstream into freshwater rivers and lakes and uses these areas as nurseries for several years before moving back into marine waters prior to maturation. Unfortunately, many of these rivers and lakes are altered by the introduction of human-made instream barriers including road crossings, weirs and hydroelectric dams, which are known to block movements of fishes (e.g. Morgan *et al.* 2005). However, as there is a paucity of data regarding the movements and habitat use patterns of Freshwater Sawfish, it is unclear if and how these modifications may impact this species.

Camballin Barrage, a barrier to migrating sawfish on the Fitzroy River, Western Australia

The previous section of this report reviewed over 62,000 human-made instream barriers located in Western Australia and identified six barriers that are likely to have the greatest impact on Freshwater Sawfish. Using this information, this chapter focuses on the movements and habitat use patterns of juvenile Freshwater Sawfish in the Fitzroy River, Western Australia, which contains two of these high priority barriers and is one of the largest, if not the largest Freshwater Sawfish nurseries in the world. This was undertaken to understand how the different sizes, types and locations of these barriers may influence Freshwater Sawfish movements and habitat use. This study was conducted with the use of acoustic telemetry, placing acoustic transmitters on Freshwater Sawfish and monitoring their large and small-scale movements via an acoustic receiver array, which was deployed throughout the river. The collected information was also used to further explore potential means to mitigate impacts these barriers may have on Freshwater Sawfish, including a continued investigation into a 'trap and haul' program as described below.

Methods

Study sites

This study was conducted in the Fitzroy River, Western Australia. The Fitzroy River is one of five major tributaries of King Sound, a large and protected embayment that experiences 11+ m tides. The Fitzroy River is an intermittent river that transitions between the wet (December to April) and dry (May/June to November) seasons. During the wet season, increased precipitation results in substantial increases in stage heights of the river and can also result in the flooding of the surrounding flood plains. During the dry season, cessation of precipitation and increased rates of evaporation lead to a drop in river discharge and stage height, until the river is transformed into a series of isolated pools, fed only by ground water from alluvial aquifers. The period in which pools become isolated varies annually, and is dependent upon the previous wet season and status of the aquifer.

The Fitzroy River is relatively pristine, but fish movement is blocked for part of the year by two road crossings (Myroodah Crossing and Fitzroy Crossing) and a small weir (the Camballin Barrage). Although the Fitzroy Crossing is a potential fish barrier, it is likely to have relatively negligible impact on fish migration due to its location in the upper reaches of the river and its minimal head loss, and was therefore not included in the study. As such, this study focussed on the habitat use and movements of

sawfish in relation to the Myroodah Crossing (128 rkm) and the Camballin Barrage (164 rkm).

Abiotic variables

Water temperature and light intensity was logged by HOBO Pendant Loggers (Onset Computer Corporation, Bourne, MA, USA), which were installed on acoustic receiver moorings in 2014. Pendant loggers were deployed on moorings at a depth of 1 m. River stage height and discharge data were obtained from the Department of Water, Government of Western Australia.

Pool depth and occurrence of submerged large woody debris were mapped in Camballin Pool and Lower Myroodah Crossing Pool. These pools were selected for this habitat mapping, as they were the two pools located in close proximity to a barrier and had the greatest concentration of receivers, allowing for the majority of the pools to be monitored. Habitat mapping was conducted using a Hummingbird Side Imaging sonar unit (Hummingbird, Brisbane, Queensland, Australia) in association with a global positioning system (GPS) unit. Pool depths were measured at 10 s intervals during two oblique-patterned transects and a single mid-stream transect. Large woody debris was characterised by wood objects approximately ≥ 10 cm in diameter, and consisted of 'permanent' snags, large branches and stumps. This debris was mapped by recording GPS points surrounding the perimeter of each cluster, rather than each individual piece, in essence creating minimum convex polygons for each grouping of large woody debris.

Tagging of sawfish

Sawfish were targeted in the lower 170 km of the Fitzroy River during the early and late dry seasons of 2013 to 2015 (Table 1). Sampled pools included Telegraph Pool (13 rkm), Pandanus Pool (35 rkm; name given by authors), Lower and Upper Myroodah Crossing Pools (126 and 129 rkm; names given by authors), Camballin Pool (160 rkm; name given by authors) as well as Lower and Upper Barrage Pools (164 and 165 rkm; names given by authors) (Figure 1). Gill nets (20 to 60 m monofilament, 152 mm stretched mesh) were primarily used to catch sawfish, although hook and line methods were used opportunistically. Captured sawfish were moved to the river banks and inverted onto their dorsal surface to induce a tonic immobility like state. Slight pressure was applied to the caudal peduncle and base of the rostrum to further reduce movement by sawfish. The spiracles, mouth and gills of each sawfish remained submerged during handling to allow for continued respiration. Morphometric measurements, including stretched total length (TL), sex, clasper development (if male) as well as the presence of scars (yolk-sac and predation) were recorded. An individually numbered Rototag (Dalton Supplies, New South Wales, Australia) was externally attached to the first or second dorsal fin of each sawfish using similar methods to those described by Heupel *et al.* (1998) and Whitty *et al.* (2009). Sawfish were also fitted externally or internally with Vemco V13-TP acoustic tags (VEMCO Division, AMIRIX Systems, Inc., Halifax, Nova Scotia, Canada). Externally fitted acoustic tags were secured to Rototags via cable ties and black marine-grade silicone, and were attached externally in similar fashion to the unmodified Rototags. Internally implanted acoustic tags were encased in a thin paraffin/beeswax coating to help reduce negative interactions that tags may have with the internal tissues, and were disinfected in an antiseptic solution prior to implantation in order to reduce the risk of infection. Tags were inserted into the peritoneal cavity via a small incision on the ventral surface of the sawfish, anterior to the pelvic fins. The incision was closed with two or three interrupted sutures.

Acoustic array

An array composed of between 14 and 20 Vemco VR2W acoustic receivers monitored the interpool (wet season) and intrapool (dry season) movements of tagged sawfish in the Fitzroy River between 2013 and 2015. Receivers were located between Telegraph Pool and Geikie Gorge. Two receivers in Pandanus Pool were removed prior to the 2014/2015 wet season, one of which was relocated to Durack Pool, Snake Creek (31.1 km from the confluence of Snake Creek and the Fitzroy River). Multiple receivers were often placed within a single pool below and above barriers, if feasible, to monitor movements or lack of movements over barriers as well as movements and habitat use of Freshwater Sawfish within pools in close proximity to barriers. Lower Myroodah Crossing had the greatest density of receivers, with 5 acoustic receivers spaced approximately 500 m apart within this 3 km pool, providing almost complete coverage.

Distances at which receivers could detect acoustic transmitters were tested in the dry season in Lower Myroodah Crossing and Camballin Pool using Vemco V13-1L acoustic 'test tags'. Test tags transmitted continuously at a set interval. Range tests consisted of mooring test tags 1 m above the river bottom for a 5 min period at intervals of 50 m upstream and downstream of a receiver. A depth of 1 m was chosen to replicate the benthic behaviour of sawfish. Research vessels were removed from the area and the engine stopped during range tests to prevent interference with acoustic transmissions.

Trap and haul

Trap and haul is an alternative means to allow sawfish to bypass a barrier and includes the manual relocation of each individual from below a barrier to upstream of the barrier. To determine the efficacy of this system on Freshwater Sawfish and to determine if Freshwater Sawfish would take advantage of this system, individuals were captured in Lower Barrage Pool, tagged with an acoustic transmitter and transported over the Barrage to the Upper Barrage Pool via a mesh sling.

Data analysis

Statistical analyses were conducted in R 3.2.4 and SigmaPlot 12.5. Maps were constructed using Google Earth.

Acoustic array environment

Detection range of VR2W acoustic receivers was calculated by comparing the observed and expected number of transmissions to be recorded at each 50 m interval during range tests (expected = test duration x tag transmission rate). Receivers were determined to be reliable in detecting transmissions at a given distance if 95% of expected transmissions were observed for that interval.

Relative coverage of large woody debris as well as mean and max depths within a 300 m radius (acoustic range of receivers, as noted below) of each receiver was calculated to determine the available habitat within acoustic range of each receiver. Relative coverage of large woody debris in each acoustically monitored area was presented as a percentage of the total coverage of large woody debris within the associated pool.

Residency index

Residency indices (RI) were calculated for individual Freshwater Sawfish in isolated freshwater pools, non-isolated freshwater pools and tidal estuarine pools to determine if Freshwater Sawfish were more transient or resident within a pool when provided with access to other pools. Residency indices were calculated by dividing the number of days an individual was detected by the number of days it was monitored (number of day between when the animal was tagged and when it was last detected). Higher RI values suggested the individual to be more resident within a pool.

Interpool movements

Stage heights in which Freshwater Sawfish can bypass the respective barriers on the Fitzroy River were estimated by comparing the dates when Freshwater Sawfish were detected to have moved over a barrier (i.e. between receivers below and above a barrier), with the daily maximum stage height. The impact of a human-made barrier was calculated by determining the number of days stage heights were lower than the minimum value a Freshwater Sawfish was observed to move over a barrier (i.e. the estimated minimum value needed to move over a barrier), and the number of days per year the stage height was lower than the level of the river when pools naturally became isolated. This was repeated for years 2002 to 2015. Annual variations in stage height are likely to alter the number of days that human-made barriers impact Freshwater Sawfish. A Pearson product moment correlation was used to test if there indeed was a relationship between mean annual stage height and the number of days that only man-made barriers were likely to impact Freshwater Sawfish movement.

Intrapool movement and habitat use

Horizontal movement and activity

Time spent at each receiver during hours of the day was estimated by using the number of visits (i.e. 10 min periods when sawfish were detected) from each animal as a proxy. Visits were used in place of single detections in this analysis to account for potential variations in a receiver's ability to detect a tag, which can be influenced by the number of tagged sawfish present, substrate type, environmental conditions, etc. A 10 min period was selected as it allows for at least three transmissions to occur and it also limits the time-frame to allow for fine-scale movement to be detected. A goodness of fit chi-square test was used to determine if the number of visits significantly varied between hours. Relative occurrence indices were also calculated for each individual to allow for visual analysis of any potential differences in sawfish presence between hours at each receiver. Due to variations in transmission intervals and monitoring periods, indices were first calculated by standardising the number of detections for each animal by dividing the number of transmissions that were detected during each hour by the total number of transmissions that were detected for that animal. Second, standardised indices were divided by the expected number of detections to occur during each hour if there was no significant difference between hours (i.e. 1/24). This established a scale for the indices, where values of >1, <1 and 1 suggested individuals to show a relative preference, avoidance or indifference, respectively, to the hour in question at a specific receiver. Confidence bands (95%) for the indices were also calculated from the standard errors observed between individuals to provide a more representative estimate.

Distance traveled and the number of receivers visited in each hour of the day (i.e. horizontal activity) of tagged sawfish was assessed for individuals. Distance traveled was calculated by summing the distance sawfish moved between receivers for every consecutive pair of detections. Resulting distances were an estimate that did not consider latitudinal movement or the detection range of receivers. However, in order to increase the accuracy of results, transmissions simultaneously detected by two receivers, a product of overlapping detection radius of neighboring receivers, were removed, as these likely represented when a sawfish was between two receivers rather than near receivers. Distances travelled during day-time (08:00 to 15:59), night-time (20:00 to 03:59 h) and twilight (04:00 to 07:59 h and 16:00 to 19:59 h) were calculated and divided by the total distances traveled for each individual to determine if there was a difference between these three periods. Also, goodness of fit chi-square tests were used for each individual to compare the total number of receivers visited between hours of the day.

Accelerometer data was analysed to explore activity patterns of sawfish and to help determine what fishway design may be appropriate for juvenile Freshwater Sawfish. Sensor readings were not validated with visual observations in this study, and thus only relative differences were used to assess activity. In all fish, there were a disproportionately high number of detections to occur at values < 0.2 m/s2 and > 0.5 m/s2, but few in between (see Fig. 2). As such, values of < 0.2 m/s2 were classified as 'resting', and those above were classified as 'active'. The number of detections when an animal was resting during the day-time, night-time and twilight hours, as described above, was divided by the total number of detections that occurred in each period, to further investigate if sawfish are less active within a specific period of the day. Additionally, the total time an individual remained active was estimated by finding the difference between the times of the first and last detections when an individual was observed to be active without resting and without going undetected. Because of the latter prerequisite, total time active is only a minimum estimate. However, due to the extensive coverage in at least Lower Myroodah Crossing Pool, estimates are likely to be reasonably accurate.

Vertical movement

Differences in sawfish depth between hours and months were statistically tested via a two-way repeated-measures ANOVA, with a Holm-Sidak post hoc. In addition, the effects of light intensity and water temperature on hourly depth of sawfish were also tested using a Generalized Additive Mixed Model (GAMM) performed in R package *mgcv*. Depth data was constricted to that acquired in 2014 to 2015, as continuous monitoring of light and temperature were only available for this time period. For the test, data was truncated to specific weeks of the year, namely week 34 (i.e. mid-August) and 43 (i.e. mid-October) to negate longterm/ seasonal effects. These weeks were selected for the analyses as they represented the earliest and latest weeks when the majority (>50 %) of the tagged sawfish were monitored (within each week), and when temperature and light data was available. In addition, these two weeks were included to help investigate changes in diel depth use between the early and late dry season. Fixed effects were water temperature, light intensity and pool (i.e. sawfish location). Individual fish were included as a random factor in each model. The most parsimonious and best fit (lowest Aikake Information Criteria (AIC) value/highest AIC weight; see Burnham & Anderson, 1998) models were selected as those that best explained Freshwater Sawfish depth selection on a daily-scale. Visual analysis of residuals and quantile-quantile plots was used to ensure most assumptions of the GAMM were met. The assumption of independence was violated, as is often the case in time series data. However, mean hourly depths of sawfish were used in place of the raw points in an effort to help reduce the degree of dependence between subsequent points.

Results and Discussion

Twenty-eight Freshwater Sawfish were detected by receivers for 2 to 458 d in 2013 to 2015. Residency indices greatly varied between individuals (0.06 to 1.00) (Table 1). The lowest RI were from individuals tagged in the estuarine pools. The highest RI were typically from individuals within the freshwater pools that were monitored only during the dry season. The low RI values were likely a result of animals moving to unmonitored pools, suggesting that when given the ability, Freshwater Sawfish will move between pools. However, additional factors may be involved that may cue a transient behaviour, such as changes in river flow and or temperature, as observed in other riverine fishes (Foster & Clugston 1997, Paragamian & Wakkinen 2008).

Acoustic array environment

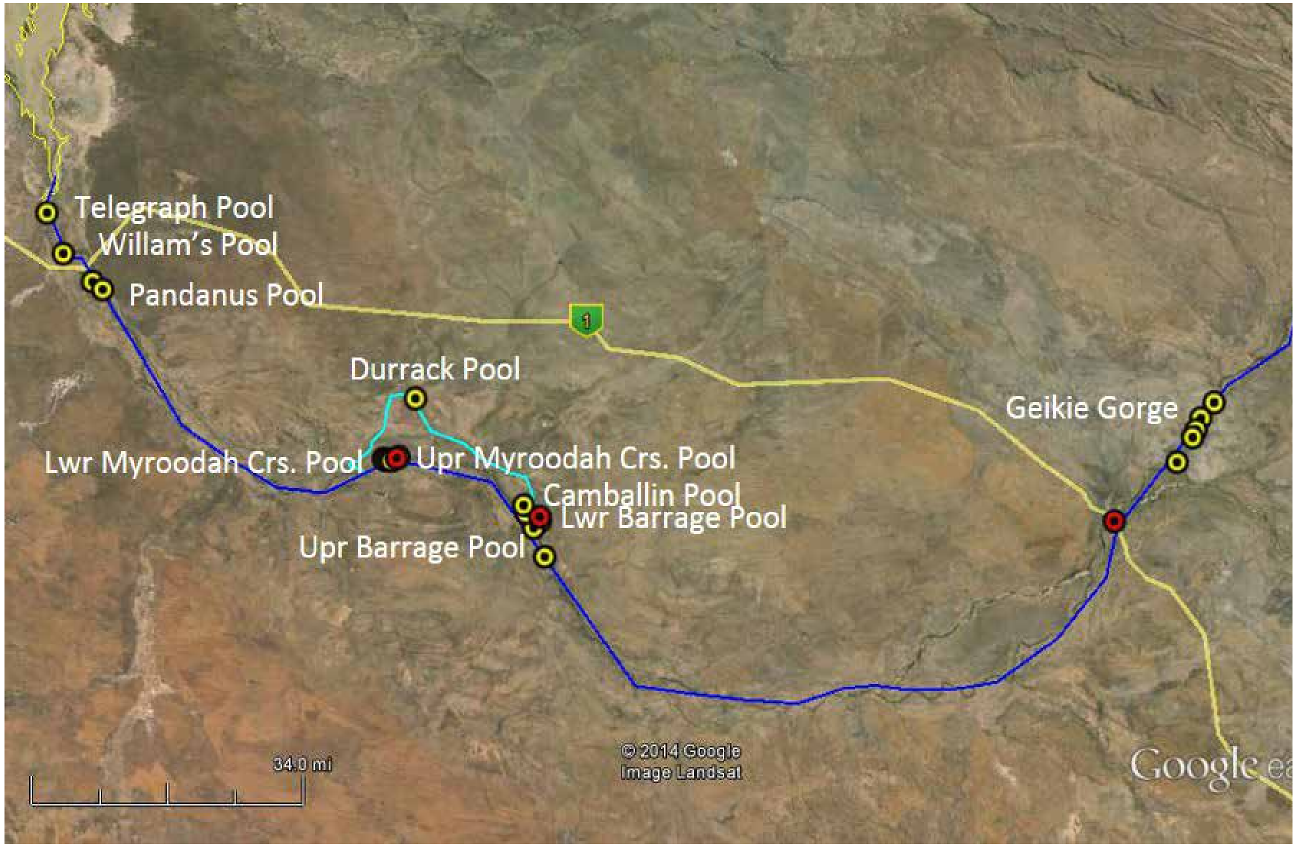
Range tests demonstrated receiver detection radiuses for 95% of expected transmissions to occur up to 300 m (± 35 SE), noting the river width is only 60 m. The number of detections rapidly decreased beyond these distances, with the maximum distance of all detections during range tests being 400 m.

