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Environmental water needs of the Daly River, Northern Territory

Final report

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Cover photograph: The Daly River upstream of Oolloo Crossing, Northern Territory. Photo: Alison King.

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Acronyms and abbreviations

AHD	Australian height datum
ALE	Accumulated local effects
ANOVA	Analysis of variance
BRT	Boosted regression tree
CDU	Charles Darwin University
CI	Confidence interval
CSIRO	Commonwealth Scientific and Industrial Research Organisation
cumec	1 cubic metre per second
DEM	Digital elevation model
DGNSS	Differential global navigation satellite system
FL	Fork length
GAMM	Generalised additive mixed-effect model
GNSS	Global navigation satellite system
LiDAR	Light detection and ranging
ML	Megalitre (1,000,000 L)
NDWI	Normalised difference water index
NT	Northern Territory
ODC	Open Data Cube
PPP	Precise point positioning
SAR	Synthetic aperture radar
SD	Standard deviation
SE	Standard error
SL	Standard length
VV	vertical transmit – vertical receive
WOfS	Water Observations from Space

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Executive summary

The Daly River has been identified as an exemplar of the potential future water demand in the region (Douglas et al. 2011). The Daly River catchment in the Northern Territory (NT) supports highly significant environmental, economic and Indigenous cultural values (Jackson 2006; Hermoso et al. 2018). The river contains a highly diverse aquatic fauna, including two nationally threatened elasmobranchs, eight of the nine freshwater turtle species in the NT and over 90 species of fish within its freshwaters (Pusey et al. 2020). The river also supports important recreational and commercial fisheries and provides significant cultural value to its Indigenous people (Jackson 2006; Hermoso et al. 2018).

Agricultural, forestry and mining development in the Daly catchment has been increasing over recent years, with concomitant increases in demand for its water resources. Future development has the potential to place increased pressure on the river system through direct impacts caused by water extraction and from indirect impacts arising from native vegetation clearing and land-use activities. The NT Water Allocation Planning Framework allocates at least 80% of river flow or aquifer in the Top End region at any time as environmental water. This precautionary approach occurs in the absence of science for more discrete environmental flow targets to be set, and currently provides a high level of protection for environmental values and security for water licence holders. However, recent assessments have found that some aquifers in the Daly catchment are over-allocated, and that further quantification of the environmental water requirements is urgently needed to support sustainable management (Northern Territory Government 2019a,b).

This research project aimed to collate existing knowledge and develop new knowledge on critical flow-ecology relationships and risk-based scenario models for key environmental assets in the Daly River. Initial project scoping and design of the proposed research was conducted in strong collaboration with NT Government water policy staff and Traditional Owners, who provided critical guidance on the project’s direction and emphasis. The project was divided into nine linked objectives, and incorporated elements from two PhD theses.

This report presents the research approach and outcomes from each of these objectives in separate sections, and provides key findings and a range of key environmental flow considerations for the Daly and Katherine rivers. Where possible, the flow considerations have been developed to be specific to reaches and discharge thresholds. In other cases, flow considerations are more general statements. These environmental flow considerations are intended to provide further insight for review of environmental flow rules in the catchment.

1. Introduction

1.1 Background

The rivers of northern Australia constitute one of the last remaining free-flowing and relatively unimpacted river networks in the world (Reidy-Liermann et al. 2012), and are among the least threatened globally by current human activities (Vörösmarty et al. 2010; Pusey et al. 2011). Unsurprisingly these northern Australian rivers are considered the most biologically diverse and healthy aquatic systems in Australia, and support highly productive and diverse ecosystems of highly significant social, cultural and economic value (Jackson 2006; Pusey et al. 2011).

However, there is growing attention on increasing agricultural production and mining within the region (Commonwealth of Australia 2015), which will increase the demand for water and place increasing pressure on the region's rivers and biota. Environmental flows in rivers that have not been significantly affected by flow-alteration largely aim to protect critical flow components to avoid degradation of environmental values (Arthington et al. 2010; King et al. 2015). Defining the environmental water requirements in the rivers of northern Australia is a critical challenge to avoid future degradation.

The Daly River, Northern Territory (NT), has been identified as an 'exemplar' of the potential future water demand in the region (Douglas et al. 2011). The Daly River catchment supports highly significant environmental, economic and Indigenous cultural values (Jackson 2006; Hermoso et al. 2018). The river contains a highly diverse aquatic fauna, including two nationally threatened elasmobranchs, eight of the nine freshwater turtle species in the NT and over 90 species of fish within its freshwaters (Pusey et al. 2020). The river also supports important recreational and commercial fisheries and provides significant cultural value to its Indigenous people (Jackson 2006; Hermoso et al. 2018). Agricultural, forestry and mining development in the Daly catchment has been increasing over recent years, with concomitant increases in demand for its water resources. Much of this expansion will depend on using groundwater resources, where the depletion may alter the magnitude, timing and extent of dry-season flows in particular (Erskine et al. 2003).

Future development has the potential to place increased pressure on the river system through direct impacts caused by water extraction and indirect impacts arising from native vegetation clearing and land-use activities. This and the environmental and Aboriginal cultural significance of the Daly River require ongoing planning and community engagement to ensure that outcomes reflect social, economic, Aboriginal cultural and environmental values (Northern Territory Government 2019a,b). The NT Water Allocation Planning Framework allocates at least 80% of river flow or aquifer in the Top End at any time as environmental water (in the absence of science or an agreed alternative under a Water Allocation Plan). This provides a high level of protection for environmental values and security for water licence holders. A recent assessment of water allocation arrangements in the catchment found that some aquifers are over-allocated, and that further quantification of the environmental and cultural water requirements of the system is urgently needed to support sustainable management (Northern Territory Government 2019a,b).

A number of studies have highlighted flow-ecology linkages for some species in the river (Erskine et al. 2003; Bayliss et al. 2008; Stewart-Koster et al. 2011; Chan et al. 2012;

Jardine et al. 2012a,b; Pusey et al. 2018; Keller et al. 2019; Turschwell et al. 2019; Pusey et al 2020). Studies in the 1990s provided specific environmental flow recommendations for some ecological values in the river (Erskine et al. 2003), which have been incorporated into water allocation arrangements (Northern Territory Government 2019a,b). However, knowledge on the flow-related ecology of most species is limited, or could be better defined for critical species; improved knowledge is important to providing robust, evidence-based risk assessments for alternative water management scenarios (King et al. 2015; Horne et al. 2019).

This research project aimed to collate existing knowledge and develop new knowledge on critical flow-ecology relationships and risk-based scenario models for key environmental assets in the Daly River. Initial project scoping and design of the proposed research was conducted in strong collaboration with NT Government water policy staff and Traditional Owners, who provided critical guidance on the project's direction and emphasis. A first step in the project was to review and synthesise previous knowledge and develop conceptual models to enable informed focus of the project (see Appendix 1).

At project inception, future water increases in the catchment were largely focused on groundwater extraction, and hence the main priority and project emphasis was to determine the risk of reduced dry-season flows on the river's ecology. However, as the project progressed, harvesting of off-stream, wet-season, flood flows have also been proposed in the catchment. Hence, where possible, our considerations and scenarios also consider flood flows and inundation events.

1.2 Objectives

This project aimed to determine the environmental water requirements for key biota and ecological processes in the Daly River catchment. The project is divided into nine linked objectives:

1. Synthesise and construct conceptual models of pre-existing flow-ecology knowledge (Appendix 1)
2. Determine floodplain inundation extent, frequency and hydrological thresholds (Section 2)
3. Conduct hydrodynamic mapping of dry-season, riverine physical habitats (Section 3)
4. Assess the dry-season habitat use by fishes and their vulnerability to water extraction (Section 4)
5. Determine the dry-season food web of the main channel of the Katherine and Daly rivers (Section 5)
6. Determine the movement of and habitat use by sooty grunter, with reference to flow requirements (Section 6, 8)
7. Determine the movement of and habitat use by pig-nosed turtles, with reference to flow requirements (Section 7)
8. Examine the flow requirements for successful breeding and recruitment of freshwater fish (Sections 9, 10).

   A further PhD student study on migration, growth and sex change of barramundi was also linked to this study (Section 11).

1.3 Study area

The Daly River catchment is ~53,000 km^2, is located in the wet-dry tropical climate region of northern Australia (Figure 1-1) and has a largely intact savanna ecosystem throughout the catchment (Schult & Townsend 2012). The catchment's population is ~10,000 people, of whom 28% are Indigenous (Larson & Alexandridis 2009). The majority of the catchment occurs at elevations <100 m above sea level with only the headwaters occurring at >400 m above sea level in the 'stone country' of the Arnhem Land escarpment. The region supports a number of agricultural industries, including forestry, horticulture, cattle and hay-growing. Land tenure is a mix of freehold, leasehold and Aboriginal land (24%) (Northern Territory Government 2019b). Tourism is also an important economic driver in the region; for example, an average of 354,000 tourists visit the Katherine-Daly region each year (Tourism NT 2018).

Figure 1-1. Map of the Daly River catchment study area.

Across the catchment, mean annual rainfall averages 1070 mm and is highly seasonal, with 90% of rainfall occurring during the wet-season months (November–April) and negligible rainfall during the dry season (May–October). This strong seasonal climate results in the rivers having a characteristic wet-dry tropical flow regime (McDonald & McAlpine 1991) (Figure 1-2), with predictable and large wet-season flows with high inter-annual variability (Kennard et al. 2010).

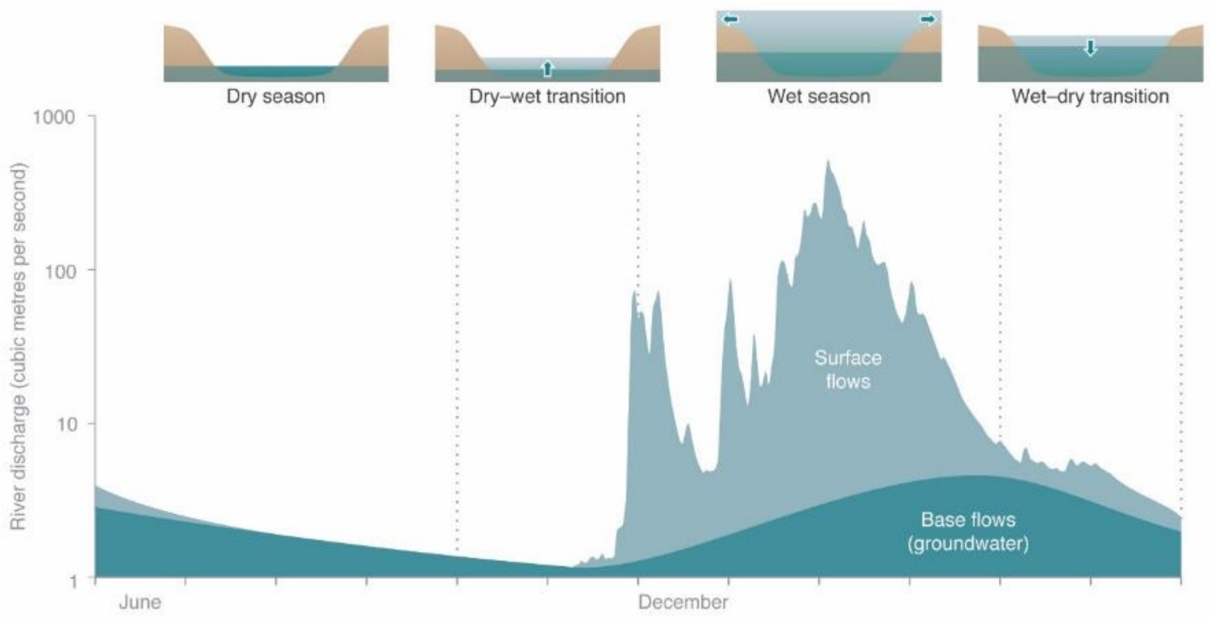

Figure 1-2. Schematic hydrological cycle of the Daly and Katherine rivers, showing conceptualised contribution of groundwater and surface waters to the total river flow. Upper panel shows a cross-section of the river channel at various flow stages.

Flow in the Daly and Katherine rivers and some tributaries is perennial, and supported from significant groundwater inputs from three karstic groundwater aquifers (Tindall, Jinduckin and Oolloo) (Jolly 1984), resulting in a lengthy period of continuous and stable dry-season base flows (May–November). Groundwater enters from discrete springs, diffuse seepage and riverbed seepage. Flow in the Daly steps from 8 m^3/s to 32 m^3/s from groundwater contributions from five discrete concentrations of springs, commencing at the boundary of the Cretaceous sandstone and the Oolloo dolostone. The Oolloo dolostone consists of an upper massive unit and a lower bedded unit, with inflows of 13 m^3/s and 3 m^3/s, respectively (Tickell 2002, 2011). In the wet season, the river is made up of rainwater of very low conductivity, whereas the river is dominated by highly buffered, highly ionic groundwater from the Oolloo limestone aquifer in the dry season.

Components of this project were conducted during, and used data from, 2006 to 2019. The hydrology during this period varied between years, and included very strong wet seasons (2011, 2016) and prolonged dry seasons (e.g. 2019) (Figure 1-3).

The Daly and Katherine rivers are sand-bed rivers that contain dispersed bedrock outcrops, mobile sand bars and gravel bars; river banks are typically steep, rising 15–20 m above the riverbed (Erskine et al. 2017; Wasson et al. 2010) (Figure 1-4). Riparian vegetation in the catchment is largely intact and natural, consisting of eucalypt woodlands, *Melaleuca* forests and closed monsoon rainforests (Lamontagne et al. 2005).

Figure 1-3. Mean daily discharge at (a) Wilden, Katherine River; (b) Upstream of Dorisvale, Daly River; and (c) Mount Nancar, Daly River, throughout the study period. Panel (b) annotated to show study periods for various project components.

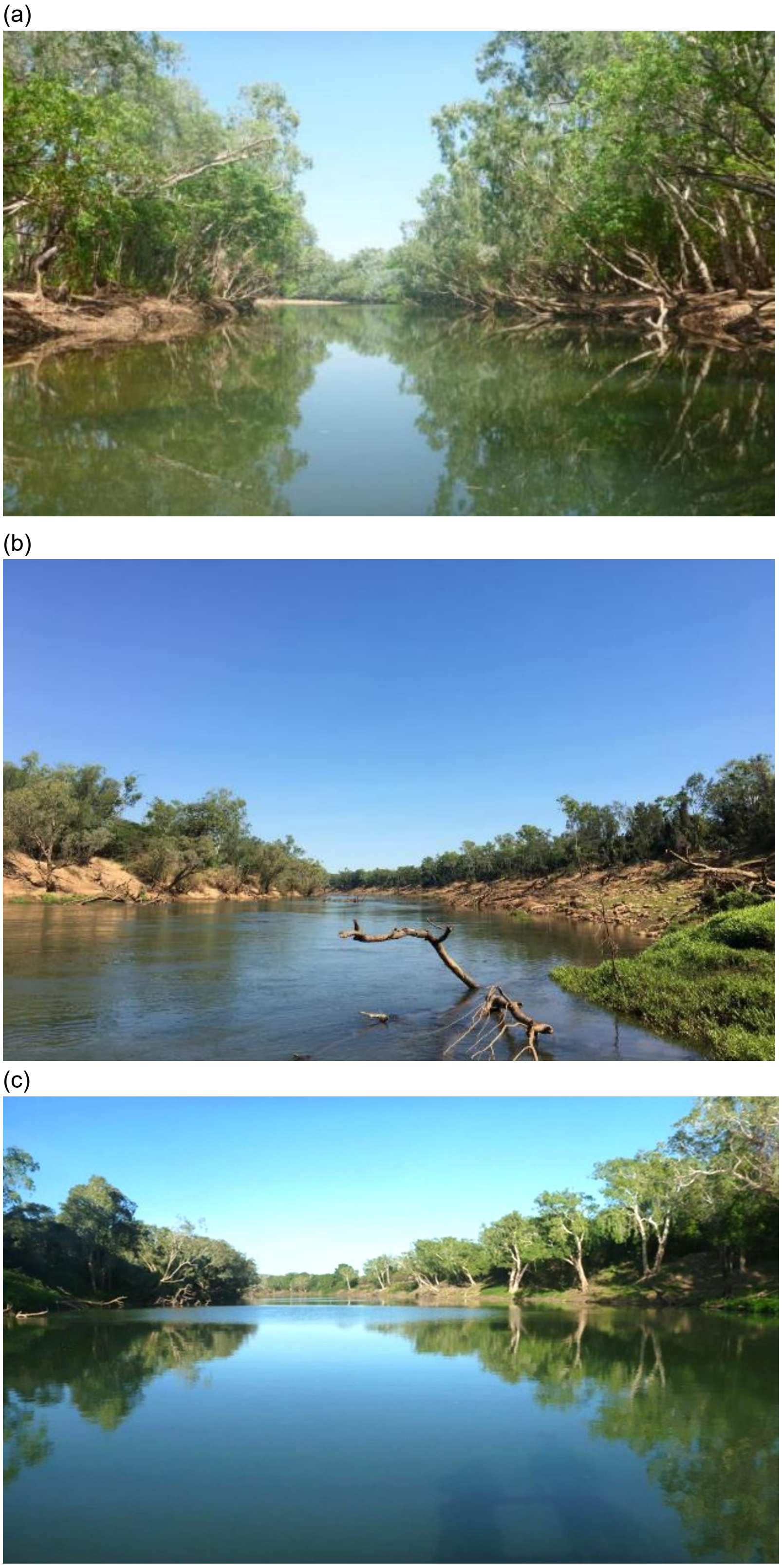

Figure 1-4. (a) The main channel of the Katherine River at Galloping Jack's; (b) Daly River upstream of Oolloo Crossing; and (c) Daly River upstream of Daly River Crossing.

2. Floodplain inundation extent, frequency and hydrological thresholds

Contributors: Shaun Levick, Stephanie Johnson

2.1 Background and aims

It is widely acknowledged that the extent, duration and frequency of floodplain inundation are the primary drivers of population productivity in tropical systems. A number of key environmental assets (e.g. barramundi catch, magpie geese nest abundance) have strong positive relationships with river flow and rainfall (Bayliss et al. 2012), but the relationships between rainfall and river flow and inundation patterns are poorly understood.

The aim of this component of the project was to better understand the relationships between rainfall, river flow and floodplain inundation. Specifically, we aimed to:

1. determine the areal extent of floodplain inundation under different rainfall regimes
2. describe the empirical relationships between river height (flow) and the extent and duration of floodplain inundation for key regions in the Daly catchment
3. determine the threshold floodplain connection discharge.

2.2 Methods

The key information required for delivering this component of the project was the areal extent of floodplain inundation (surface water) for different years, and for different times of each year. Once these spatial patterns had been mapped spatially through time, they could be explored further and compared with rainfall and river gauge height patterns.

We adopted a satellite image analysis approach for assessing the spatial extent of floodplain inundation by using archives of historical imagery to establish long-term temporal patterns of surface water occurrence. We also explored recent developments in spaceborne imaging technology to provide higher-resolution insights over the shorter term.

2.2.1 Historical trends

The Landsat mission from NASA has played a pivotal role in providing multi-spectral imagery from space with a spatial resolution of 30 m since the 1970s (Wulder et al. 2012). NASA's commitment to Landsat continuity has seen a number of different Landsat satellites operational in space, and a combination of Landsat 5 (launched 1984), Landsat 7 (1999) and Landsat 8 (2013) provides an archive of multi-spectral imagery over Australia from 1986 to the present, at bi-monthly intervals on average. The availability of this record provides an opportunity to quantify the presence of surface water over this time period at 30 m pixel resolution.

2.2.2 Water observations from space

Water Observations from Space (WOfS) is a collaborative initiative between Geoscience Australia, the CSIRO and the National Computational Infrastructure that provides surface water observations derived from satellite imagery for all of Australia. It is hosted through Digital Earth Australia and is built upon the Open Data Cube (ODC). The current WOfS product (version 2.1.5) includes observations taken from 1986 to the present, from the Landsat 5, 7 and 8 satellites. WOfS covers all of mainland Australia and Tasmania. The WOfS product enables better understanding of where water is normally present in a landscape, where water is seldom observed and where inundation has occurred occasionally by building a time-series of water presence in the landscape for each pixel (Figure 2-1). The details of the WOfS algorithm and derived statistics are described by Mueller et al. (2016).

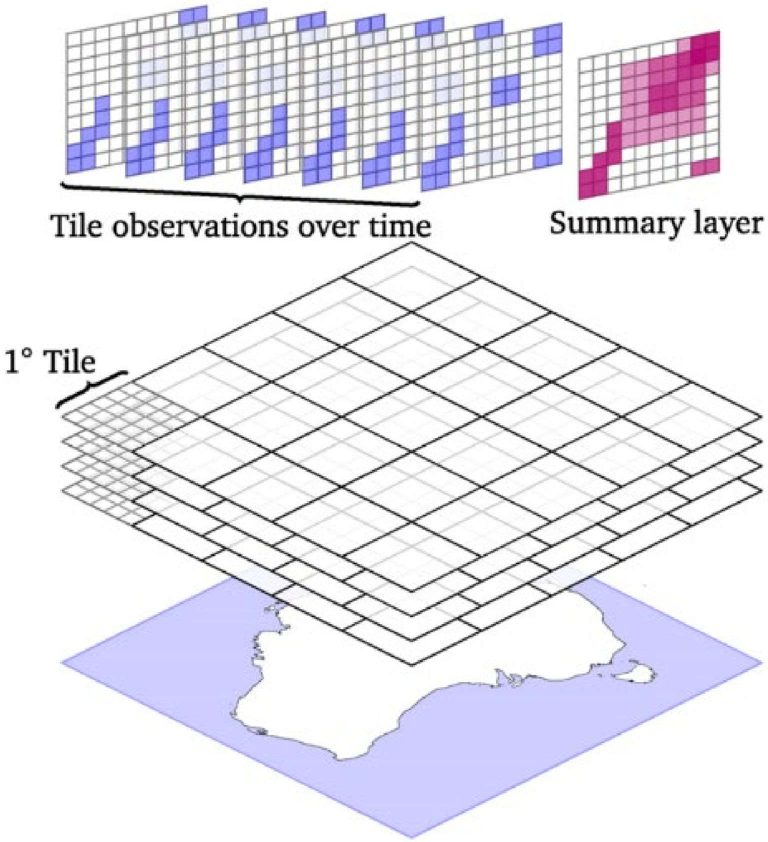

Figure 2-1. Conceptual overview of water observations from space. The pixels in each tile are classified as 'water' or 'not-water'. The classifications over time are aggregated into a summary layer that gives the proportion of times that water was detected. From Mueller et al. (2016).

WOfS is based on a regression tree classifier that was trained and validated with 183,874 water and non-water samples. WOfS classification accuracies range from 74% for complex situations (water mixed with vegetation) to 98% for more simple ones (large waterbodies and rivers) (Mueller et al. 2016). WOfS is an Australia-wide product and is a very large dataset, as each layer is provided in a 1-to-1 relationship with the input data. In order to work with this complex data in an efficient manner, we made use of the CSIRO's Earth Analytics Science and Innovation (EASI) Hub. The EASI Hub is built upon the ODC, shares many features of the Digital Earth Australia implementation, and is more efficient and flexible for processing Big Data.

2.2.3 Normalised difference water index

In addition to making use of the WOfS surface water classification layers, we also queried the raw imagery to calculate a spectral index of water probability for each available image. We extracted every available Landsat image (from the Landsat 5, 7 and 8 satellites) that intersected the study region from January 1986 to December 2020, in the EASI Hub cloud-based, distributed-processing environment. After masking out cloud cover, we retained 1,222 scenes from Landsat 5 (1986–1999), 1,570 scenes from Landsat 7 (1999–2012) and 2,176 scenes from Landsat 8 (2013–20). We computed the median surface reflectance value on a per-pixel basis across the entire catchment to serve as a common base map for subsequent analyses (Figure 2-2).

Our processing chain mapped the probability of surface water at the pixel level, using the normalised difference water index (NDWI). The NDWI is a spectral index that utilises the ratio of the green (G) and near-infrared (NIR) wavelengths to identify waterbodies:

$$NDWI = \frac{(G - NIR)}{(G + NIR)}$$

NDWI values range from −1 to 1, with values >0.3 having a high probability of being open water (McFeeters 1996). The use of this index has proven to be reliable in a number of studies around the globe for floodwater mapping (Feyisa et al. 2014; Mueller et al. 2016; Yamazaki et al. 2015).

NDWI was calculated for each image in the raster stack, enabling patterns of NDWI to be explored over time and space. Across the whole study site, this amounted to 4,968 Landsat images, and for a given location, there were 711 images in the time-series (equating to 21 images per year per location). As such, the Landsat archive provides an avenue of accessing patterns of historical floodplain inundation with a temporal resolution of every 16 days on average. This resulting raster stack can be queried for any reach of the catchment, enabling the retrieval of the actual image for a given date, or the median reflectance over a date range (e.g. Figure 2-3).

Maps of NDWI for a given date were then stacked in time and queried on a per-pixel basis to retrieve the number of months in which water was present in a pixel over the full time period (771 images). The product of this analysis is a map of inundation frequency, which reveals spatial patterns in the presence of surface water over time – akin to those produced by WOfS.

Our dual approach to the analysis of the historical Landsat imagery allowed us to make use of both classified surface water layers with well validated accuracy (WOfS) and temporal trends in the underlying spectra (NDWI).

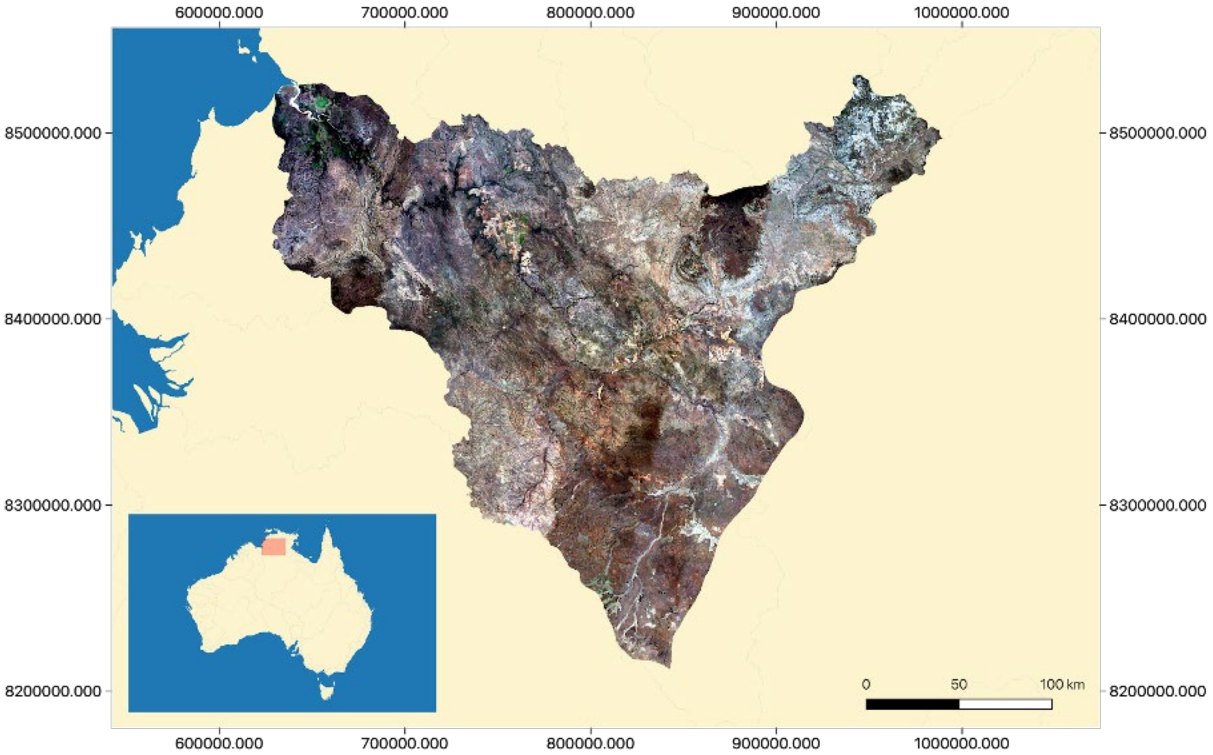

Figure 2-2. Overview of the Daly River catchment area of study. True-colour rendering of the median reflectance value of every available Landsat image for the catchment. Coordinate reference system: UTM52S WGS84.