Analysis of depth and river geometry within a 300 m radius of each receiver demonstrated four receivers to be primarily located within shallow water environments (mean depth ≤1.6 m) and three receivers to be primarily located within deep water environments (mean depth >1.6 m) (Table 2). However, the acoustic range of receivers did occasionally cover additional neighboring microhabitat types, which should be considered in interpreting the results. Large woody debris was found to be in relatively low abundance in shallow water environments (Table 2).

Interpool movements

Largescale movements of Freshwater Sawfish were observed to only occur during the wet season when stage heights were elevated and movement between pools was possible. During this time, 13 Freshwater Sawfish were recorded to have moved between pools. Four of these individuals, which ranged in size between 1870 to 2093 mm TL, undertook large scale movements between the freshwater and estuarine pools. During the wet season, Freshwater Sawfish were observed to travel over 320 km at rates of 5.5 km d^{-1} when moving upstream, and 20 km d^{-1} when moving downstream. Eight of these individuals were observed to move over Myroodah Crossing at least once, and one was observed to move over the Camballin Barrage on two different days. Movement over Myroodah Crossing occurred on 18 different occasions. Movement upstream and downstream of Myroodah Crossing and the Camballin Barrage occurred on days when maximum stage height for the day was at least 10.7 and 11.1 m, respectively (measured at the Camballin Barrage Station). Between 2002 and 2015, there were a mean of 103 d yr^{-1} (± 7.1 SE) and 67 d yr^{-1} (± 7.7 SE) when the stage height at the Camballin Barrage Station was ≥10.7 and ≥11.1 m, respectively.

The limited number of recorded movements of Freshwater Sawfish over the Camballin Barrage at times when Freshwater Sawfish were detected in neighbouring pools (i.e. Camballin Pool, Upper Barrage Pool), suggests this to be a barrier to Freshwater Sawfish. Morgan *et al.* (2005) determined that fish movement over the Camballin Barrage was only possible at stage heights of ≥10.99 m, when there is no perceived fall in water from the barrage to the downstream pool. Observing Freshwater Sawfish to move over the barrier at a stage height of approximately 11.1 m, supports Morgan's finding and suggests that this is likely to represent the minimal stage height needed for sawfish to transverse this barrier. As such, this finding suggests that the Camballin Barrage is a barrier to Freshwater Sawfish movements for the majority of the year (i.e. approximately 10 months in an average year). Morgan *et al.* (2011), conducted an in-depth desktop study of the hydraulic geometry of the Fitzroy River and determined that the nearest upstream (13.69 km upstream of the barrage) and downstream (9.46 km downstream of the barrage) natural barriers to the Camballin Barrage form at a stage height of approximately 10.35 m, although this may vary between years due to changes in the geometry of the river. Applying Morgan *et al.*'s findings to this study, it was determined that the Camballin Barrage reduces the time Freshwater Sawfish have to move between pools near its location before being obstructed by natural barriers, by, on average (2002 to 2015), 184 d (± 5.0 SE).



Locations of instream barriers (red dots) and acoustic receivers (yellow dots) on the Fitzroy River, Western Australia. Image sourced from Google Earth.

However, annual values did vary and were observed to have a moderate positive correlation with mean annual stage height ($p = 0.04$, $r = 0.57$). This is because in a relatively dry year, natural barriers emerge earlier and exist longer, and thus have a larger impact on fish movements than in years with large wet seasons. In 2005, which had the smallest wet season between 2002 and 2015, the window that Freshwater Sawfish had to move between pools was only shortened by the barrage by 99 d, before movements were naturally prevented. In 2011, which had one of the largest wet seasons in recorded history, this window was reduced by 242 d.

Although large wet seasons can allow sawfish to move greater distances and access additional habitat, barriers along the river can impact these benefits to a degree. For example, in 2011, 155 0+ Freshwater Sawfish were captured in Camballin Pool, just downstream of the Camballin Barrage. In previous years, one to five Freshwater Sawfish are captured in the pool. The likely reasoning for the increase in numbers was the extraordinary wet season in 2011, which would have allowed the 0+ Freshwater Sawfish, which are pupped near the river mouth area, to move upstream for a relatively extended period of time. However, stage heights were not great enough to allow for the movement of many of the 0+ Freshwater Sawfish above the Camballin Barrage. As a result, a large number of Freshwater Sawfish became trapped in the 2.5 km pool. Although the carrying capacity of a pool for Freshwater Sawfish is unknown, the 31+ fold increase in number of Freshwater Sawfish in this pool would have substantially increased intra-specific competition and decreased fitness levels in these individuals (Morgan *et al.* 2011). Without the barrier or with a means to bypass the barrier, the 0+ Freshwater Sawfish would have been able to be distributed more uniformly throughout the river.

The relatively low crest height and geometry of the Myroodah Crossing was hypothesised to make this less of an obstacle for Freshwater Sawfish. Adopting 10.35 m as an estimate for stage height when natural barriers are formed in proximity to this barrier as well, which is located 36 km downstream from the Camballin Barrage, the natural movement window was found to be reduced by, on average (2002 to 2015), 149 d (±12.4 SE; range = 54 (2005) to 197 d (2011). This data demonstrates that Myroodah Crossing does have a smaller impact on fish movement, although the difference is minor. Fish only have one month on average, where movement over Myroodah Crossing and neighbouring natural barriers but not Camballin Barrage is possible, demonstrating the need to mitigate both barriers.

Trap and haul

Between 2013 and 2015 only two Freshwater Sawfish (2020 and 2030 mm TL) were captured below the Camballin Barrage. Both of these were fitted with an acoustic tag and released into the Upper Barrage Pool. An additional Freshwater Sawfish (1860 mm TL) was captured, tagged and released in Upper Barrage Pool. Due to the low numbers of trapped and hauled Freshwater Sawfish, four Bull Sharks (935 to 1363 mm TL) were also included in this study and were tagged and released upstream of the barrier. Movements of individual Freshwater Sawfish and Bull Shark post release varied. Of the six animals, only one Freshwater Sawfish and one Bull Shark remained in the lower 3 km of Upper Barrage Pool for the remainder of the dry season, as did the one Freshwater Sawfish that was captured in the same pool. The remaining individuals appeared to have moved upstream of a shallow run into an unmonitored region of the pool (the receiver in this region of the pool malfunctioned) and were not detected for the remainder of the dry season. During the wet season, no tagged fishes were observed to move downstream, even though downstream movement was temporarily possible. One Freshwater Sawfish remained or frequented Upper Barrage Pool until the following May, whereas detections from the other Freshwater Sawfish and Bull Sharks in the lower region of Upper Barrage Pool ceased between December to January, when stage heights increased. One Bull Shark that went undetected in the dry season was observed approximately 200 km upstream in Geikie Gorge the following February, where it remained until the final receiver download (the following November).

Additionally, two Freshwater Sawfish that we tagged below the Barrage were found deceased in December 2015 at Geikie Gorge following a fish kill event. One (tag # 1218) was first tagged in June 2011 when it measured 1077 mm TL, but had grown to 1914 mm TL, the second (tag #363) was first tagged in October 2013 where it grew from 2510 mm TL to 2620 mm TL at the time of its death. Such evidence demonstrates that if allowed, Freshwater Sawfish and Bull Sharks will use habitats upstream of the Camballin Barrage for extended periods of time. Future receiver downloads should provide more evidence of the fate of these fishes and how they use these upper reaches.

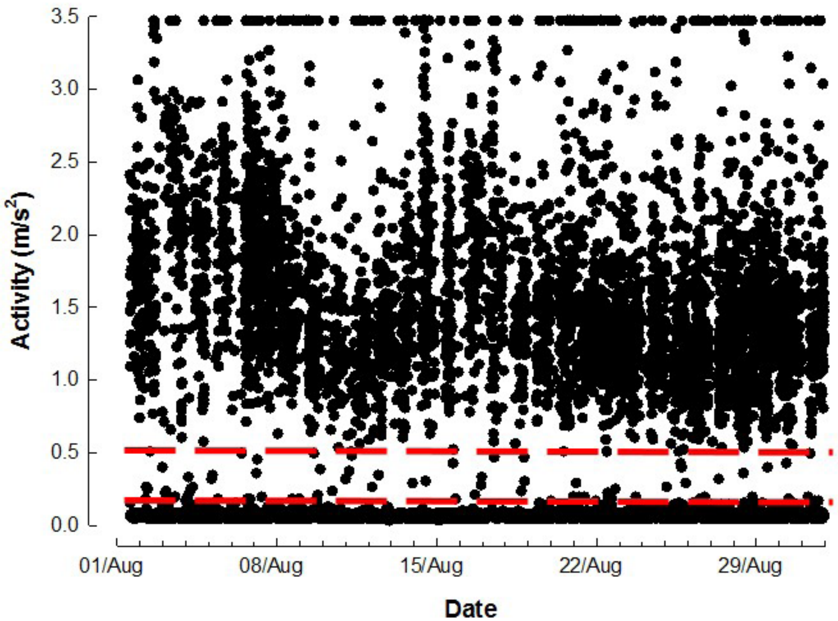
Intrapool dry season movements/habitat use

Twenty-one Freshwater Sawfish were monitored in isolated freshwater pools in the Fitzroy River between 2013 and 2015. Eighteen of these were monitored in pools located in close proximity to the unnatural instream barriers (i.e. Upper Barrage Pool, Camballin Pool and Lower Myroodah Pool).

Table 1. Tagging information of Freshwater Sawfish detected in the Fitzroy River in 2013 to 2015. Information of tagged *Carcharhinus leucas* is also provided for purposes of the trap and haul study. TL: Total length (mm)

Species	Tag	TL	Tag location	Tag date	Final date	Days monitored	Days detected	RI
P. pristis	1143410	1870	Camballin Pl	11-Aug-12	23-Aug-13	235*	33	0.14
P. pristis	1167477	2280	Camballin Pl	18-Aug-13	29-Aug-13	12	12	1.00
P. pristis	1167478	1885	Camballin Pl	18-Aug-13	03-Jan-14	138	133	0.96
P. pristis	1167484	2063	Camballin Pl	20-Aug-13	29-Oct-13	71	70	0.99
P. pristis	1167487	2310	Lwr Myroodah Pl	20-Aug-13	04-Jan-14	138	130	0.94
P. pristis	1167474	2345	Telegraph Pl	21-Aug-13	22-Dec-13	124	9	0.07
P. pristis	1167479	2247	Telegraph Pl	22-Aug-13	20-Dec-13	121	31	0.26
P. pristis	1167485	1925	Telegraph Pl	22-Aug-13	28-Dec-13	129	8	0.06
P. pristis	1167486	2093	Telegraph Pl	22-Aug-13	16-Jan-14	148	14	0.09
P. pristis	1167481	2510	Camballin Pl	30-Oct-13	25-Dec-13	57	54	0.95
P. pristis	1167482	1780	Camballin Pl	30-Oct-13	06-Oct-14	342	255	0.75
P. pristis	1183000	2030	Lwr Barrage Pl	23-Jul-14	20-Jan-15	182	113	0.62
P. pristis	1182999	2020	Lwr Barrage Pl	24-Jul-14	25-Jul-14	2	2	1.00
P. pristis	1183003	2093	Camballin Pl	25-Jul-14	07-Oct-14	75	67	0.89
P. pristis	1183004	1835	Camballin Pl	25-Jul-14	06-Jan-15	166	140	0.84
P. pristis	1183005	2145	Camballin Pl	26-Jul-14	26-Oct-15	458	184	0.40
P. pristis	1183006	1023	Snag Pl	29-Jul-14	18-Aug-14	21	7	0.33
P. pristis	1194191	1011	Pandanus Pl	30-Jul-14	04-Sep-14	37	32	0.86
P. pristis	1194193	1594	Pandanus Pl	30-Jul-14	09-Oct-14	72	53	0.74
P. pristis	1183008	2062	Lwr Myroodah Pl	02-Aug-14	28-Jan-15	450	353	0.78
P. pristis	1167483	2116	Lwr Myroodah Pl	03-Aug-14	06-Jan-15	157	143	0.91
P. pristis	1200103	1860	Upr Barrage Pl	05-Oct-14	29-May-15	237	150	0.63
P. pristis	1167476	2238	Telegraph Pl	09-Oct-14	27-Oct-14	19	19	1.00
P. pristis	1167480	1978	Telegraph Pl	09-Oct-14	24-Oct-15	381	26	0.07
P. pristis	1200100	2105	Lwr Myroodah Pl	12-Oct-14	25-Dec-14	75	68	0.91
P. pristis	1215259	2191	Lwr Myroodah Pl	06-Aug-15	25-Oct-15	81	80	0.99
P. pristis	1215266	2190	Lwr Myroodah Pl	06-Aug-15	25-Oct-15	81	81	1.00
P. pristis	1215260	2551	Onion Patch Pl	11-Aug-15	20-Oct-15	71	70	0.99
C. leucas	1182998	935	Lwr Barrage Pl	23-Jul-14	16-Apr-15	269	56	0.21
C. leucas	1167475	1363	Lwr Barrage Pl	24-Jul-14	27-Jul-14	4	4	1.00
C. leucas	1183001	1260	Lwr Barrage Pl	24-Jul-14	24-Dec-14	154	135	0.88
C. leucas	1183002	1216	Lwr Barrage Pl	24-Jul-14	26-Jul-14	3	3	1.00

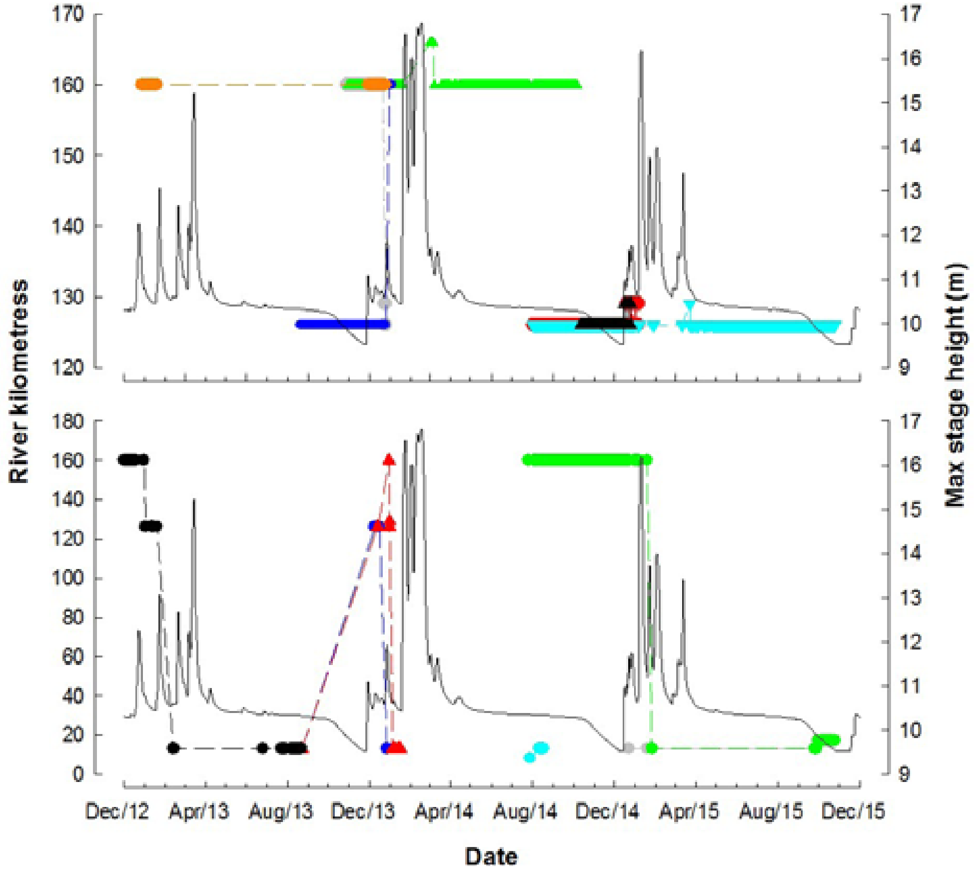
*Days monitored was constricted to only those days within the study period. Start of monitoring period for this individual was set at 1/Jan/2013.



Accelerometer data from juvenile Freshwater Sawfish for August 2014. Red-dashed lines represent the cut-off values for resting (0 to 0.2 m/s^2) and active (>0.5 m/s^2).

Table 2. Lower Myroodah Pool and Camballin Pool late dry season habitat composition. Reported habitat is for a 300 m radius around each receiver. % debris: percentage of large woody debris (debris in detection range of receiver/debris in pool).