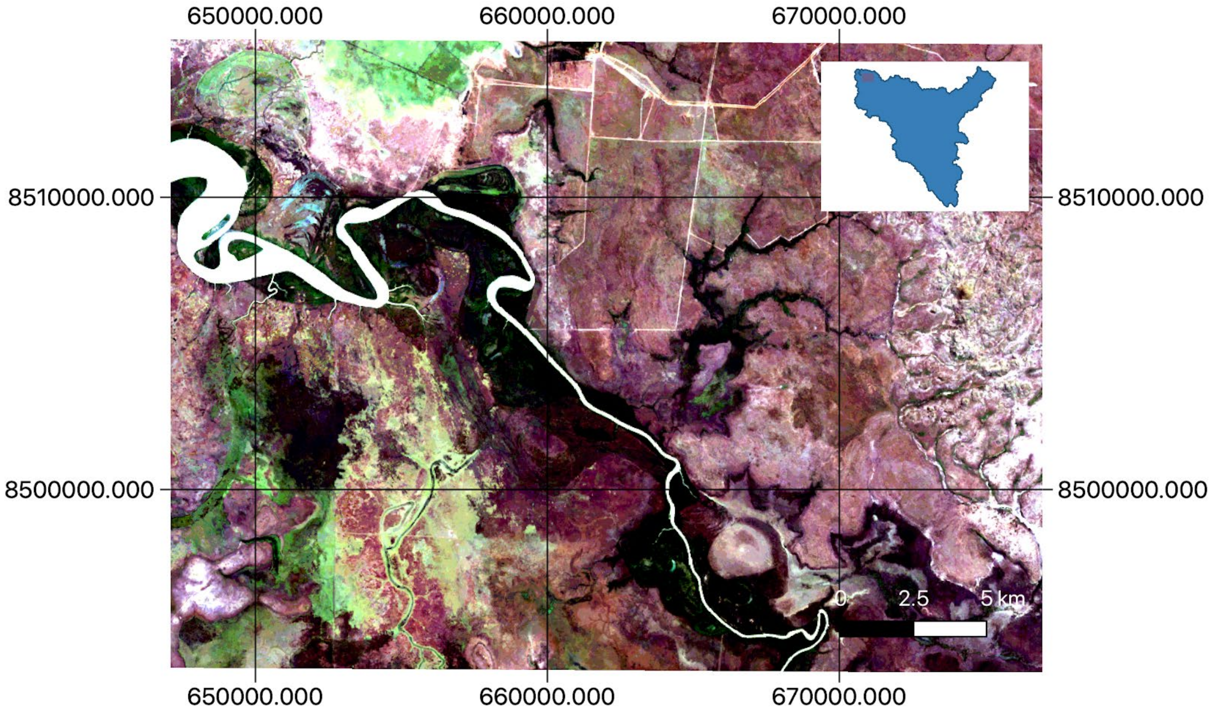

Figure 2-3. True-colour rendering of a subset of a Landsat 8 image, showing the heterogeneity of the floodplain environment. Coordinate reference system: UTM52S WGS84.

2.2.4 Hydrological data

Historical rainfall and stream discharge data were acquired from the Bureau of Meteorology (bom.gov.au/nt/flood/rain_river.shtml). We used data available from the three lowest catchment gauges – Police Station, Mount Nancar and Gourley – and from three central reaches – Oolloo Crossing, Dorisvale and Katherine Railway Bridge.

We used the river discharge data to generate flow duration curves at key points along the river, following procedures developed by Digital Earth Australia (Krause et al. 2021). Flows for each day were ranked from highest to lowest flow, enabling the exceedance probability to be estimated. Exceedance refers to the percentage of the time the river was at that flow or higher, and is calculated as follows:

$$P = 100 * \frac{M}{n+1}$$

where

- *P* = the probability that a given flow will be equalled or exceeded (% of time)
- *M* = the ranked position on the listing
- *n* = the number of events for the period of record.

Considering the river discharge data in terms of exceedance enabled us to extract the historical imagery that related to particular river-flow conditions, rather than by day alone. Plots derived from this analysis can therefore be used to examine events where the stream gauge reported values greater than, or less than, a specific threshold.

2.3 Results and discussion

2.3.1 Linking hydrology with historical inundation patterns

The generation of NDWI images from the Landsat archive enabled calculation and visualisation of the maximum spatial extent of floodplain inundation for different reaches of the Daly River (e.g. Figure 2-4). These spatial patterns provide an overview of which parts of the landscape have a higher probability of being inundated than others, and by stacking these probabilities through time it was possible to quantify the frequency of inundation (Figure 2-5).

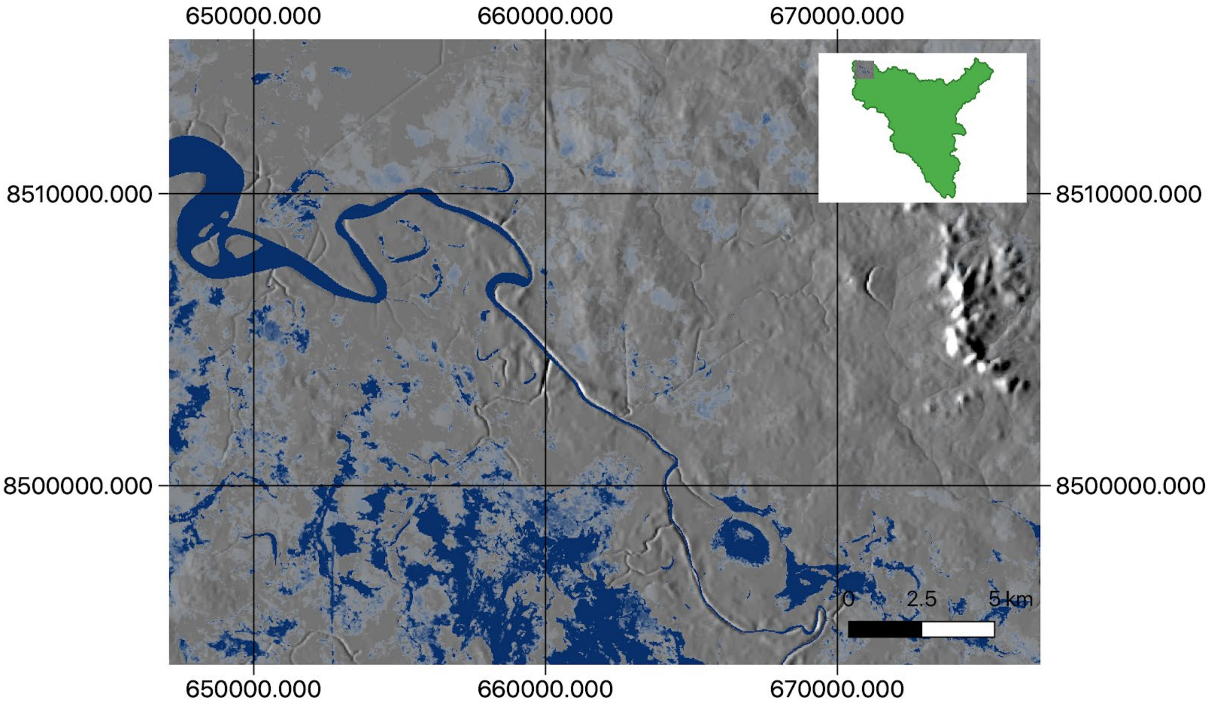

Figure 2-4. Surface water probability map derived from the Landsat archive, showing maximum spatial extent of surface water (darker blues indicate higher probability). Topographic relief is derived from 30 m data from the Shuttle Radar Topography Mission (SRTM). Coordinate reference system: UTM52S WGS84.

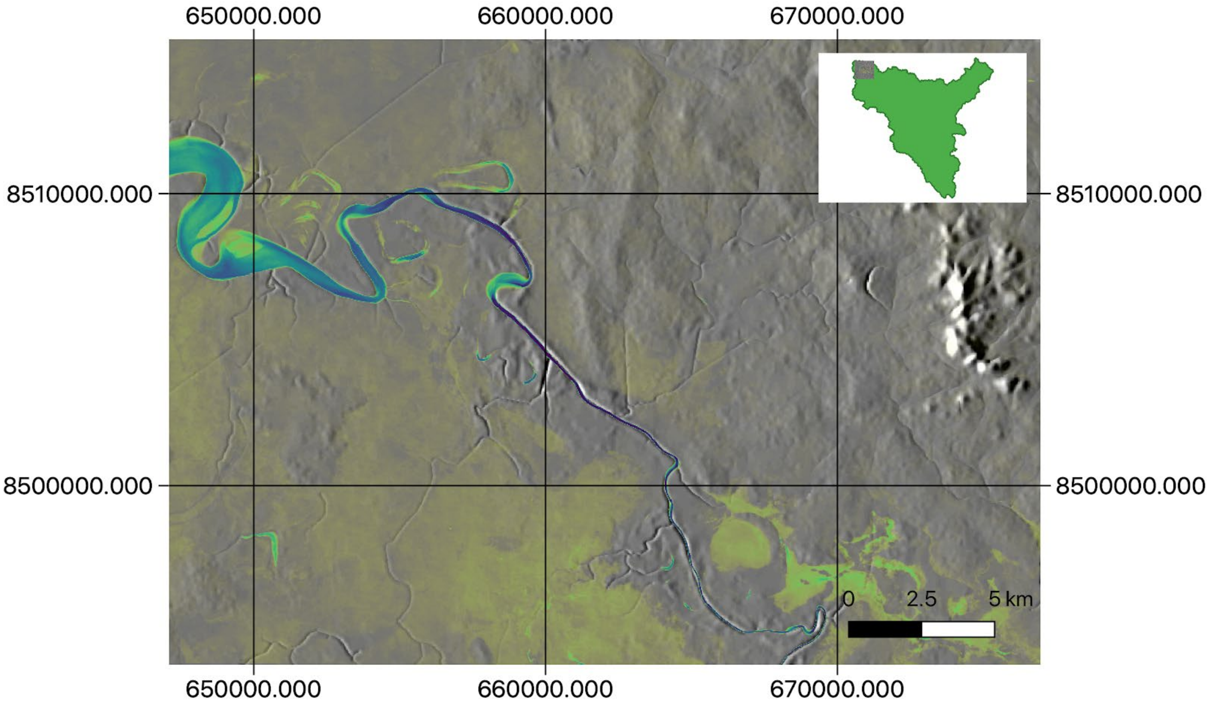

Figure 2-5. Frequency of inundation map. Blue colours represent areas that have consistently contained water over the last 33 years. Shades of green show dynamics zone, while areas in yellow have very periodic presence of surface water. Topographic relief is derived from 30 m data from the Shuttle Radar Topography Mission (SRTM). Coordinate reference system: UTM52S WGS84.

The frequency of inundation patterns largely followed our expectations, with river channels and billabongs showing the most consistent inundation through time, with less frequent wetting on the floodplains. The tropical context of the Daly River provided some unique challenges to the NDWI mapping, such as the high sediment loads in the lower reaches of the river and interruptions in the satellite image time-series due to high cloud cover. Nonetheless, given the length of the time-series and the systematic coverage, the Landsat archive provides useful insight into inundation trends and was rich enough to provide clear imagery for a broad range of corresponding flow discharge conditions.

In the upper reaches of the catchment (Katherine Railway Bridge; Figure 2-6), flow was largely confined to the main channel under lower-flow conditions (10–100 m^3/s [cumecs], 50% exceedance probability). However, as flow increased (100–1,000 cumecs, 20% exceedance probability), the tributaries and waterholes swelled enough to enable detection from space. Sustained wetting of the adjacent floodplains was only associated in the imagery with very-high-flow conditions (>1,000 cumecs, 2% exceedance probability). Similar patterns were observed in the central reaches at Dorisvale (Figure 2-7) and Oolloo Crossing (Figure 2-8), whereby floodplain inundation was only detectable from the satellite imagery when the probability of discharge exceedance was ~5% (>1,000 cumecs). The pattern in the lower catchment (discharge measured at Mount Nancar) was slightly different, however, with records of floodplain inundation associated with lower discharges and higher exceedance probabilities (Figure 2-9).

The floodplain inundation patterns in the lower catchment (Figure 2-9) therefore appear to be less tightly coupled to the main channel discharge than are the upper and central reaches. Higher frequency of inundation on the lower floodplain was still associated with very high flows, but periods of floodplain inundation were also recorded under considerably lower-flow conditions. This pattern could be an artefact of temporal lags, whereby surface water resides on the floodplain for longer periods and is thus still present once flow in the main channel has subsided. Alternatively, this pattern could be driven by local rainfall on the floodplain itself, or flow coming in from the adjacent tributaries that feed directly onto the floodplain.

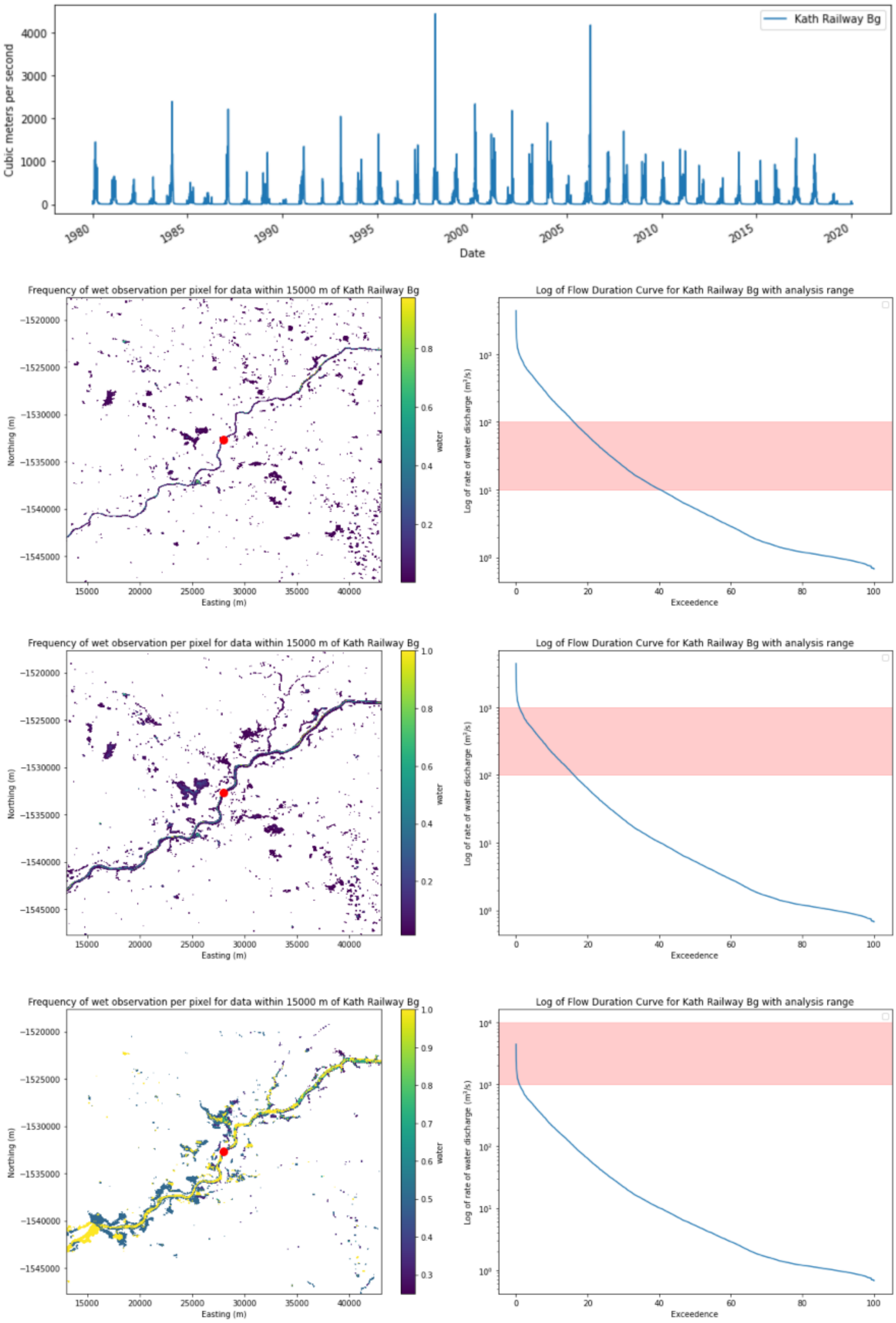

Figure 2-6. Relationship between inundation patterns and river discharge at Katherine Railway Bridge. Inundation frequency (left panel) is plotted from the corresponding periods of water discharge rate, indicated by the red bar on the flow duration curve (right), following procedures developed by Digital Earth Australia Sandbox (Krause et al. 2021).

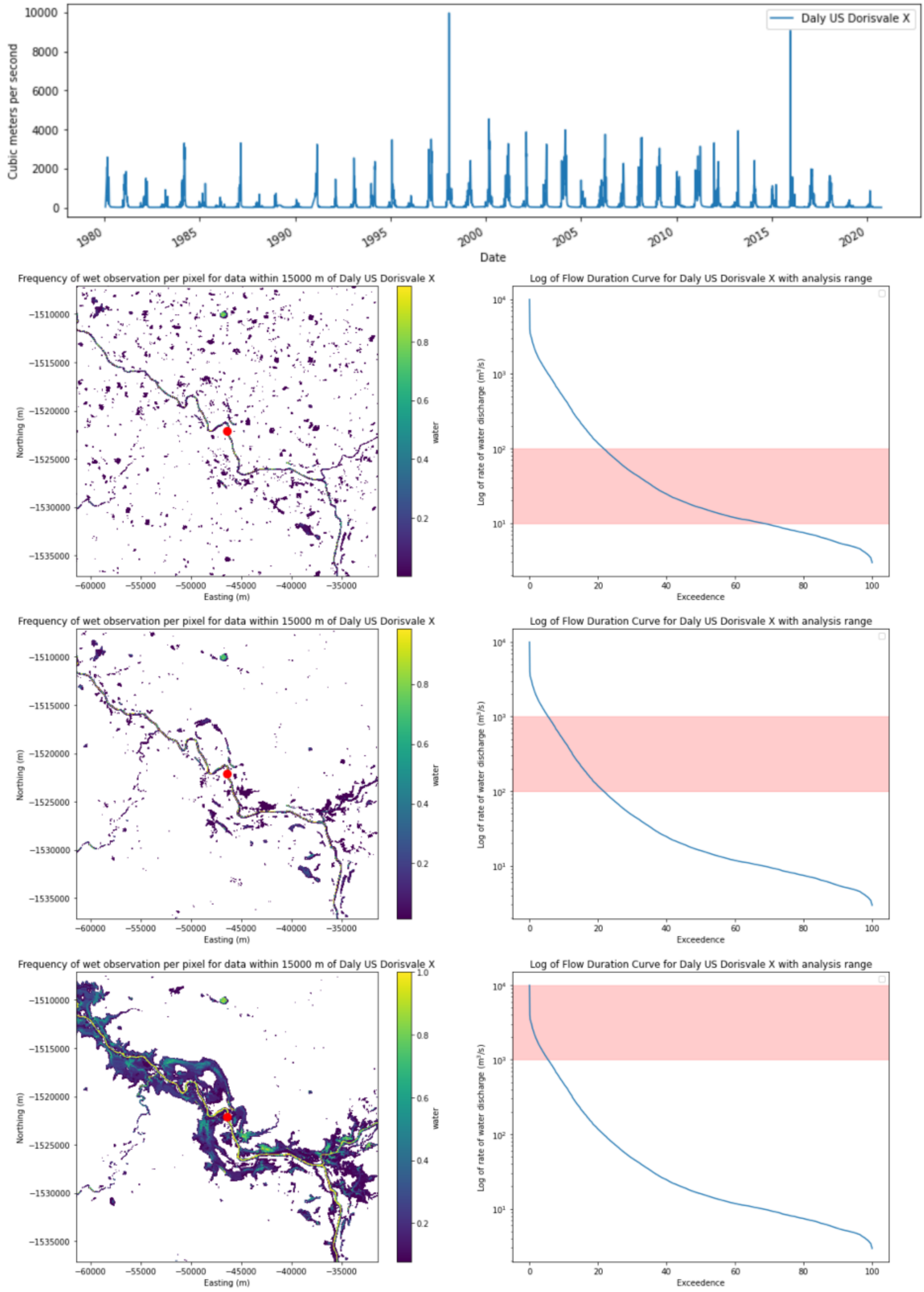

Figure 2-7. Relationship between inundation patterns and river discharge at Dorisvale. Inundation frequency (left panel) is plotted from the corresponding periods of water discharge rate, indicated by the red bar on the flow duration curve (right panel).

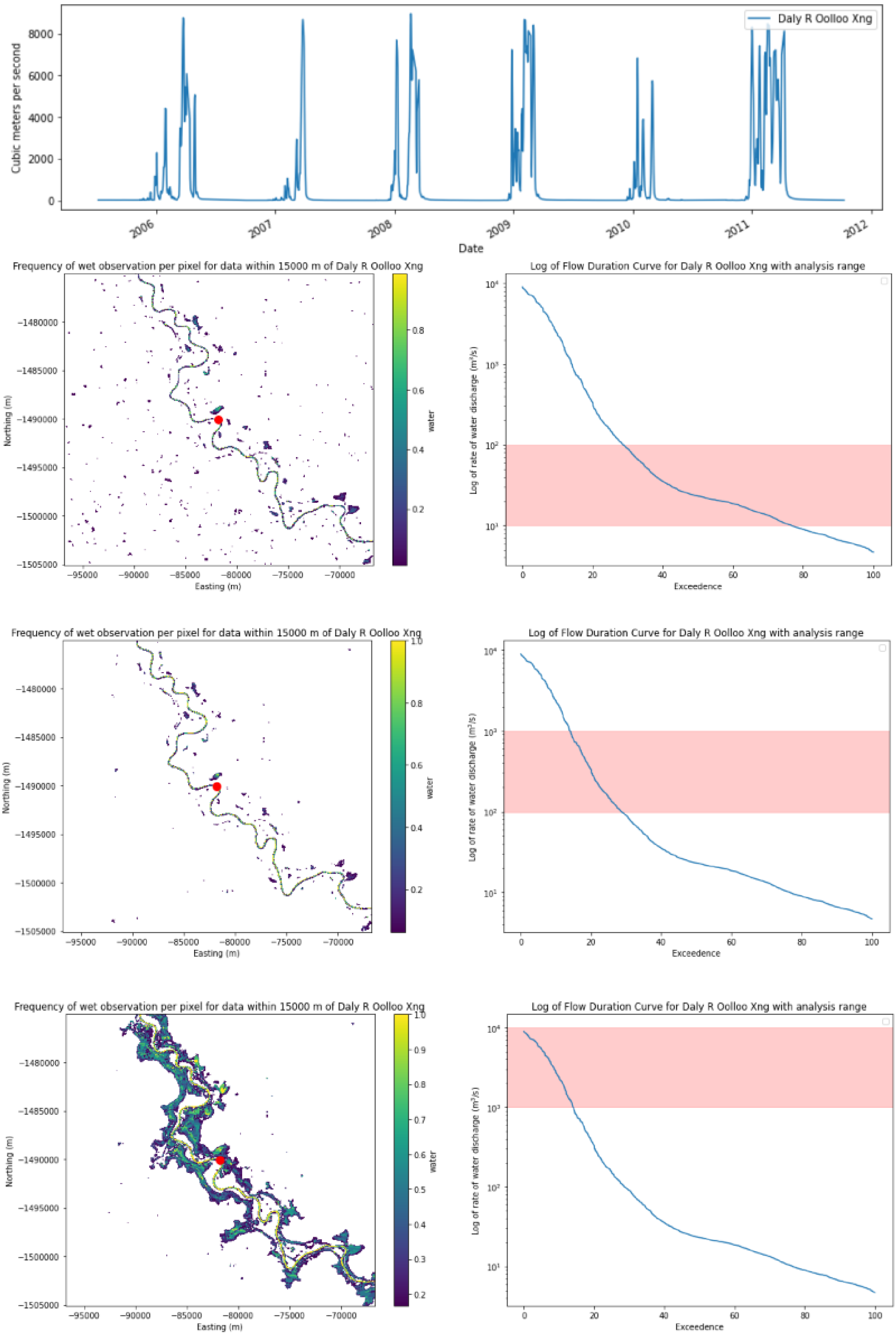

Figure 2-8. Relationship between inundation patterns and river discharge at Oolloo Crossing. Inundation frequency (left panel) is plotted from the corresponding periods of water discharge rate, indicated by the red bar on the flow duration curve (right panel).

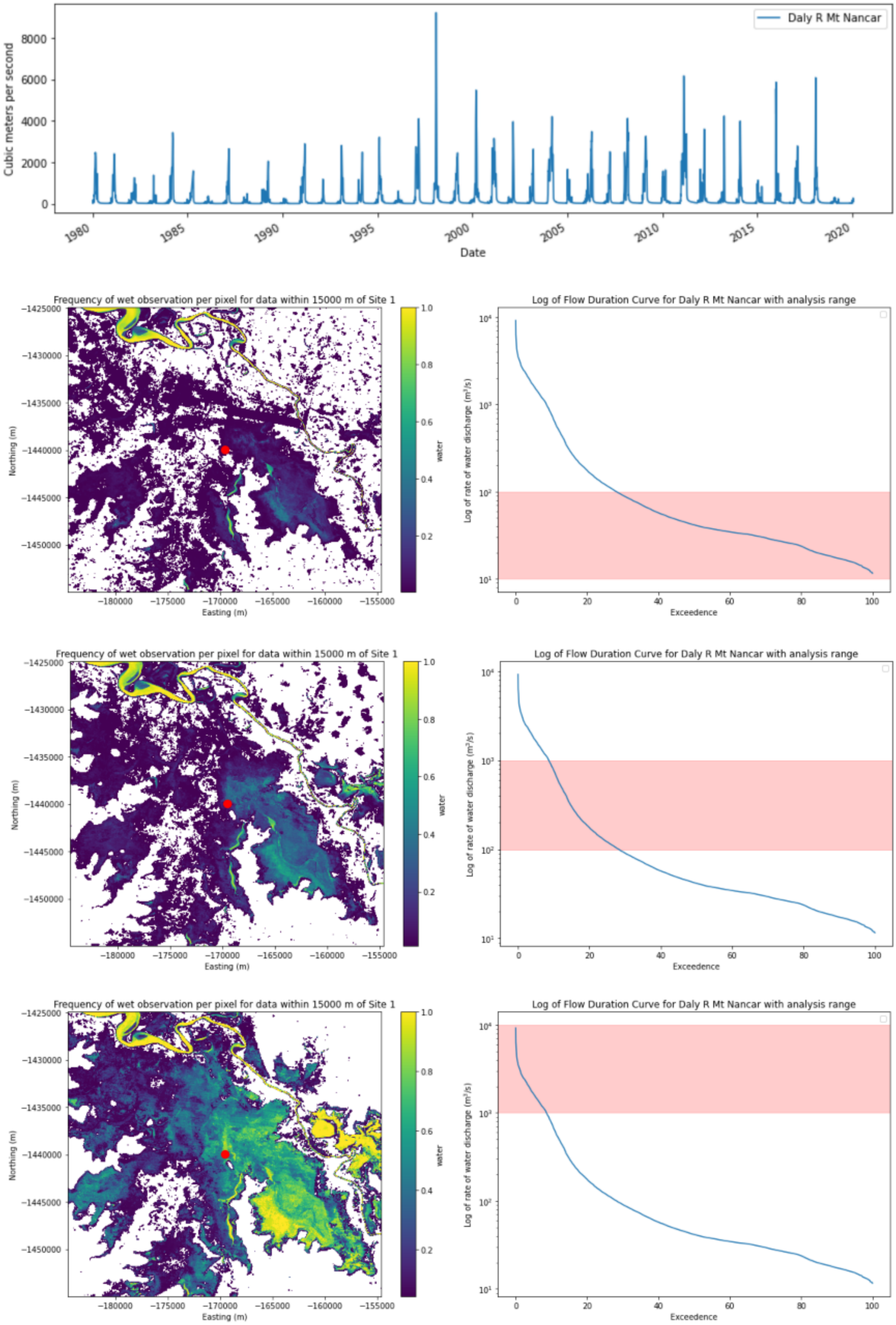

Figure 2-9. Relationship between inundation patterns and river discharge at Mount Nancar. Inundation frequency (left panel) is plotted from the corresponding periods of water discharge rate, indicated by the red bar on the flow duration curve (right panel).

2.3.2 Limitations and avenues for future research

Analysis of the full Landsat archive provided a high degree of flexibility for querying spatio-temporal patterns in water inundation over time. However, despite the relatively high spatial (30 m) and temporal (16 days) resolution of this archive, smaller water features in both time and space might have gone undetected, especially during periods of high cloud cover. As such, while this data cube provides useful historical context that covers a broad range of rainfall conditions, its limitations need further exploration, particularly with regard to informing understanding of the relationships between rainfall, river discharge and floodplain inundation. In particular, the degree of cloud cover during the wet season presents a major challenge to conducting this type of analysis in northern Australia's tropical climate.

To gain insight into what might be missed from Landsat-based analyses, we also explored higher-resolution radar data from the European Space Agency's Copernicus program. The European Space Agency has led the way forward in defining a new era of earth observation, building constellations of satellites to address global monitoring needs (Showstack 2014). Sentinel-1 was among the first successes of the Copernicus program, launching a radar satellite (Sentinel-1a) in 2013 and its twin (Sentinel-1b) in 2016. The two Sentinel-1 satellites operate C-band synthetic aperture radar (SAR) sensors, and orbit opposite each other in constellation to provide redundancy and improve revisit time (Torres et al. 2012). A big advantage of SAR sensors is their ability to penetrate cloud cover and capture imagery under a broader range of atmospheric conditions than optical sensors. SAR backscatter is also very sensitive to water, making it a good candidate for surface water and flood mapping (Westerhoff et al. 2013).

We used the ODC to query the available Sentinel-1 images for the lower Daly River catchment, which are available every 10 days on average. Our processing chain consisted of extracting the 'vertical transmit – vertical receive' (VV) backscatter intensity channel, applying terrain corrections and speckle filters, and classifying the presence of standing water on a per-pixel basis using a backscatter intensity threshold. Spatial investigation of the Sentinel-1 data record showed good potential for informing inundation research with patterns of flooding showing up clearly during peak times of the wet season, despite a high degree of cloud clover (Figure 2-10). Our classification of inundated water extent identified imagery from 1 February 2018 as containing greater than usual surface water. Examination of the VV backscatter intensity image from that date (Figure 2-10b) shows floodplains of the lower Daly fully inundated with water. On this day, the area was covered with 80% cloud cover and optical satellites could not capture these patterns. Prior to the floodplains filling up, only small amounts of water were present on the south-eastern edge of the image (late January; Figure 2-10a). Patterns of drainage off the floodplain can also be observed over the next few weeks of the record (Figure 2-10c,d). These findings highlight the need for high temporal resolution data to capture the finer details of floodplain inundation dynamics, and particularly for establishing thresholds for floodplain connection to the main channel.

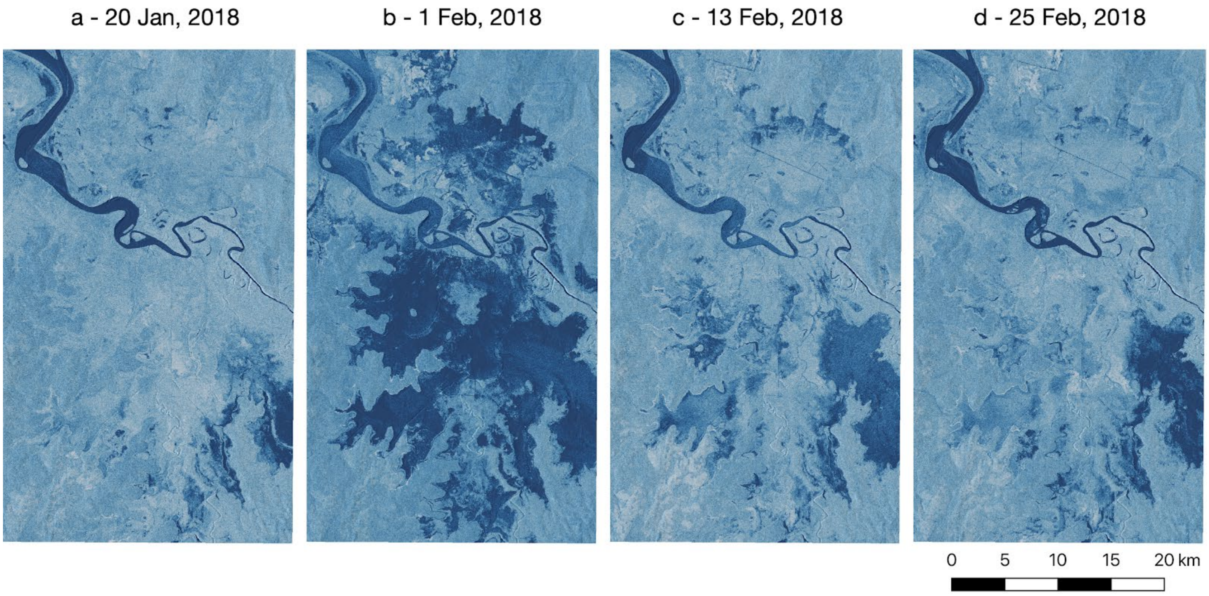

Figure 2-10. Sentinel-1 C-band synthetic aperture radar imaging of the lower Daly River. Dark blue areas of the VV backscatter intensity image indicate surface water. Image sequence progresses from 20 January 2018 (a) through to 25 February 2018 (d). Coordinate reference system: UTM52S WGS84.

2.4 Summary and recommendations

- Periods of extensive floodplain inundation correlate well with peak discharge events of less than 10% exceedance probability.
- Floodplain inundation behaviour changes throughout the catchment. Discharge is a good indicator of floodplain inundation in the middle-to-upper reaches of the Daly and Katherine rivers. However, in the lower reaches, inundation of the floodplain is influenced by main river channel discharge, rainfall and tributary inflows. Further analysis of spatial and temporal inundation patterns is required in the lower reaches to further progress quantitative ecological linkages of discharge or inundation to ecological responses.
- WOfS is a valuable resource, but the hard classifier (water/non-water) has some drawbacks when trying to interpret correlations with rainfall and river discharge – reverting to the original imagery data or spectral indices (NDWI) is often insightful.
- The Landsat satellite record provides important context and historical trends, providing good insight into frequency of inundation patterns. However:
  - The 30 m spatial resolution is too coarse for detecting fine-scale water features (particularly in the confined upper reaches).
  - The temporal resolution (11–16 days) is too coarse for interpreting dynamic hydrological conditions such as floodplain–river connection discharge.
- We recommend a multi-sensor approach for future investigation, that integrates both Sentinel-1 (SAR) and Sentinel-2 (multi-spectral) data into an analysis framework with the Landsat archive to provide higher spatial and temporal resolution.

3. Hydrodynamic mapping of dry-season, riverine physical habitats

Contributors: Peter Waugh, Julia Schult, Peter Dostine, Brett Miller (University of NSW)

3.1 Background

Reduced river flow in Australia's Top End may result from poor wet-season recharge of key groundwater storages, or through abstraction from groundwater or surface water resources for consumptive use. A key consideration for water-use planning aimed at balancing consumptive use for economic development with environmental and cultural requirements is to understand the impact of reduced river flow on ecosystem function, including habitat availability and connectivity, for key species to ensure in-stream ecosystems remain viable.

We used hydrodynamic models to explore how habitat availability was affected at various flow scenarios at two specific reaches, Wilden on the Katherine River and Mentabie on the Daly River. Hydrodynamic models are commonly used to describe water elevations, depths and velocities along a selected reach at various flows; however, these models must be sensitive enough to adequately represent the hydraulic parameters required at a scale suitable for selected indicator species. Hydraulic requirements of selected species for the Daly River Environmental Flow project required the development of high-resolution hydrodynamic models, ideally capable of representing changes in depth of 0.1 m at high spatial resolutions suitable for identifying hydraulic changes over riffle sections within the Wilden and Mentabie study areas.

3.2 Aims and objectives

This project component aimed to:

1. develop a high-resolution digital elevation model (DEM) of the study reaches suitable for the development of a high-resolution hydrodynamic model for the Wilden and Mentabie study areas
2. develop high-resolution hydrodynamic models for each study area that will allow differentiation of key habitat parameters, including water depth and velocity, under different flow scenarios at a scale suitable for study species for which preferential habitat data has been collected
3. test a range of flow scenarios to determine available habitat and identify potential barriers to movement for key study species (Sections 7 and 8).

3.3 Survey and mapping methods

Generating a broadscale DEM over an entire model reach to a high resolution and accuracy is complicated due to the size of the model domain, complexity of riffle sections and the difficulty of undertaking bathymetric surveys over shallow, fast-moving water. Figure 3-1 shows two typical riffle sections surveyed in the Mentabie study area. Interpolation of the riverbed between surveyed point data introduces smoothing into the modelled surface that, while broadly representative of riffle sections, may not reflect the complexity of the riffle, inadequately representing the required hydraulic processes.

Figure 3-1. Photos of two riffle sections surveyed and modelled within the Mentabie study area.

Higher-resolution bathymetric surveys improve the representation of the modelled surface to the actual surface, allowing a better representation of surface complexity. Figure 3-2 illustrates the difference between a modelled surface and the actual surface. Hydraulic impacts resulting from the heterogeneity of the modelled surface can be addressed through modification of the bed friction parameter (Mannings ‘n’) in the hydrodynamic model, allowing better representation of hydraulic processes and more realistic water elevations and velocities through the model domain. Ideally, different bed friction parameters should be applied to represent different in-stream habitats within the modelled reach (riffle, pool, control etc.), allowing better representation of the hydraulic effects over different habitat features in the modelled reach.

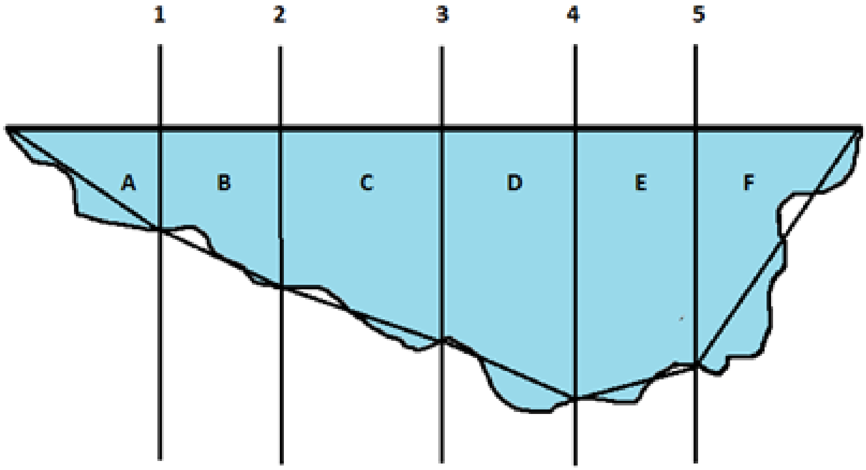

Figure 3-2. Effect of interpolating between surveyed points. The non-uniform shape of the bed is represented by straight lines between the surveyed points 1–5. Loss of detail between surveyed points is apparent. Image from Kalnach et al. 2013.

Industry standard bathymetric survey techniques were used to collect a series of longitudinal and lateral transects across the study reaches. For both study areas, the number of transects varied according to river width and section type. Riffle and control sections were surveyed at higher resolution than pool sections due to the increased complexity of riffle habitats, and their importance to connectivity and as potential barriers to movement of study species across the riffle and control sections.

Depth measurements were taken using a SonTek M9 Hydrosurveyor instrument coupled with a Trimble R10 differential global navigation satellite system (DGNSS) antenna for position and elevation data (Figure 3-3). GNSS position and height data were collected for each depth point so that river surface and bed elevation could be calculated in Australian height datum (AHD). Minor variations in surface elevation readings through the various survey sections were post-processed to provide an averaged, uniform water surface elevation for each section from which riverbed elevations were recalculated. Only GNSS height data with a 2σ measurement uncertainty (95% confidence interval [CI]) of <0.030 m were used to produce the post-processed water elevation surface.

Figure 3-3. (a) Bathymetric survey equipment, and (b) survey of non-navigable areas.

Additional shallow area and above-water survey data were collected using DGNSS and range pole to better define non-navigable riffle sections and water's edge, and to establish bank gradients to provide additional context to channel geometry. A light detection and ranging (LiDAR) device was available for part of the Mentabie Reach survey allowing high-resolution topographic point data collection of the above-waterline bank and channel features. The resulting LiDAR point cloud combined with the bathymetric point cloud provides a far more detailed representation of the river edge and bank gradient, particularly in areas difficult to access using boat-mounted survey equipment, and too dangerous to manually stake out due to the presence of crocodiles in the survey area. Figure 3-4a shows the combined LiDAR and bathymetric survey point cloud for a section of the Mentabie Reach.

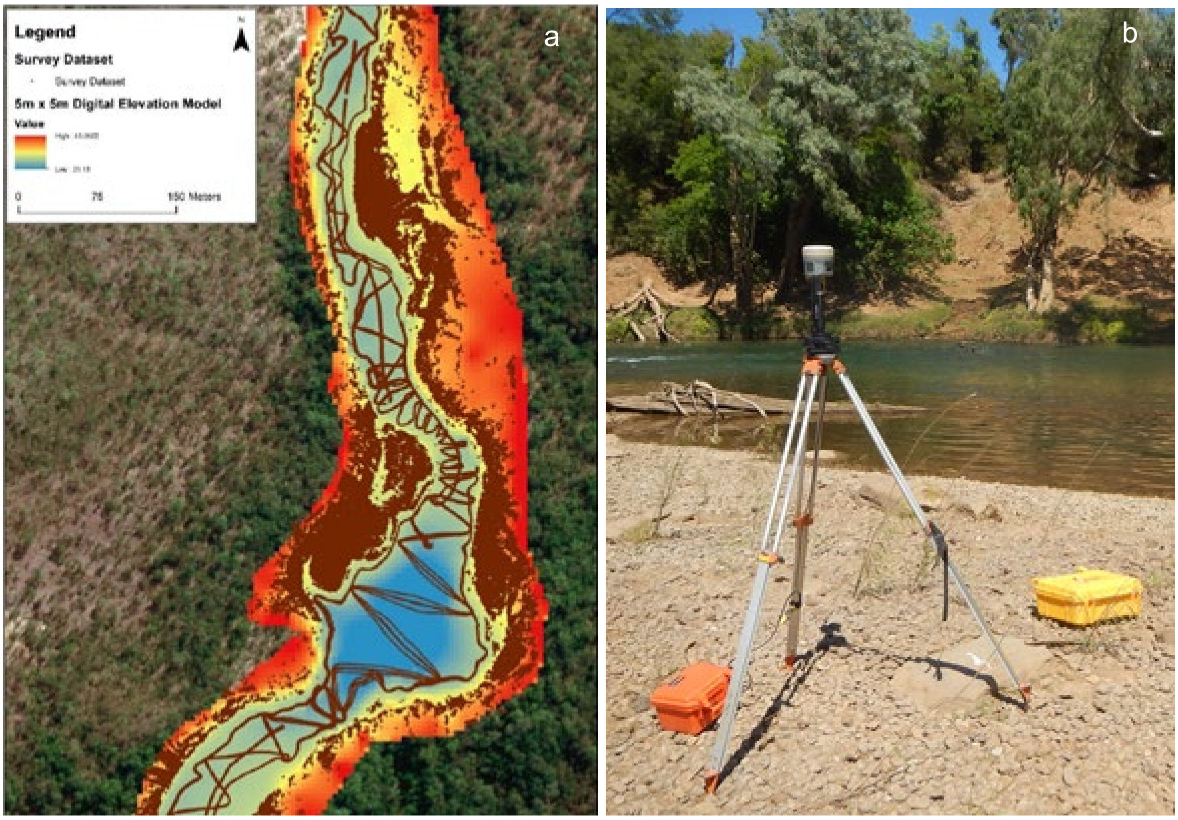

Figure 3-4. (a) Combined LiDAR and bathymetric point cloud, and (b) GNSS base station setup.

Survey control for the Wilden study area was provided by an established benchmark at a river gauging station located at the upstream end of the study area. Due to the remote location of the Mentabie study area and lack of survey control infrastructure, survey control was created through establishment of a series of benchmarks through the study area using GNSS precise point positioning (PPP). Position and elevation corrections were provided to the survey vessel from a base station set up over one of these benchmarks (Figure 3-4b). Inertial movements from the survey vessel were compensated for using the M9 Hydrosurveyor internal sensors.

All data was collected or uploaded into the HYPACK bathymetric software suite to process. Corrections to the depth measurement datum (water surface elevation) were applied to bathymetric datasets, data spikes and other spurious data were removed, and a continuous point cloud for each study location was produced. Point clouds were thinned for data processing and interpolation.

Qualitative data assurance was provided through the crossover pattern of overlaying transects to ensure consistent depth readings were recorded over common positions. Systemic data uncertainty from instrument movement/mounting inaccuracy was calculated using the instrument specifications and by reducing the effect of vessel instability when measuring depth of transducer deployment through repeatable readings. Vertical uncertainty due to variations in GNSS observations were managed through adoption of the mean observed antenna elevation and calculation of 95% CI values using only readings below the observation quality-control threshold of $\sigma < 0.015$ m (or $2\sigma < 0.030$ m). All riverbed levels were recalculated using the adopted antenna height for each section to ensure depth readings were calculated from the common GNSS elevation.

Overall relative accuracy of the point cloud data was calculated as being within +/− 0.100 m (Table 3-1) for bathymetric data points, while absolute accuracy is likely to be within the +/− 0.150–0.250 m range due to standard conversion uncertainty from the GNSS ellipsoid to AHD (provided by Geoscience Australia).

Table 3-1. Sources of measurement uncertainty.

Source of uncertainty	Magnitude of uncertainty
Control point position (PPP) = 2σ	+/− 0.050 m
95% CI for observed variability for adopted water surface level	+/− 0.080 m
Depth transducer precision	+/− 0.020 m
Ellipsoid to AHD conversion	+/− 0.100 m
Validation water-level measurement = 2σ	+/− 0.050 m

AHD = Australian height datum, PPP = precise point positioning

LiDAR data was registered into the horizontal (GDA94) and vertical (AHD) datum using surveyed reference points collected specifically for LiDAR registration using PPP, with calculated water surface elevation derived from the averaged GNSS measurements.

3.4 Hydrodynamic model development

A high-resolution hydrodynamic model was constructed for each study location using the RMA2 finite element modelling package (King 2006). RMA2 has been widely used to calculate water levels and flow distributions in waterways and floodplains for over 30 years. A series of in-stream low-flow scenarios were modelled for each study location to determine the impacts of reduced stream flows on preferred habitat availability for various study species. Full hydrodynamic modelling reports are shown in Appendix 2 and Appendix 3.

3.4.1 Wilden Reach

Bathymetric and DGNSS survey data for the Wilden Reach were processed in ArcGIS software to produce a 1.0 m × 1.0 m DEM over the 1.5 km long study area. A fine-resolution (~1.0 m) triangular mesh was developed through the model domain to represent localised channel features and riffles. The model was run in steady state (non-variable flow) conditions for each of the provided flow scenarios driven by a constant upstream flow boundary condition and constant downstream water elevation.

The main parameters applied to the model were eddy viscosity and bed friction. Eddy viscosity was set to 0.5 based on development of models for similar systems, while bed friction was applied using a Manning’s ‘n’ value of 0.030 for the main flow channel, 0.055 for vegetated overbank areas and 0.040 for riffle sections.

Modelled outputs were generated for each flow scenario at a 0.5 × 0.5 m grid resolution for water depth, velocities, bed shear and Froude number.

3.4.2 Mentabie Reach

Point cloud data from the bathymetric survey, LiDAR and DGNSS survey for the Mentabie Reach was processed in ArcGIS using the ‘Spline’ interpolation tool to generate a 5.0 × 5.0 m DEM of the 16 km long study area. A finite element mesh of <5.0 × 20.0 m was generated throughout the model domain to determine water elevations, depth and velocity over the constructed DEM during a series of low-flow scenarios. A global bed friction factor of Manning’s ‘n’ = 0.030 was used to represent channel roughness throughout the model. This is a mid-range value for natural slow-moving channels with deeper sections.

Significant groundwater contributions occur along the Mentabie Reach, which can more than double the river discharge between the modelled input and output boundaries. For the purpose of modelling, it was assumed that diffuse groundwater discharges occur evenly along the entire length of the modelled reach. Figure 3-5a shows groundwater inflows from a typical spring that occurs throughout the study area, while Figure 3-5b shows groundwater emerging from the riverbed. Different flow scenarios included either an average (mean) or low (10th percentile) scenario based on recorded groundwater inflow contributions to reflect periods of low groundwater recharge or over-extraction of groundwater.

Figure 3-5. (a) Typical spring along Mentabie Reach, and (b) in-stream groundwater contributions.

Modelled outputs were generated at a 1.0 × 1.0 m grid due to file size and overall DEM resolution being insufficient to justify the higher 0.5 × 0.5 m resolution. Outputs for each scenario included water depth, water surface elevation, velocity, Froude number and bed shear.

3.5 Model scenarios

3.5.1 Wilden

Ten flow scenarios were run through the Wilden model to test habitat parameters for the fish sooty grunter (*Hephaestus fuliginosus*) through the Wilden Reach. These ranged from 0.5 m^3/s to 12 m^3/s. Table 3-2 lists the flow scenarios tested for the Wilden model. All flow scenarios considered all water within the reach to be contributed through the upstream inflow boundary, with no groundwater or tributary contributions known to occur through the Wilden model domain.

*Table 3-2. Flow scenarios used for Wilden Reach. *Scenario 6 is the water level when fieldwork for juvenile sooty grunter habitat determination was conducted.*

Model reference scenario number	Upstream inflow (m^3/s)	Downstream water-level boundary
1	0.50	75.95
2	1.00	76.06
3	1.50	76.07
4	2.00	76.11
5	2.50	76.15
6	2.76*	76.18
7	4.00	76.27
8	6.00	76.40
9	8.00	76.51
10	12.00	76.70

3.5.2 Mentabie

Ten flow scenarios were also run through the Mentabie model to test habitat parameters for sooty grunter and the pig-nosed turtle (*Carettochelys insculpta)*. Table 3-3 shows the inflow boundary and groundwater contribution scenarios tested for the Mentabie model.

Table 3-3. Flow scenarios used for Mentabie Reach.

Model reference scenario number	Inflow at top of reach (m^3/s)	Groundwater inflow (m^3/s)	Outflow at the bottom of reach (m^3/s)
1	1.0	9.8	10.8
2	2.0	9.8	11.8
3	3.0	9.8	12.8
4	4.0	3.2	7.2
5	4.0	9.8	13.8
6	5.0	9.8	14.8
7	6.0	3.2	9.2
8	6.1	9.8	15.9
9	8.1	9.8	17.9
10	10.2	9.8	20.0

3.5.3 Model validation

Validation measurements were undertaken for the Wilden and Mentabie models in 2019 and 2020, respectively, after two poor wet seasons led to extreme low-flow conditions along the Katherine River, and to a lesser extent the Daly River. Collection of water elevations, cross-sections, velocity and flow measurements allowed some of the modelled scenarios to be confirmed against observed levels.

Validation measurements at Wilden Reach were taken when discharge was at 1.7 m^3/s, midway between Scenarios 3 and 4. Observed velocities and water levels were consistent with modelled outputs at all but one position. This was due to localised hydraulic complexities derived from rocks and in-stream features specific to that position. Overall, the modelled results were consistent with observed results and the model is considered to accurately represent conditions within the Wilden Reach for each of the modelled scenarios.

The Mentabie model was more difficult to validate due to the length of the reach and multiple flow inputs, including the upstream input boundary and groundwater inflows along the length of the reach. Representative scenarios were selected to match expected in-stream conditions at each validation location; however, the likelihood of both the hydrological and hydrogeological conditions matching the modelled conditions at the same time is low. As such, validation of the selected scenarios requires some interpolation to ensure validation results are compared to the most suitable modelled parameters at the validation location.

Further complication to validation of the Mentabie Reach model resulted from a significant flood event that occurred through the study area between the time of survey and time of validation measurements, potentially leading to discrepancies between observed and modelled results due to changes in river geomorphology. The Daly River is highly dynamic and this is possibly the reason for inconsistent water elevations for the upstream model input boundary. Figure 3-6 demonstrates changes at this location over a period from 2014 to 2017.

Figure 3-6. (a) Modelled upper riffle in Mentabie Reach showing the modelled outputs overlaying a pre-September 2014 satellite image of the area; (b) The large sandbank that had established at the same location by 2017 when the bathymetric work was undertaken.

In Figure 3-6a, modelled depths are overlaid on a satellite image taken prior to September 2014. The modelled output reflect the river channel in 2017 when the bathymetric survey was performed, although the imagery shows a different wetted area in the channel. Figure 3-6b shows the sandbank at the time of the bathymetric survey in 2017, demonstrating the highly dynamic nature of the study area over 4 to 5 years.

Validation measurements for the Mentabie model, including observed water elevations, depth and velocity measurements, were collected along with total flow. Measured flow at the upstream end of the model was 7.0 m^3/s, resembling Scenario 8, while downstream flow was 12.9 m^3/s, resembling Scenario 3. The groundwater contribution of 5.9 m^3/s was between the average and lower groundwater inflow scenarios modelled. Scenario 5 was considered to most accurately represent conditions through the middle of the Mentabie Reach at the time of validation measurements.

Water elevation measurements were undertaken using GNSS PPP and incur a measurement uncertainty of +/− 0.050 m, putting cumulative uncertainty between surveyed water elevations and verification water elevations at up to +/− 0.180 m. Modelled water elevations throughout the Mentabie Reach were generally within the expected uncertainty of surveyed water elevations (white and green shading in Table 3-4), with the exception of modelled elevations being notably higher at the model input boundary and uppermost riffle section (up to 0.260 m higher than surveyed), and the model output boundary and lowest modelled riffle section at Black Bull Yard (0.8 m higher than surveyed at the output boundary). A comparison of modelled versus observed parameters for several validation locations is shown in Table 3-4.

Table 3-4. Validation checks of Mentabie model at [1] Downstream Black Bull Yard riffle, [2] 500 m upstream Black Bull Yard, [3] Riffle upstream Stray Creek, [4] Cross-section 1 Pool 4, [5] Upstream Hill Spring, [6] 125 m downstream of Top of Mentabie Reach, [7] Upstream Mentabie Reach. Red shading indicates where observed validation parameters did not match modelled parameters well, green shading indicates where observed validation parameters were a very good match with modelled, and white shading is where observed and modelled values were around the uncertainty limit (and therefore are acceptable values).

Scenario	Mentabie model			Observed validation			Bathymetric survey
	Water elevation (mAHD)	Maximum depth (m)	Mean velocity (m/s)	Water elevation (mAHD)	Maximum depth (m)	Mean velocity (m/s)	Minimum bed elevation (mAHD)
3[1]	33.20	1.30	0.1	32.43	–	–	31.3
3[2]	33.26	0.83	0.43	33.24	0.84	0.39	32.5
5[3]	33.90	0.48	1.60	34.00 (est.)	0.47	1.35	33.5
5[4]	34.60	1.68	0.14	34.50	3.75	0.16	32.0
5[5]	35.50	1.16	0.27	35.22	1.42	0.23	33.7
8[6]	35.90	0.83	0.50	35.64	1.79	0.52	32.8
8[7]	35.95	1.47	0.08	35.69	–	–	35.1

mAHD = metres above Australian height datum, DS = downstream, est. = estimate, US = upstream

The upstream anomaly appears to be largely due to geomorphological changes to the unstable sandbar and channel during the 2018 flood event as modelled water elevations for Scenario 10 correspond well to discharge and water elevation measured at the time of the bathymetric survey at the input boundary. The use of a global roughness value rather than attributing localised roughness values to different stream sections may also be a contributing factor. The downstream anomaly appears to be largely governed by a common output water elevation that was the same for every model scenario (33.2 m) and was significantly higher (0.4 m) than the measured water elevation at the time of the bathymetric survey.

Despite these exceptions, modelled water depths and velocities were a good match for validation measurements throughout the modelled reach. Validation measurements taken

500 m upstream of the Black Bull Yard riffle matched the modelled outputs very well. A significant riffle upstream of Stray Creek (5^3) was well represented by the model, despite the riffle being difficult to measure due to poor GNSS reception and water depths being below the measurement range of the instrument (0.25 m) for much of the transect. During the validation survey, depths along the transect were no greater than 0.5 m at their deepest point and typically 0.2 m along most of the transect, with measured maximum measured water velocity of 1.5 m/s.

Scenarios 5^4 and 5^5 are representative of average conditions along most of the Mentabie Reach where riffles and controls have less influence on the river. The measured parameters collected during the validation surveys demonstrate that the model accurately represents observed conditions. The modelled bed elevation discrepancy for Scenario 5^5 is most likely an artefact of the changed geomorphology due to the 2018 flood event.

3.6 Results and discussion

Results from the modelled reaches are provided as a series of high-resolution gridded spatial overlays. Each flow scenario resulted in five overlays, including water elevation, water depth, water velocity, bed shear stress and Froude number. These outputs effectively describe the hydraulic conditions for each grid unit across the entire study area for each scenario modelled.

Validation measurements of the various modelled outputs from the Wilden model show water velocities and depths are consistent with those observed during the validation surveys. In particular, riffle sections are well represented for depth and velocity relative to pool sections, with associated parameter values reflecting both observed and expected values. Similarly, Mentabie Reach validation depths and velocities through riffles are consistent with those observed during the surveys (with the exception of the lower Black Bull Yard riffle), and are well represented relative to pool sections. Modelled parameter values correlate well to observed and expected values throughout the model. While water elevations are not always well represented in the model, water depth and velocity are typically well represented and are the key determinants for habitat suitability.