Pool	Receiver	Mean depth (m ± SE)	Max depth (m)	% debris
Lwr Myroodah	Myr - 1	1.9 ± 0.001	4.7	22.6
Lwr Myroodah	Myr - 2	1.7 ± 0.0009	4.4	23.4
Lwr Myroodah	Myr - 3	1.9 ± 0.0004	3.1	24.9
Lwr Myroodah	Myr - 4	1.4 ± 0.0005	3.5	18.6
Lwr Myroodah	Myr - 5	1.3 ± 0.0008	4.0	13.8
Camballin	Cam - 1	1.6 ± 0.001	5.3	16.4
Camballin	Cam - 4	1.2 ± 0.0008	3.4	5.8



Inter-pool movements of sawfish between (top) only freshwater pools (Upper Barrage Pool: 166 rkm, Camballin Pool: 160 rkm, Upper Myroodah Crossing Pool: 129 km, Lower Myroodah Crossing Pool: 126 rkm) as well as between (bottom) estuarine and freshwater pools (Camballin Pool: 160 rkm, Upperr Myroodah Crossing Pool: 129 rkm, Lower Myroodah Crossing Pool: 126 rkm, Telegraph Pool: 13 rkm) in comparison with stage height recorded at Camballin Barrage Station. Stage height was made available by the Department of Water, Government of Western Australia.

Table 3. Freshwater Sawfish movements over Myroodah Crossing and the Camballin Barrage. Departed: date of last detection in respective pool; Arrived: date of first detection in respective pool; Stag: stage height at Camballin Barrage monitoring station.

Tag serial #	Date	Departed	Arrived	Stage height (m)
1143410	31-Dec-12	Camaballin Pl	...	10.9
1143410	02-Jan-13	...	Lwr Myroodah Pl	10.7
1167481	25-Dec-13	Upr Myroodah Pl	Lwr Myroodah Pl	10.7
1167486	14-Dec-13	Lwr Myroodah Pl	...	10.7
1167486	30-Dec-13	...	Camballin Pl	11.1
1167486	31-Dec-13	Upr Myroodah Pl	Lwr Myroodah Pl	10.9
1167483	20-Dec-14	Lwr Myroodah Pl	Upr Myroodah Pl	11.0
1167483	24-Dec-14	Upr Myroodah Pl	Lwr Myroodah Pl	11.2
1167483	01-Jan-15	Lwr Myroodah Pl	Upr Myroodah Pl	10.8
1167483	02-Jan-15	Upr Myroodah Pl	Lwr Myroodah Pl	10.7
1167483	05-Jan-15	Lwr Myroodah Pl	Upr Myroodah Pl	10.7
1183008	12-Mar-15	Lwr Myroodah Pl	...	
1183008	23-Mar-15	...	Upr Myroodah Pl	
1183008	23-Mar-15	Upr Myroodah Pl	Lwr Myroodah Pl	10.8
120100	16-Dec-14	Lwr Myroodah Pl	Upr Myroodah Pl	11.0
120100	20-Dec-14	Upr Myroodah Pl	Lwr Myroodah Pl	11.0
120100	20-Dec-14	Lwr Myroodah Pl	Upr Myroodah Pl	11.0
120100	20-Dec-14	Upr Myroodah Pl	...	
120100	25-Dec-14	...	Lwr Myroodah Pl	
120100	25-Dec-14	Lwr Myroodah Pl	Upr Myroodah Pl	11.6
1167487	26-Dec-13	Lwr Myroodah Pl	...	11.5
1167487	31-Dec-13	...	Camballin Pl	10.9
1183005	19-Jan-15	Camaballin Pl	...	11.2
1183005	26-Jan-15	...	Telegraph	11.8
1167482	19-Jan-14	Camaballin Pl	...	12.2
1167482	02-Mar-14	...	Upr Barrage Pl	11.7
1167482	06-Mar-14	Upr Barrage Pl	...	11.3
1167482	08-Mar-14	...	Camballin Pl	11.1

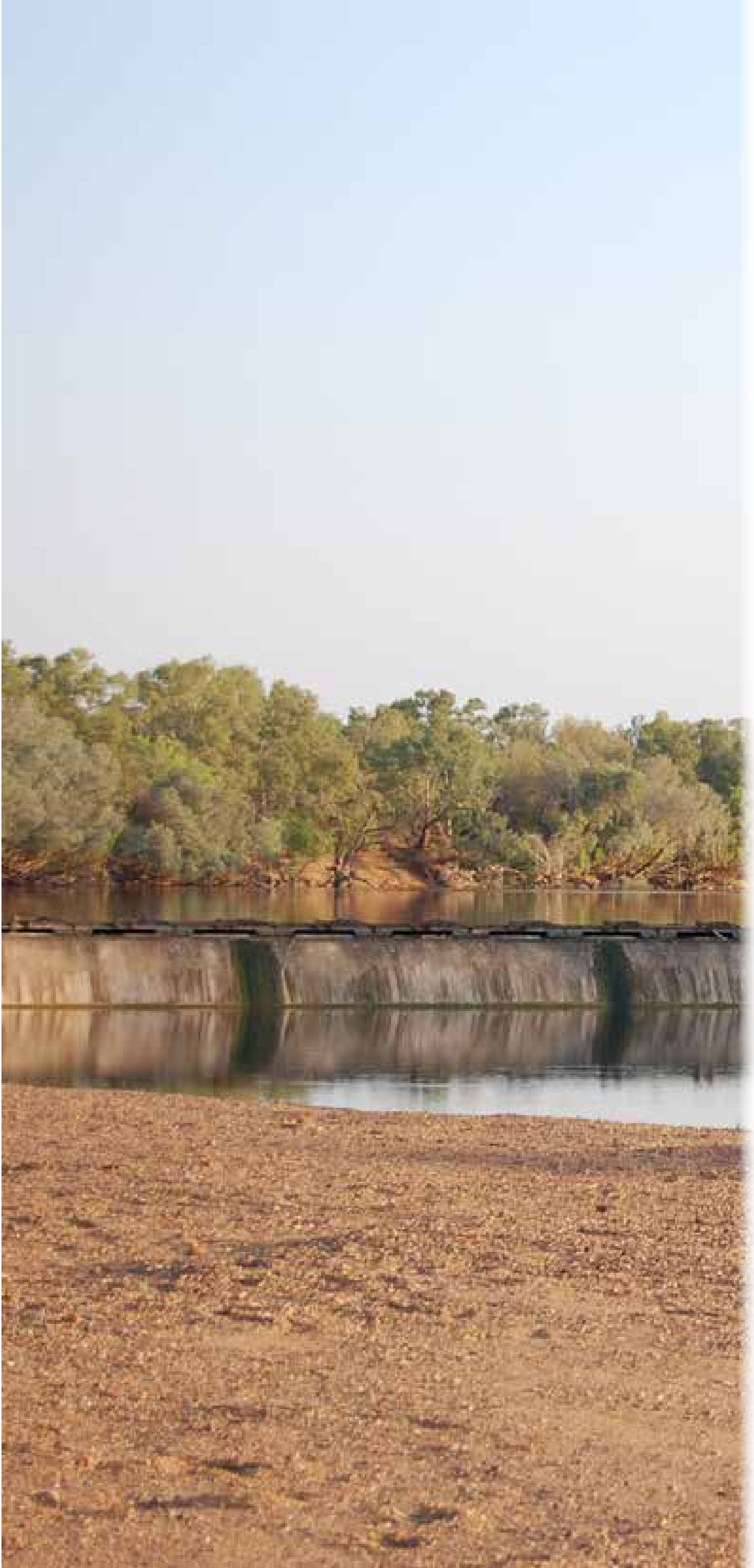
Releasing a Freshwater Sawfish above the Barrage on the Fitzroy River.

These individuals ranged in size between 1780 and 2510 mm TL, which equates approximately to ≥2+ year old Freshwater Sawfish. A lack of captures of younger cohorts prevented their inclusion in this study, as discussed previously.

Activity

All but one Freshwater Sawfish were observed to travel further at night-time and/or during twilight hours than during day-time hours. Of the total movement between receivers, a mean of 48, 41 and 11 % occurred at night, twilight and day hours, respectively. Additionally, the number of receivers visited by individuals was also found to increase at night-time and most twilight hours, although this difference was only observed to be significant ($p < 0.05$, d.f. =23) for five of the eight tested individuals. Data derived from accelerometer sensors also demonstrated Freshwater Sawfish to be more active in night-time hours than in day-time hours, with individuals observed to rest for a mean of 76% (0.03 SE) and 58% (0.1 SE) of the time they were detected in the day and night-time, respectively. Other elasmobranchs have been shown to be less active in the day-time and more active at night-time, a pattern suggested to stem from these animals foraging at night and resting in the day (Sims *et al.* 2006, Andrews *et al.* 2009). Such behaviour has been suggested to maximise net energy gain by increasing foraging efficiency and minimising energy expenditure (Sims *et al.* 2006), which aids to increase fish growth and fitness.

Accelerometer sensors also demonstrated that Freshwater Sawfish remain continuously active (>0.2 m/s^2) for up to at least 212 min (mean = 15.3 min. ± 0.3 SE). Although, many other elasmobranchs, such as the Bull Shark, are ram



ventilators and continuously swim. These data demonstrate that Freshwater Sawfish often 'rest'. Morgan *et al.* (2011a) also observed Freshwater Sawfish to undertake burst events in activity, similar to those required to ascend through a fishway, but only for very brief moments. Although, the swimming capacity of Freshwater Sawfish is not fully understood and requires further testing, it does suggest that Freshwater Sawfish are unlikely to swim continuously for prolonged periods of time, which needs to be considered in designing a fishway for sawfish.

Horizontal movements

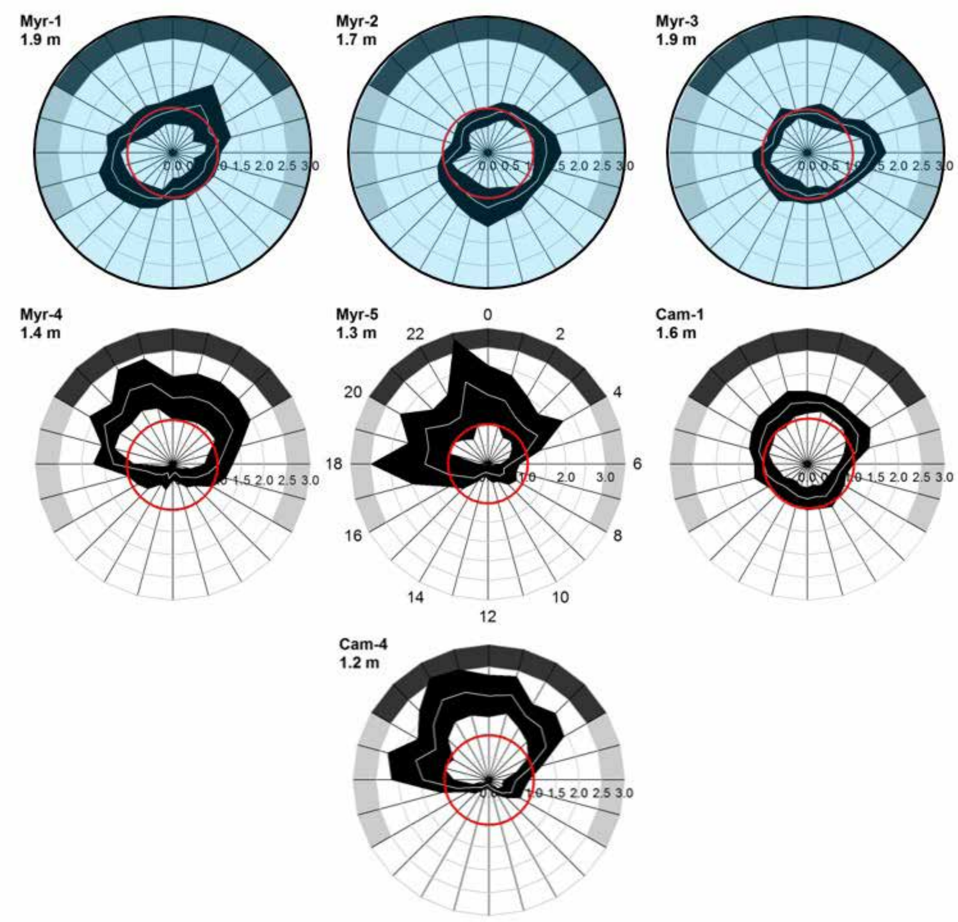
Freshwater Sawfish were observed to partake in diel horizontal migrations, occupying specific habitats at different hours of the day. A chi-square goodness of fit test demonstrated that the number of visits that occurred at each hour were significantly different at each receiver ($p < 0.001$, d.f. = 23). Visual analysis of plots of the relative occurrence indices suggested sawfish avoided shallow water habitat in day-time hours, and showed preference towards them during twilight and night-time hours, when sawfish activity was greater. Whitty (2011) demonstrated that sawfish prey species are in greater abundance in these shallow water habitats at night, as opposed to the day. Moving into these shallow waters at night would thus increase prey encounters, and the shallow water environment would provide prey with fewer escape routes.

In Lower Myroodah Crossing Pool, sawfish showed more of a general indifference between hours in the deeper habitats, with minor relative preferences of such habitat in some twilight and/or day-time hours. Occurrence of Freshwater Sawfish in the deeper water areas during the day-time, when activity levels are lowest, suggests that juvenile Freshwater Sawfish use such habitat to 'rest'. As these deeper waters are often cooler than surface waters, especially in the dry season when the water column begins to stratify (Whitty 2011), the cooler temperatures would decrease the metabolism and thus energetic costs of Freshwater Sawfish (Sims *et al.* 2006). Additionally, the presence of high concentrations of large woody debris in these areas also suggests that they may use these habitats as sanctuaries where they can avoid or at least reduce the risk of predation from sharks and crocodiles. Active acoustic tracking of Freshwater Sawfish in Lower Myroodah Crossing Pool demonstrated individuals to reside within or below large woody debris during the day-time, often returning to the same structures over at least several days.

Vertical movements

Depths occupied by Freshwater Sawfish varied significantly between hours of the day ($p < 0.05$), with Freshwater Sawfish occupying relatively deep water during the day-time and shallower water at night-time, and moving between these depths at sunrise and sunset, regardless of habitat type. Similar diel vertical migrations (DVM) are not uncommon in other fishes, and often occur due to the need of an animal to acquire resources located in two different habitats, such as prey, sanctuary or optimal temperatures (Holland *et al.* 1993; Cartamill *et al.* 2003). The timing of these movements can aid in determining the reason for the migrations. Light intensity, endogenous rhythmicity and temperature can cue the movement of fishes (Nelson & Johnson 1970; Gruber *et al.* 1988; Gibson 1997).

AIC comparisons of multiple models involving light intensity and/or water temperature on the hourly depth of Freshwater Sawfish demonstrated that the best fit and most parsimonious model involved the fixed effects light intensity and water temperature for the investigated weeks in August (i.e. week 34) and October (i.e. week 43) (Table 3). This model suggested light intensity had a strong positive effect on Freshwater Sawfish depth when between 0 and 1000 lux, but was weak at intensities >1000 lux. This model also suggested water temperature had a strong negative effect on Freshwater Sawfish depth at lower available temperatures (e.g. 19 and 23 ºC in August and between 30 and 32 ºC in October). However, the influence of temperature on sawfish depth was relatively minor at the relatively higher available temperatures (i.e. 23 to 25.5 ºC in August, 32 to 33.5 ºC in October). Overall the influence of both variables in the single model appeared to diminish between investigated weeks, a likely result of a decrease in depth use by Freshwater Sawfish during the dry season. Further investigation into the relationship between these variables and depth of Freshwater Sawfish, showed a consistently moderate and positive relationship with light intensity in August through October ($p < 0.001$, $r = 0.273$ to 0. 501, mean = 0.40 ± 0.02 SE). Conversely, temperature and depth of Freshwater Sawfish had a negative relationship, which decreased with time. Starting with a moderate relationship in mid-August ($p < 0.001$, $r = 0.415$), the relationship between depth and temperature progressively decreased until week 39 (i.e. mid-September) when no significant relationship was observed ($p > 0.05$). Together, this information suggests that on a diel scale, light is likely the main cue for the observed DVM. Observing light to be the predominate cue, suggests that the diel movements are most likely related to foraging and or predation, as both are partially dependent on vision, i.e. light. However, Freshwater Sawfish are also likely to benefit from the thermal regimes they experience. Movement into warmer shallow waters in the early evening when foraging, would potentially increase their muscle performance and thus foraging efficiency. Moving



Mean (white line) relative occurrence indices for respective hours and receivers/mean depths, with 95 % confidence bands (black shading). Red circles highlight index values of 1 (values >1: relative preference; values <1: relative avoidance; values = 1: indifference). Outer dark grey, light grey and white shading denote night-time, twilight and day-time hours, respectively. Blue shaded circles: deep water habitat with high concentration of large woody debris, non-shaded circles: shallow water environments.

into the deeper cooler waters during the day when Freshwater Sawfish is resting, would decrease the metabolic demands of Freshwater Sawfish (Sims *et al.* 2006).