The downstream riffle at Black Bull Yard appears to be significantly affected by the standard model output water elevation condition, which is the same for every modelled scenario, and is 0.4 m higher than the observed water level during the bathymetric survey, when observed flow was greater than that of any of the modelled scenarios. While depths through the Black Bull Yard riffle are well represented, water velocities are lower than observed. Additionally, the modelled channel through Black Bull Yard riffle is wider than surveyed, probably due to incorrect linking of survey points during creation of the DEM. Other limitations with both models include the assumption that water velocity is the same at the surface and the bed. In fact, the velocity profile varies throughout the depth range, with average velocity typically found at 0.6 × water depth. In an open channel, water velocity at the surface is greater than that in the bottom half of the water column and, as such, it is likely that surface velocity is greater than, and bed velocity is less than, the average velocities calculated in the model results. The stated water velocity for each grid is the average velocity and is considered a reasonable approximation of water velocity throughout the water column.

Despite the model limitations and some concern about the adequacy of a global roughness parameter used to describe the entire Mentabie Reach, model results from both models are considered to be a very good representation of hydraulic conditions within the study areas, particularly for water depth and velocity which are the key parameters for habitat suitability. Validation measurements of selected scenarios demonstrate the approach taken for data collection and model development resulted in accurate model scenario runs, and the models are suitable for the assessment of habitat parameters under the differing flow conditions. It is acknowledged that geomorphological conditions within the river will change over time, with the model becoming less representative of the physical conditions within both the Wilden and Mentabie reaches. Nevertheless, the modelled conditions should be considered indicative of normal conditions within the river, and the utility of the modelled outputs should be considered valid for the near to medium term unless significant changes occur within the catchment.

By developing hydrodynamic models that realistically represent physical parameters such as water depth and velocity under different flow scenarios, robust testing of the impacts of flow reductions (including from water extraction) on those parameters can be undertaken. When cross-referenced with the eco-hydrological habitat requirements of aquatic species, expected impacts of flow reductions on those species can be determined. This provides a methodology to test the direct impact of flow reductions on aquatic species for individual waterways or waterway reaches.

Establishing the eco-hydrological requirements of key ‘umbrella’ species, and modelling the incidence of those parameters under various flow scenarios, can support water planning initiatives by establishing impacts-based flow thresholds to guide environmental flow determinations. High-resolution hydrodynamic modelling allows expected impacts of reduced flows on fish abundance and species assemblages to be assessed, resulting in a science-based approached to water management.

4. Dry-season habitat use by fishes and their vulnerability to water extraction

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4.1 Background

Riverine fish are closely associated with physical habitat attributes at a range of spatial scales, which can vary considerably within and between reaches and river systems (Grossman et al. 1998; Webb et al. 2011). For example, water depth and flow velocity are hypothesised to be important factors influencing habitat use by fishes, along with other physical attributes such as substrate composition, submerged vegetation, and wood and root masses (Gorman & Karr 1978; Jowett 1993; Jackson et al. 2001). Alterations to river flow (whether natural or artificial) can affect the availability of habitat quantity and quality, and in turn influence fish species composition (assemblage), distribution and abundance.

In the wet-dry tropics of northern Australia, the effect of flow on habitat is particularly evident at the end of the dry season, when water levels are at their lowest and factors such as competition and predation can strongly influence the resulting fish community structure (Magoulick 2000; Pusey et al. 2018). The combination of persistent, predictable flows and habitat complexity are thought to be important in promoting and maintaining species specialisation and diversification in tropical rivers (Gorman & Karr 1978; Willis et al. 2005; Rayner et al. 2008). However, knowledge of fish habitat requirements across northern Australia is sparse, and therefore our ability to predict likely outcomes of changed water discharge scenarios and how they might influence fish habitat availability is limited.

4.2 Aims and objectives

This project component aimed to:

1. determine the dry-season habitat use by freshwater fishes in the Daly River, using a data-rich, multi-year dataset to quantify fish–habitat associations during the dry season
2. predict the change in area of suitable habitat available for fishes at two reaches representative of the Katherine River (Wilden Reach) and Daly River (Mentabie Reach) under various dry-season discharge scenarios.

4.3 Methods

Methods for the first aim are described in detail in Keller et al. (2019) but are briefly described here. We used fish abundance data collected using electrofishing, from surveys at six sites from Katherine township to Oolloo Crossing, conducted biannually (early and late dry season) over a 10-year period (2006–2015). At each sampling point, fish habitat characteristics within the area of fishing location were quantitively described.

A total of 22 taxa, with six taxa separated into juvenile and adult life stages, were prevalent enough in our data for further analysis of their habitat use, resulting in 54,739 taxa–habitat data points. Fish habitat variables were assessed for their potential to influence the abundance of each fish taxon across electrofishing shots using boosted regression trees (BRTs). For each taxon, partial dependence functions were fitted for the top two most influential variables to visualise relationships between fish abundances and each variable. Hierarchical cluster analysis with complete linkage distance was also used to group fish taxa abundance and habitat variables into habitat guilds.

We utilised the taxa-specific partial dependence plots from the BRT modelling to assess the change in suitable habitat available for each taxon with various water scenarios at the two modelled hydrodynamic reaches (see Section 3). Only taxa that had either depth or velocity identified as the first- or second-most important contributing variable following the BRT analyses (see Keller et al. 2019) were used in this analysis. We assessed the partial dependence plot for each taxon and developed habitat selection criteria for each (Table 4-1). These habitat suitability criteria were then used to query and extract the amount of suitable habitat available for each taxon at each water-level scenario from the Wilden and Mentabie hydrodynamic model reaches (Table 4-2, Table 4-3; also see Section 3). Plots were then created to describe the change in suitable habitat available for each taxon relative to base water scenarios (e.g. average dry-season flow or existing environmental flow rules).

Table 4-1. Habitat suitability criteria for each taxon, determined from the partial dependence plots of Keller et al. (2019). J = juvenile, A = adult, – parameter not important in models. Note that some taxa in Keller et al (2019) were not used here as velocity and depth were not important predictors of habitat use.

Scientific name	Common name	Velocity (cm/s)	Depth (cm)
Amniataba percoides	Barred grunter	–	20–130
Craterocephalus stercusmuscarum	Flyspecked hardyhead	–	>230
Craterocephalus stramineus	Blackmast	0–30	0–30
Glossamia aprion	Mouth almighty	–	60–130
Glossogobius spp.	Gobies	–	0–85
Hephaestus fuliginosus	Sooty grunter (J)	>45	0–80
Hephaestus fuliginosus	Sooty grunter (A)	–	>90
Lates calcarifer	Barramundi (J)	–	>80
Lates calcarifer	Barramundi (A)	–	>100
Leiopotherapon unicolor	Spangled perch	–	0–90
Planiliza ordensis	Diamond mullet	–	>80
Melanotaenia australis	Rainbowfish	0–30	>95
Mogurnda mogurnda	Northern trout gudgeon	0–15	0–40
Neoarius spp.	Forktailed catfish	>25	–
Neosilurus ater	Black catfish	–	>80
Nematalosa erebi	Bony bream	–	>75
Oxyeleotris lineolata	Sleepy cod (A)	0–35	–
Strongylura krefftii	Longtom	–	>75
Syncomistes butleri	Butler’s grunter (J)	>50	–
Syncomistes butleri	Butler’s grunter (A)	0–75	>75
Toxotes chatareus	Sevenspot archerfish	–	>90

*Table 4-2. Model hydrology scenarios used in Wilden Reach hydrodynamic modelling using upstream inflows at Wilden gauge, Katherine River. *Scenario 6 used as base water scenario, because 2.76 cumecs was the discharge when the juvenile sooty grunter tracking study was being undertaken (see Section 3) and is also within the band described as 'average conditions' for use in announced allocations for the Katherine Tindall Limestone Aquifer Water Allocation Plan 2019–2024 (modelled natural flow conditions [2.1–2.9 cumecs] at 1 November) (Northern Territory Government 2019a).*

Scenario number (Appendix 2)	Upstream inflow (cumecs)	Justification
1	0.50	Extreme scenario
2	1.00	
3	1.50	
4	2.00	
5	2.50	0.5 cumec intervals down from modelled average
6	2.76	*Base water scenario: Represents average modelled natural flow on 1 November
7	4.00	
8	6.00	
9	8.00	
10	12.00	Extreme scenario

*Table 4-3. Model hydrology scenarios used in Mentabie Reach hydrodynamic modelling using upstream inflows at Claravale Crossing gauge, Daly River. *Scenario 8 used as base water scenario, as it is the current environmental flow threshold at Claravale gauge based on research of pig-nosed turtles (Erskine et al. 2003, 2004). Rule is water extractions should not exceed >8% discharge when flows <6.2 cumecs, and 20% when >6.2 cumecs. #Low groundwater scenarios not used in this analysis (Northern Territory Government 2019b).*

Scenario number. (Appendix 3)	Upstream inflow at Claravale (cumecs)	Groundwater inflow scenario (cumecs)	Outflow at bottom of modelled reach (Theyona gauge, cumecs)	Justification
1	1.0	9.8	10.8	Extreme scenario, half of lowest observed flow
2	2.0	9.8	11.8	1 cumec intervals down from previous threshold
3	3.0	9.8	12.8	1 cumec intervals down from previous threshold
4	4.0	3.2	7.2	1 cumec steps for flows below threshold with low groundwater levels#
5	4.0	9.8	13.8	1 cumec steps for flows below threshold, with average groundwater input levels
6	5.0	9.8	14.8	1 cumec steps for flows below threshold
7	6.1	3.2	9.2	1 cumec steps for flows below threshold with low groundwater input levels
8	6.1	9.8	15.9	*Base water scenario. At average groundwater input levels. Represents current environmental flow threshold at Claravale
9	8.1	9.8	17.9	2 cumec steps above threshold
10	10.2	9.8	20.0	90th percentile of annual minimum dry-season flows (1960–2019). Higher flows are not relevant to the project

4.4 Results

4.4.1 Habitat use by fishes

Twelve habitat variables were identified as the top two most important contributors to the BRT models for all taxa analysed. Water depth was the top habitat contributor variable for 16 taxa, while velocity was the second-most important variable, occurring as one of the top two contributors for 12 taxa (Figure 4-1). Six taxa (*L. unicolor*, juvenile *H. fuliginosus*, *M. mogurnda*, juvenile *O. selheimi*, *C. stramineus*, *Glossogobius* spp.) were most abundant in shallow habitats (0–100 cm, while *C. stercusmuscarum* and *P. ordensis* were more likely to occur in deeper habitats (>200 cm), with the remainder abundant in moderate to deep habitats. Taxa that were most abundant in low-velocity habitats (0–30 cm/s) included adult *O. lineolata*, *C. stramineus*, *G. aprion*, *M. australis*, *M. mogurnda*, *T. chatareus* and adult *S. butleri*, while juvenile *H. fuliginosus* and *P. ordensis* were most abundant in fast-flowing habitats (>90 cm/s). The remaining taxa, juvenile *S. butleri*, *N. ater* and *Neoarius* spp., were most abundant in habitats with moderate to high velocities (30–90 cm/s). Submerged wood, root mass, leaf litter, rock, sand, fine gravel, coarse gravel, bedrock, filamentous algae and overhanging vegetation were the next most important contributors.

Analysis of fish–habitat relationships revealed four distinct habitat-use guilds (Figure 4-2; Keller et al. 2019), comprising:

Guild I: fishes occupying deep pools containing root masses and undercut banks (juvenile and adult *O. lineolata* (sleepy cod), *M. australis*, *G. aprion*, adult *S. butleri*, *N. erebi*, *N. ater*, *Neoarius* spp. and *T. chatareus*)

Guild II: large-bodied fishes occupying deep pools containing wood (juvenile and adult *L. calcarifer*, adult *H. fuliginosus*, adult *O. selheimi*, *S. krefftii* and *P. ordensis*)

Guild III: a mixed habitat-use guild of small-bodied fishes (*L. triramus* (freshwater sole), *M. mogurnda*, *C. stercusmuscarum*, juvenile *O. selheimi*, *C. stramineus* and *A. percoides*)

Guild IV: small-bodied fishes occupying shallow riffles with high water velocities and coarse substrates (juvenile *H. fuliginosus*, juvenile *S. butleri*, *Glossogobius* spp. and *L. unicolor*).

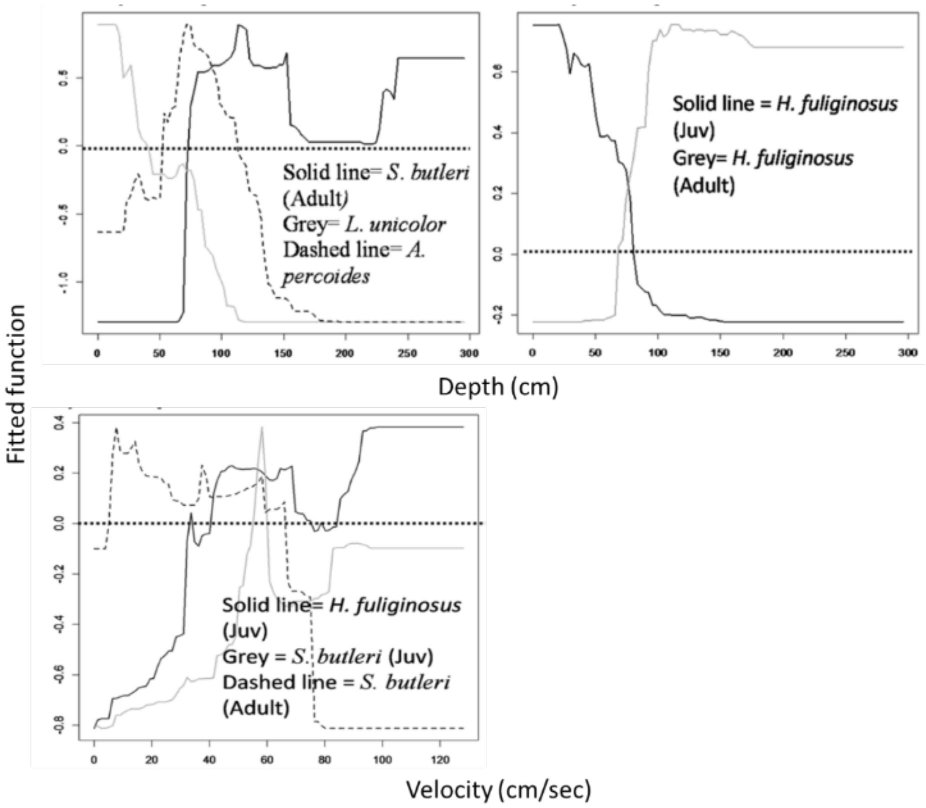

Figure 4-1. Examples of partial dependence plots showing relationships between taxa abundance and habitat use for depth (top) and velocity (bottom) for Terapontidae species. See Keller et al. (2019) for more detail and other taxa–habitat use plots.

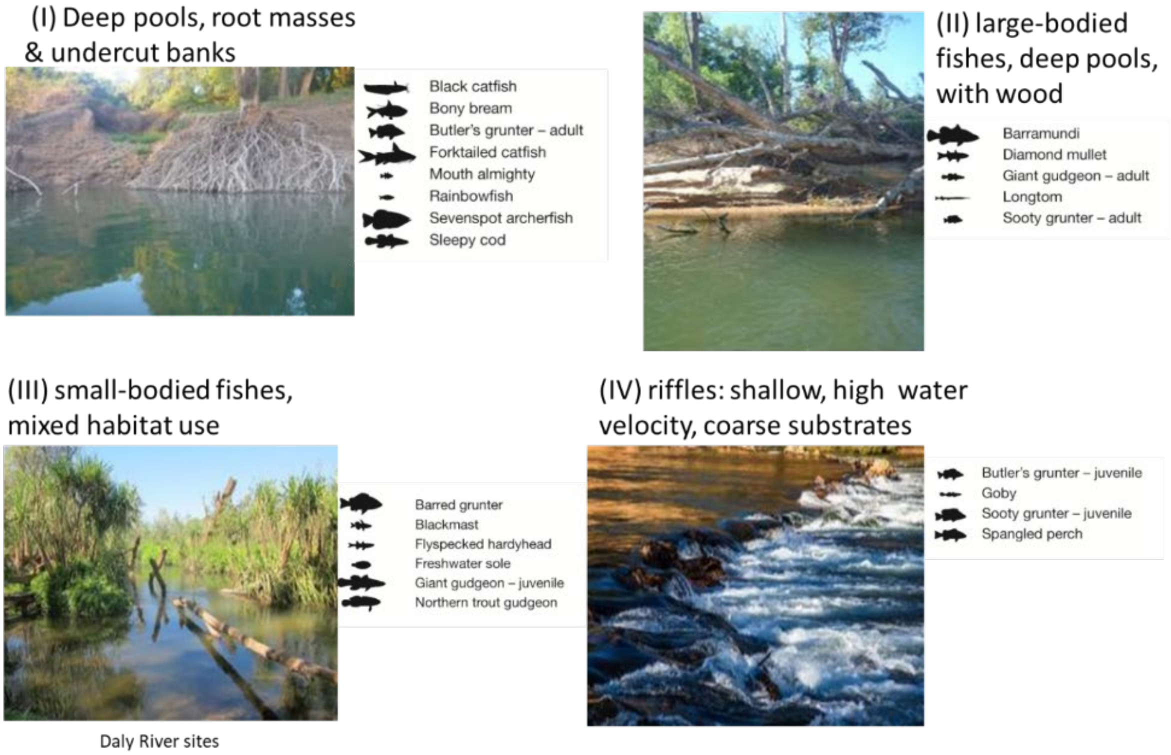

Figure 4-2. Pictorial representation of four fish habitat guilds in the Daly River fish assemblage determined using cluster analysis (see Keller et al. [2019] for further details).

4.4.2 Optimal habitat availability with various water scenarios

Water depth and velocity were important habitat descriptors for 18 species in the dry season (Table 4-1).

At the Wilden Reach, declines in dry-season water discharge (relative to the average dry-season low-flow discharge [2.8 cumecs]) reduced suitable habitat area for 10 taxa with depth habitat preferences (*C. stercusmuscarum, N. ater,* juvenile and adult *L. calcarifer*, *M. australis, T. chatareus, S. krefftii,* juvenile and adult *H. fuliginosus*, *Glossogobius* spp., adult *S. butleri*, *N. erebi*), and for three taxa with velocity preferences (*Neoarius* spp., and juvenile *H. fuliginosus* and *S. butleri*) (Figure 4-3). Water discharge scenarios resulted in little or no change in habitat area for some species (depth preference: *A. percoides, C. stramineus, M. mogurnda, G. aprion, L. unicolor*; velocity preference: *C. stramineus, M. mogurnda, M. australis,* adult *O. lineolata,* adult *S. butleri*). The greatest predicted loss of suitable habitat with declining discharge scenarios occurred for *Neoarius* spp., and juveniles of *H. fuliginosus* and *S. butleri*. Substantial declines of suitable habitat occurred for *C. stercusmuscarum* and juvenile *H. fuliginosus* and *S. butleri* with discharge <2 cumecs.

At the Mentabie Reach, the predicted change in suitable habitat area declined for 10 taxa with depth preferences (*G. aprion*, juvenile and adult *L. calcarifer*, adult *H. fuliginosus, S. krefftii, P. ordensis*, adult *S. butleri, N. erebi, N. ater, M. australis, C. stercusmuscarum*) with lower-water-level scenarios below the current environmental flow rule of 6.2 cumecs (Figure 4-4). This group of species were mostly large-bodied species with deeper water habitat requirements. For example, the amount of habitat suitable for adult barramundi (*L. calcarifer*) declined by nearly 20% at the lowest-water-level scenarios. Conversely, there was an increase in suitable habitat available for other species with shallow water preferences (i.e. *T. chatareus, L. unicolor, Glossogobius* spp., juvenile *H. fuliginosus, C. stramineus, M. mogurnda*). There were only eight taxa with specific velocity requirements, with four taxa (adult *O. lineolata, M. australis, C. stramineus*, adult *S. butleri*) demonstrating no change in availability of suitable habitat with decreasing water levels (Figure 4-4b). Three taxa had major declines in suitable habitat area related to velocity preferences, with the area of suitable habitat available for juveniles of both *S. butleri* and *H. fuliginosus* dropping by >40% at discharges <4 cumecs.

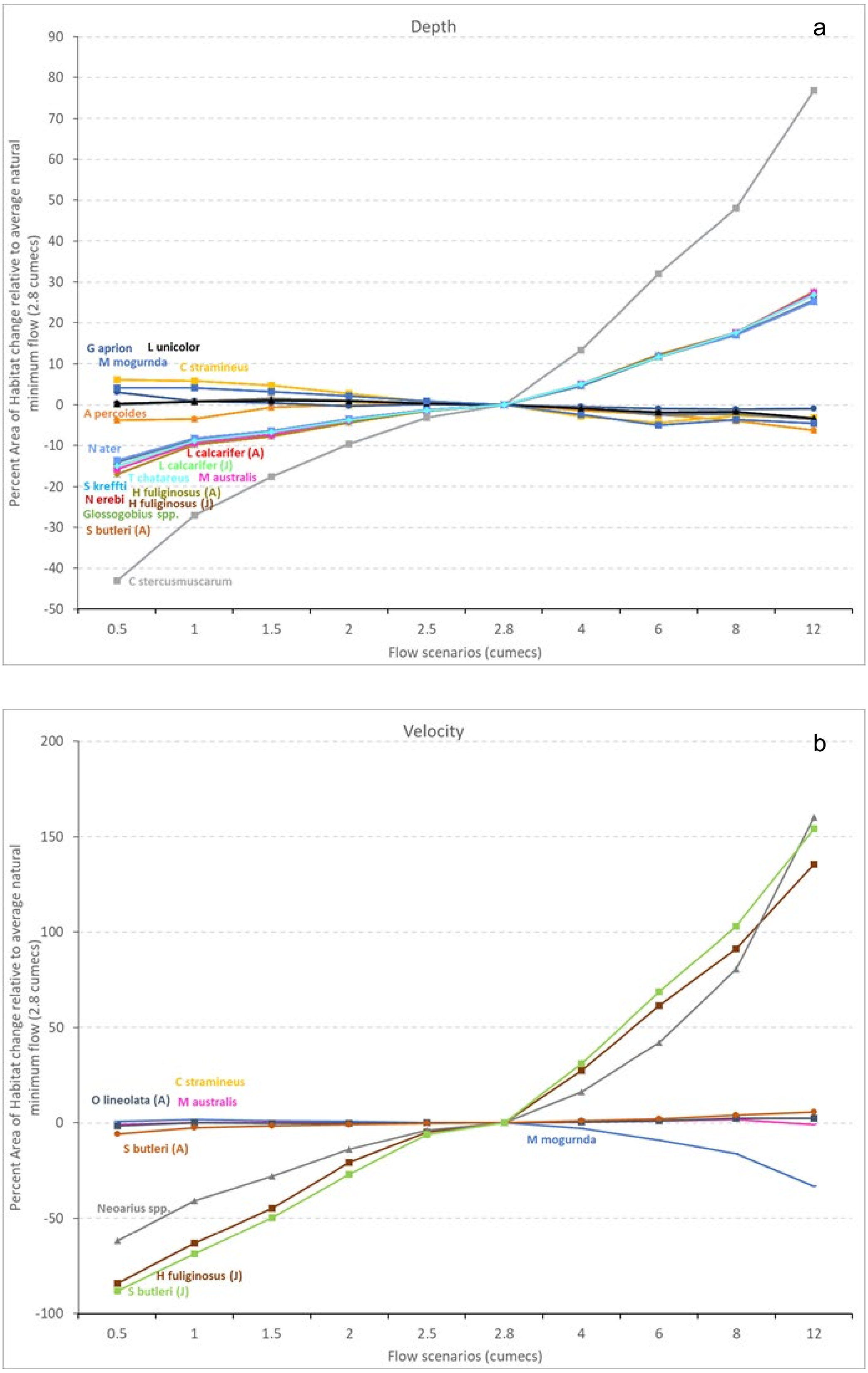

Figure 4-3. Predicted change in area of suitable habitat for various water scenarios at Wilden Reach, Katherine River (see Table 4-2) using (a) depth and (b) velocity preferences for 18 species of fish. Percent change in available habitat area calculated relative to average natural flow on 1 November (2.8 cumecs) (Northern Territory Government 2019a).

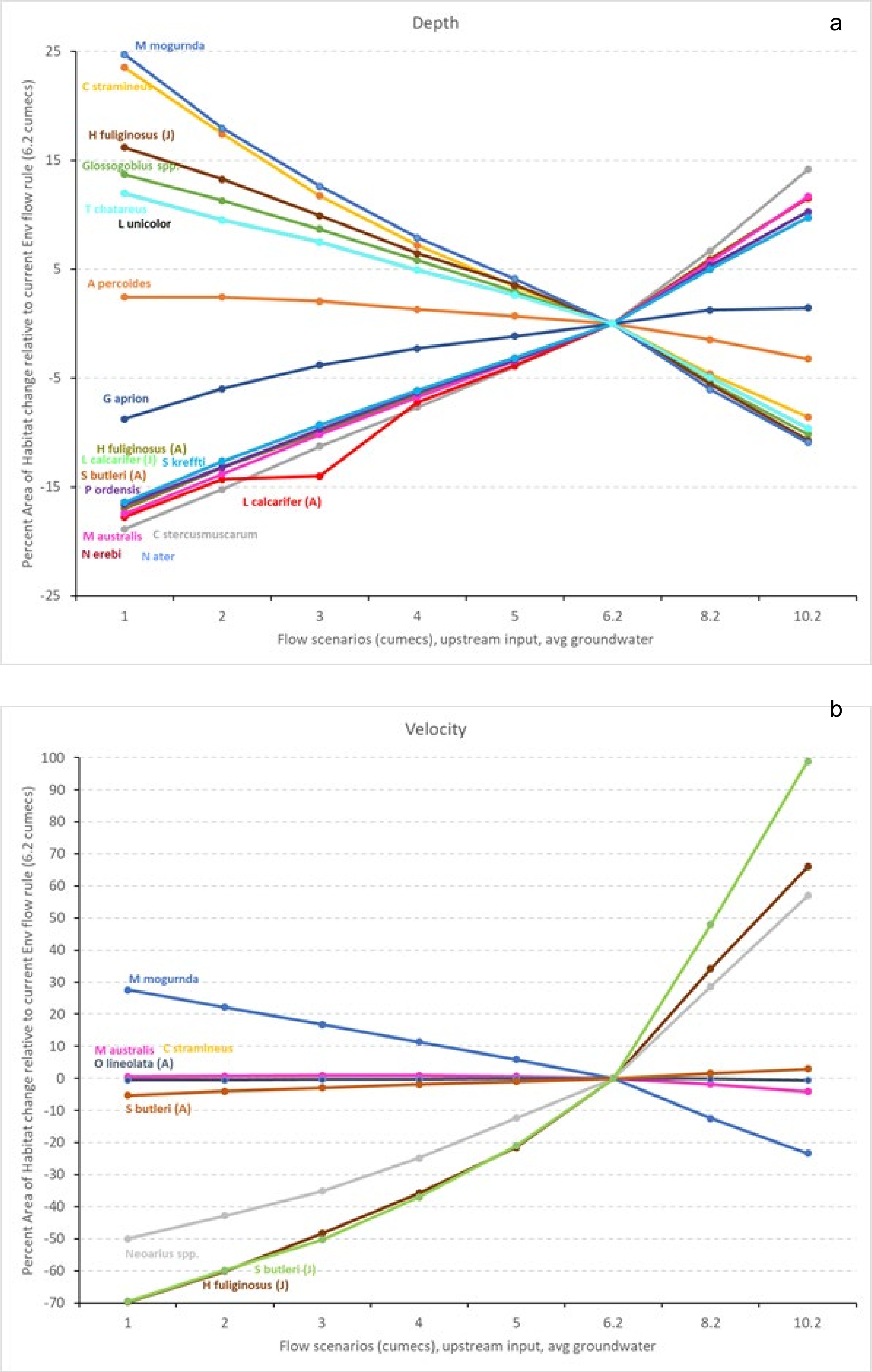

Figure 4-4. Predicted change in area of suitable habitat for various water scenarios at Mentabie Reach, Daly River (see Table 4-3) using (a) depth and (b) velocity preferences for 18 species of fish. Percent change in available habitat area calculated relative to current environmental flow rule (6.2 cumecs) using average groundwater levels.

4.5 Discussion and key findings

The patterns of habitat use revealed in this study significantly improve our understanding of the habitat requirements of a range of fish taxa during the dry season in northern Australian rivers. The study quantified fish–habitat use associations for a large number of common taxa in the region and identified four distinct habitat-use guilds (Keller et al. 2019; Figure 4-5). The diversity of habitats utilised by fish highlights the importance of maintaining flows during the dry season and habitat complexity in this important river system. While a range of habitat variables were important descriptors of habitat for taxa, unsurprisingly water depth and velocity were key factors influencing dry-season habitat use by fish (Keller et al. 2019).

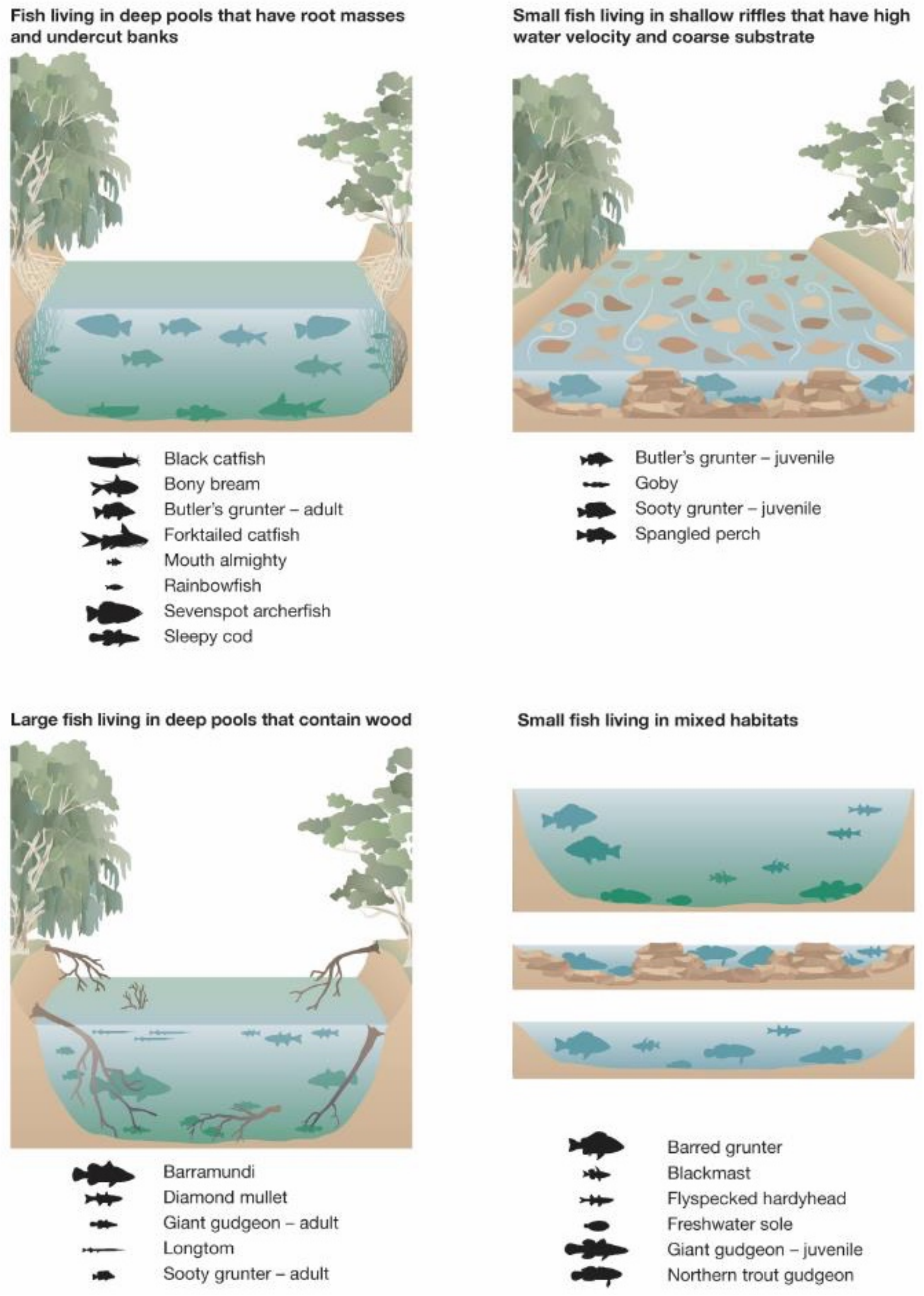

Figure 4-5. Conceptual diagram of four fish habitat guilds in the Daly River.

We used the generated habitat suitability criteria for depth and velocity for 21 taxa/life stages to predict the change in suitable habitat under scenarios using hydrodynamic models in our two reference reaches (Wilden and Mentabie). Our findings suggest that not all species will be affected by a change in dry-season water discharge; however, a reduction in dry-season flows will reduce the amount of suitable habitat area available for some species, and will have a larger impact on species with strong associations with higher velocity flows and shallower depths.

Three taxa – *Neoarius* spp. and juveniles of *S. butleri* and *H. fuliginosus* – were predicted to have major declines in suitable habitat area with decreasing flow conditions in both reaches. In the Wilden Reach, >20% loss of suitable habitat occurs for these species and *C. stercusmuscarum* at flows <2 cumecs (Wilden gauge). In the Mentabie Reach, >20% loss of suitable habitat occurred below 5 cumecs (Claravale gauge) for *Neoarius* spp. and juveniles of *H. fuliginosus* and *S. butleri*. All other species were predicted to experience either only marginal declines or no change in suitable habitat at lower discharges or, in a few cases, an increase in suitable habitat.

Chan et al. (2012) previously incorporated fish–habitat relationships in predictions of the impact of reduced flows in the Daly River on barramundi and sooty grunter population abundance. They reported some impacts of dry-season water extraction on both species, particularly for juvenile sooty grunter, due to the amount of suitable riffle habitat declining. This study and the research described in Section 6 of this report confirm that juvenile sooty grunter are likely to be highly affected by water-level declines that result in reduction in suitable available habitat for the species. However, in using this approach, we suggest this outcome is also likely to be true for *S. butleri* and, to a lesser extent, *Neoarius* spp.

The fish–habitat associations described allow scientists and managers to explore and predict habitat availability for the protection and conservation of critical habitats for fish. The fish habitat guild approach is useful in summarising and simplifying communication of fish habitat-use requirements to managers and the broader community.

5. Dry-season food web of the Katherine and Daly rivers

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5.1 Background

Previous broadscale studies of food webs in wet-dry tropical rivers have shown that while stable isotope ratios of benthic invertebrates are generally tightly coupled to local in-stream sources of primary production (biofilms), those of fish are often less well-linked to local sources, especially in rivers with a long duration of floodplain inundation (Jardine et al. 2012a,b; Warfe et al. 2013).

In the Katherine and Daly rivers, the extreme seasonal flow patterns alternate between wet-season floods and sustained dry-season baseflows. In the wet season, the drainage network is predominantly connected as a single system from its headwaters to its coastal floodplain. In contrast, during the dry season most low-order streams and some higher-order rivers cease to flow, riparian billabongs become isolated and the river's floodplain drains to retain no water. Dry-season flow is groundwater-fed and limited to the main channel of the Daly and Katherine rivers and major tributaries that lie within the Daly groundwater basin.

This highly seasonal and spatial pattern of flow, connectivity and floodplain inundation is reflected in a corresponding pattern of primary production. Potential food sources for the Daly River are algae and aquatic vegetation from the floodplain (wet season only) and from the river channels (mainly during the dry season for high-order rivers), as well as inputs from terrestrial vegetation and marine sources that are available all year. During the wet season, fish are highly mobile and utilise external resources originating from floodplain and marine production where there is hydrological connectivity to those habitats. Dry-season food webs are likely to rely more heavily on internal sources of primary productivity.

Dry-season primary productivity in the Daly River is linked to flow regimes and the hydraulic environment (e.g. Rea et al. 2002; Townsend & Padovan 2005; Townsend et al. 2017). Reductions in dry-season flows caused by increased groundwater extraction for consumptive use and the associated hydraulic impacts, such as a decrease in wetted rapid and riffle areas and a reduction in current speeds, are likely to impact primary production and food webs through changes in the extent and distribution of available habitat.

5.2 Aims and objectives

This project component aimed to:

1. develop a dry-season food web model for the Daly and Katherine rivers and identify key sources of primary production supporting invertebrates and fishes at two sites in the Daly River catchment, at a higher resolution than was achieved previously
2. assess the dependency of the dry-season food web on river (main channel) and other, external carbon sources
3. infer the potential impact of anthropogenically reduced dry-season flows on the river's dry-season food web.

5.3 Methods

The dry-season food web of the Daly and Katherine rivers was modelled using stable isotope ratios for carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$), from a range of primary producers and consumers.

Samples of all available local in-stream production sources and consumers were collected from two sites, Galloping Jack's on the Katherine River and Oolloo Crossing on the Daly River, over the dry seasons of 2016 and 2017. Production sources included seston (particles suspended in the water column, including algae), biofilms (microscopic algae growing on submerged rocks [epilithon], sand [epipsammon], wood [epixylon] and plants [epiphyton]), filamentous macroalgae (*Spirogyra* spp., charophytes, blue-green algae, red algae), emergent and submerged aquatic vegetation, and leaf litter, all of which (except leaf litter) were classed as internal sources. Consumers included a range of aquatic insects, molluscs, shrimp and fish. Table 5-1 gives an overview of sample collection dates. All samples were processed and analysed according to protocols described in detail in Jardine et al. (2012a).

Juvenile fish from the Daly River floodplain were collected in March 2020 to represent stable isotope values for floodplain resources. The use of primary consumers to determine a baseline for an entire habitat allows the integration of spatial and temporal variations in primary producers of that habitat (Jardine et al. 2017). Stable isotope values for savanna vegetation and coastal marine habitats were obtained from a previous study (Jardine et al. 2017). Data for these latter, external sources of production were drawn from sampling done at Kakadu National Park.

Both $\delta^{13}C$ and $\delta^{15}N$ were used to examine source proportions for consumers. For the model, sources were combined when they were related both taxonomically and isotopically (Phillips et al. 2005). This resulted in a 12-source model for Oolloo Crossing and an 11-source model for Galloping Jack's. Mixing models were run in the program MixSIAR (Stock et al. 2018), which provides posterior distributions of potential source contributions to the diet of consumer species.

Table 5-1. Sample collection dates (indicated with an X) for stable isotope analysis.

	2016				2017				2020
Taxon	Jul	Aug	Sep	Oct	Jun	Aug	Sep	Oct	Mar
Fish (river channel)				X	X			X	
Fish (floodplain)									X
Macroinvertebrates	X	X	X		X	X	X		
Biofilm	X	X	X		X	X	X		
Macroalgae	X	X	X		X	X	X		
Emergent and submerged macrophytes	X	X	X		X	X	X		
Riparian vegetation			X				X		
Seston						X	X		

5.4 Results and discussion

The dry-season diets of invertebrate species at both study sites were predominantly based on internal sources of production. The macroalga *Spirogyra* contributed substantially to invertebrate diets at both sites, as did charophytes (Daly River), and the submerged macrophyte *Blyxia* and red algae (Katherine River). Most invertebrate species had contributions from these sources of between 20% and 60% (Table 5-2, Table 5-3), with consistent patterns between the two sites. Only Hemipterans had a lower than 10% contribution from algal sources. Leaf litter never contributed more than 10% to invertebrate diets.

External food sources were negligible for most invertebrate taxonomic groups, except for Pleidae that fed on resources from the surrounding savanna (33–47%; Table 5-2, Table 5-3, Table 5-4), and Palaemonid prawns and Cherabin that showed evidence of marine organic matter in their tissues (Table 5-2, Table 5-3, Table 5-5).

Fishes used significantly more external sources than did invertebrates (Table 5-5, Table 5-6), consistent with earlier work by Jardine et al. (2017). Barramundi, catfishes and some of the grunters at both sites used significant proportions of marine sources (20–25%), while archerfish and sleepy cod had a large proportion of terrestrial sources in their diets (~30%; Table 5-2, Table 5-3).

For macroinvertebrates, the proportions of internal and external resources were similar at both sites, while overall, fish had a higher reliance on external resources in the Katherine River compared to the Daly River at Oolloo Crossing. This may be related to differences in primary productivity between the two reaches. However, this pattern was not consistent for all fish species. For instance, sooty grunters used ~75% internal resources at Galloping Jack’s compared to only 58% at Oolloo Crossing (Table 5-6).

Table 5-2. Outputs from a 12-source model for consumers collected at Galloping Jack's on the Katherine River, Northern Territory. Only the top-ranked food source providing the highest dietary contribution is shown for each consumer taxon.

Taxon	Common name	Feeding guild	Top-ranked food source	Proportion of top-ranked food source
Ephemeroptera	Mayflies	Herbivore	Red algae	0.34
Elmidae	Riffle beetles	Herbivore	Red algae	0.20
Philopotamidae	Finger net caddisflies	Herbivore	Red algae	0.24
Leptoceridae	Long-horned caddisflies	Herbivore	Spirogyra	0.13
Bivalvia	Mussels	Herbivore	Spirogyra	0.25
Hydropsychidae	Net-spinning caddisflies	Herbivore	Red algae	0.31
Palaeomonidae	Shrimp	Herbivore	Spirogyra	0.24
Diptera	True flies	Herbivore	Red algae	0.18
Corixidae	Water boatmen	Herbivore	Red algae	0.20
Pyralidae	Pyralid moths	Herbivore	Spirogyra	0.28
Tipulidae	Crane flies	Predator	Spirogyra	0.28
Odonata	Dragonflies	Predator	Red algae	0.17
Dytiscidae	Predaceous diving beetles	Predator	Savanna	0.28
Pleidae	Pygmy backswimmers	Predator	Savanna	0.47
Nematalosa erebi	Bony bream	Herbivore	Schoenoplectus	0.13
Amniataba percoides	Barred grunter	Omnivore	Schoenoplectus	0.17
Neoarius graeffei	Blue catfish	Omnivore	Marine	0.17
Syncomistes butleri	Butler's grunter	Omnivore	Epiphyton + epixylon	0.14
Ambassis spp.	Glassfish	Omnivore	Savanna	0.25
Neoarius midgleyi	Midgley's catfish	Omnivore	Savanna	0.29
Glossamia aprion	Mouth almighty	Omnivore	Marine	0.16
Melanotaenia australis	Rainbowfish	Omnivore	Savanna	0.24
Hephaestus fuliginosus	Sooty grunter	Omnivore	Schoenoplectus	0.20
Craterocephalus stramineus	Strawman hardyhead	Omnivore	Schoenoplectus	0.14
Lates calcarifer	Barramundi	Predator	Savanna	0.18
Oxyeleotris lineolata	Sleepy cod	Predator	Savanna	0.26
Megalops cyprinoides	Tarpon	Predator	Savanna	0.28

Table 5-3. Outputs from a 12-source model for consumers collected at Oolloo Crossing on the Daly River, Northern Territory. Only the top-ranked food source providing the highest dietary contribution is shown for each consumer taxon.

Taxon	Common name	Feeding guild	Top-ranked food source	Proportion of top-ranked food source
Pyralidae	Pryalid moths	Herbivore	Charophyte	0.28
Hydropsychidae	Net-spinning caddisflies	Herbivore	Charophyte	0.27
Palaeomonidae	Shrimp	Herbivore	Spirogyra	0.33
Gastropoda	Snails	Herbivore	Spirogyra	0.30
Diptera	True flies	Herbivore	Spirogyra	0.47
Corixidae	Water boatmen	Herbivore	Charophyte	0.21
Odonata	Dragonflies	Predator	Spirogyra	0.54
Notonectidae	Backswimmers	Predator	Spirogyra	0.12
Naucoridae	Saucer bugs	Predator	Charophyte	0.21
Dytiscidae	Predaceous diving beetles	Predator	Savanna	0.16
Hydrometridae	Water treaders	Predator	Charophyte	0.12
Pleidae	Pygmy backswimmers	Predator	Savanna	0.33
Macrobrachium rosenbergii	Cherabin	Omnivore	Marine	0.24
Nematalosa erebi	Bony bream	Herbivore	Spirogyra	0.31
Planiliza ordensis	Diamond mullet	Herbivore	Spirogyra	0.12
Amniataba percoides	Barred grunter	Omnivore	Spirogyra	0.34
Neosilurus ater	Black catfish	Omnivore	Spirogyra	0.16
Neoarius graeffei	Blue catfish	Omnivore	Marine	0.30
Syncomistes butleri	Butler’s grunter	Omnivore	Spirogyra	0.34
Ambassis spp.	Glassfish	Omnivore	Spirogyra	0.36
Neoarius midgleyi	Midgley’s catfish	Omnivore	Marine	0.31
Glossamia aprion	Mouth almighty	Omnivore	Spirogyra	0.30
Hephaestus fuliginosus	Sooty grunter	Omnivore	Marine	0.35
Leiopotherapon unicolor	Spangled grunter	Omnivore	Spirogyra	0.33
Craterocephalus stramineus	Strawman hardyhead	Omnivore	Spirogyra	0.43
Anodontiglanis dahli	Toothless catfish	Omnivore	Marine	0.19
Toxotes chatareus	Sevenspot archerfish	Predator	Savanna	0.31
Lates calcarifer	Barramundi	Predator	Marine	0.32
Strongylura krefftii	Longtom	Predator	Marine	0.24
Oxyeleotris lineolata	Sleepy cod	Predator	Savanna	0.26
Megalops cyprinoides	Tarpon	Predator	Blue-green algae	0.13

Table 5-4. Sum proportions of internal (autochthonous – seston, biofilms, filamentous macroalgae, emergent and submerged aquatic vegetation) and external (allochthonous – leaf litter, floodplain, savanna, marine) sources to the diets of aquatic insects at two sites in the Daly River, Northern Territory.*

Oolloo Crossing			Galloping Jack's		
Taxon	Internal	External	Taxon	Internal	External
Ephemeroptera	0.95	0.03	Ephemeroptera	0.89	0.12
Odonata	0.92	0.05	Hydropsychidae	0.89	0.11
Diptera	0.89	0.08	Pyralidae	0.88	0.12
Philopotamidae	0.85	0.10	Tipulidae	0.88	0.12
Leptoceridae	0.85	0.09	Philopotamidae	0.85	0.15
Pyralidae	0.83	0.12	Corixidae	0.84	0.17
Ecnomidae	0.81	0.13	Diptera	0.82	0.18
Hydropsychidae	0.81	0.13	Odonata	0.80	0.20
Elmidae	0.80	0.13	Elmidae	0.79	0.21
Corixidae	0.80	0.13	Leptoceridae	0.77	0.23
Notonectidae	0.79	0.13	Dytiscidae	0.46	0.54
Naucoridae	0.79	0.14	Pleidae	0.31	0.69
Hydrometridae	0.72	0.19			
Dytiscidae	0.60	0.32			
Pleidae	0.50	0.44			

*Sum of probabilistic Bayesian estimates does not always equal 100%.

Table 5-5. Sum proportions of internal (autochthonous – seston, biofilms, filamentous macroalgae, emergent and submerged aquatic vegetation) and external (allochthonous – leaf litter, floodplain, savanna, marine) sources to the diets of non-insect invertebrates at two sites in the Daly River, Northern Territory.*

Oolloo Crossing			Galloping Jack's		
Taxon	Internal	External	Taxon	Internal	External
Palaeomonidae	0.86	0.09	Mussels	0.88	0.12
Gastropoda	0.84	0.10	Shrimp	0.85	0.15
Cherabin	0.60	0.35			

*Sum of probabilistic Bayesian estimates does not always equal 100%.

Table 5-6. Sum proportions of internal (autochthonous – seston, biofilms, filamentous macroalgae, emergent and submerged aquatic vegetation) and external (allochthonous – leaf litter, floodplain, savanna, marine) sources to the diets of fishes at two sites in the Daly River, Northern Territory.*

Oolloo Crossing			Galloping Jack's		
Taxon	Internal	External	Taxon	Internal	External
Bony bream	0.83	0.10	Sooty grunter	0.75	0.25
Glassfish	0.83	0.12	Barred grunter	0.73	0.27
Mouth almighty	0.82	0.13	Strawman hardyhead	0.72	0.28
Strawman hardyhead	0.82	0.14	Bony bream	0.71	0.29
Butler's grunter	0.79	0.16	Butler's grunter	0.62	0.38
Barred grunter	0.78	0.18	Mouth almighty	0.57	0.43
Diamond mullet	0.77	0.14	Barramundi	0.49	0.52
Black catfish	0.74	0.19	Blue catfish	0.48	0.52
Tarpon	0.71	0.20	Rainbowfish	0.47	0.53
Spangled grunter	0.67	0.30	Sleepy cod	0.47	0.53
Sooty grunter	0.58	0.40	Tarpon	0.46	0.54
Toothless catfish	0.55	0.38	Glassfish	0.42	0.58
Blue catfish	0.52	0.42	Midgley's catfish	0.41	0.59
Longtom	0.51	0.42			
Barramundi	0.49	0.45			
Sleepy cod	0.46	0.47			
Midgley's catfish	0.43	0.51			
Sevenspot archerfish	0.42	0.52			

*Sum of probabilistic Bayesian estimates does not always equal 100%.

Given the high contributions of benthic macroalgae and macrophytes to diets of invertebrates, flow reduction is likely to have a significant effect on the dry-season food web through its effect on resource availability. Hydrodynamic modelling shows that a decrease in flow from 2 to 1 m^3/s near Galloping Jack's, Katherine River, could result in a decrease in area of suitable velocities for *Spirogyra* spp. by one third (Miller 2018). Such a reduction would have the potential to significantly reduce resource availability.

However, the extent of impact of flow reduction on primary producers in the Daly River system is poorly understood and difficult to predict, since habitat requirements vary between primary producers. While some macrophytes and macroalgae such as *Vallisneria nana* and *Spirogyra* spp. prefer relatively high current speeds of 0.2–0.8 m/s (Townsend & Padovan 2005; Rea et al. 2002), charophytes like *Chara* spp. and *Nitella* spp. can thrive in lower velocity areas (Schult, pers. obs.) and may be favoured by discharge reductions.

While flow velocity is only one of several limiting factors that determine the occurrence and distribution of primary producers across a reach, hydrodynamic modelling of the Oolloo/Mentabie Reach (see Chapter 3, Miller 2020) indicates that the availability of optimal velocity habitat for *Spirogyra* spp. and *Vallisneria* reduces substantially with decreased discharge (Figure 5-1). On average, a flow reduction of 1 m^3/s at the top of the reach results in an estimated 14% reduction in habitat availability.

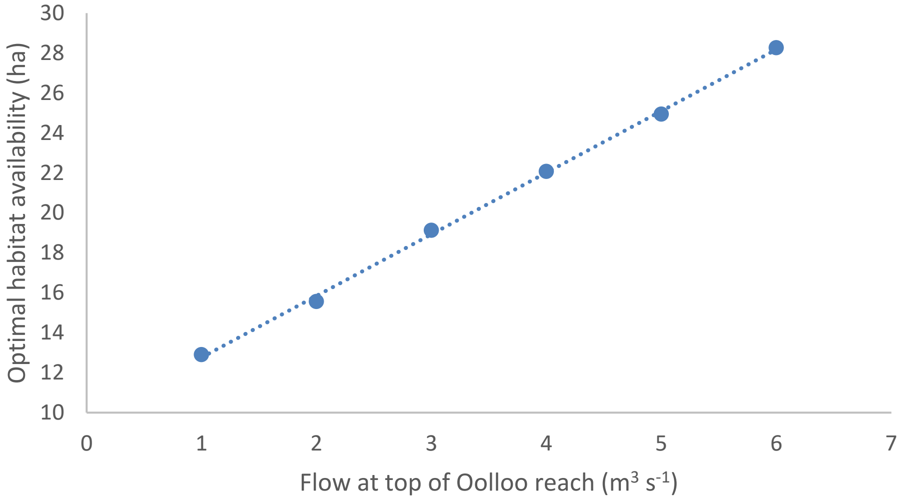

Figure 5-1. Change in optimal velocity habitat availability for Spirogyra spp. in the Oolloo Reach with reduced flows.

5.5 Key findings

This study has improved our understanding of dry-season food webs in the Katherine/Daly system. The findings highlight that a mixture of internal and external resources support consumers, and emphasise the strong role for both locally produced algae and externally produced subsidies in this system.

- The dry-season food web relies on both internal (e.g. in-stream algae) and external (floodplain and marine) resources. Invertebrates are generally more reliant on internal resources than fish.
- Fish had a higher reliance on external resources in the Katherine River compared with the Daly River at Oolloo Crossing, while the proportions of internal and external resources were similar for macroinvertebrates. Site differences may be related to differences in internal resource availability with potential links to flow.
- The relatively high reliance of some fish on external food resources, even during the dry season, may indicate that they possess a degree of resilience to reduced dry-season flows and changes in in-stream resources, as long as there is sufficient wet-season access to productive external habitats and sources of productivity.
- Although fish overall were less reliant on in-stream resources, species that utilise a higher proportion of in-stream resources, such as sooty grunter, and some of the small-bodied species may be more vulnerable to changes in in-stream resource availability due to flow reduction.
- Flow is likely to have a significant effect on the dry-season food web through its impact on resource availability. High contributions of benthic macroalgae and macrophytes to diets of macroinvertebrates indicate that hydraulic shifts will differentially favour some species. For instance, a 20% reduction in flow would result in a 15% reduction in macroalgae (*Spirogyra*) habitat in the Oolloo Reach, potentially leading to significantly reduced availability of an important food resource.

6. Diel habitat preferences and minimum environmental flow requirements to protect habitat for juvenile sooty grunter

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6.1 Background

Sooty grunter (also known as black bream; Figure 6-1) are distributed across the wet-dry tropics regions of Australia and southern New Guinea (Pusey et al. 2004). They are of high significance as a food source for Aboriginal people across northern Australia, including in the Daly River catchment (Finn & Jackson 2011; Jackson et al. 2014), and are also commonly targeted by recreational fishers (Pusey et al. 2004). Sooty grunter predominantly inhabit permanent river reaches, large intermittent streams and floodplain wetlands (Pusey et al. 2020).

Many of the rivers inhabited by sooty grunter are experiencing increased water-resource development for agriculture and mining, which impacts the flow regime and presents a range of threats to aquatic fauna, including fish (Stewart-Koster et al. 2011; King et al. 2015). In the Daly River catchment, a recent assessment of water allocation arrangements found that some aquifers are over-allocated and that further quantification of the environmental and cultural water requirements of the system is urgently needed to support sustainable management (Northern Territory Government 2019a,b). Dry-season river flows in the Daly catchment are entirely dependent on discharge from the underlying Tindall Limestone Aquifer and are influenced by the amount of abstraction from the aquifer allowed under water extraction licences.

A particular concern for water management is that the availability of shallow, fast-flowing habitat may be reduced by increased groundwater abstraction in the dry season, a period when river flows are at their lowest and water abstraction is likely to have its greatest effects (King et al. 2015). Although previous research suggests that juvenile sooty grunter exhibit a strong preference for shallow, fast-flowing habitat during dry-season, low-flow periods (Chan et al. 2012; Keller et al. 2019), these studies have several potential limitations, in that they: 1) did not consider diel variation in habitat use; 2) developed habitat suitability curves using data from different electrofishing methods (back pack in riffles, boat-mounted in other habitats); and 3) estimated habitat preference using fish abundance and habitat data that were not spatially matched. Given the importance of maintaining critical fish habitat as a controlling criterion for water management in the Daly River catchment, managers identified a need for further evaluation and quantification of relationships between river discharge and the availability of habitat for smaller size classes of sooty grunter during the dry season.

Figure 6-1. Juvenile sooty grunter.

6.2 Aims and objectives

The aim of this study was to quantify the diurnal and nocturnal habitat preferences of juvenile sooty grunter and to determine the effects of different water abstraction scenarios on habitat availability. We used radiotelemetry to obtain fine-scale locations of individual fish for day and night over a 10-day period. This information was integrated with a detailed hydrodynamic model of the study reach to identify preferred hydraulic habitat. The hydrodynamic model was then used to examine different river discharge scenarios to explore the potential effects of water management on the availability of preferred habitat for juvenile sooty grunter.

6.3 Methods

6.3.1 Study area

The study was conducted in a representative reach ~1.2 km in length in the Katherine River at Wilden Station (Figure 6-2, Figure 6-4). At the time of tracking, the water surface width ranged from ~15 to 50 m with a maximum depth of 4.7 m. The proportion of mesohabitat types was visually estimated for each 10 m section of the focal reach to determine habitat availability. Mesohabitat classes were subjectively classified in the field as riffles (shallow, fast-flowing), runs (slow-flowing and of intermediate depth) or pools (deep, with slow or no discernible flow). Water quality was measured twice daily (early morning and mid-afternoon) and remained relatively constant over the study period (temperature 32.38 ºC ± 0.04 (mean ± standard error [SE]); conductivity 0.623 μS/cm ± 0.003; dissolved oxygen 87.31% ± 0.82, 6.32 mg/L ± 0.06; pH 7.66 ± 0.01). River discharge was steady over the 10-day tracking period, ranging from 2.7 to 2.9 m^3/s (mean 2.8 m^3/s).

Figure 6-2. Map of the study site on the Katherine River in the Daly River catchment, Northern Territory. Catchment of Katherine River (excluding Dry River and King River sub-catchments) is shown in dark grey.