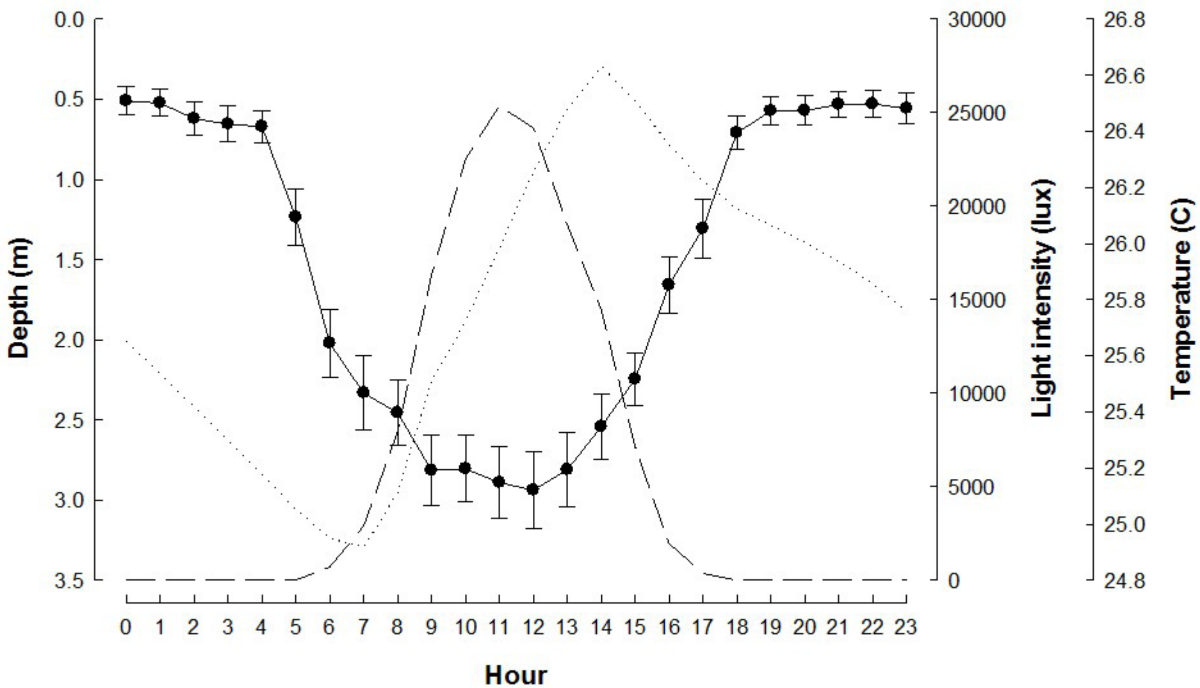
The diel horizontal and vertical movement patterns displayed by Freshwater Sawfish give evidence that this species depends upon several mesohabitats within its heterogeneous environment. As such, removal of these habitats may negatively impact Freshwater Sawfish. Lack of deepwater environments with large woody debris could potentially increase risk of predation and/or introduce Freshwater Sawfish into unfavourable thermal regimes. A lack of shallow water environments may make foraging efforts more difficult, resulting in an unfavourable net energy scenario. Often barriers such as large dams can disturb the environments downstream of the structures. This is evident at the Camballin Barrage where altered flows and the introduction of concrete structures has resulted in a small pool without any large woody debris and very limited to no deepwater habitat. As suggested earlier, the use of trap and haul methods would greatly benefit those individuals within degraded pools immediately downstream of the Camballin Barrage.

CONCLUSION

This study demonstrated that instream barriers can have a major effect on the movements of juvenile Freshwater Sawfish. However the degree and type of disturbance varies between the magnitude of the wet season, location and size of the barrier and the size class of Freshwater Sawfish involved. Highly mobile Freshwater Sawfish rely on elevated stage heights to allow them access to up and downstream habitats and resources. Introduction of a barrier, especially one far downstream on a river will

Table 3. Comparisons of Generalized Additive Mixed Models constructed to describe Freshwater Sawfish depth in the freshwater pools of the Fitzroy River, Western Australia on a diel scale. Individual tags were treated as a randomized variables (i.e. random=list(Tag=~1)) in each model. Light: hourly mean light intensity (lux) at 1.0 m depth; Temp: hourly mean water temperature (ºC) at 1.0 m depth; Pool: location of sawfish; Tag: unique sawfish number

Model	df	AIC/AIC Weight Diel (34)	Diel (43)
Depth~1	1	2816.6/0.0	1176.2/0.0
Depth~s(Temp)	5	2728.4/0.0	1144.3/0.0
Depth~s(Light)	5	2275.5/0.0	961.6/0.0
Depth~s(Temp)+s(Light)**	7	1994.1/0.68	930.3/0.16
Depth~s(Temp)+Pool	6	2730.4/0.0	1143.6/0.0
Depth~s(Light)+Pool	6	2274.8/0.0	958.6/0.0
Depth~s(Temp)+s(Light)+Pool	8	1995.6/0.32	927.0/0.84

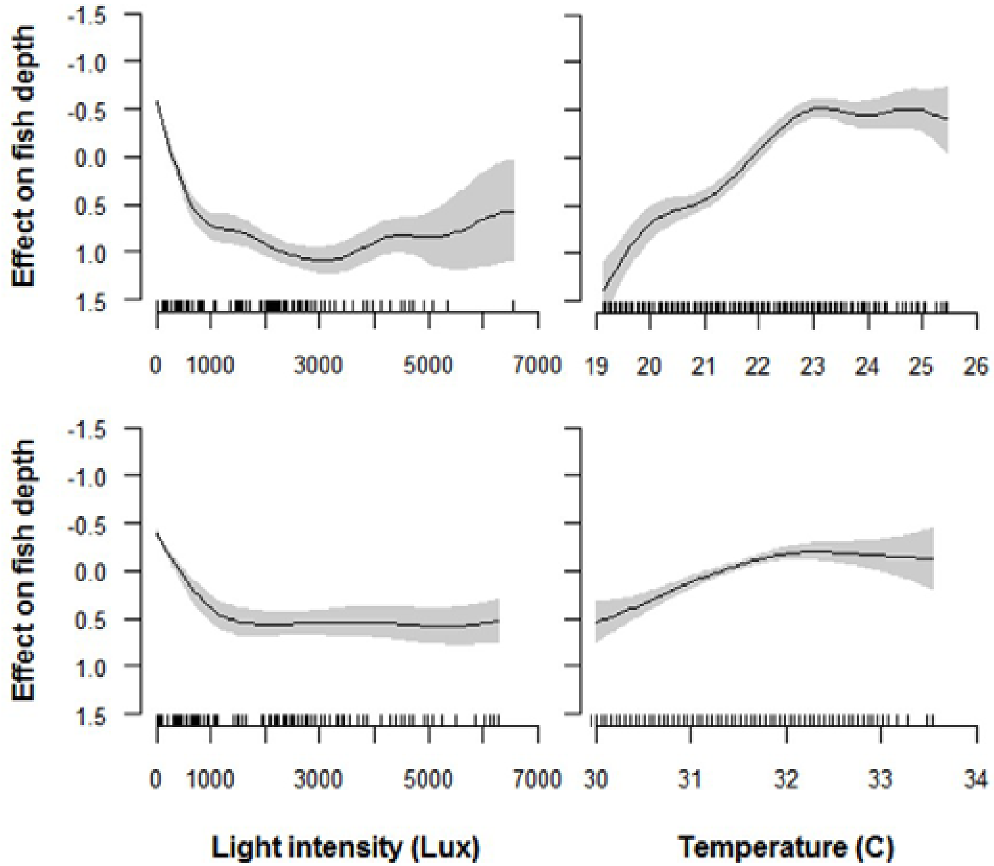


Mean depth (± se) of all Freshwater Sawfish monitored in the freshwater pools of the Fitzroy River, Western Australia in the dry season, plotted with representative dry season light intensity (lux) and temperature (ºC) diel patterns.

interrupt those movements and possibly lead to increased intra-specific competition and predation. Only when stage heights are great enough can Freshwater Sawfish move beyond these barriers.

The following conclusions can be drawn from potential impacts of the unnatural barriers in the Fitzroy River:

- Freshwater Sawfish are highly transient, and move between pools when possible, with larger individuals moving 100's of kilometres upstream and downstream during the wet season.
- In the Fitzroy River, in an average year, unnatural barriers impact movement for 5-6 months of year depending on barrier size, but have an even greater impact in years with large wet seasons.
- Sawfish use multiple microhabitats to optimise their fitness. Migrating Freshwater Sawfish from the homogenous Lower Barrage Pool to the heterogeneous Upper Barrage Pool via trap and haul will likely provide the immediate benefit of increased resources and diversity of habitats to these individuals.
- This study also demonstrated that once above the barriers, Freshwater Sawfish, as well as Bull Sharks, may continue their migration upstream. However, manual relocation of Freshwater Sawfish over Myroodah Crossing would only lead to short upstream benefit as further upstream their movement would blocked by the Camballin Barrage.
- Predation pressure may be relieved below barriers.
- Freshwater Sawfish appear to be highly sedentary, and were observed to rest frequently, with bursts of movement occurring over a short period of time. This suggests that fishways for sawfish should allow areas of low flow where sawfish can rest. However, further research is required to understand the full capacity of the swimming abilities of Freshwater Sawfish.



Generalized Additive Mixed Model derived effects of (left) light intensity and (right) water temperature on depth of Freshwater Sawfish in weeks (top) 34 and (bottom) 43 of the year. Shaded regions represent 95% confidence bands.

The Ashburton River as a pupping site and nursery area for Green Sawfish (*Pristis zijsron*)

Summary

Passive acoustic telemetry of 37 juvenile *Critically Endangered* Green Sawfish (*Pristis zijsron*) (<3000 mm total length), in the Pilbara region of Western Australia, revealed the movement patterns of several age classes. Neonates, which were presumed to have been pupped in October 2011, had a high site fidelity to the mouth of this arid zone river, where they were initially tagged. They remained adjacent to the mouth of the river (<700 m upstream), which only floods periodically following cyclonic rainfall events, until it flooded in January 2012. All age classes had a strong affinity with the river mouth or the mouths of adjacent tidal creeks. Movement between sites within and among creeks increased with sawfish size. The high CPUE and localised movements suggest that the area is of global significance for this species, which has undergone a major decline in range and for which contemporary records are scant, providing significant opportunity for management to protect this critical habitat. Long-term interannual variation in recruitment should be assessed against environmental criteria.

Introduction

The largest and least studied sawfish species is the Green Sawfish. Globally, this species is believed to have undergone a major decline (38%) from its former Indo-Pacific range (Moore 2015, Duly *et al.* 2016) and it is listed as *Critically Endangered* by the IUCN. The species is thought to have become extinct in most of eastern Australia, parts of South-east Asia and is South Africa's first marine elasmobranch extinction (Everett *et al*. 2015, Dulvy *et al*. 2016). There are few reliable contemporary records of the species throughout its former range, and most recent records are from northern Australia, including Western Australia; the coastal waters represent a globally important refuge for four species (Peverell 2005, Morgan *et al*. 2011b, 2015). In the current study, passive acoustic telemetry was used to examine habitat associations of juvenile Green Sawfish that were recently discovered in an estuary and adjacent mangrove creeks in the eastern Indian Ocean (Pilbara) region of Western Australia. In this section, we seek to identify the importance of the area for sawfish both regionally and globally, by documenting the site fidelity of different age classes in the region in order to provide the first data regarding the potential for management to conserve this important population.

Methods

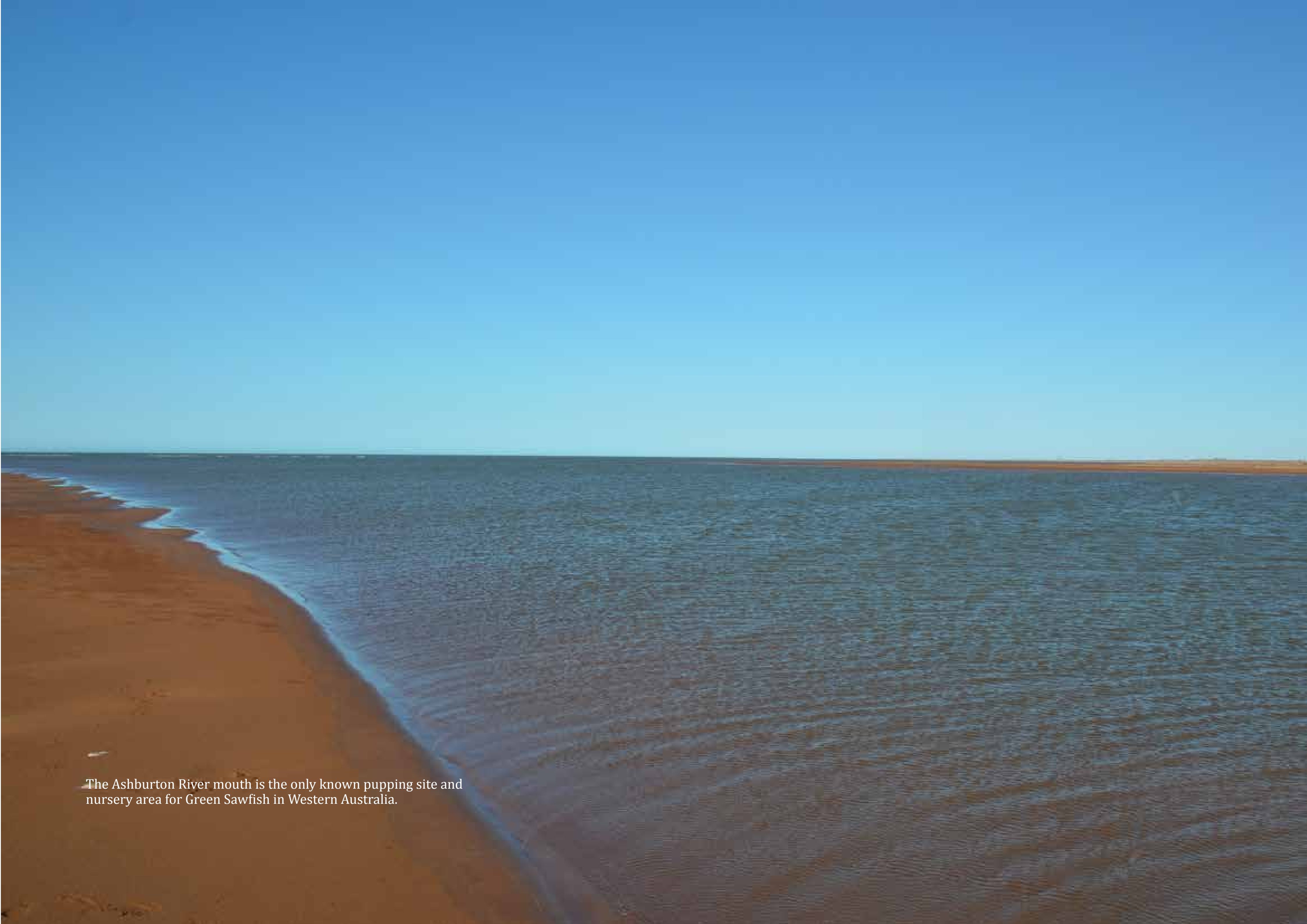
Site selection, sampling methods, tagging

Targeted sampling for sawfish near Onslow, Western Australia, namely the Ashburton River mouth, Hooleys Creek and Four Mile Creek, occurred during April and October 2011 (Figure 1) (see Morgan *et al*. 2015). Sampling occurred at several sites in the tidal waters of the Ashburton River mouth and its delta, and a number of sites within two adjacent tidal mangrove creeks that were accessible by road, i.e. Hooleys Creek and Four Mile Creek.

Sampling consisted of setting gill nets (100 or 150 mm monofilament stretched mesh, of 60 m length) perpendicular to the bank. A total of 44 net sets soaked for a total of 128 h pooled across all sites and seasons, including: 13, 28 and 22 h in Four Mile Creek, Hooleys Creek and the Ashburton Estuary, respectively, in April (late wet season), and 15, 17 and 32 h in those localities in October (see Morgan *et al.* 2015).

The majority of Green Sawfish captured were fitted with a 69 kHz, coded V13TP acoustic transmitter (Vemco). Tag attachment method was synonymous with that used by Whitty *et al*. (2009). Acoustic transmitters were attached to Gallagher Supertags (Rototags) and then fastened to the first dorsal fin of each sawfish. With larger individuals, an additional rototag was secured to the second dorsal fin which acted as a reserve identification tag that may also allow us to determine whether the acoustic tag was shed. Before deployment, each transmitter was tested using a VR2W acoustic receiver. Each transmitter was fitted with temperature and pressure sensors that had a temperature range of 0–40°C and a depth range of 0–50 m, respectively. Each tag randomly transmitted a signal at intervals of between 50 and 90 sec. The estimated battery life of the tag was 514 days.

Prior to the tagging of sawfish with acoustic transmitters, 12 VR2W acoustic receivers were installed throughout the study area. Site selection adhered to conditions provided by the Department of Transport, Government of Western Australia, and the mooring system included a surface buoy fitted with reflective tape. The acoustic receivers in the array included two units placed within Four Mile Creek, two outside the mouth of Four Mile Creek, two placed within Hooleys Creek, one placed in the mouth of Hooleys Creek and one outside of the mouth of Hooleys Creek, and three receivers were placed within the Ashburton River and one outside



The Ashburton River mouth is the only known pupping site and nursery area for Green Sawfish in Western Australia.

of the Ashburton River mouth. Additionally, during October 2011, VR4-Global receivers (Vemco) were installed in the mouth of the Ashburton River, Hooleys Creek and in the mouth of Four Mile Creek.

Data analysis

A residency index was calculated for each tagged sawfish, with the index value equaling the number of days a fish was detected divided by the number of days it was at liberty (i.e. the number of days between when the sawfish was tagged and when it was last detected). A sawfish was considered to be present in an area if it was detected more than once in a day. Single detections were excluded from analyses to reduce the risk of incorporating false positive detections and only accounted for 0.06% of all detections. Mean residencies of sawfish within the different regions (tributary and ocean) and size classes were compared to determine differences in spatial and temporal habitat use. This was performed by running log-transformed residency index values through an ANOVA. As the log-transformation did not follow a normal distribution, but was homoscedastic, a significance value of 0.01 was used. The number of contiguous days a sawfish was present and absent from the study area was also calculated.