Figure 6-3. A riffle in the study reach.

6.3.2 Fish collection and tracking

Twenty-nine sooty grunter (68–240 mm standard length [SL], mean = 136 mm, SE ± 9 mm) were caught by hook-and-line fishing from the focal reach in the Katherine River on 4–5 October 2017. Sampling effort was spread across all mesohabitat types to minimise the potential for habitat bias. Radio transmitters (Lotek NanoTag NTQ-2, 0.31 g, 5–6 s on/off burst interval, ~33 days battery life) were surgically implanted into the peritoneal cavity under anaesthesia through an incision ~1.5 cm in length, using a syringe needle to exit the antenna of each transmitter ~1 cm posterior to the incision (Figure 6-4).

Figure 6-4. Radio-tagged juvenile sooty grunter showing trailing antenna; inset shows size of transmitter.

To record the locations of tagged fish, numbered markers were placed at 10 m intervals along the banks of the focal reach. A GPS coordinate (latitude/longitude) was recorded for each marker using a handheld GPS and exported to Google Earth (V7.1.5.1557) on a laptop computer. Day (11:00–14:00) and night (20:00–24:00) tracking surveys were conducted over 10–20 October 2017 using a handheld 3-element Yagi antenna and a portable receiver (Figure 6-5). The locations of the fish were estimated by triangulation and adjustment of the receiver gain, and coordinates obtained for each location estimate by marking the location with reference to the numbered markers using a Google Earth map of the reach. Mesohabitat type and coordinates for each point location estimate were recorded for each tagged fish once during the day and night, and data were plotted and viewed in ArcGIS for processing and analysis.

Figure 6-5. Radio-tracking in the study reach.

6.3.3 Reach bathymetry and hydrodynamic modelling

A detailed bathymetric survey of the study reach was undertaken from a boat on 14–15 March 2018 using a multi-beam depth sounder and GNSS to provide depth and position measurements along the reach. Bathymetric software was used to collect and process the data. Bathymetric transects and cross-sections were undertaken during a period of high flow (~129 m^3/s) to ensure detailed data collection across all low- to mid-flow features including channel beds, shelves, banks and control features. The bathymetry data was then verified by surveyed spot heights collected on 25 June 2018 during a period of low flow (~5 m^3/s). Bathymetry data and spot heights were processed to produce a triangulated irregular network (TIN) model of the channel geometry throughout the study reach. Hydrodynamic modelling of the study reach was undertaken by the University of New South Wales (Water Research Laboratory) using the RMA-2 finite element model. A fine-resolution (~1 m) triangular mesh was developed throughout the model domain to represent localised channel features and riffles in the bathymetric survey. The hydrodynamic model was used to estimate water depths and velocities within the reach for 10 management-relevant dry-season flow scenarios, including the river discharge at the time of fish tracking.

6.3.4 Habitat preference analysis

Mesohabitat (riffle, run, pool) preference was examined for the day and night periods using selection ratio analysis (Design II, Manly et al. 2002). Selection ratios (W_i = used/available) were calculated for each fish, with values >1 indicating positive selection and values <1 indicating avoidance. Selection indices with simultaneous Bonferroni confidence intervals

(CIs) were used to analyse the degree of selectivity for each mesohabitat type across all fish. Selection ratios with Bonferroni-adjusted 95% CIs that did not include 1 were considered to be statistically significant (i.e. $\alpha = 0.05$).

Hydraulic microhabitat preference was modelled using generalised additive mixed-effect models (GAMMs) with fish detections as the dependent variable and the explanatory habitat variables water velocity and water depth. Fish identity was included as a random factor to account for the lack of independence caused by multiple individual detections. A total of 317 presence data points were collected from 17 radio-tracked fish (164 locations during the day and 153 locations at night; Table 6-1). Explanatory habitat variables for water velocity and depth were extracted for each fish location from the hydrodynamic model for a river discharge representative of the period of fish tracking (2.8 m^3/s). We extracted 10,000 random data points for water depth and velocity from the hydrodynamic model for Scenario 6 (2.8 m^3/s) to use as background data in the GAMMs. Data points near the river edge with depth values equal to or below zero and missing velocity values were removed, which resulted in 6,535 background data points. The same set of background data was used to contrast both day and night occurrence data in two separate models, as well as in a combined day-night model. To test if sooty grunter habitat preferences change between day and night, time of day was used as factor to test for interactions with the habitat explanatory variables. The predicted response values of each model were standardised between 1 (maximum response value) and −1 (minimum response value).

6.3.5 Effects of river discharge on habitat availability

The availability of preferred sooty grunter habitat under different flow scenarios was examined based on data from the combined day-night GAMM model for Scenario 6 (river discharge at the time of the radio-tracking survey). Habitat suitability criteria were established by extracting values of preferred depth and velocity using a selectivity cut-off of zero. This cut-off assumes that any value above zero is preferred habitat and is positively correlated with occurrence; conversely, values below zero represent habitat that is avoided and thus negatively correlated with occurrence. The area of preferred habitat for each flow scenario was calculated in square metres based on the proportion of 100,000 random points within the reach meeting the habitat suitability criteria multiplied by the total wetted area for each scenario. R version 3.3.2 (R Development Core Team 2016) was used to run the selection ratio analyses using the R package ‘adehabitatHS’ (Calenge 2018) and the GAMM models were fitted using the ‘mgcv’ package (Wood 2017). Data were extracted from the hydrodynamic models using the point sampling tool plugin in the open-source software QGIS (version 3.8.2, www.qgis.org) with the GRASS extension (version 7.6.1).

6.4 Results

Seventeen (59%) of the 29 radio-tagged fish were located during the 10-day radio-tracking monitoring period (Table 6-1, Figure 6-6). The remaining 12 (41%) fish were unable to be detected, despite repeated attempts to locate the fish by searching for tagged fish ~2 km upstream and downstream of the focal reach. Reasons for the failure to locate these fish are unclear, but could include transmitter failure, predation or rapid, large-scale movement away from the study reach. The extent of movement (linear distance along the river channel) by individual fish ranged from 18 m to 578 m, with most of the 17 tracked fish remaining within the focal reach over the entire 10-day tracking period (Table 6-1). Seven (41%) of the tracked fish exhibited movements of <100 m. Although most fish utilised the same general area of the study reach both day and night, four (Fish IDs 17, 22, 28 and 40; 117–205 mm SL) made repeated movements of up to ~350 m between distinct day and night areas during the study.

Table 6-1. Details of the 17 radio-tagged sooty grunter tracked during the 10-day period.

Fish ID	Standard length (mm)	No. of locations (day, night)	Extent of movement (m)
11	142	10, 10	42
14	134	8, 10	71
17	145	10, 10	278
18	125	10, 10	62
20	240	9, 10	297
21	134	10, 8	67
22	117	10, 9	326
23	134	9, 8	578
26	68	10, 10	172
28	132	9, 9	264
29	125	10, 10	111
31	132	8, 8	97
32	110	10, 9	18
34	124	10, 3	141
36	133	10, 10	54
37	115	8, 10	134
40	205	9, 10	363

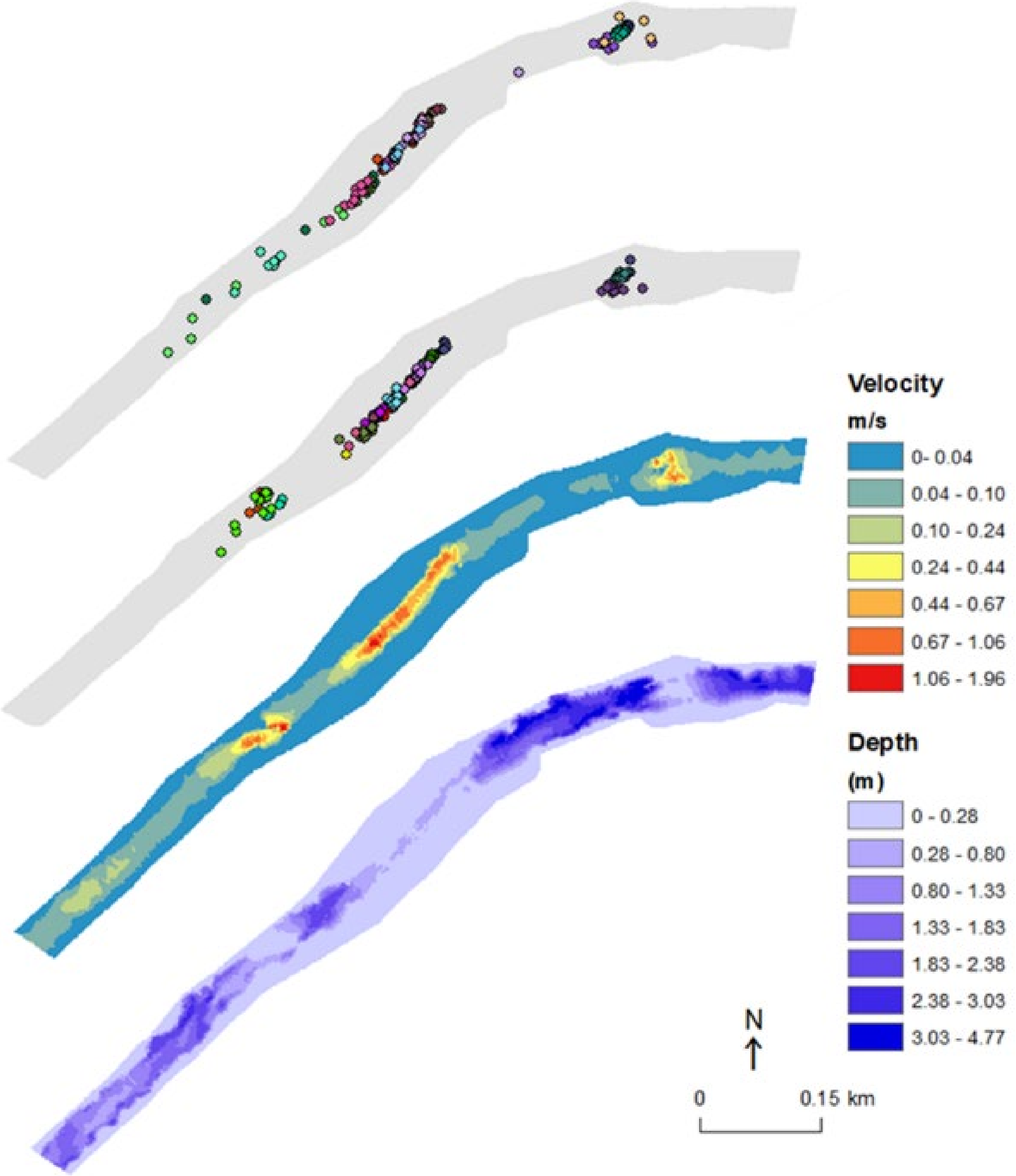


Figure 6-6. Map of the focal reach showing velocity, depth and fish locations during the day (top) and night (second from top) during the 10-day radio-tracking period. Different coloured dots represent different individual fish.

Sooty grunter exhibited a significant overall preference for riffles during the day and riffles and runs at night (Table 6-2, Figure 6-7). Pool habitats were used much less frequently than their proportional availability in the reach, in both the day and night (Table 6-2), although two fish (including the largest fish tagged in the study) showed positive selection of pool habitat during the day (Fish ID 20 and 23; 240 mm and 134 mm SL, respectively; Figure 6-7a).

Table 6-2. Selection ratios for the availability and use of mesohabitats for day and night over the 10-day tracking period.

Day						
Habitat	Available (%)	Used (%)	*Wi*	SE	Lower CI	Upper CI
Pool	0.60	0.16	0.27*	0.12	−0.01	0.54
Riffle	0.09	0.40	4.44*	0.87	2.18	6.33
Run	0.31	0.44	1.42	0.22	0.92	1.99
Night						
Habitat	Available (%)	Used (%)	*Wi*	SE	Lower CI	Upper CI
Pool	0.60	0.10	0.17*	0.08	−0.01	0.35
Riffle	0.09	0.34	3.78*	0.95	1.37	5.90
Run	0.31	0.56	1.81*	0.29	1.14	2.53

CI = confidence interval, SE = standard error, Wi is the selection ratio (used/available), * P<0.05.

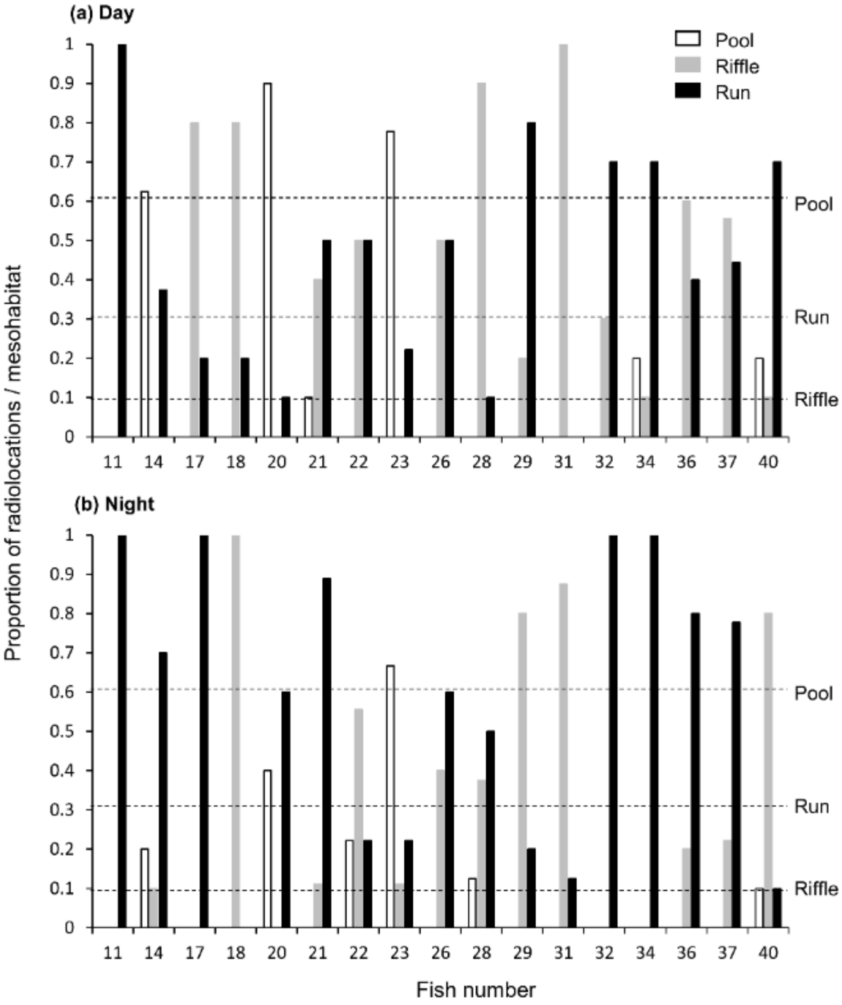


Figure 6-7. Mesohabitat use (proportion of radiolocations) by individual sooty grunter over the 10-day radio-tracking period for day (top) and night (bottom). Dashed lines show the availability of each mesohabitat type within the focal reach. Positive selection by an individual fish is indicated when the proportion of radiolocations in a mesohabitat (bars) exceeds the availability of that mesohabitat type within the focal reach (dashed lines).

The GAMM analysis of hydraulic microhabitat preference showed a significant effect of velocity and depth on the probability of sooty grunter presence for both day and night (Table 6-3, Figure 6-8). The effect of time of day was not significant at P<0.05 in the combined day-night GAMM and inclusion of the day-night parameter did not improve model fit (Table 6-3). On this basis, preferred hydraulic habitat criteria were defined using the combined day-night model as locations with velocities of 0.26–1.42 m/s and depths <0.69 m (Figure 6-8). River discharge scenarios based on the outputs of the hydrodynamic model showed that the estimated area of preferred habitat was highest at a discharge of 8 m^3/s, with habitat declining both above and below this, and rapidly below 2.0 m^3/s (Figure 6-9a,b).

Table 6-3. Parameters of the generalised additive mixed-effect model of the daytime habitat selection by juvenile sooty grunter as a function of water velocity and depth, with fish individual identity as a random effect. The first model (A) split the data into day detections and night detections. The second model (B) combined all data and tested the significance of daytime as an explanatory factor. Estimated degrees of freedom (edf), estimate (± standard error), test statistics (F- and t-values); probability (P) in bold denotes significance at P<0.05.

Model A				
Day	Velocity	edf = 4.42	*F* = 32.68	**P<0.001**
	Depth	edf = 1	*F* = 40.35	**P<0.001**
Night	Velocity	edf = 4.02	*F* = 40.02	**P<0.001**
	Depth	edf = 1	*F* = 33.28	**P<0.001**
Model B				
Combined day-night	Velocity	edf = 5.03	*F* = 56.6	**P<0.001**
	Depth	estimate = −1.18 (± 0.16)	*t* = −5.35	**P<0.001**
	Daytime	estimate = −0.07 (± 0.12)	*t* = −0.66	P=0.50

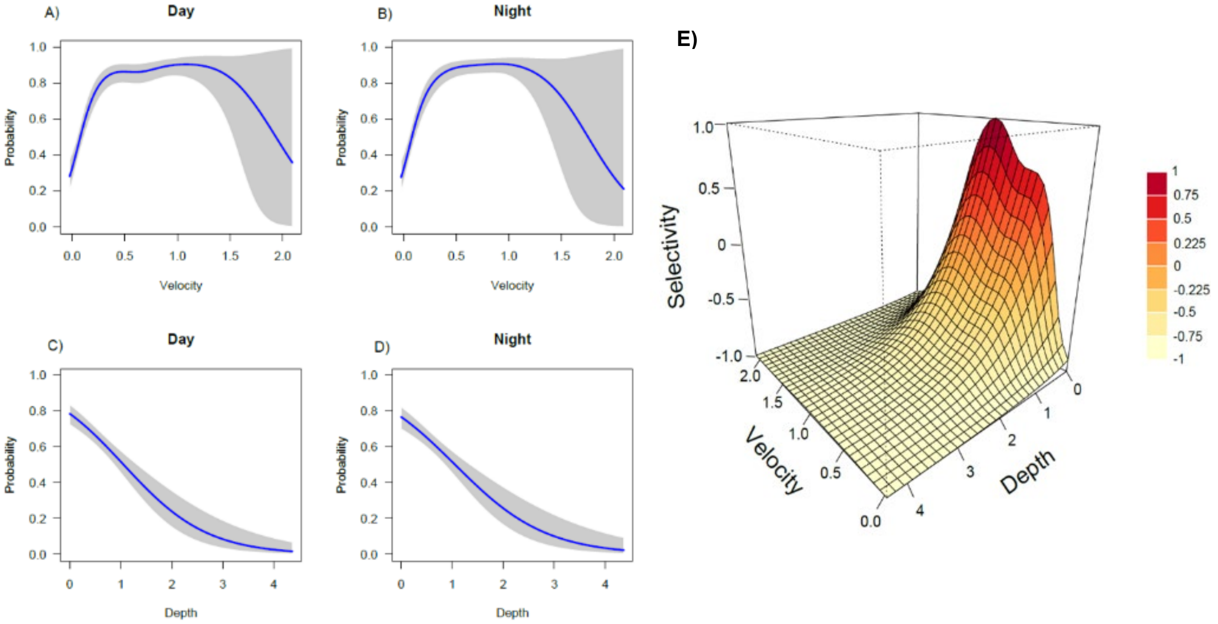


Figure 6-8. Partial-effect plots of the effect of habitat explanatory variables on the probability of detection during daytime (A, C) and night-time (B, D). Habitat selectivity of radio-tagged sooty grunter in relation to habitat depth (m) and velocity (m/s) for the combined day-night generalised additive mixed-effects model (E).

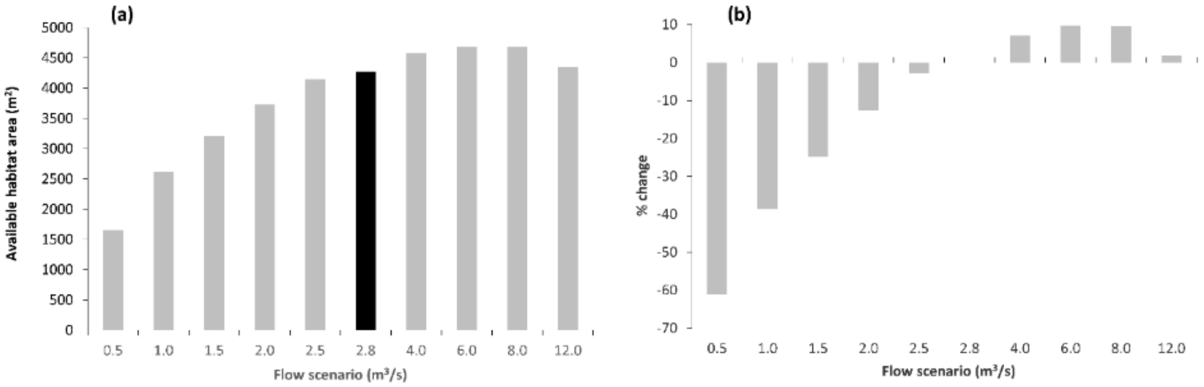


Figure 6-9. Availability of preferred hydraulic habitat for sooty grunter (a), and percentage reductions in the area of preferred habitat relative to the maximum available area (b) under different river discharge scenarios in the focal reach. River discharge at the time of fish tracking is shown in black.

6.5 Discussion

The results of the study demonstrate that juvenile sooty grunter exhibit a strong preference for shallow, fast-flowing hydraulic habitat during the dry season. These findings are broadly compatible with those of previous studies by Chan et al. (2012) and Keller et al. (2019), who both concluded that juvenile sooty grunter prefer shallow, fast-flowing riffle areas and that preservation of riffles during the dry season is critical to the viability of sooty grunter populations. However, while Chan et al. (2012) emphasised the importance of riffle habitat for juvenile sooty grunter, their analyses suggested optimal velocities of 0–0.6 m/s and depths of 0.3–0.6 m (Table 6-4). The preference for slow to moderate velocities reported by Chan et al. (2012) differs from the current analysis and Keller et al. (2019), which both suggest a strong decline in habitat suitability at low velocities (Table 6-4). Similarly, neither the current study nor Keller et al. (2019) found a decline in habitat suitability below 0.3 m depth, as reported by Chan et al. (2012) (Table 6-4). The habitat associations reported by Keller et al. (2019) based on BRT modelling overlap with the current study's results, although the values for preferred depth (<0.8 m) and velocity (>0.4 m/s) cover a broader range than the values generated from our analyses (Table 6-4).

Table 6-4. Comparison of hydraulic habitat preference values derived from three studies of juvenile sooty grunter.

Study	Preferred depth (m)	Preferred velocity (m/s)	Fish size (SL mm)	Data source	Criteria used
Chan et al. (2012)	0.3–0.6	<0.6	<150	Backpack and boat-mounted elecrofishing, 55 sites, 1–6 surveys per site over 3 years	>0.7 optimal habitat suitability criterion
Keller et al. (2019)	<0.8	>0.4	<150	Backpack and boat-mounted elecrofishing, 6 sites, 20 surveys per site over 10 years	Positive values in partial dependence plots from boosted regression tree modelling
Current study – day-night combined	<0.69	0.26–1.42	68–240 (median: 132)	Radiotelemetry, 10-day period, single site	Generalised additive mixed-effects modelling, predictive response >0

SL = standard length

One of the key differences between the current study and previous studies of sooty grunter habitat preference is that our analysis was based on individual fish locations for which depth and velocity were estimated simultaneously. This allowed us to generate a three-dimensional surface (Figure 6-8) to explore the interactive effects of depth and velocity on habitat preference. In contrast, Chan et al. (2012) and Keller et al. (2019) generated habitat preference/use curves independently for depth and velocity based on reach-scale catch per unit effort and habitat availability data. From these habitat preference curves, Chan et al. (2012) derived optimal habitat metrics for depth and velocity based on >0.7 suitability criterion using the approach described by Groshens and Orth (1994). Locations within the river that exceeded the 0.7 suitability criterion for both depth and velocity were classified as 'optimal' habitat using a hydrodynamic model, and the availability of optimal habitat was then assessed under different flow management scenarios. The different methodological approaches likely explain at least some of the variation in the hydraulic habitat preference estimates across the three studies. Other possible factors include the characteristics of the study site(s), different data collection methods, the spatial resolution and extent of sampling, and the different statistical techniques employed. Despite differences in hydraulic habitat preference estimates, however, the strong preference by juvenile sooty grunter for riffle mesohabitat is consistent across the studies.

Based on the hydraulic habitat preference criteria from our analyses, a series of water management scenarios was examined to explore the effects of water abstraction on the availability of habitat for sooty grunter (Figure 6-9). These analyses showed that preferred habitat declined sharply as dry-season river discharge reduced. At flows of 0.5 m^3/s, habitat availability was reduced by ~61% compared with the flows experienced during the radio-tracking study (2.8 m^3/s). Hydrology data collected at the study site since 2008 show that minimum dry-season flows seldom fell below 2 m^3/s and typically ranged from ~2.5 to 3.0 m^3/s (Figure 6-10), suggesting that severe habitat limitation for sooty grunter due to low flows has been rare over the past decade. In 2019 and 2020, however, dry-season minima dropped well below 2 m^3/s after poor wet-season rainfall, with a resulting reduction in preferred juvenile sooty grunter habitat of ~13% compared with conditions during the radio-tracking survey in October 2017 (Figure 6-10).

Our analysis suggests that this level of water abstraction, to flows <2 m^3/s at Wilden gauge, reduces the area of preferred juvenile sooty grunter habitat by ~14% compared with modelled natural flows during that period. Thus, while the seasonal scaling of announced allocations reduces the amount of water that can be abstracted during dry periods, water abstraction continues to exacerbate the loss of preferred sooty grunter habitat during dry periods under this management regime. The potential impacts of this habitat loss are not limited to sooty grunter, as several other fish species in the study area are also strongly associated with riffle habitats (e.g. *Syncomistes butleri, Glossogobius* spp.; Keller et al. 2019). With predictions of increased temperatures and variability in rainfall across northern Australia resulting from anthropogenic climate change (Moise et al. 2015), it appears likely that habitat limitation for riffle-dwelling fishes at the end of the dry season will become increasingly prevalent in the future. This will require additional management interventions – for example, environmental flow rules to meet the minimum habitat requirements of key taxa – to protect the ecological and cultural values of the system.

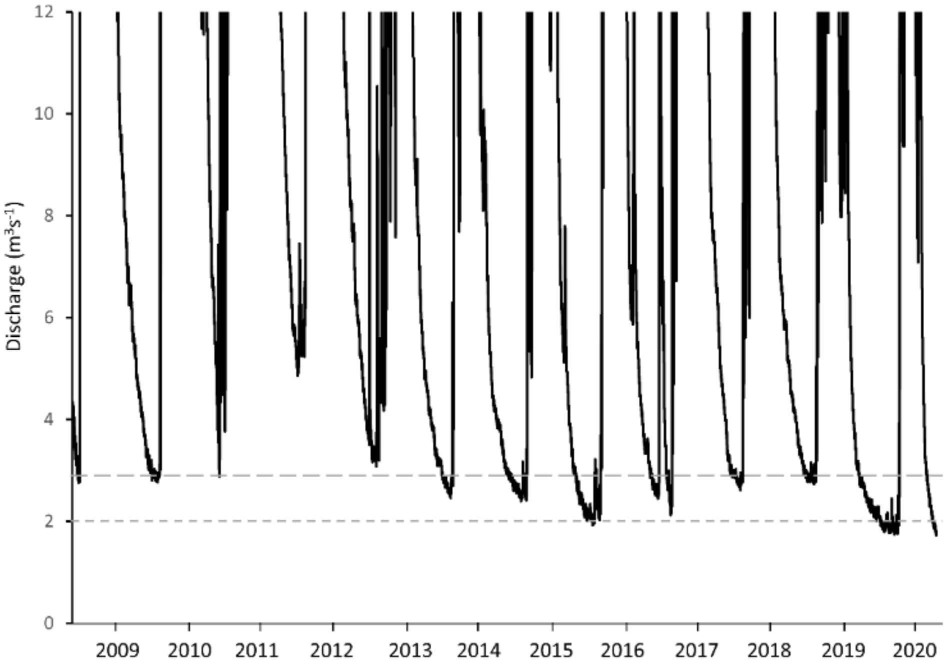


Figure 6-10. Dry-season flows at Wilden Station study site for 2008–2020. Discharge above 12 m^3/s is not shown. Long-dashed grey line shows discharge at the time of the radio-tracking survey. Short-dashed grey line shows discharge of 2 m^3/s, below which preferred habitat for sooty grunter declines rapidly.