The distance and frequency in which sawfish moved between creeks was calculated by summing the total inter-creek distance traveled by an individual sawfish. The total distance a sawfish traveled was standardised with the number of days the fish was at liberty. A Pearson product moment correlation was used to compare the inter-creek distance traveled with the total length of the fish. A Pearson product moment correlation was used to analyse the correlation between the various size classes and the percentages of those size classes to move between creeks.

A goodness of fit chi-square analysis was used to test the null hypothesis that the direction of sawfish movements to and from a tributary were not influenced by tidal flow, i.e. movements in and out of tributaries were equally likely with and against the direction of flow. In the analysis the observed number of fish moving with the flow and those moving against the flow were compared with an even distribution of the total number of movements. Only detections recorded in a tributary and then subsequently in the ocean, or vice versa, within a two hour period were included in this analysis. Detections beyond this two hour window were excluded to help ensure that the movements occurred during either an ebbing or flooding tide, but not both. Movements to and from the Ashburton River were also excluded because the ocean area near the river was unmonitored.

Results

Sawfish captured

A total of 39 Green Sawfish were captured during the study, including 10 in April and 29 in October (Table 1). Of these, 37 were fitted with acoustic transmitters within the Ashburton River (n = 29), Hooleys Creek (n = 3) and Four Mile Creek (n = 5) in April (n = 10) and October (n = 27) 2011 (Table 1).

Total length of tagged individuals ranged between 767 and 2933 mm (April, 1122 to 2447 mm; October, 767 to 2933 mm) (Table 1). Uncalcified claspers indicated that all of the captured males were sexually immature. Most sawfish within the smallest cohort (i.e. Green Sawfish of 767 to 972 mm TL) had open or partly healed yolk-sac wounds, with one possessing the remnants of a yolk-sac and rostral teeth that had just begun to emerge from the rostral sheath. However, in April all yolk-sac scars found on the smallest captured sawfish were completely healed. It is therefore presumed that the small individuals captured in October were neonates. The total CPUE of Green Sawfish caught across all sites and seasons was 1.90 individuals in 500 m net^{-1} day^{-1}. Relative mean abundance (CPUE) of Green Sawfish was higher in Four Mile Creek and Hooleys Creek in April (73 and 22 individuals in 500 m net day^{-1}, respectively) than in October (45 and 0 individuals 500 m net day^{-1}, respectively). In contrast, mean CPUE was higher in the Ashburton River mouth in October (265 individuals in 500 m net day^{-1}) than in April (31 individuals in 500 m net day^{-1}). The considerably high CPUE of Green Sawfish in the Ashburton River in October (total CPUE of 18 individuals caught in 500 m net day^{-1}) was the result of a recent pupping event, with neonates making up almost half of the sawfish caught at this time.

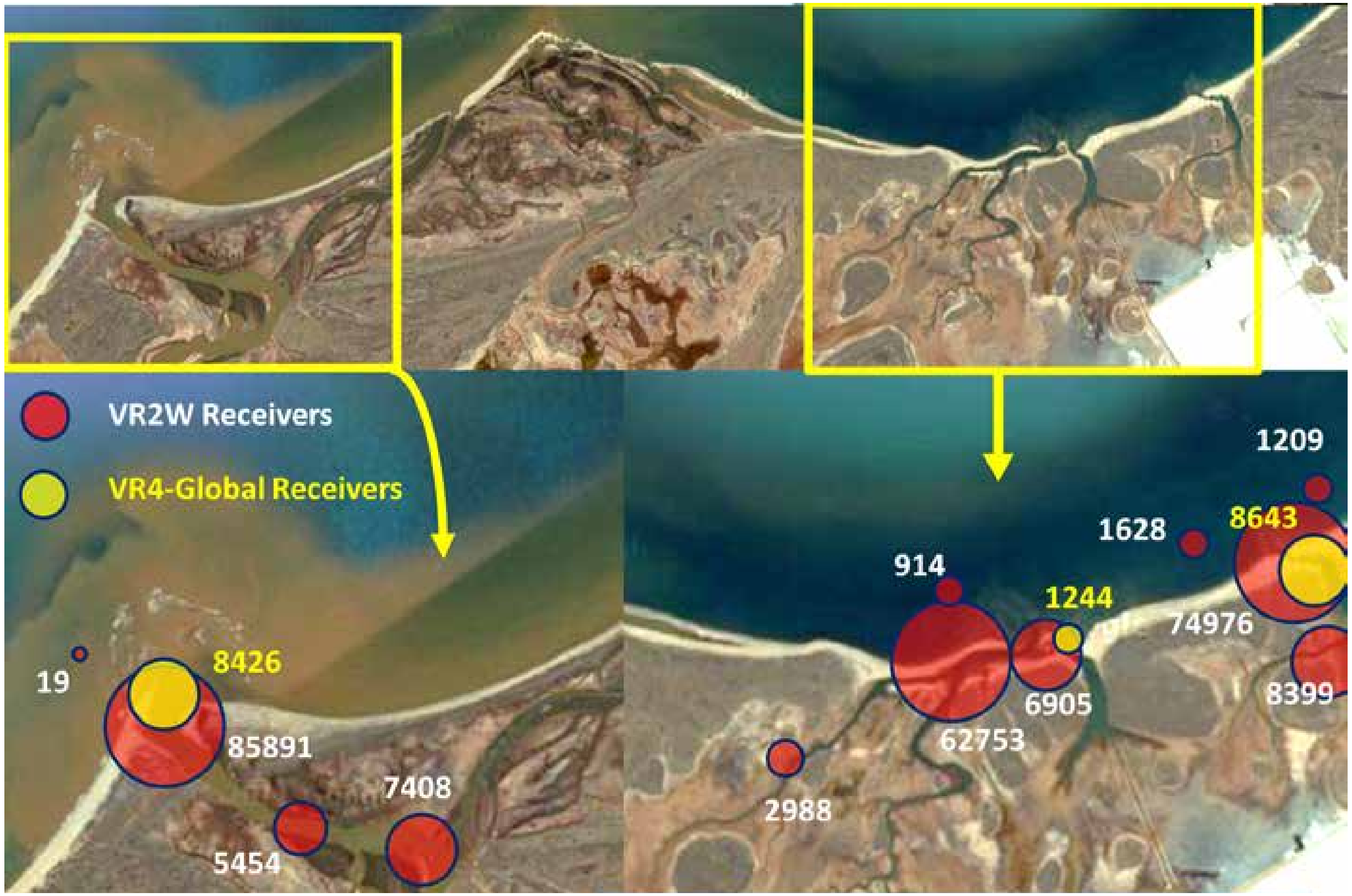
Additionally, two Freshwater Sawfish (female 2578 mm TL and a male 2830 mm TL) were captured in April sampled and fitted with an acoustic tag.

Receivers

All except one of the VR2W receivers were retrieved and downloaded. The unit deployed outside the mouth of the Ashburton River was unable to be located despite a thorough search in the vicinity of the GPS co-ordinates where it was originally deployed. To maintain the integrity of the receiver array, a replacement VR2W unit was deployed at these co-ordinates. Two of the VR4-Global receivers ceased functioning in early 2012. The unit deployed at the mouth of Hooleys Creek began malfunctioning during the week prior to 23rd January 2012, and the unit deployed at the mouth of the Ashburton River malfunctioned during the week prior to 12th March 2012.

Acoustic detections

The total number of detections recorded by the



The detections of sawfish in the Ashburton River and adjacent tidal creeks.

VR2W receivers in the study area was 287404, with a mean of 7668 (± 1992 S.E.) detections/sawfish and a range of 12 to 41283 detections. Sawfish were at liberty (i.e. number of days between the day the sawfish was tagged and the day the tagged sawfish was last detected) for between 14 and 525 d (median = 85 d), noting that estimated tag life was 514 d (Table 1). During these periods sawfish were detected on one to 484 d (median = 50 d) (Table 1). Two tags were prematurely removed from the study area during the study period (i.e. sawfish #6 was found dead in an illegal gill net and sawfish #30 had its tag removed by a recreational fisher).

In total 29, 14 and 9 individually tagged sawfish were detected in the Ashburton River, Hooleys Creek and Four Mile Creek, respectively. Fish were detected within the array throughout the entire study, which demonstrates a good surveillance capacity of the array (Table 1). All tagged sawfish left the Ashburton River during a large flow event in January 2011, but many returned after flows declined a few weeks later, and this included the neonates that were tagged in October 2011. Tagged sawfish occupied water temperatures ranging from between ~15 and 35°C, with highest temperatures (range of 26 to 35°C) recorded during late summer and early autumn.

Primary habitat of tagged sawfish (i.e. the site where the greatest number of detections occurred for an individual sawfish) included the mouth of the Ashburton River (43.5 to 100% of individual detections, n = 28), Hooleys Fork (26.4 to 100% of individual detections, n = 6) and the mouth of Four Mile Creek (83.2 to 83.7% of individual detections, n = 3). The majority (89%) of the tagged sawfish were most commonly detected within the tributary in which they were initially tagged.

The number of contiguous days that a sawfish occupied the study area ranged between one and 344 d (median = 16 d) (Fig. 6). The number of contiguous days that a sawfish did not occupy the study area ranged between one and 124 d (median = 12 d; Fig. 6). The RI of tagged individuals within the study site ranged between 0.07 and 1.0 (Table 1). The RI of neonate Green Sawfish (0.37 ± 0.08) was significantly smaller than all other size classes ($p < 0.05$), including larger 0+ Green Sawfish, however they were almost exclusively detected on 1 or 2 receivers adjacent to the site of their initial tagging, i.e. the mouth of the Ashburton River. Excluding the neonates, mean RI decreased with size and was 0.83 (± 0.06SE) for older 0+ Green Sawfish, 0.77 (± 0.10SE) for 1+ fish, and 0.66 (± 0.05SE) for fish of 2 years of age and older, although this difference was not significant. Residency of tagged individuals within the monitored systems ranged from between 0.07 and 1.0 (mean = 0.60 ± 0.05) (Table 1). Only 13 of the 37 tagged Green Sawfish were detected in the coastal habitat. Residency of Green Sawfish in coastal habitats ranged between 0.06 and 0.48 (0.12 ± 0.04). The mean residency value of Green Sawfish in the monitored ocean region was significantly lower than those in the tributaries ($p < 0.001$, d.f. = 12).

Movement between creeks varied, with 37.8 % of tagged fish moving between creeks at least once, and 10.8% of tagged sawfish moving between creeks at least 10 times (Fig. 7). The standardised total distance (takes into account the distance and frequency of movements) traveled between creeks was observed to have a moderate positive correlation with total length of sawfish ($R = 0.56$, $p < 0.001$) (Fig. 8). In addition, the percentage of tagged sawfish of each size class to move between creeks also increased with size. The sawfish that were tagged in either Hooleys or Four Mile Creek were observed to move at least once between these neighbouring creeks (a distance of 2 km) corresponding to 50, 100 and 100% of 0+, 1+ and >1+ Green Sawfish, respectively (no neonates were observed in these creeks). Movement of Green Sawfish between the Ashburton River and Hooleys or Four Mile Creek (a distance of 13.5 to 15.5 km) occurred at least once in 0, 0, 14 and 42% of neonate, 0+, 1+ and >1+ Green Sawfish, respectively.

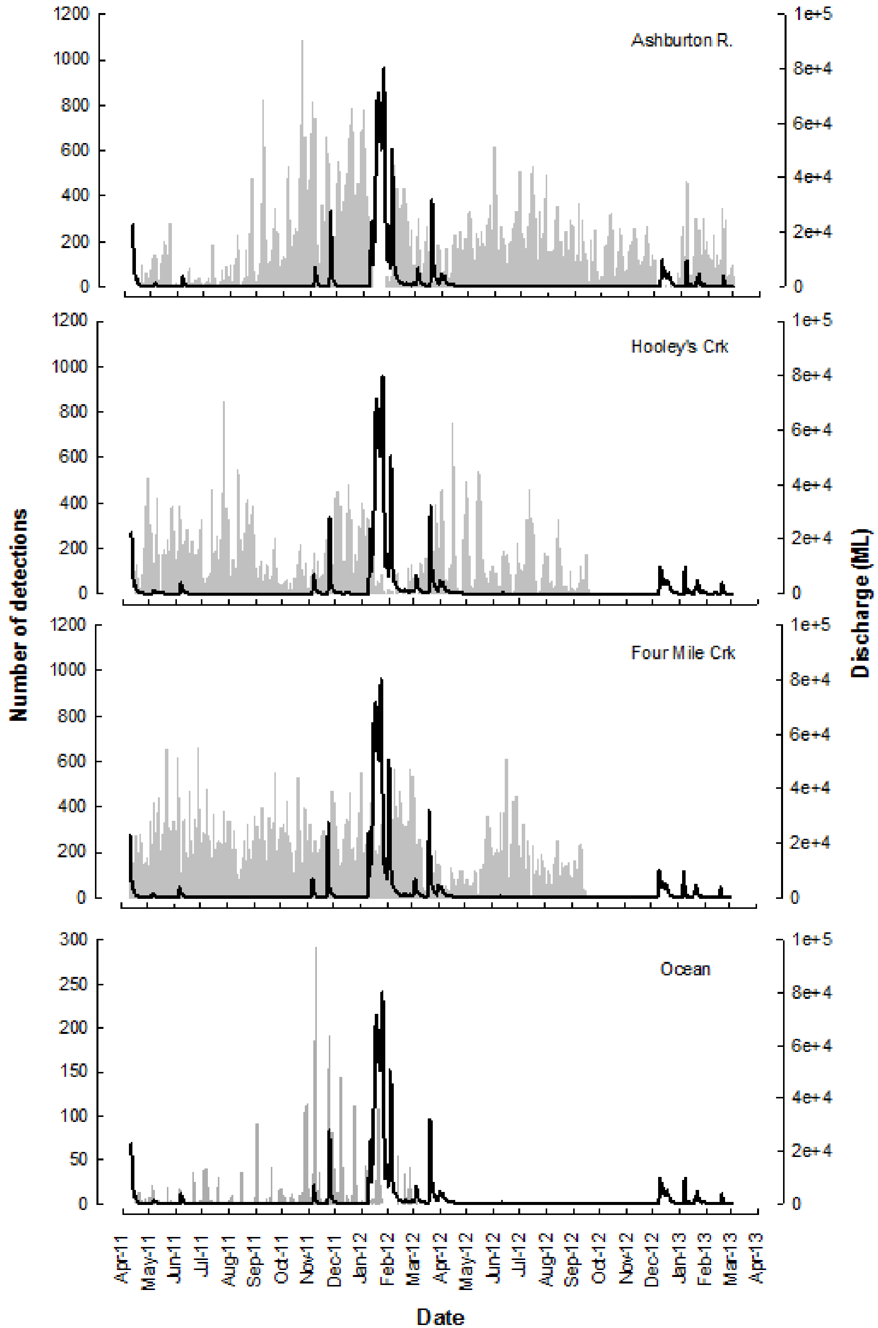
The average number of receivers at which sawfish were detected in the first 90 days following initial capture for Green Sawfish <1m, 1-2m, and >2m TL was 1.14 (±0.12), 2.61 (±0.58), and 5.77 (±1.00), respectively. These data were found to be heteroscedastic so were log-transformed. However, this did not achieve homogeneity of the data and therefore significant differences were assumed at a more conservative $p<0.01$ level. Subsequent GLM indicated that there was an overall significant difference in the mean number of receivers at which sawfish were detected between size classes ($p = 0.00$). Tukey's post hoc tests between the three size classes revealed that Green Sawfish >2m in length showed significantly greater movement within the receiver array than animals <1m in length ($p = 0.00$), but not with 1-2m animals at the more conservative significance level ($p = 0.018$). The smaller two size classes were not significantly different ($p = 0.09$).

The two sub-adult Freshwater Sawfish individuals were only detected at receivers located in the Ashburton River or just outside the river's mouth; the male having 12,312 detections and the female 3,641 detections. It is noteworthy that 85.4% of detections at the receiver deployed the furthest upstream in the Ashburton River (i.e. #112997, 2.75 km upstream of the river mouth) were of the two Freshwater Sawfish. Both individuals also exhibited extensive daily movement, with the male and female being detected at all three VR2W receivers in the lower Ashburton on 44% and 61% of the days they were detected in the first few months at liberty,

Table 1. Capture and residency information of Green Sawfish (*Pristis zijsron*) tagged in the study area. TL, total length; FMC, Four Mile Creek; HC, Hooleys Creek; AR, Ashburton River mouth; Cont. days preset, greatest period of contiguous days a sawfish was present; Cont. days absent, greatest period of contiguous days a sawfish was absent.