The reduction in habitat area under low flows has important implications for management of water in the Katherine River and the underlying Tindall Limestone Aquifer. The current water allocation plan (Northern Territory Government 2019a) does not consider the environmental flow requirements of specific fauna or flora, but instead protects a proportion of river flows to meet non-consumptive (environmental and cultural) water requirements. This proportion varies between 87% and 70% of modelled natural flow, depending on seasonal conditions (Table 6-5), with annual water allocations announced at the start of the dry season based on modelled natural end-of-dry-season flows. In dry conditions (as experienced in 2019/20), where modelled natural end-of-dry-season flows are 1.81–2.10 m^3/s, 20% of the groundwater discharge is accessible for consumptive use (predicted impacted flow 1.45–1.68 m^3/s) (Table 6-5).

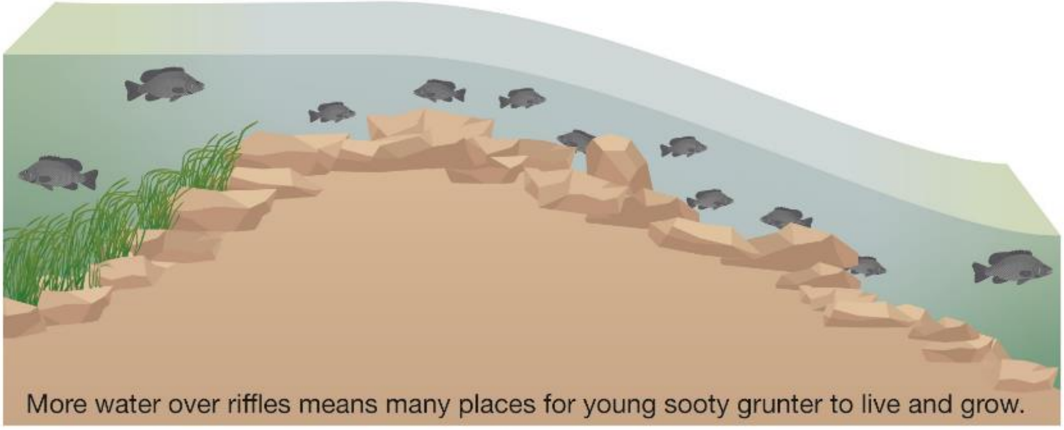
Table 6-5. Flow information (based on modelled natural flows at Wilden Station) used in annual allocations of water for consumptive use from the Katherine Tindall Limestone Aquifer (reproduced from Northern Territory Government 2019a).

River-flow scenario	Proportion of modelled flow to be reserved for non-consumptive requirements	Modelled natural 1 November flow (unimpacted flow)		Resultant flow to be preserved for non-consumptive use (impacted flow)		Allowable impact of consumptive use (total level of extraction)	
		cumecs	ML/day	cumecs	ML/day	cumecs	ML/day
Very dry	87%	1.73–1.80	149–156	1.51–1.57	130–135	0.22–0.23	19–20
Dry	80%	1.81–2.10	156–181	1.45–1.68	125–145	0.36–0.42	31–36
Average	70%	2.11–2.90	182–251	1.48–2.03	128–175	0.63–0.87	55–75
Wet	70%	2.91–3.60	251–311	2.04–2.52	176–218	0.87–1.08	75–93
Very wet	70%	3.61–4.47	312–386	2.53–3.13	218–270	1.08–1.34	94–116

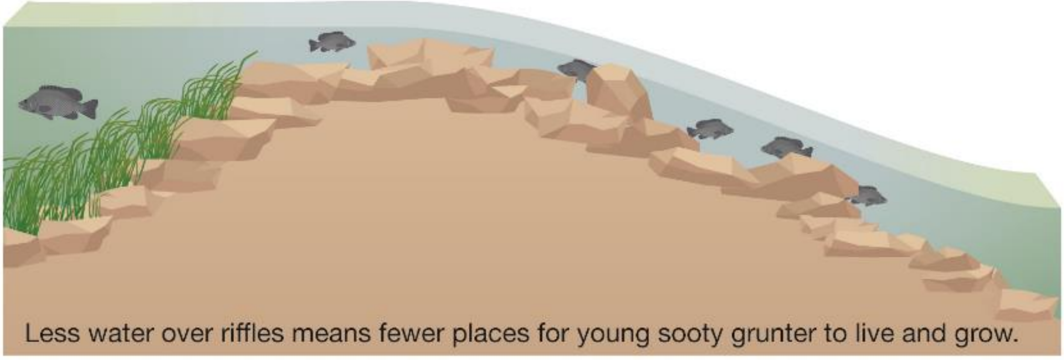
Interestingly, the estimated area of preferred habitat did not continue to increase at higher river discharges (12 m^3/s). While the focus of our study was to identify minimum flows required to protect critical fish habitat, this finding raises the important point that artificially high flows during the dry season could pose potential risks to populations of riffle-dwelling fishes, as shallow riffles may become drowned out with increasing river height. This issue does not have immediate relevance for river management in the Daly River catchment given the current absence of major dams or other flow-regulating infrastructure. However, artificially elevated flows are prevalent in many regulated river systems around the world (Poff & Zimmerman 2010) and, with major water-resource development on the horizon, this may become an important consideration for water management in northern Australia in the future.

6.6 Conclusions

The results of the study have utility as supporting information for the development of environmental flow rules to manage water allocations in the Daly River catchment and, potentially, other catchments across the range of sooty grunter (Figure 6-11). While some of our findings are likely to have broad geographic applicability (e.g. preference for riffle and run mesohabitats; see also Pusey et al. 2004), previous studies have shown that hydraulic microhabitat criteria for fish cannot necessarily be transferred across regions (Gebhard et al. 2017). Location-specific hydraulic habitat criteria may therefore be required for evaluations of the microhabitat requirements of sooty grunter in different regions. Further, as fish behaviour and habitat preference may change under different river flows (Vilizzi et al. 2004), application of the hydraulic habitat criteria presented here also needs to consider dependencies between habitat preference and river discharge. Our objective was to quantify the habitat requirements of sooty grunter during the critical late dry-season period: our conclusions regarding habitat preference cannot necessarily be directly transferred to other times of year or different hydrological conditions (e.g. high-flow periods during the wet season). Finally, although the identification of flows required to preserve hydraulic habitat for fish is critical for effective environmental flow management, it is only one of a much broader set of ecological requirements that must be met to support resilient fish populations into the future (Rolls et al. 2012; Railsback 2016; Poff et al. 2017).



More water over riffles means many places for young sooty grunter to live and grow.



Less water over riffles means fewer places for young sooty grunter to live and grow.

Figure 6-11. Simple conceptual diagram of the effect of lower water levels on juvenile sooty grunter habitat.

7. Movement of and habitat use by pig-nosed turtles, with reference to flow requirements

Contributors: Peter Dostine, David Crook, Krystle Keller, Dion Wedd, Alison King

This research is being prepared as a separate publication.

7.1 Background

Understanding the spatial ecology of mobile and migratory aquatic taxa is fundamental to the sustainable management of rivers, as altered flow regimes may disrupt connectivity and fail to provide the ecological requirements of riverine animals (Crook et al. 2015). In the wet-dry tropics of northern Australia, the pig-nosed turtle, *Carettochelys insculpta*, is an iconic species that is potentially vulnerable to the impacts of flow regime alteration (Doody 2002; Erskine et al. 2003; Georges et al. 2008a,b). The species is listed as Endangered on the International Union for Conservation of Nature (IUCN) Red List (Eisemberg et al. 2018) and is of great social and cultural significance to First Nations Traditional Owners of the region (Jackson et al. 2012, 2014). While some Australian populations of pig-nosed turtles are located within protected areas such as Kakadu National Park in the Alligator Rivers Region, populations in the Daly River are subject to potential impacts from ongoing agricultural development in the catchment and increasing pressure for groundwater extraction to support agricultural development (King et al. 2015). Such development is likely to alter the flow regime, potentially leading to reduced dry-season discharge, disruption of hydrologic connectivity, elevated nutrients, loss of key nesting habitat and altered thermal regime (Erskine et al. 2003; King et al. 2015).

The ecology of the pig-nosed turtle has been well-documented by research studies since the late 1980s in Papua New Guinea (Georges et al. 2008a,b; Eisemberg et al. 2015), Kakadu National Park (Georges et al. 1989; Georges & Kennett 1989) and the Daly River (Georges 1992; Doody et al. 2001, 2002, 2003a,b, 2006, 2009a,b; Welsh et al. 2017). Several aspects of the species' ecology in the Daly River, including relatively small body size, biennial reproduction, extensive home range and use of thermal springs, are purported to be linked to the low energy content of the species' primarily plant-based diet (Georges et al. 2008a,b).

Doody et al. (2002) used radio-tracking to describe patterns of movement and habitat use by pig-nosed turtles between August and December (i.e. during and after the breeding season) along an 11 km stretch near Oolloo Crossing in the Daly River. Females had significantly longer linear home ranges than males (8.3 ± 2.88 km vs 3.2 ± 1.32 km). Males had significantly larger linear home ranges, and were significantly more active, when females were gravid compared to when reproductive females were not gravid. Females usually nested within their normally occupied home range, which included several nesting beaches, and rarely made extensive forays outside of the home range for nesting. Within a home range, turtle activity was focused on 'activity hotspots' including foraging areas (often focused on dense beds of ribbonweed, *Vallisneria nana*), thermal springs and nesting beaches. Thermal spring basking behaviour was observed to occur during the cooler months of May to September (Doody 2002), and has been hypothesised to facilitate an extended foraging period (Davies 2005).

7.2 Aims and objectives

We sought to describe the timing and extent of large-scale movements of pig-nosed turtles within the core habitat of the species in the Daly River. This work sought to build on previous studies of the spatial ecology of the species in the Daly River. There are several key differences between this study and the radio-tracking study by Doody et al. (2002). We used acoustic telemetry to collect continuous data over approximately two years, in two study areas of the Daly River; the first area (Oolloo) overlapped the study area of the previous study, and the second (Mentabie) was in the upper reaches of the species' core distribution in the river. Both study areas included at least one significant flow control point that may impede movement by turtles at low flows. The specific aims of the study were to (i) identify seasonal patterns in the large-scale movement behaviour of male and female pig-nosed turtles in the Daly River, (ii) quantify flow conditions during passage events across specific control points in the river, (iii) model flow scenarios to predict connectivity thresholds in the river, and (iv) describe any implications of these results for the management of river flows and pig-nosed turtles in the Daly River.

Initial additional research questions about specific habitat use by pig-nosed turtles and short-term movement patterns were originally attempted in the project but had to be abandoned due to logistical issues.

7.3 Methods

7.3.1 Study area

The Daly River contains a diverse turtle fauna (Price et al. 2000), including eight of the nine species of freshwater turtles present in the NT. The core habitat of pig-nosed turtles in the Daly River occurs from upstream of Stray Creek to upstream of the Douglas River confluence, where elevated water temperature, high spring inflow and extensive ribbonweed beds occur. The species is known to also occur upstream and downstream of this reach, but are not known to occur in the brackish tidal reaches of the lower Daly River below Daly River Crossing.

There are several flow control points in the middle reaches of the Daly River, including riffles and road crossings at Dorisvale Crossing, Oolloo Crossing and Beeboom Crossing, that may impede longitudinal movements by pig-nosed turtles at low flows. Most control points occur in the reach upstream of Oolloo Crossing; there are few control points downstream of Oolloo Crossing (Figure 7-1). Earlier hydrological surveys identified 34 breakpoints (i.e. depths <0.5 m) between Dorisvale Crossing and Cattle Creek, downstream of Oolloo Crossing (Georges et al. 2002). Control points CP12 and CP13 were predicted to inhibit pig-nosed turtle movement at flows of <7.6 m^3/s.

7.3.2 Acoustic telemetry

We deployed 35 VR2W-180Hz acoustic receivers (Vemco, Halifax, Canada) along the main channel of the Daly River to track movements of pig-nosed turtles. Receivers were attached to bankside trees by 4 mm plastic-coated stainless steel cable, weighted with a short length of anchor chain, and held upright in the water column by SHE-10 net floats. The acoustic array consisted of two sections: (i) a 37.7 km downstream section of 20 receivers accessed from Oolloo Crossing (numbered 24–43), and (ii) a 26.3 km upstream section of 15 receivers (numbered 5–18) accessed from a site adjacent to Theyona gauging station on Black Bull Station and a site on Mentabie Station (Figure 7-1). Receivers were deployed at ~2 km intervals, except for receiver 9a, which was located between receivers 9 and 10 downstream of a large spring inflow and in an area known to be favoured by pig-nosed turtles. The intervening reach between these two sections (bracketed by receivers 18 and 24) could not be accessed to deploy receivers. Receivers in the downstream section were deployed in mid-July 2017, with two additional receivers (#42 and #43) deployed in mid-July 2018 to extend the downstream limit of the array; receivers in the upstream section were deployed in late June 2018. All receivers were removed on 25–28 September 2019.

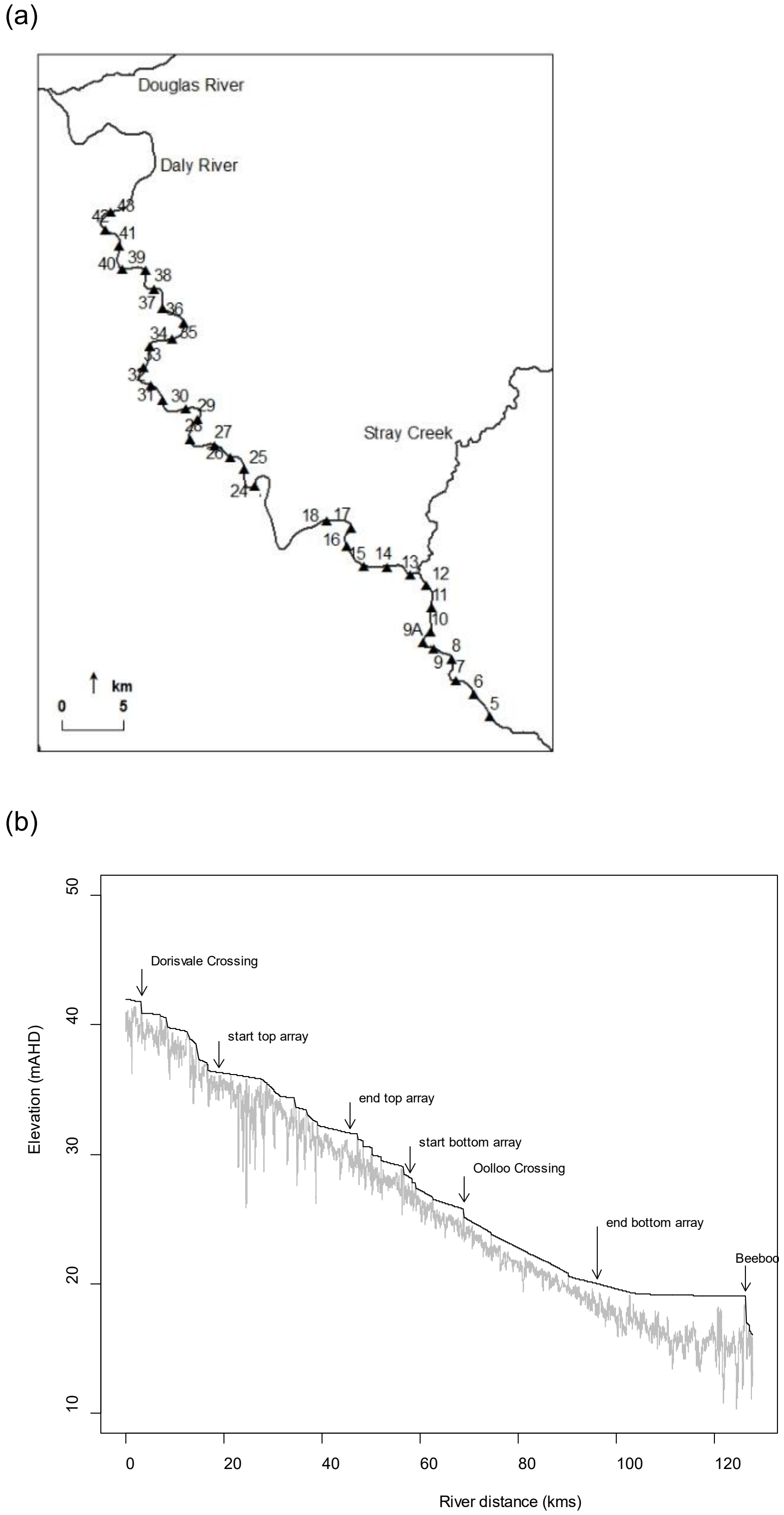


Figure 7-1. (a) Map of the study area in the Daly River, showing distribution of the receivers in the upstream Mentabie sub-array (5–18) and the downstream Oolloo sub-array (24–43). Oolloo Crossing is located between receivers 29 and 30; (b) Longitudinal profile of water level and bed elevation (metres above Australian Height Datum) of the study region from bathymetric surveys conducted in June 2016. Potential control points were located between receivers 29 and 30 (Oolloo Crossing), and between receivers 12 and 13 (CP13), and receivers 9A and 10 (CP12).

7.3.3 Turtle capture and tagging procedures

We captured 29 pig-nosed turtles: 15 at the Oolloo site and 14 at the Mentabie site. At the Oolloo study site, turtles were captured using a throw-net or landing net after being spotted from a small boat. At the Mentabie study site, most turtles were captured using baited traps. Turtle body weight was measured using a top-loading balance (DS-671 Digital Weighing Scale, Teraoka, China); straight-line carapace length was measured using large calipers (Haglof, Sweden); and stretched tail length beyond the edge of the carapace was measured using calipers (Figure 7-2). The sex of turtles was determined based on tail morphology and size, or by detection of the male hemipenes. Gravid females were not distinguished from non-gravid females. No juvenile pig-nosed turtles were seen or captured during this study. The smallest individual in this study was an adult male with a carapace length of 30.2 cm.

Pig-nosed turtles were tagged with V13 acoustic transmitters (Vemco, Halifax, Canada) by surgical implantation or by external attachment. Surgery was conducted in the field after training by wildlife veterinarians. Transmitters were inserted in the peritoneal cavity through the inguinal region of the right rear leg using approved surgical procedures. We administered doses of the antibiotic ceftazidime and the analgesic meloxicam by intramuscular injections in the foreleg prior to release at the point of capture.

7.3.4 Data analysis

The R software package V-Track (Campbell et al. 2012) was used to plot detection histories, and to calculate data on the timing and duration of residence and non-residence events, and the rate of movement. Residence events are defined as the period between the first and last transmission detected at a specific receiver. The timing of the event was initiated by the first detection at a new receiver and terminated if no further detections were recorded within a time-out window of 10 minutes. Non-residence events were defined as the period between the last and first detection between adjacent receivers.

For each turtle we calculated the linear home range, defined as the distance between upstream and downstream limits of detection; the cumulative distance moved as estimated by non-residence events; and the number of non-residence events. Data on the number of detections, linear home range, cumulative distance moved and number of non-residence events are presented for each turtle. Distance moved per day was calculated for each turtle for each month and presented for selected turtles using box plots. Temporal variability in rate of movement in relation to water temperature is shown for selected turtles with sufficient data.

Figure 7-2. Pig-nosed turtle being measured for carapace length on surgery table.

7.3.5 Movements by turtles across flow control points

Data on non-residence events for all turtles were used to identify passage events across three hydraulic flow control points (shallow, fast-flowing riffles) in the reach. We determined the last and first time of detection of turtles at loggers bracketing control points, only using data where the difference between detection times was less than a day. For each passage event, we extracted data on concurrent mean daily flow at Dorisvale and Theyona flow gauging stations. Minimum flows for observed passage events at each riffle were identified from these analyses.

7.3.6 Hydrodynamic modelling

Hydrodynamic modelling of a 16 km reach centred on the Mentabie site was undertaken by the Water Research Laboratory of the University of New South Wales, with field data provided by the NT Department of Environment and Natural Resources (see Section 3). A hydrodynamic model was constructed using the RMA-2 finite element model (King 2006) (Section 3; Appendix 3), and used to simulate the distribution of depth and velocity under 10 late dry-season flow scenarios (Table 7-1). Modelling outputs included raster files of depth and velocity with a cell size of 1 m^2. ArcGIS was used to map fragmentation of the river channel under the 10 flow scenarios, using depth thresholds of >0.4 m and >0.5 m. Maximum depth at two control points within the modelled reach (referred to as ‘CP12’ and ‘CP13’ in Georges et al. 2002) were derived using the interpolate line feature and rasters of the wetted area in each flow scenario.

Table 7-1. Parameters of 10 flow scenarios used in modelling of the distribution of depth and velocity in a 16 km reach centred on the Mentabie study area. All flows in cumecs.

Scenario	Dorisvale flow	Flow at top of modelled reach	Flow at bottom of modelled reach	Spring inflow
1	1	1.0	10.8	9.8
2	2	2.0	11.8	9.8
3	3	3.0	12.8	9.8
4	4	4.0	7.2	3.2
5	4	4.0	13.8	9.8
6	5	5.0	14.8	9.8
7	6	6.0	9.2	3.2
8	6	6.1	15.9	9.8
9	8	8.1	17.9	9.8
10	10	10.2	20	9.8

7.4 Results

7.4.1 Detection histories

A total of 843,824 detection records from 27 pig-nosed turtles were retrieved from the receiver array, with no detections recorded for two individuals (Table 7-2). The median period of detection (i.e. number of days between first and last detection) was 637.3 days (range 41.5–755.8; *n*=14) for turtles tagged at Oolloo, and 147.5 days (range 30.1–360.2; *n*=13) for turtles tagged at Mentabie. There was a prominent gap in detection records in the early months of 2018 during high wet-season flows (Figure 7-3). The few detection records at this time tended to coincide with low-flow events within the wet season. There is no similar gap in records in the wet season of 2018/2019, which was characterised by much lower discharge than the previous year. Externally attached transmitters on turtles tagged at Mentabie appear to have been shed by most turtles by mid wet season.

Table 7-2. Sex, length, capture date, number of detections, detection period (i.e. number of days between first and last detection), cumulative distance moved, linear home range and number of non-residence events for 29 pig-nosed turtles from two study locations in the Daly River.

Reach	ID	Sex	CL (cm)	Capture date	No. dets	Days	Cumulative distance (kms)	LHR (kms)	No. non-residence events
Oolloo	31441	M	30.2	11/7/17	38,788	755.8	56.2	26.1	24
Oolloo	31443	F	40.5	1/8/17	50,195	749.8	255.2	14.2	75
Oolloo	31442	F	33.3	12/7/17	79,050	676.9	49.7	2.1	24
Oolloo	31466	F	39.0	1/8/17	56,155	657.4	101.7	12.2	29
Oolloo	31467	F	37.2	1/8/17	55,447	653.2	70.3	6.1	34
Oolloo	31438	M	35.1	11/7/17	64,405	638.0	469.6	8.1	238
Oolloo	31440	M	35.0	11/7/17	59,385	634.8	368.2	6.0	190
Oolloo	31444	M	35.1	1/8/17	6,186	600.1	56.8	4.0	28
Oolloo	31439	M	36.5	11/7/17	47,903	655.6	292.1	3.8	146
Oolloo	31446	F	37.8	2/8/17	7,979	636.5	338.3	23.5	126
Oolloo	31445	M	34.2	2/8/17	3,076	543.2	107.2	4.2	42
Oolloo	31447	F	37.2	14/8/17	21,845	602.7	86.2	4.2	33
Oolloo	31463	F	39.0	14/8/17	42,715	462.6	22.4	1.9	12
Oolloo	51849	F	37.2	12/5/17	0	–	–	–	–
Oolloo	51850	F	38.4	12/5/17	936	41.5	9.3	2.3	4
Mentabie	24129	M	35.6	17/7/18	32,622	140.5	49.7	4.0	43
Mentabie	24128	M	35.1	17/7/18	42,332	179.7	162.1	4.9	105
Mentabie	24132	F	40.2	16/7/18	30,153	254.1	22.6	4.9	18
Mentabie	24131	M	34.8	17/7/18	31,313	360.2	237.7	4.9	156
Mentabie	24130	M	32.9	17/7/18	28,569	204.6	226.3	8.1	143
Mentabie	24127	F	38.1	17/7/18	4,932	30.1	42.4	9.1	22
Mentabie	24123	M	34.6	16/8/18	16,501	141.0	15.5	5.2	7
Mentabie	24117	F	39.4	16/8/18	10,467	121.6	48.2	14.1	22
Mentabie	24119	F	39.0	16/8/18	15,861	130.2	30.7	2.0	15
Mentabie	24118	F	38.9	16/8/18	20,135	147.5	53.3	2.0	26
Mentabie	24125	M	34.2	9/8/18	54,234	158.5	0	0	0
Mentabie	24115	M	33.4	16/8/18	1,097	136.9	0	0	0
Mentabie	24126	M	34.7	9/8/18	21,543	186.4	2.0	2.0	1
Mentabie	24124	M	34.4	9/8/18	0	–	–	–	–

CL = straight-line carapace length, dets = detections, LHR = linear home range.

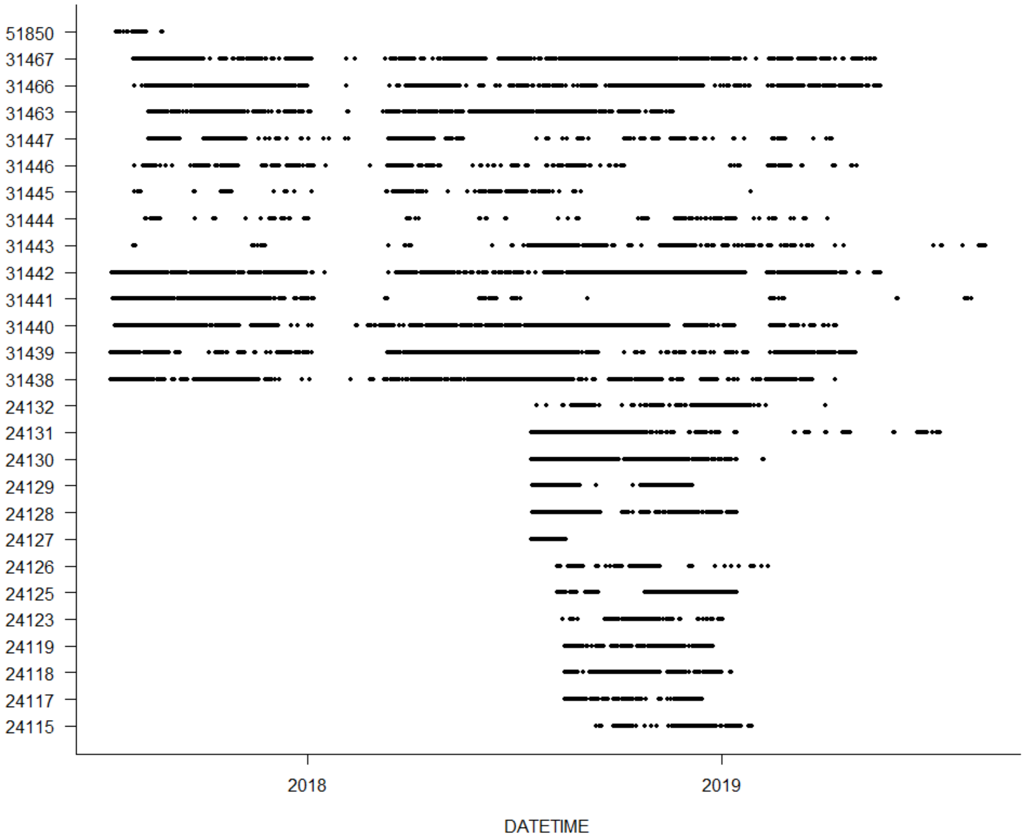


Figure 7-3. Detection histories for 27 pig-nosed turtles tagged with acoustic transmitters in the Daly River. Numbers on y axis are individual tag numbers on each monitored turtle.

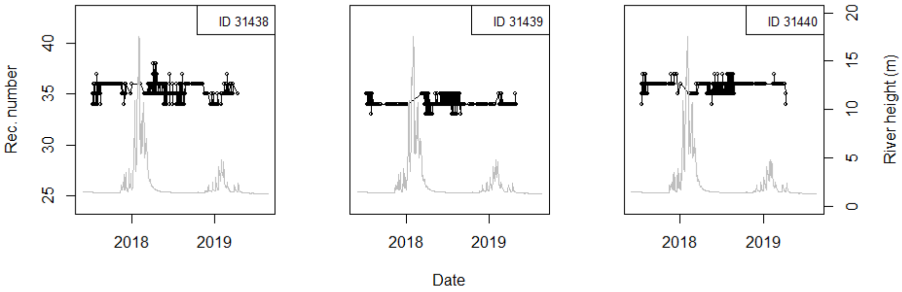
7.4.2 Movement patterns of selected individuals

Detection patterns from individuals of both sexes from both sites revealed considerable heterogeneity in movement behaviour (Figure 7-4). Some males from both sites shared similar movement features, such as a lack of long-distance forays, periods of intense short-range movement in the dry season, relative inactivity in the late dry season, and high site fidelity (Figure 7-4a,c). Three female pig-nosed turtles captured in the Oolloo study area undertook multiple long-distance excursions in the early and late wet seasons, with limited data on mid-wet-season behaviour, and a lack of intense repeated movements in the early to mid dry season (as shown by many males) (Figure 7-4b).