ID	TL (mm)	Tagging Site	Tagging date	Days at liberty	Days present	Cont. days present	Cont. days absent	Residency index
1	1122	FMC	11-Apr-11	525	484	79	3	0.92
2	1215	HC	17-Apr-11	525	391	130	27	0.75
3	1242	HC	14-Apr-11	235	227	109	2	0.97
4	1260	HC	17-Apr-11	244	213	112	4	0.87
5	1317	AR	16-Apr-11	460	293	61	18	0.64
6	1492	AR	16-Apr-11	387*	287	44	22	0.74
7	1644	FMC	11-Apr-11	335	334	334	1	1.00
8	1855	AR	16-Apr-11	165	63	9	12	0.38
9	2284	FMC	11-Apr-11	355	242	46	14	0.68
10	2447	AR	16-Apr-11	185	87	25	43	0.47
11	844	AR	22-Oct-11	77	27	8	14	0.35
12	861	AR	25-Oct-11	53	33	16	7	0.62
13	864	AR	22-Oct-11	142	13	6	124	0.09
14	870	AR	25-Oct-11	40	4	2	35	0.10
15	878	AR	25-Oct-11	26	23	16	2	0.89
16	887	AR	26-Oct-11	58	15	3	14	0.26
17	917	AR	26-Oct-11	141	34	5	45	0.24
18	927	AR	25-Oct-11	16	14	8	1	0.88
19	930	AR	26-Oct-11	136	38	34	66	0.28
20	936	AR	26-Oct-11	78	21	6	22	0.27
21	942	AR	22-Oct-11	69	42	13	7	0.61
22	953	AR	26-Oct-11	14	1	1	13	0.07
23	972	AR	26-Oct-11	68	11	2	35	0.16
24	1350	AR	25-Oct-11	200	66	10	32	0.33
25	1380	AR	26-Oct-11	319	239	72	17	0.75
26	1413	FMC	20-Oct-11	149	148	125	1	0.99
27	1526	AR	26-Oct-11	494	412	186	17	0.83
28	1949**	AR	27-Oct-11	75	28	7	22	0.37
29	1990	AR	26-Oct-11	75	48	10	5	0.64
30	2084	FMC	20-Oct-11	89*	88	73	1	0.99
31	2170	AR	22-Oct-11	61	49	26	9	0.80
32	2226	AR	22-Oct-11	72	48	14	8	0.67
33	2440	AR	25-Oct-11	59	52	15	2	0.88
34	2550	AR	25-Oct-11	80	50	14	8	0.63
35	2660	AR	22-Oct-11	75	37	7	11	0.49
36	2873	AR	22-Oct-11	85	62	41	5	0.73
37	2933	AR	26-Oct-11	78	69	41	3	0.89

*Tag removed from study area (i.e. Fish #6 was found dead in illegal net, tag of fish #30 was removed by fisher); **Estimated total length based off a body length of 1445 mm



Daily detections of all tagged Green Sawfish (*Pristis zijsron*) during the study and the discharge of the Ashburton River.

respectively. Each fish occupied the full range of depths available, but did not venture into waters <0.2m deep, which is in direct contrast to small juveniles of the species, and may be an adaptation to avoiding being stranded in shallow (tidal) waters (see Whitty *et al*. 2009).

The male Freshwater Sawfish fish was detected between April and May (during a flood event) and was again detected six months later (6 November 2011) at the mouth of the river where it was regularly detected by all of the receivers in the Ashburton until 15 January 2012, when it appears to have left the river. It is possible that the fish stayed or was trapped upstream in the river between 12 May 2011 and 6 November 2011 due to low water levels limiting its ability to migrate; its appearance in November coincided with a small flood pulse in the river. The exodus from the river coincided with a large flood event in January 2012.

The occurrence of these fish in the Ashburton River may have been linked to feeding, with the river experiencing consistent flows and possibly increased productivity during April and from November 2011 to at least March 2012. The large number of detections recorded at the most upstream receiver, suggests that they may have been moving into the non-tidal reaches of the river.

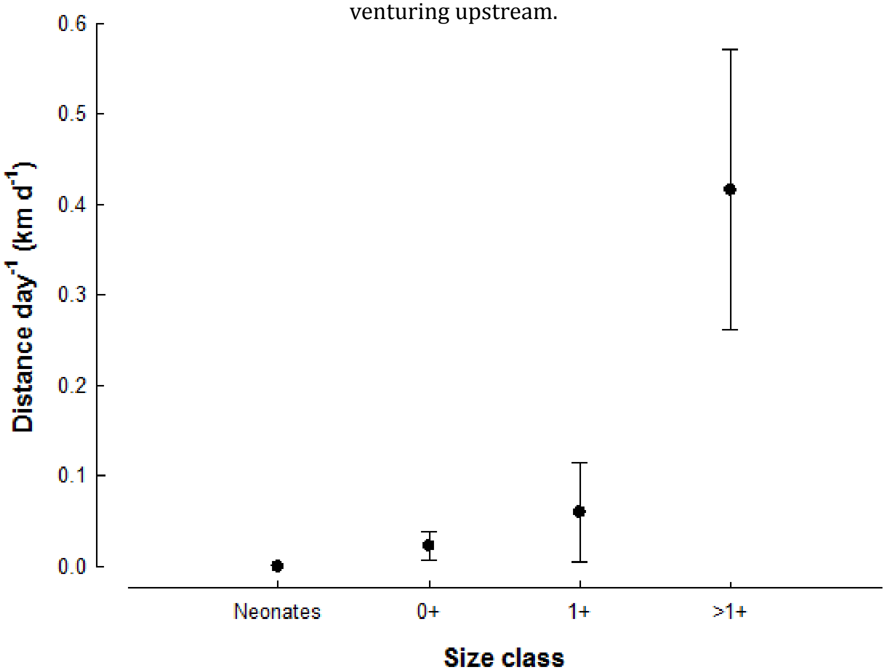
Discussion

Findings of the current study support the hypotheses that home-range size increases with growth and development in Green Sawfish. Neonates generally stayed close to their initial tagging locations for at least their first few months of life and larger size classes of juveniles became increasingly mobile with increasing body size. These findings generally parallel the use of space by juvenile Smalltooth Sawfish (*Pristis pectinata*) as reported from a telemetry study in coastal Florida (Hollensead *et al.* 2014). However, while tide seemed to have negligible effect on the amount of space used by *P. pectinata* (Hollensead *et al.* 2014), Green Sawfish were more likely to be recorded outside of the estuaries during low tides and particularly at night based on our study. This has potential ramifications for port management including protecting a subset of river mouths in complex deltas as is the case with the Ashburton River. That all neonates, as well as older juvenile Green Sawfish emigrated from the Ashburton River mouth during high periods of freshwater discharge, suggests that the low salinity waters do not provide favourable conditions. This contrasts Hooleys Creek and Four Mile Creek which are tidal mangrove creeks without large catchments and substantial freshwater discharge. Our findings also contrasts the behaviour of Freshwater Sawfish, which utilise freshwaters, whereby neonates migrate upstream during freshwater flows, but is similar to *P. pectinata* which move downstream during freshwater flow events (Poulakis *et al*. 2013). Freshwater Sawfish also appeared in the Ashburton River predominantly during high flow events. Smalltooth Sawfish and Freshwater Sawfish move further upstream than Green Sawfish which, in the case of the Ashburton River, remain close (<1 km upstream of the river mouth) to the mouth of the river. For example, only two of the 14 tagged neonates ventured further upstream than 700 m from the mouth of the river, and did so only briefly. Similarly, only two of the 15 older juveniles (fish ID 5, with 5 detections on one day in February 2012, and fish ID 37, with 962 detections between late November 2011 and 3rd January 2012) known to have been in the river at some stage, were recorded by the most upstream receiver; which contrasts the two Freshwater Sawfish monitored.

The relatively low residency indices of neonates compared to larger juveniles, may be a consequence of the receivers failing to detect them when in extremely shallow habitats, as >90% of depth detections were in less than 50 cm of water. Occupancy of the shallow expanse at the mouth of the Ashburton River, where these fish were initially captured, may have frequently rendered them undetectable. Conversely, Simpfendorfer *et al.* (2010) found residency of the younger individuals of Smalltooth Sawfish in a riverine system in Florida to be far less than larger individuals, but hypothesised that this may be due to the limited habitat and prey availability of these individuals forcing them to move to other areas. They also found that smaller juveniles had relatively short site fidelity to specific locations, as is the apparent case for neonate Green Sawfish in the current study.

The Ashburton River estuary provides critical habitat for Green Sawfish in the southern Pilbara. The overwhelming majority of tagged individuals (29/37) were found in the mouth of the Ashburton River, and neonates were present for the first several months of the year which included their first few months of life. In the absence of comparable data from any other studies, this suggests the southern Pilbara to represent critical habitat for the species. The global importance of the Ashburton River for neonate Green Sawfish, and the nearby tidal creeks for larger 0+ and older juveniles is highlighted in the high CPUE of Green Sawfish in the study area. Peverell (2005) provides the only comparable CPUE records of Green Sawfish with a total of 0.21 individuals caught in 500 m net day^{-1} across that entire study in Queensland. However, as mesh sizes, lengths of nets, and habitat types sampled varied between that and our study, comparisons of CPUE should be interpreted cautiously. With this in mind, the total CPUE of Green Sawfish in Hooley's Creek, Four Mile Creek and the Ashburton River

Area of the Ashburton River mouth occupied by Green Sawfish. The majority of detections of neonates was in the two downstream-most receivers (yellow triangles), with only two venturing upstream.



Distance travelled by different age classes of Green Sawfish.

One of the authors with a Green Sawfish

mouth across all seasons of 1.90 sawfish caught in 500 m net day^{-1} was substantially higher than in the nearshore waters of the Gulf of Carpentaria, Queensland (Peverell 2005). The total CPUE in the Ashburton River in October was 17.98 Green Sawfish caught in 500 m net day^{-1}. The extraordinarily high CPUE in the Pilbara may be a reflection of the complete absence of commercial fishing (and its deleterious effects on sawfishes) in the river mouths and tidal creeks in the vicinity of the Ashburton River, which is in contrast to the presence of commercial fishing in similar habitats in the Gulf of Carpentaria (Peverell 2005). Although the juvenile nursery habitats in Western Australia are not subjected to commercial fishing, sub-adults and adults that move into deeper waters of the Pilbara are captured in the Pilbara Fish Trawl Fishery (4 tonnes in 2001) (Stephenson & Chidlow 2003). The number of contiguous days that juvenile Green Sawfish were recorded within and outside of study area suggest that juveniles do not stray too far from these habitats.

The timing of the capture of neonates suggest that Green Sawfish pup as late (or early) as October on the Pilbara coast. This was evident through observations of closed and healed yolk-sac wounds during April, and open yolk-sac wounds in October.

Findings of substantial numbers and size (age) classes of Green Sawfish that remained within or in association with this estuary system for in excess of the current study duration (> 1 year of telemetry) indicates the importance of the Onslow region as a sawfish nursery. However to truly determine the significance of this nursery it will be important to develop a more comprehensive understanding of the distribution and habitat use of Green Sawfish along the Western Australian coastline particularly in the Pilbara. Based on the current study, the survey of major river mouths and bays is a priority for subsequent surveys, partly to determine small scale hotspots for neonates within greater nursery areas (Nagelkerken *et al*. 2015). This type of approach recognises that the population extent of this species is potentially substantial but that the distribution of nurseries is essentially unknown (e.g. the entire Pilbara coastline).

Peverell (2005), drawing on scientific collections and commercial fishery catch records, demonstrated a continuum in use of freshwater, estuarine and marine use of habitat across sawfish species in the Gulf of Carpentaria (Northern Australia). This reinforces the importance of recognising spatial habitat mosaics and complexity within seascape nurseries rather than over simplifying these nurseries (Nagelkerken *et al*. 2015). Specifically, Peverell (2005) showed that Green Sawfish occupy sand and mud flats outside of river mouths, whereas Dwarf Sawfish also occupy upper estuarine habitat and Freshwater Sawfish also occupy freshwaters. Further surveys of marine, estuarine and freshwater habitat is required to resolve the nursery grounds of sawfishes in Western Australia. The expansive and sparsely populated coastline of central and northern Western Australia provide one of the few global refuges for sawfishes, probably as a result of very little human pressure on those populations, both in terms of intact habitat and low fishing pressure. Despite this, it is of concern that in the few short visits to Onslow by our research team, we evidenced trophy collecting of saws and illegal gill netting impacting sawfish and as the human population is still drastically increasing in this area; such incidences will undoubtedly become more prevalent. It would therefore appear that management decisions should be taken to avoid Western Australian populations of sawfishes to suffer the same fate as those of so many other coastlines globally. Indeed, the highly restricted movement of juvenile Green Sawfish suggests that even small management interventions could have significant benefits in conserving a hot-spot for this species, whether these are marine protected areas, better enforcement or simple campaigns educating the public about the conservation status of sawfishes. Western Australia is in the fortunate situation where any management can be pre-emptive and prevent large scale population collapses, rather than other areas where management decisions are largely trying to recover from historically low levels of abundance. Based on the global importance of the site, it would be prudent to act while populations remain healthy and before human pressure will skyrocket in these previously remote places.

Conclusions

The mouth of the Ashburton River is pupping site and nursery for Green Sawfish, which may stay within the river mouth and adjacent tidal creeks for many years, as indicated by some individuals being detected for the life of the acoustic tags (i.e. 525 days).

Additionally, two large sub-adult Freshwater Sawfish appeared to use the river as an opportunistic feeding ground during high flow events, but the river does not appear to be a nursery for Freshwater Sawfish. The occurrence of Freshwater Sawfish in the river following discharge events should be examined across years; particularly as the river may act as a feeding locality for sub-adults.

The majority of acoustic detections of Green Sawfish were from the receivers closest to the river mouth, and only two individuals migrated beyond. Interannual variation in the recruitment of Green Sawfish should be examined to assess the long-term importance of the Ashburton River mouth as a nursery and pupping site for Green Sawfish.

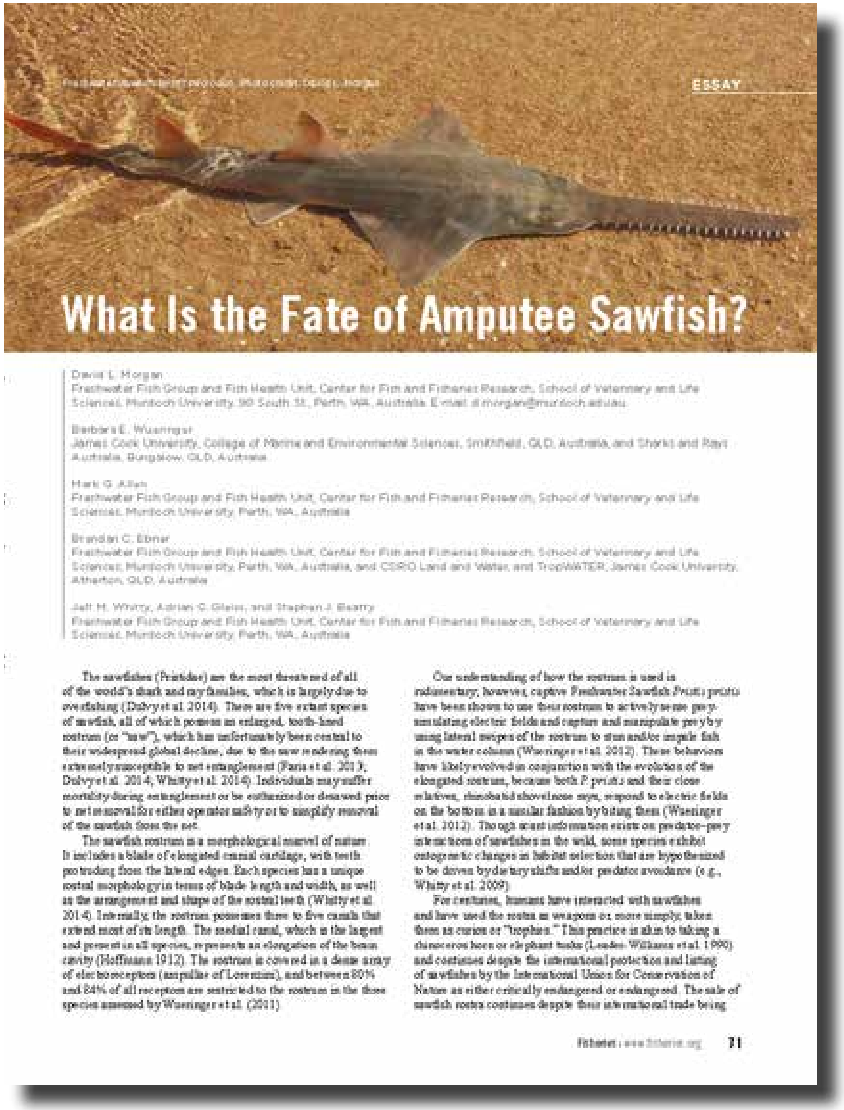
Human interactions with sawfish

During the last few years, numerous killed or mutilated sawfish have been encountered by our team. Killed sawfish have included a number of individuals that we had previously tagged, and two others have had their rostra removed since we initially tagged them. The global decline of sawfish has occurred largely as a result of their susceptibility to entanglement in fishing nets and through loss of habitat. However, the compounding effect of the removal of rostra from live sawfish is unknown, nor is the capture by illegal netting, and the numbers of affected individuals is hard to quantify.

The study by Whitty *et al*. (2014) readily gained access to over 1000 rostra that had been removed from sawfishes in northern Australia, which indicates that the practice of saw removal is not uncommon.

Greater education programs are required, particularly as the human population of northern Western Australia increases, which will inevitably lead to an increase in public encounters with sawfish. That gill netting in Western Australian rivers is illegal, together with the currently low human population in the north of the State, is a major factor that the region is one of the last global refuge for sawfishes.

Recent evidence, using acoustic monitoring in the Onslow region and in the Fitzroy River, suggests that sawfish die a lingering death following rostrum removal (see "What is the fate of amputee sawfish?" by Morgan *et al*. 2016).



ESSAY

What Is the Fate of Amputee Sawfish?

David L. Morgan
Freshwater Fish Group and Fish Health Unit, Center for Fish and Fisheries Research, School of Veterinary and Life Sciences, Murdoch University, 90 South St., Perth, WA, Australia. E-mail: d.morgan@murdoch.edu.au

Barbara E. Wueringer
James Cook University, College of Marine and Environmental Sciences, Smithfield, QLD, Australia, and Sharks and Rays Australia, Bungalow, QLD, Australia

Mark G. Allen
Freshwater Fish Group and Fish Health Unit, Center for Fish and Fisheries Research, School of Veterinary and Life Sciences, Murdoch University, Perth, WA, Australia

Brendan C. Ebner
Freshwater Fish Group and Fish Health Unit, Center for Fish and Fisheries Research, School of Veterinary and Life Sciences, Murdoch University, Perth, WA, Australia, and CSIRO Land and Water, and TropWATER, James Cook University, Atherton, QLD, Australia

Jeff M. Whitty, Adrian C. Gleiss, and Stephen J. Beatty
Freshwater Fish Group and Fish Health Unit, Center for Fish and Fisheries Research, School of Veterinary and Life Sciences, Murdoch University, Perth, WA, Australia

The sawfishes (Pristidae) are the most threatened of all of the world's shark and ray families, which is largely due to overfishing (Dulvy et al. 2014). There are five extant species of sawfish, all of which possess an enlarged, tooth-lined rostrum (or "saw"), which has unfortunately been central to their widespread global decline, due to the saw rendering them extremely susceptible to net entanglement (Faria et al. 2013; Dulvy et al. 2014; Whitty et al. 2014). Individuals may suffer mortality during entanglement or be euthanized or dewsawed prior to net removal for either operator safety or to simplify removal of the sawfish from the net.

The sawfish rostrum is a morphological marvel of nature. It includes a blade of elongated cranial cartilage, with teeth protruding from the lateral edges. Each species has a unique rostral morphology in terms of blade length and width, as well as the arrangement and shape of the rostral teeth (Whitty et al. 2014). Internally, the rostrum possesses three to five canals that extend most of its length. The medial canal, which is the largest and present in all species, represents an elongation of the brain cavity (Hoffmann 1912). The rostrum is covered in a dense array of electroreceptors (ampullae of Lorenzini), and between 80% and 84% of all receptors are restricted to the rostrum in the three species assessed by Wueringer et al. (2011).

Our understanding of how the rostrum is used is rudimentary; however, captive Freshwater Sawfish *Pristis pristis* have been shown to use their rostrum to actively sense prey-simulating electric fields and capture and manipulate prey by using lateral swipes of the rostrum to stun and/or impale fish in the water column (Wueringer et al. 2012). These behaviors have likely evolved in conjunction with the evolution of the elongated rostrum, because both *P. pristis* and their close relatives, rhinobatid shovelnose rays, respond to electric fields on the bottom in a similar fashion by biting them (Wueringer et al. 2012). Though scant information exists on predator–prey interactions of sawfishes in the wild, some species exhibit ontogenetic changes in habitat selection that are hypothesized to be driven by dietary shifts and/or predator avoidance (e.g., Whitty et al. 2009).

For centuries, humans have interacted with sawfishes and have used the rostra as weapons or, more simply, taken them as curios or "trophies." This practice is akin to taking a rhinoceros horn or elephant tusks (Leader-Williams et al. 1990) and continues despite the international protection and listing of sawfishes by the International Union for Conservation of Nature as either critically endangered or endangered. The sale of sawfish rostra continues despite their international trade being

Fisheries | www.fisheries.org 71

Trashed: Freshwater Sawfish in a bin, Snake Creek, Fitzroy River

One of our tagged Green Sawfish was killed in an illegal fishing net in Four Mile Creek, near Onslow (Photograph Geoff Herbert)

Dead tagged Freshwater Sawfish, Geikie Gorge, Fitzroy River, - natural death caused by deoxygenation of pool following a significant rainfall event during December 2015

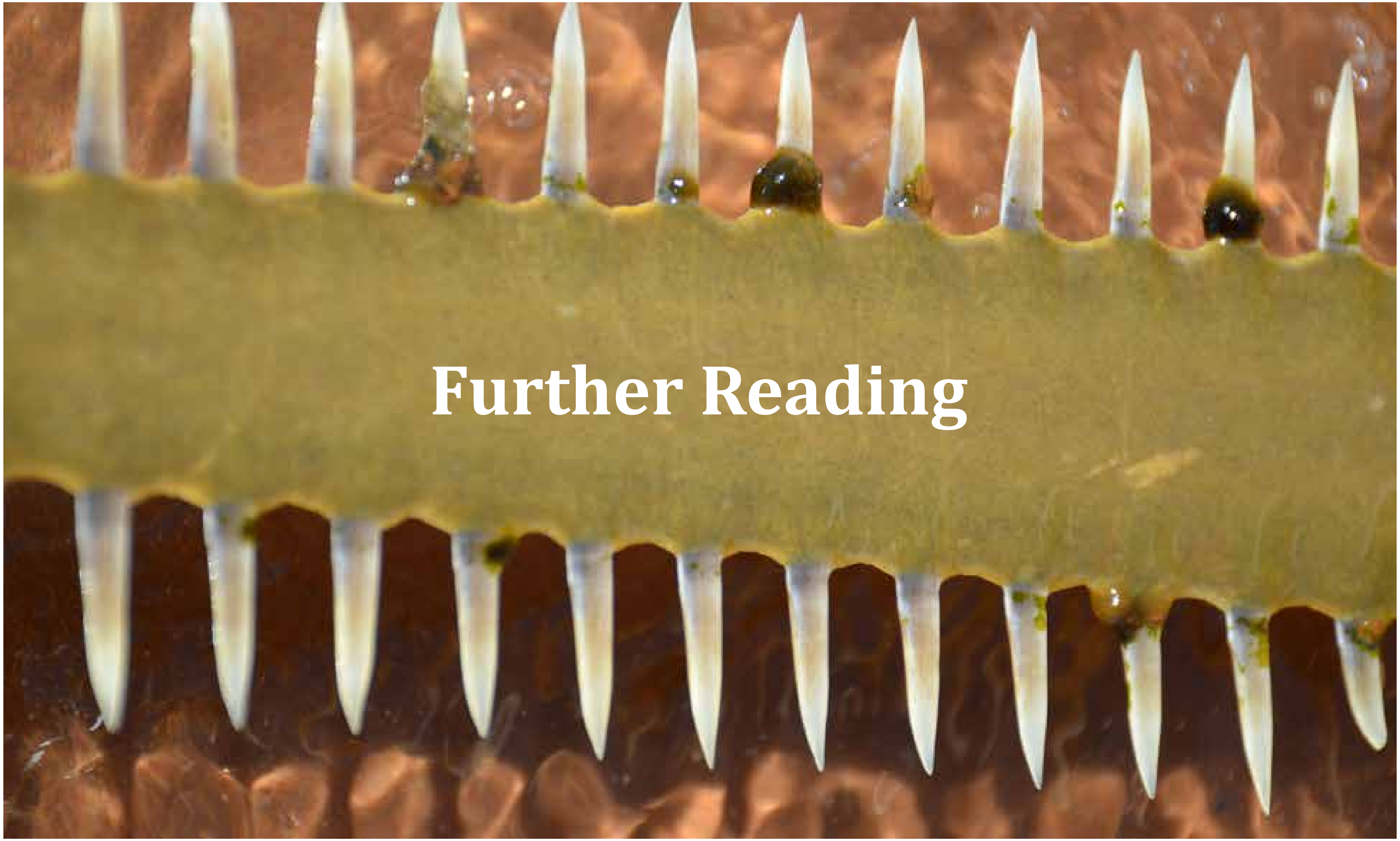
De-headed Freshwater Sawish, Snake Creek, Fitzroy River

We came across three killed neonate Freshwater Sawfish in Telegraph Pool, Fitzroy River

Sawfish rostrums adorn numerous walls in Western Australia

This Freshwater Sawfish in Telegraph Pool, Fitzroy River, had been captured on line on a number of occasions

Amputee Green Sawfish (see also inset) in the Ashburton River



Further Reading

BOOKS

Morgan, D.L., Allen, M.G., Beatty, S.J., Ebner, B.C. & Keleher, J.J. (2014). *A field guide to the freshwater fishes of Western Australia's Pilbara Province*. Freshwater Fish Group & Fish Health Unit, Murdoch University, Murdoch, W.A.

OTHER PUBLICATIONS

Ebner, B.C., Morgan, D.L., Kerezsy, A. Hardie, S., Beatty, S.J., Seymour, J.E., Donaldson, J.A., Linke, S., Peverell, S., Roberts, D., Espinoza, T., Marshall, N., Kroon, F.J., Burrows, D.W. & McAllister, R.R.J. (2016). Enhancing conservation of Australian freshwater ecosystems: identification of freshwater flagship fishes and relevant target audiences. *Fish and Fisheries*.

Gleiss, A.C., Potvin, J., Keleher J., Whitty J., Goldbogan, J.A. & Morgan D.L. (2015). Mechanical challenges to freshwater residency in sharks and rays. *Journal of Experimental Biology* 218: 1099-1110.

Morgan, D.L., Allen, M.G., Ebner, B.C., Whitty, J.M. & Beatty, S.J. (2015). Discovery of a pupping site and nursery for critically endangered Green Sawfish (*Pristis zijsron*). *Journal of Fish Biology* 86: 1658-1663.

Morgan, D.L., Allen, G.R., Pusey, B.J. & Burrows, D.W. (2011). A review of the freshwater fishes of the Kimberley region of Western Australia. *Zootaxa* 2816: 1-64.

Morgan, D., Beatty, S., Allen, M., Gleiss, A., Keleher, J. & Whitty, J. (2011). *Addressing knowledge gaps and questions from the Fitzroy River (Kimberley region, Western Australia) fishway review*. Freshwater Fish Group, Murdoch University, report to the Department of Water, Government of Western Australia.

Morgan, D.L., Wueringer, B.E., Allen, M.G., Ebner, B.C., Whitty, J.M., Gleiss, A.C. & Beatty, S.J. (2016). What is the fate of amputee sawfish? *Fisheries* 41: 71-73.

Morgan, D.L., Unmack, P.J, Beatty, S.J., Ebner, B.C., Allen, M.G., Keleher, J.J., Donaldson, J.A. & Murphy, J. (2014). An overview of the 'freshwater fishes' of Western Australia. *Journal of the Royal Society of Western Australia* 97(2): 263-278.

Morgan, D.L., Whitty, J.M., Phillips, N.M., Thorburn, D.C., Chaplin, J.A. & McAuley, R. (2011). North-western Australia as a hotspot for endangered elasmobranchs, with particular reference to sawfishes and the Northern River Shark. *Journal of the Royal Society of Western Australia* 94: 345-358.

Phillips, N.M., Chaplin, J.A., Morgan, D.L. & Peverell, S.C. (2011). Population genetic structure and genetic diversity of three critically endangered *Pristis* sawfishes in northern Australian waters. *Marine Biology* 158: 903-915.

Phillips, N.M., Chaplin, J.A, Morgan, D.L. & Peverell, S.C. (2016). Contrasting population structures of three *Pristis* sawfishes with different patterns of habitat use. *Marine & Freshwater Research*.

Thorburn, D.C., Gill, H.S. & Morgan, D.L., (2014). Predator and prey interactions of fishes of a tropical Western Australia river revealed by dietary and stable isotope analyses. *Journal of the Royal Society of Western Australia* 97(2): 363-388.

Whitty, J.M., Phillips, N.M., Thorburn, D.C., Simpfendorfer, C.A., Field, I., Peverell, S.C. & Morgan, D.L. (2014). Utility of rostra in the identification of Australian sawfishes (Chondrichthyes: Pristidae). *Aquatic Conservation: Marine and Freshwater Ecosystems* 24: 791-804.

CONFERENCE ABSTRACTS

Beatty, S. & Morgan, D. (2014). Vulnerability of Western Australian fishes to changing flow. Fish responses to environmental flows: moving beyond patterns to understand process. *Australian Society for Fish Biology and Australian Society for Limnology Conference, Darwin*.

Morgan, D.L., Allen, M.G., Ebner, B.C., Whitty, J.M. & Beatty, S.J. (2014). Habitat utilisation of juvenile Green Sawfish (*Pristis zijsron*) in Western Australian waters. *Sharks International 2014. Durban, South Africa. June 2-6, 2014.*

Morgan, D., Beatty, S. & Allen, M. (2013). Threatened fish related research in the north-west. *WAMSI North West Marine Science Symposium, 21 February 2013, WA Maritime Museum*.

Whitty, J., Keleher, J., Gleiss, A., Ebner, B. & Morgan, D. (2016). Heterogeneous habitat use of the critically endangered largetooth sawfish (*Pristis pristis*) in a riverine nursery. *Biology and Ecology of Sawfishes, Joint Meeting of Icthyologists and Herpetologists & American Elasmobranch Society, New Orleans, Louisiana, 6-10 July, 2016.*

Whitty, J.M., Morgan, D.L., Gleiss, A., Thorburn, D.C. & Keleher, J. (2014). A review of the Fitzroy River, Western Australia sawfish project and the implications of its findings in regards to anthropogenic disturbances. *Sharks International 2014. Durban, South Africa. June 2- 6, 2014.*

REFERENCES

Andrews, K.S., Williams, G.D., Farrer, D., Tolimieri, N., Harvey, C.J., Bargmann, G. & Levin, P.S. (2009). Diel activity patterns of sixgill sharks, *Hexanchus griseus*: the ups and downs of an apex predator. *Animal Behaviour* 78: 525-536.

Beatty, S., Allen, M., Lymbery, A., Storer, T., White, G., Morgan, D. & Ryan, T. (2013). *Novel methods for managing freshwater refuges against climate change in southern Australia*. Supporting Document 4: Evaluating small barrier removal to improve refuge connectivity - A global review of barrier decommissioning and a process for southern Australia in a drying climate. National Climate Change Adaptation Research Facility, Gold Coast; 73 pp.

Beck, M.W., Heck, K.L. Jr, Able, K.W., Childers, D.L., Eggleston, D.B., Gillanders, B.M., Halpern, B., Hays, C.G., Hoshino, K., Minello, T.J., Orth, R.J., Sheridan, P.F. & Weinstein, M.P. (2001). The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates. *Bioscience* 51: 633-641.

Buckle, D., Storey, A., Humphrey, C. & Chandler, L. (2010). *Fish and macroinvertebrate assemblages of the upper Ord River catchment*. Internal Report 559, January, Supervising Scientist, Darwin, Northern Territory.

Burnham, K.P. & Anderson, D.R. (1998). *Model selection and inference: a practical information-theoretic approach*. Springer-Verlag, New York, NY. 353 pp.

Carlisle, A.B. & Starr, R.M. (2009). Habitat use, residency, and seasonal distribution of female Leopard Sharks *Triakis semifasciata* in Elkhorn Slough, California. *Marine Ecology Progress Series* 380: 213-228.

Cartamil, D.P., Vaudo, J.J., Lowe, C.G., Wetherbee, B.M. & Holland, K.N. (2003). Diel movement patterns of the Hawaiian Stingray, *Dasyatis lata*: implications for ecological interactions between sympatric elasmobranch species. *Marine Biology* 142: 841-847.

Castro, J.I. (1993). The shark nursery of Bulls Bay, South Carolina, with a review of the shark nurseries of the southeastern coast of the United States. *Environmental Biology of Fishes* 38: 37-48.

Doupé, R.G., Morgan, D.L. & Gill, H.S. (2005). Prospects for a restorative fishery enhancement of Lake Kununurra: a high-level tropical impoundment on the Ord River, Western Australia. *Pacific Conservation Biology* 11: 136-146.

Doupé, R.G. & Pettit, N.E. (2002). Ecological perspectives on regulation and water allocation for the Ord River, Western Australia. *River Research and Applications* 18: 307-320.

Dulvy, N.K., Fowler, S L., Musick, J.A., Cavanagh, R.D., Kyne, P.M., Harrison, L.R., Carlson, J.K., Davidson, L.N.K., Fordham, S.V., Francis, M.P., Pollock, C.M., Simpfendorfer, C.A., Burgess, G.H., Carpenter, K.E., Compagno, L.J.V., Ebert, D.A., Gibson, C., Heupel, M.R., Livingstone, S.R., Sanciangco, J.C., Stevens, J.D., Valenti, S. & White, W.T. (2014). Extinction risk and conservation of the world's sharks and rays*. eLife* 3:e00590.

Dulvy, N.K., Davidson, L.N.K., Kyne, P.M., Simpfendorfer, C.A., Harrison, L.R., Carlson, J.K. & Fordham, S.V. (2016). Ghosts of the coast: global extinction risk and conservation of sawfishes. *Aquatic Conservation: Marine and Freshwater Ecosystems* 26: 134-153.

Everett, B.I., Cliff, G., Dudley, S.F.J., Wintner, S.P. & van der Elst, R.P. (2015). Do sawfish *Pristis* spp. represent South Africa's first local extirpation of marine elasmobranchs in the modern era? *African Journal of Marine Science* 37: 275-284.

Fernandez-Carvalho, J., Imhoff, J.L., Faria, V.V., Carlson, J.K. & Burgess, G.H. (2014). Status and the potential for extinction of the largetooth sawfish *Pristis pristis* in the Atlantic Ocean. *Aquatic Conservation: Marine and Freshwater Ecosystems* 24: 478–497.

Hollensead, L.D., Grubbs, R.D., Carlson, J.K. & Bethea, D.M. (2016). Analysis of fine-scale daily movement patterns of juvenile *Pristis pectinata* within a nursery habitat. *Aquatic Conservation: Marine and Freshwater Ecosystems* 26: 492-505.

Jennings, D.E., Gruber, S.H., Franks, B.R., Kessel, S.T. & Robertson, A.L. (2008). Effects of large-scale anthropogenic development on juvenile lemon shark (*Negaprion brevirostris*) populations of Bimini, Bahamas. *Environmental Biology of Fishes* 83: 369-377.

Foster, A.M. & Clugston, J.P. (1997). Seasonal migration of Gulf Sturgeon in the Suwannee River, Florida. *Transactions of the American Fisheries Society* 126: 302-308.

Gehrke, P. (2009). *Ecological patterns and processes in the lower Ord River and estuary*. Report to Water for a Healthy Country Flagship. 96 pp.

Gibson, R.N. (1997). Behaviour and the distribution of flatfishes. *Journal of Sea Research* 37: 241-256.

Gill, H., Morgan, D.L., Doupé, R.G. & Rowland, A.J. (2006). The fishes of Lake Kununurra, a highly regulated section of the Ord River in northern Western Australia. *Records of the Western Australian Museum* 23: 1-6.

Gruber, S.H., Nelson, D.R. & Morrissey, J.F. (1988). Patterns of activity and space utilization of lemon sharks, *Negaprion brevirostris*, in a shallow Bahamian Lagoon. *Bulletin of Marine Science* 43: 61-76.

Heupel, M.R., Carlson, J.K. & Simpfendorfer, C.A. (2007). Shark nursery areas: concepts, definition, characterization and assumptions. *Marine Ecology Progress Series* 337: 287-297.

Heupel, M.R., Simpfendorfer, C.A. & Bennett, M.B. (1998). Analysis of tissue responses to fin tagging in Australian carcharhinids. *Journal of Fish Biology* 52: 610-620.

Holland, K.N., Wetherbee, B.M., Peterson, J.D. & Lowe, C.G. (1993). Movements and distribution of hammerhead shark pups on their natal grounds. *Copeia* 1993: 495-502.

Last, P.R. & Stevens, J.D. (2009). *Sharks and rays of Australia*. 2nd Edn. (CSIRO Publishing: Melbourne).

Leeney, R.H. & Poncelet, P. (2015). Using fishers' ecological knowledge to assess the status and cultural importance of sawfish in Guinea-Bissau. *Aquatic Conservation: Marine and Freshwater Ecosystems* 25: 411-430.

McDavitt, M. (1996). The cultural and economic importance of sawfishes (family Pristidae). *Shark News* 8: 10-11.

Messel, H. (1981). The Blyth-Cadell Rivers System Study and the status of *Crocodylus porosus* in tidal waterways of Northern Australia: methods for analysis, and dynamics of a population of *C. porosus*. (Surveys of tidal river systems in the Northern Territory and their crocodile populations: Monograph 1). Oxford, New York: Pergamon Press. 463 pp.

Moore, A.B.M. (2015). A review of sawfishes (Pristidae) in the Arabian region: diversity, distribution, and functional extinction of large and historically abundant marine vertebrates. *Aquatic Conservation: Marine and Freshwater Ecosystems* 25: 656-677.

Morgan, D.L., Allen, M.G., Bedford, P. & Horstman, M. (2004). Fish fauna of the Fitzroy River in the Kimberley region of Western Australia – including the Bunuba, Gooniyandi, Ngarinyin, Nyikina and Walmajarri Aboriginal names. *Records of the Western Australian Museum* 22: 147-161.

Morgan, D.L., Allen, M.G., Ebner, B. & Beatty, S. (2012). *Sawfish Monitoring Project – Wheatstone*. Centre for Fish & Fisheries Research, Murdoch University Report to Chevron Australia. 83 pp.

Morgan, D.L., Allen, M.G., Ebner, B.C., Whitty, J.M. & Beatty, S.J. (2015). Discovery of a pupping site and nursery for critically endangered Green Sawfish (*Pristis zijsron*). *Journal of Fish Biology* 86: 1658-1663.

Morgan, D.L., Allen, G.R., Pusey, B.J. & Burrows, D.W. (2011c). A review of the freshwater fishes of the Kimberley region of Western Australia. *Zootaxa* 2816: 1-64.

Morgan, D., Beatty, S., Allen, M., Gleiss, A., Keleher, J. & Whitty, J. (2011a). *Addressing knowledge gaps and questions from the Fitzroy River (Kimberley region, Western Australia) fishway review*. Report for the Department of Water, Government of Western Autralia. pp 57.

Morgan, D., Thorburn, D., Fenton, J., Wallace-Smith, H. & Goodson, S. (2005). *Influence of the Camballin Barrage on fish communities in the Fitzroy River, Western Australia*. Report to Land and Water Australia, Australian Government, Canberra.

Morgan, D.L., Whitty, J.M., Phillips, N.M., Thorburn, D.C., Chaplin, J.A. & McAuley, R. (2011b). North-western Australia as a hotspot for endangered elasmobranchs with particular reference to sawfishes and the northern river shark. *Journal of the Royal Society of Western Australia* 94: 345-358.

Morgan, D.L., Wueringer, B.E., Allen, M.G., Ebner, B.C., Whitty, J.M., Gleiss, A.C. & Beatty, S.J. (2016). What is the fate of amputee sawfish? *Fisheries* 41: 71-73.

Nagelkerken, I., Sheaves, M., Baker, R. & Connolly, R.M. (2015). The seascape nursery: a novel spatial approach to identify and manage nurseries for coastal marine fauna. *Fish and Fisheries* 16: 362-371.

Nelson, D.R. & Johnson, R.H. (1970). Diel activity rhythms in the nocturnal, bottom-dwelling sharks, *Heterodontus francisci* and *Cephaloscyllium ventriosum*. *Copeia* 1970: 732-739.

Norton, S. & Storer, T. (2011). *Prioritising fish barriers in Western Australia*. Water science technical series report, Department of Water, Perth, Western Australia.

Paragamian, V.L. & Wakkinen, V.D. (2008). Seasonal movement of burbot in relation to temperature and discharge in the Kootenai River, Idaho, USA and British Columbia, Canada. *American Fisheries Society Symposium* 59: 55-77.

Pettit, N.E., Froend, R.H. & Davies, P.M. (2001). Identifying the natural flow regime and the relationship with riparian vegetation for two contrasting western Australian river. *Regulated Rivers: Research and Management* 17: 201-215.

Peverell, S.C. (2005). Distribution of sawfishes (Pristidae) in the Queensland Gulf of Carpentatria, Australia, with notes on sawfish ecology. *Environmental Biology of Fishes* 73: 391-402.

Peverell, S.C. (2009). *Sawfish (Pristidae) of the Gulf of Carpentaria, Queensland Australia*. MSc Thesis, James Cook University.

Phillips, N.M., Chaplin, J.A., Morgan, D.L., Peverell, S.C. (2011). Population genetic structure and genetic diversity of three critically endangered *Pristis* sawfishes in Australian waters. *Marine Biology* 158: 903-915.

Phillips, N.M., Chaplin, J.A, Morgan, D.L. & Peverell, S.C. (2016). Contrasting population structures of three *Pristis* sawfishes with different patterns of habitat use. *Marine & Freshwater Research*.

Poulakis, G.R., Stevens, P.W., Timmers, A.A., Stafford, C.J. & Simpfendorfer, C.A. (2013). Movements of juvenile endangered smalltooth sawfish, *Pristis pectinata*, in an estuarine river system: use of non-main-stem river habitats and lagged responses to freshwater inflow-related changes. *Environmental Biology of Fishes* 96: 763-778.

Poulakis, G.R., Stevens, P.W., Timmers, A.A., Wiley, T.R. & Simpfendorfer, C.A. (2011). Abiotic affinities and spatiotemporal distribution of the endangered smalltooth sawfish, *Pristis pectinata*, in a south-western Florida nursery. *Marine and Freshwater Research* 62: 1165-1177.

Seitz, J.C. & Poulakis, G.R. (2002). Recent occurrence of sawfishes (Elasmobranchiomorphi: Pristidae) along the southwest coast of Florida (USA). *Florida Scientist* 65: 256–266.

Seitz, J.C. & Poulakis, G.R. (2006). Anthropogenic effects on the smalltooth sawfish (*Pristis pectinata*) in the United States. *Marine Pollution Bulletin* 52: 1533–1540.

Simpfendorfer, C.A. (2000). Predicting population recovery rates for endangered western Atlantic sawfishes using demographic analysis. *Environmental Biology of Fishes* 58: 371-377.

Simpfendorfer, C.A., Freitas, G.G., Wiley, T.R. & Heupel, M.R. (2005). Distribution and habitat partitioning of immature bull sharks (*Carcharhinus leucas*) in a southwest Florida estuary. *Estuaries* 28: 78-85.

Simpfendorfer, C.A., Wiley, T.R. & Yeiser, B.G. (2010). Improving conservation planning for an endangered

sawfish using data from acoustic telemetry. Biological Conservation 143: 1460-1469.
Sims, D.W., Weathermouth, V.J., Southall, E.J., Hill, J.M., Moore, P., Rawlinson, K., Hutchinson, N., Budd, G.C., Righton, D., Metcalfe, J.D., Nash, J.P. & Morritt, D. (2006). Hunt warm, rest cool: bioenergetic strategy underlying diel vertical migration of a benthic shark. *Journal of Animal Ecology* 75: 176-190.

Start, A.N. & Handasyde, T. (2002). Using photographs to document environmental change: the effects of dams on the riparian environment of the lower Ord River. *Australian Journal of Botany* 50: 465-480.

Storey, R.H., Froend, P.M. & Froend, R.H. (2001). *Fitzroy River system: environmental values*. Report prepared for the Waters and Rivers Commission, Perth.

Storey, A.W. (2003). *Lower Ord River: fish habitat survey*. Report to Water and Rivers Commission. 83 pp.

Thorburn, D.C. & Rowland, A.J. (2008). Juvenile bull sharks *Carcharhinus leucas* (Valenciennes, 1839) in northern Australian rivers. *The Beagle, Records of the Museums and Art Galleries of the Northern Territory* 24: 79-86.

Thorburn, D.C. (2006). Biology, ecology and trophic interactions of elasmobranchs and other fishes in riverine waters of northern Australia. PhD Thesis, Murdoch University.

Thorburn, D.C., Morgan, D.L., Rowland, A.J. & Gill, H.S. (2007). Freshwater Sawfish *Pristis microdon* Latham, 1794 (Chondrichthyes : Pristidae) in the Kimberley region of Western Australia. *Zootaxa* 1471: 27-41.

Thorburn, D., Morgan, D., Gill, H., Johnson, M., Wallace-Smith, H., Vigilante, T., Gorring, A., Croft, I. & Fenton, J. (2004). Biology and cultural significance of the freshwater sawfish (*Pristis microdon*) in the Fitzroy River Kimberley, Western Australia. Report to the Threatened Species Network.
Water and Rivers Commission. (2003). *Productivity and water flow regulation in the Ord River of North-Western Australia*. Report for Environmental Flows Initiative Project. 115 pp.

Web, G.J.W. & Manolis, S.C. (2010). Australian Freshwater Crocodile *Crocodylus johnstoni*. In 'Crocodiles. Status Survey and Conservation Action Plan'. (Eds Manolis, S.C. and Stevenson, C.). pp. 66-70.

Wetland Research and Management. (2002). Lower Ord River fish response to lowered Ord River flow. Report to Water and Rivers Commission.

Whitty, J.M. (2011). *Utility of a multi-faceted approach in determining the habitat use of endangered euryhaline elasmobranchs in a remote region of northern Australia*. MPhil Thesis, Murdoch University, Murdoch, Western Australia.

Wolanski, E., Moore, K., Spagnol, S., D'Adamo, N. & Pattiaratchi, C. (2001). Rapid, human-induced siltation of the macro-tidal Ord River Estuary, Western Australia. *Estuarine, Coastal and Shelf Science* 53: 717-732.

Yoshikane, M., Kay, W.R., Shibata, Y., Inoue, M., Yanai, T., Kamata, R., Edmonds, J.S. & Morita, M. (2006). Very high concentrations of DDE and toxaphene residues in crocodiles from the Ord River, Western Australia: an investigation into possible endocrine disruption. *Journal of Environmental Monitoring* 8: 649-661.

Geikie Gorge fish kill event 2015

During Novemebr 2015, following a localised flooding event, our team was contacted by Darngku Tours and the Department of Parks and Wildlife to investigate the appearance of a number of dead Bull Sharks and Freshwater Sawfish in Geikie Gorge; including some Bull Sharks and Freshwater Sawfish that we had previously tagged downstream of the Barrage (some 200 km downstream).

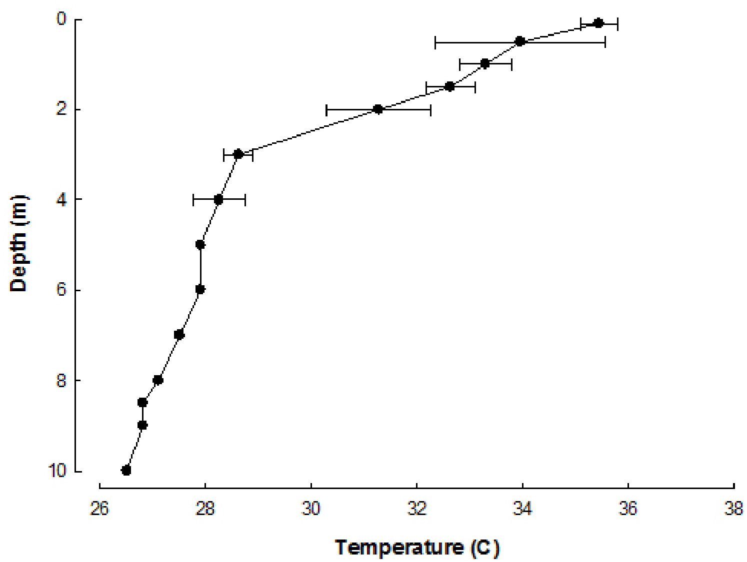
Water quality samples were taken on 29 and 30 November 2015 and delivered to the Department of Water, Friday 4th December. Samples were collected from throughout the water column at 10 different sites within the approximately 15 km of Geikie Gorge that was accessible via boat (Figure 1). In addition, water quality samples were collected from the mouth of Margaret River, Anabranch Pool (upstream of the old Fitzroy Crossing; 14.6 rkm downstream of Geikie Gorge) and from the run between Geikie Gorge and Anabranch Pool (1.4 rkm downstream from Geikie Gorge).

Oxygen profiles revealed no dissolved oxygen in waters below 2 m depth, and very low oxygen between 1 and 2 m depth. Temperature profiles did not appear to vary significantly and thus regions of Geikie Gorge were combined. Thermocline appears to be around 3 m.

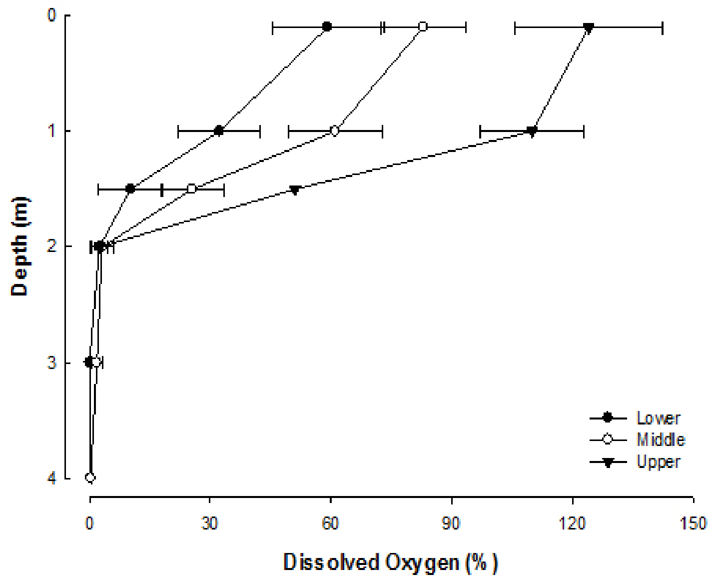
12 Freshwater Sawfish (*Pristis pristis*), ranging in total length from 1160 to 2592 mm, 9 Bull Sharks (*Carcharhinus leucas*) ranging in length from 1236 to 1585 mm; 1 Freshwater Whipray (disc width 870 mm), numerous bivalves, 1 Lesser Salmon Catfish (*Neoarius graeffei*) and numerous Cherabin (*Macrobrachium spinipes*) were found deceased. Mary Aitken reported Bony Bream (*Nematalosa erebi*) and Lesser Salmon Catfish dead opposite Robbies Rock. Surface fishes (Kimberley Archerfish (*Toxotes kimberleyensis*) and Bony Bream (*N. erebi*)) were seen alive on 29 and 30 November.

Cause: The most likely cause of the fish kill was linked to a localised rainfall event that flowed from tributaries into this section of the river. The water was black, tannin stained, and likely to have carried large amounts of biologically active matter where rapid bacterial decomposition occurred. This resulted in low dissolved oxygen and was compounded by extremely high temperatures. Daily air temperature was 46°C on each of these days.

DL Morgan, J Whitty & T Ryan.



Mean water temperature profile for Geikie Gorge.



Mean dissolved oxygen at various depths during the fish kill. Lower, middle and upper regions were 0 – 3.4, 6.7-10.7 and 11.8-14.4 km upstream from the downstream end of Geikie Gorge. Standard error bars are present for depths/regions where three or more samples were taken.

We would like to extend our sincere gratitude to the Traditional Owners of the Pilbara and Kimberley. We would particularly like to thanks those people that were directly involved in our research. We would also like to extend thanks to all people that assisted in our project in Derby, Onslow and Fitzroy Crossing.

Freshwater Fish Group &
Fish Health Unit
Centre for Fish & Fisheries Research

Murdoch
UNIVERSITY

Centre for Fish and
Fisheries Research

Chevron
Wheatstone Project

western australian
marine science institution