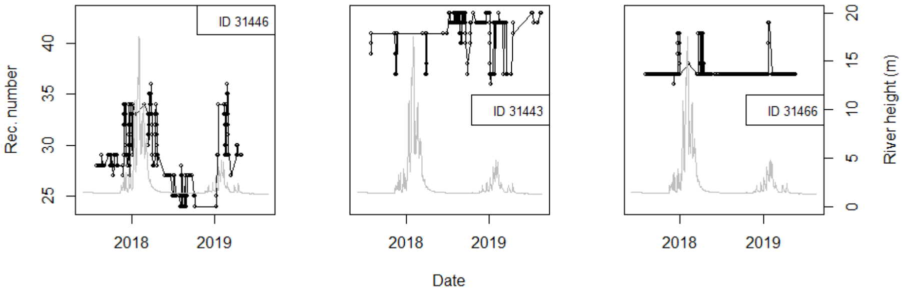
There is a single unambiguous example of a female undertaking a long-distance movement foray beyond its normally occupied home range. Turtle #24117 moved 14 km downstream in late October, passing through a number of riffles or flow control points, before returning within the vicinity of its starting location a month later (Figure 7-5d). There was no evidence of substantial forays by male pig-nosed turtles beyond their normally occupied home range, with the exception of the anomalous behaviour exhibited by #31441, which, unlike all other tagged turtles, failed to return to its normally occupied reach after a substantial downstream movement.

The complexity of movement behaviour by some individuals is well illustrated by #24130 (Figure 7-5c). This individual was tagged at Mentabie on 17 July 2018, spent much of the mid to late dry season near or upstream of the boundary of the high temperature spring inflow zone, and made several excursions beyond a probable nesting beach between receivers 7 and 8. This was followed by a phase of relative inactivity near receiver 9, and then movement downstream passing through a shallow riffle and sand-bed zone to receiver 11 in the vicinity of patches of *Vallisneria nana* until the early wet season, followed by a return upstream to near the boundary of the warm water zone, with the last detection at site 10 in the mid wet season.

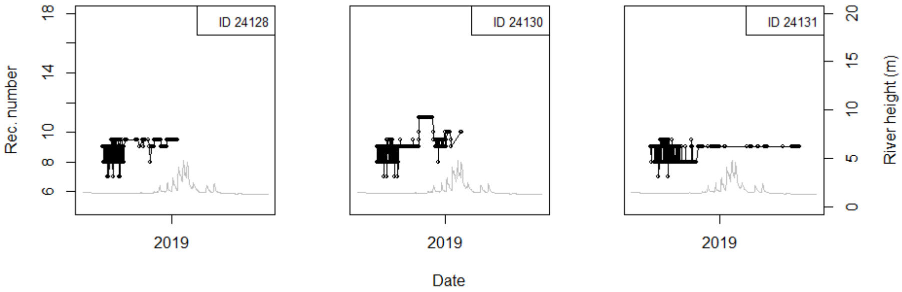
(a) Oolloo ♂



(b) Oolloo ♀



(c) Mentabie ♂



(d) Mentabie ♀

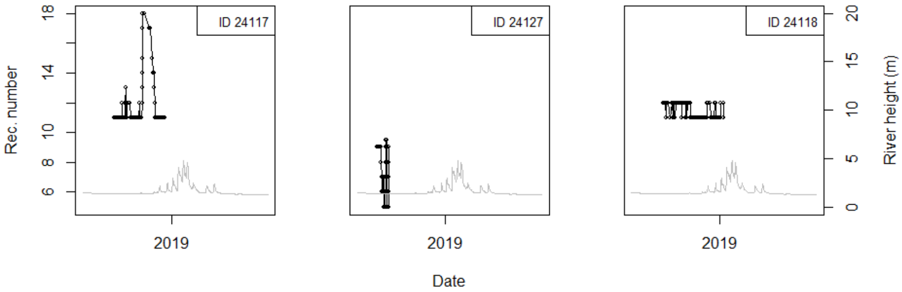
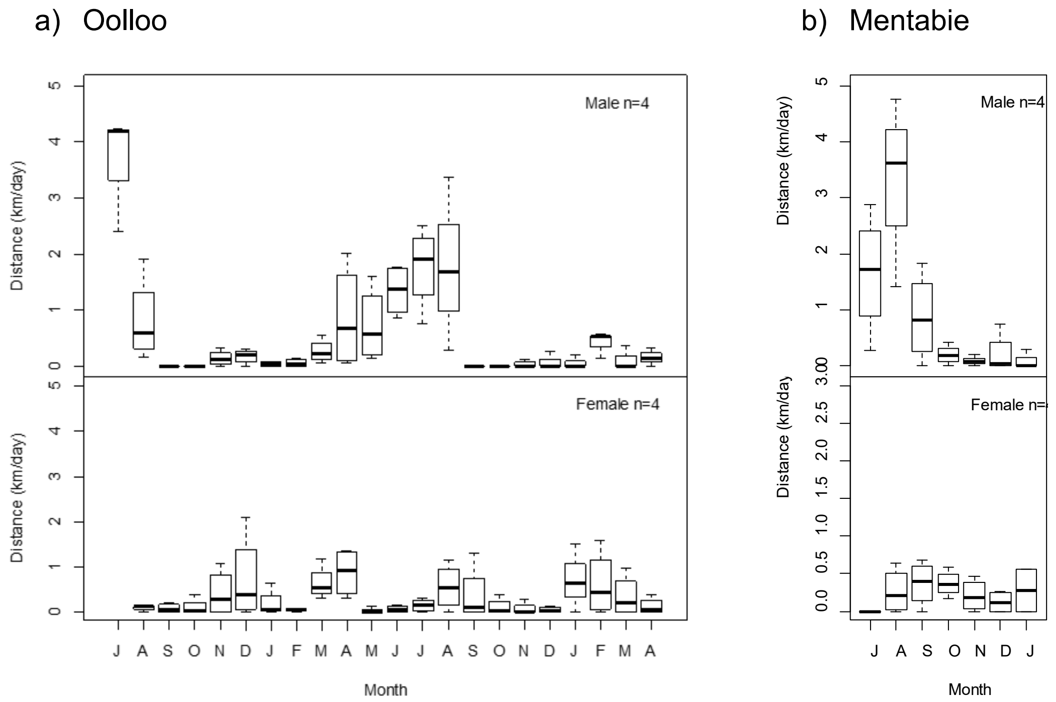


Figure 7-4. Movement plots for selected individual pig-nosed turtles of both sexes from Oolloo and Mentabie study areas.

There was considerable variability among individuals in total distance moved and linear home range (Table 7-2). There was no significant difference in linear home range between male and female pig-nosed turtles across reaches (*W*=55.5, *p*=0.23; female: 8.03 km ± 6.79 SD [standard deviation], *n*=12; male:4.25 km ± 2.52 SD, *n*=13; Levene's test of inequality of variances: *F*=11.01, *d.f.*=1, 23, *p*=0.003).

There were major differences between sexes in the monthly patterns of activity (Figure 7-5). Males were highly active within the 5-month period from April to August (early dry season) and were typically confined to <2 km (i.e. the distance between receivers) at other times of the year, with limited longitudinal movement during wet-season months. In contrast, female pig-nosed turtles undertook only limited movements during the early dry season, the period of peak male activity. There was substantial movement activity by females during both the early and late phases of the wet season in 2017/2018 and 2018/2019 (Figure 7-5). The rate of movement during non-residence events for individual turtles was also different between the sexes (Figure 7-6). Male activity was concentrated in dry-season months during the period of cooler water temperatures; female activity was mostly concentrated in the late dry-season and wet-season months.


a) Oolloo

b) Mentabie

Figure 7-5. Box plots of monthly variation in mean daily distance moved by male and female pig-nosed turtles from (a) the Oolloo study reach of the Daly River from July 2017 to April 2019 (male turtle IDs = 31438, 31439, 31440 and 31445; female turtle IDs = 31443, 31446, 31447 and 31466), and (b) the Mentabie study area of the Daly River.

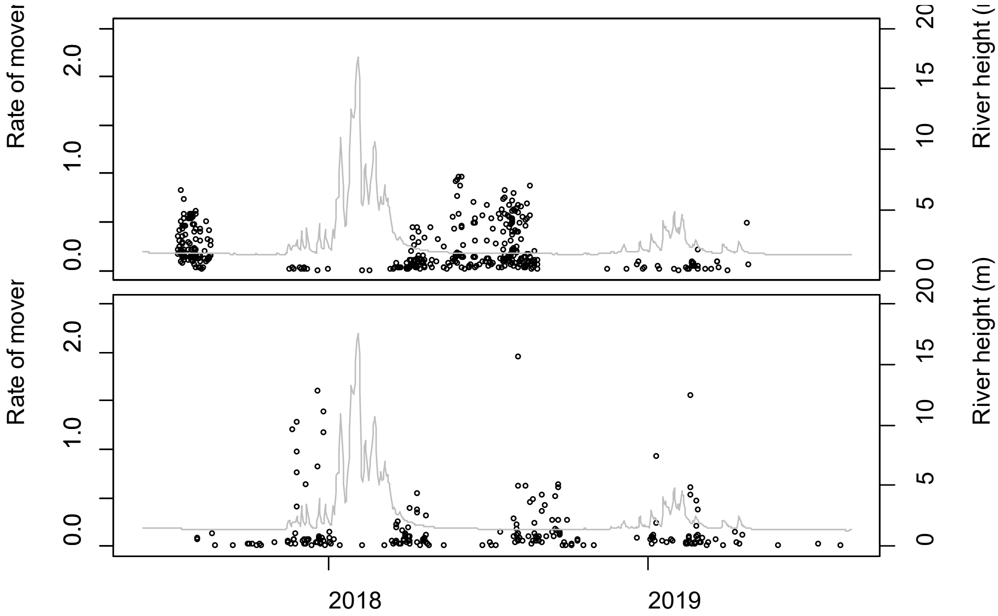


Figure 7-6. Seasonal variation in rate of movement (m/s) of male (top) and female (bottom) pig-nosed turtles from the Oolloo study area of the Daly River (male turtle IDs = 31438, 31439, 31440 and 31445; female turtle IDs = 31443, 31446, 31447 and 31466).

7.4.3 Movement across flow control points

There were 19 records of pig-nosed turtles moving between logger pairs bracketing flow control points (Table 7-3). Turtle #31446 crossed over the rock barrier at CP25 (Oolloo Crossing) on seven occasions in the 2017/2018 wet season from 26 November 2017 to 22 April 2018, and on four occasions in the 2018/2019 wet season. The minimum flow at which turtles were observed to move across CP25 was 33.2 m^3/s, with this crossing seemingly presenting a movement barrier to turtles during the mid to late dry season in most years. Two turtles, #24129 and #24130, crossed through the CP12 riffle on four occasions in the late dry season and early wet season, with a minimum mean daily flow at the time of crossing of 9.2 m^3/s (Dorisvale gauging station on 28 October 2018). Turtle #24117 crossed riffles including CP13 in the vicinity of the junction with Stray Creek on four occasions in the late dry season of 2018, with a minimum mean daily flow at the time of crossing of 9.9 m^3/s (Dorisvale gauging station on 23 October 2018).

Table 7-3. Mean daily flow (m^3/s) at Dorisvale gauging station (GS8140067) and Theyona gauging station (GS8140098) during passage of pig-nosed turtles across three flow control points (riffles) in the reach. Records with minimum flow values for each control point shown in bold. Flow at Oolloo predicted from the relationship between flow at Oolloo and Theyona. Q = discharge.

Turtle ID	Logger pair	Control point	Date	Dorisvale Q m^3/s	Theyona Q m^3/s	Oolloo Q m^3/s
24129	9.5_10	CP12	13/8/18	11.3	20.2	
24129	10_9.5	CP12	13/8/18	11.3	20.2	
24130	**9.5_10**	**CP12**	**28/10/18**	**9.2**	**18.2**	
24130	10_9.5	CP12	3/12/18	48.5	74.3	
31446	29_32	CP25 (Oolloo)	26/11/17	44.6	59.2	60.3
31446	30_29	CP25 (Oolloo)	8/12/17	42.6	58.8	59.9
31446	29_30	CP25 (Oolloo)	19/12/17	256.0	287.7	274.1
31446	30_29	CP25 (Oolloo)	21/12/17	68.3	89.4	88.5
31446	29_30	CP25 (Oolloo)	25/12/17	167.4	118.5	115.8
31446	29_31	CP25 (Oolloo)	12/4/18	40.4	51.3	52.9
31446	30_29	CP25 (Oolloo)	22/4/18	29.1	40.5	42.8
31446	30_29	CP25 (Oolloo)	17/2/19	49.0	64.7	65.4
31446	29_30	CP25 (Oolloo)	18/2/19	65.0	68.4	68.9
31446	**29_30**	**CP25 (Oolloo)**	**10/4/19**	**15.9**	**30.3**	**33.2**
31446	30_29	CP25 (Oolloo)	11/4/19	54.0	37.1	39.6
24117	12_13	CP13	12/9/18	10.2	18.8	
24117	13_12	CP13	13/9/18	10.3	18.8	
24117	**12_13**	**CP13**	**23/10/18**	**9.9**	**18.9**	
24117	13_12	CP13	21/11/18	14.6	26.2	

7.4.4 River fragmentation and movement thresholds

Using modelled hydrodynamic flow scenarios, the maximum depth at control points declines with flow, with a marked difference between scenarios for high and low groundwater levels (Figure 7-7). For example, predicted depth at CP12 with a flow at Dorisvale of 6 m^3/s and high groundwater level is 0.48 m, and at low groundwater level is 0.38 m. Both are less than the 0.5 m depth adopted as the threshold depth for passage by pig-nosed turtles through control points, and suggests that flows below 6 m^3/s risk dry-season isolation of pig-nosed turtles in specific reaches. The current flow recommendation for Dorisvale Crossing is 6.2 m^3/s (Erskine et al. 2003).

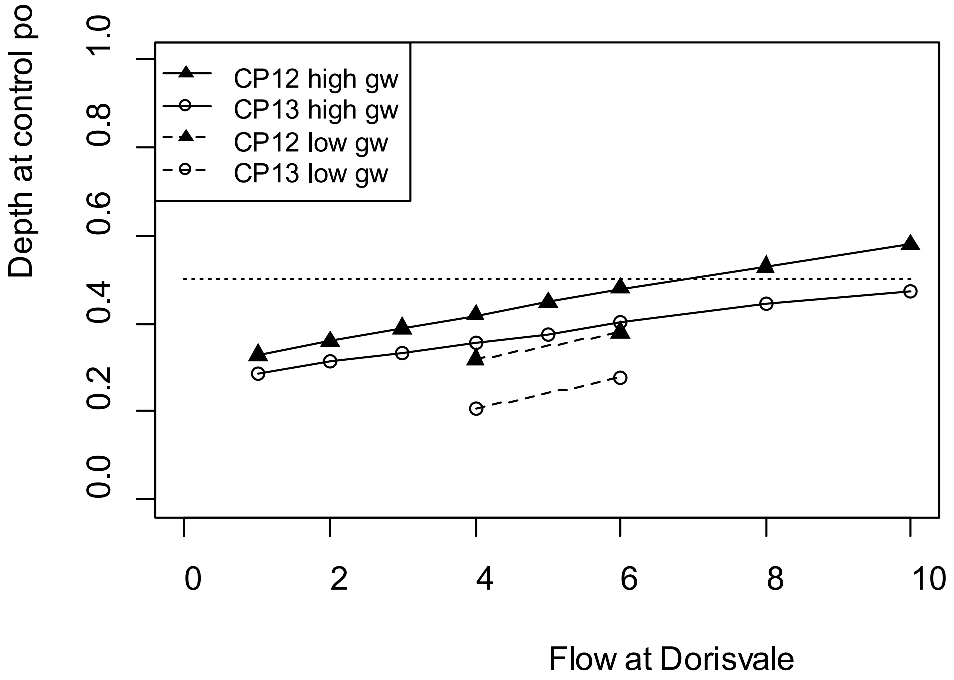


Figure 7-7. Relationship between flow (m^3/s) measured at Dorisvale and maximum depth at flow control points CP12 and CP13, at high and low groundwater (gw) levels, in the modelled reach in the Daly River. Depth derived from interpolated profiles.

7.5 Discussion

This study provides year-round information on the extent and timing of movements of adult pig-nosed turtles in the Daly River. The study highlights high variability in movement behaviour among individuals and confirms previous observations on sex-related differences (Doody et al. 2002). A high proportion of individuals of both sexes were resident (for >80% of the duration of residence times) within range of a single receiver. Few individuals ranged widely throughout the river, with the extreme example of female #31446 with a linear home range of 23.5 km. This is almost certainly a minimum estimate given the likelihood of unrecorded movements beyond the upper boundary of the receiver array (unpub data Dostine). Other females demonstrated wide-ranging behaviour during wet-season months. Despite this variability, the differences in temporal patterning in movement responses between sexes is unambiguous. Male pig-nosed turtles exhibited a consistent pattern of movement, with intense activity during the dry-season months of April to August, and relatively low activity from September to March. The timing of the cessation of intense activity by males in early September corresponds to an increase in mean daily water temperature and coincides with the reported commencement of nesting. Most large-scale movements by female pig-nosed turtles occurred in the late dry season and the wet season. The data presented here suggest that the period of active movement by females in the dry season occurs slightly later than for males. Males appear to be less active during the period that females are nesting. The biological explanation for these sex-based differences in the timing and extent of movements is not clear, but potentially relates to differential use of thermal springs for basking, and changes in the receptiveness of females to mating.

Pig-nosed turtles use riverbed thermal springs during dry-season months, when there is a temperature differential between groundwater input (springs; ~30°C) and upstream derived river water. Females may use springs more frequently than males (Doody et al. 2001). Of 157 observations of turtles resting on thermal springs, 93.6% were of females (Doody et al. 2001), though this result is biased by repeated observations of telemetered females. Individual females were observed to use thermal springs 79% and 85% of the time over a 9.5-hour period of intensive radio-tracking. Furthermore, there is some evidence that gravid females use thermal springs more frequently than non-gravid females (Doody et al. 2001). A potential explanation for the observed patterns may be that males are excluded from thermal basking opportunities by the larger-bodied females and are forced to search more extensively for vacant or unattended hotspots.

The average home ranges of males and females observed in this study are within the range of estimates from previous studies based on radio-tracking but cannot be directly compared given differences in methodology between studies. In a previous study, Doody (2002) used 95% of radiolocation points to define the home range of individual turtles, that is, excluding 2.5% of the number of points from the lower and upper range of values. Estimates of linear home range in the present study are derived at a much coarser scale and are likely to underestimate home range due to undetected movements beyond receivers at the boundary of the home range. Nevertheless, linear home range estimates are comparable between these studies: females 8.3 km versus 8.03 km; males 3.2 km versus 4.25 km. Several aspects of the movement ecology of this species remain to be explored, in particular, wet-season habitat use, and habitat use and spatial ecology of hatchlings and juveniles.

Published knowledge of wet-season habitat use by pig-nosed turtles is confined to observations of aerially tracked turtles, which clustered in flooded riparian forest in and near small tributary creeks during the wet season (Doody 2002). This study significantly extends our knowledge of the extent and frequency of movements of pig-nosed turtles within the river channel in wet-season months. Several females undertook long-distance forays in the early wet season, soon after the first minor flow pulses of the wet season, and again in the late wet season. However, floodplain movements may potentially occur throughout the entire wet season, and the lack of evidence of movements is probably due to poor detection on receivers within the channel system (not on the floodplain) during periods of high water levels. Alternatively, pig-nosed turtles may be occupying flooded riparian forest, as previously described for some individuals by Doody (2002). Flooded riparian habitats provide a range of resources not normally available during the dry season, including the fruit and figs of riparian trees, or roosts of flying foxes. Elsewhere within their range in the NT, pig-nosed turtles have been described to have a generalised diet including the fruit of riparian trees and carrion (Georges & Kennett 1989; Georges et al. 1989). Wide-ranging movements by females in the wet season may be searches for resources that are spatially discrete and temporally unpredictable. Opportunities to access these higher energy resources may be fleeting, and depend on fluctuating water levels as well as temporal and spatial variability in fruiting phenology (Bach 2002). There is evidence that reproductive parameters, such as egg and clutch size, and the timing of laying are positively related to the magnitude of the previous wet season (Doody 2002), and presumably also to the duration of the period of access to resources available in the flooded riparian zone. Male pig-nosed turtles in our study seemingly did not display similar patterns of movement as observed for females during the wet season, lending some support to the hypothesis that females require access to food-rich riparian habitats to support energy requirements for breeding.

The ecology of post-hatchling pig-nosed turtles is poorly known. Pig-nosed turtle nests are located on sandy banks adjacent to the river channel (Doody et al. 2003a,b). Hatching is triggered after termination of embryonic diapause by the flooding of nests in the early wet season (Doody 2002), and the high turbidity of these flows may offer protection from visual predators such as barramundi, *Lates calcarifer* (Abrahams & Kattenfeld 1997; Georges et al. 2008a,b; Townsend 2019). However, the fate of post-hatchling juveniles is largely a mystery. It has been hypothesised that pig-nosed turtles have an amphidromous life cycle, where young are transported to estuarine or marine environments prior to a return migration. Sub-adult individuals have been rarely observed despite extensive fieldwork in the Daly River over several decades. The smallest individual in this study measured 30.2 cm (carapace length), though Welsh et al. (2017) recorded the presence of juveniles (6 of 74 animals captured) in a dietary study in 1998, following record flooding of the Katherine River. The species most likely has periodic recruitment allied to major flood and resource pulses, driven by large wet-season events, as has been described for other species in northern Australia such as the freshwater sawfish (Lear et al. 2019) and barramundi (see Section 10; Crook et al. submitted). Elucidation of the relationship between pig-nosed turtle recruitment and inter-annual variation in flow regime is a research priority.

Groundwater inputs to the Daly River play a key role in the ecology of pig-nosed turtles. Dry-season flow is maintained by groundwater from the Cretaceous sandstone, Oolloo dolostone and Tindall limestone aquifers (Northern Territory Government 2019b). The core habitat of pig-nosed turtles in the Daly River encompasses the zone with high spring inflows, warmer river temperature, and extensive, dense ribbonweed meadows, with the core habitat commencing at the boundary of the Cretaceous sandstone and Oolloo dolostone. The carbonate-rich spring waters precipitates suspended material in the water column in the early dry season, leading to high light attenuation into the water and subsequently driving strong primary production in the river (Webster et al. 2005). Groundwater inputs also influence the thermal regime of the entire river. This thermal spring input into the river is likely to provide a critically important resource for pig-nosed turtles, allowing them to bask on the warmer water patches at a local scale, and regulate and maintain their body temperature (thermoregulation). Thermal springs may also provide a critical resource for other aquatic taxa (see, for example, Laist & Reynolds 2005), such as potential increased growth rates for juvenile fish. The ecological importance of riverbed thermal springs in the Daly River requires further investigation.

The ecological consequences of groundwater extraction for agriculture include reduced dry-season flows, leading to habitat loss and disruption of functional connectivity (King et al. 2015). Species that rely on flow-dependent habitats, and/or which move widely throughout the river to locate spatially isolated specific habitats (such as nesting beaches, feeding areas and basking areas for pig-nosed turtles), may be negatively impacted. For pig-nosed turtles, these impacts potentially include a decline in extent, or quality, of key feeding habitat; loss or decline in the number of thermal springs; and loss of access to nesting beaches. However, vulnerability to these impacts is not spatially uniform throughout the reach. Throughout most of the reach downstream of Oolloo Crossing, there are few flow control points and no impediments to movement. The upper reaches of the core habitat area around Mentabie Reach have higher gradients, with several control points and greater opportunity for disruption of connectivity. The extent of risk posed by disruption of connectivity may have been over-emphasised for the low-gradient reach of the core habitat area. In this zone, nesting frequently occurs within the occupied home range, and there were few substantial movements outside normally occupied habitat (Doody et al. 2002). However, reduced flows will increase exposure of ribbonweed meadows on the pavements of the lower bedded units of Oolloo dolostone, with the threshold for rapid change in exposure estimated at 12 m^3/s (Rea et al. 2002). Disruption of connectivity is more likely to occur in the upper, high-gradient reaches of the study area.

The maintenance of healthy populations of pig-nosed turtles should be one of the key indicators of the success of water-resource management of the Daly River system. Indeed, meeting the strict habitat requirements of pig-nosed turtles is likely to provide protection to a range of species with less stringent requirements (Doody et al. 2000); therefore, the pig-nosed turtle is an umbrella species. In general terms, water management should seek to avoid an increase in the frequency of low-flow years, maintain spring inflows and the thermal regime in the core habitat area, maintain variability in dry-season flows, and avoid decoupling of wet-season and dry-season flows. This project obtained limited data on the depth threshold for movement across riffles by pig-nosed turtles. A quantitative relationship between depth and the probability of passage requires data collected during periods of lower flows (and water levels) than were available during this study. Minimum flows at which passage movements were observed were 33.2 m^3/s at Oolloo Crossing, 9.2 m^3/s (measured at Dorisvale) at CP12 and 9.9 m^3/s (measured at Dorisvale) for CP13. Oolloo Crossing probably presents a barrier to dry-season movement by pig-nosed turtles in most years. Modelled depths at control points CP12 and CP13 at this time were ~0.5 m, lending support to the threshold adopted in previous studies. Modelled depths are sensitive to regional groundwater levels, and flow recommendations need to be cognisant of the importance of variation in groundwater inputs. The current flow recommendation for faunal passage in the Daly River (Erskine et al. 2003) may require marginal upward revision during years of low groundwater levels.

We recommend ongoing research on this species with a focus on the drivers of recruitment, the dynamics of ribbonweed meadow loss and recovery, wet-season habitat use, and the ecology of hatchlings and juveniles. In the absence of long-term data on population size or recruitment, we suggest that a cautious approach to water-resource management in the region is essential.

8. Broadscale movements of adult sooty grunter, with reference to flow requirements

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This research is being prepared as a separate publication.

8.1 Background

Many rivers across northern Australia are experiencing increased demands for consumptive water use for agriculture and mining, which has the potential to alter the flow regimes of rivers and to adversely affect aquatic fauna (King et al. 2015). The research described in this chapter focuses on the mid-reaches of the Daly River catchment: a region that has experienced a rapid increase in agricultural development (particularly irrigated horticulture) over recent decades. Dry-season river flows in the study area are entirely dependent on discharge from the underlying Tindall Limestone Aquifer and are influenced by the amount of abstraction allowed from the aquifer under water extraction licences. A recent assessment of water allocation arrangements in the catchment found that some aquifers are over-allocated and that further quantification of the environmental and cultural water requirements of the system is urgently needed to support sustainable management (Northern Territory Government 2019a,b). A particular concern for the sustainable management of the Daly River is that increased groundwater abstraction may reduce the amount of water flowing over shallow riffles in the dry season, potentially reducing habitat availability and longitudinal connectivity in the system and, thereby, adversely affecting fish, turtles and other aquatic fauna.

The Daly River contains a diverse fish fauna of at least 94 species, including three elasmobranch species of conservation significance (Pusey et al. 2020). One of the most common and widespread fishes in the Daly River is the sooty grunter (also commonly known as black bream). This species can exceed 450 mm SL and occurs in permanent river reaches, large intermittent streams and floodplain wetlands across the wet-dry tropics of Australia and southern New Guinea (Pusey et al. 2004). Sooty grunter are of high significance as a food source for Aboriginal people across northern Australia (Finn & Jackson 2011; Jackson et al. 2014) and are also commonly targeted by recreational fishers (Pusey et al. 2004).

In the wet-dry tropics, male sooty grunter mature at ~200 mm fork length (FL) and females at 250–320 mm FL (Pusey et al. 2004), and they appear to undertake an ontogenetic habitat shift, with small fish utilising shallow, fast-flowing riffle habitats and larger fish preferring deep, slow-flowing pools (Pusey et al. 2004; Chan et al. 2012; Keller et al. 2019; Crook et al. 2021; Section 6 of this report). Although there are some previous anecdotal observations of sooty grunter movements (Bishop et al. 1995; Pusey et al. 2004), to our knowledge there have been no previous studies of individual-level movements for this species, and the frequency and spatial scales of movement remain unclear.

8.2 Aims and objectives

The aim of this study was to address this important knowledge gap by using acoustic telemetry to document the broadscale movements of sooty grunter. The results of the study are discussed in relation to the potential vulnerability of sooty grunter to reduced flow connectivity that may result from future increases in consumptive water use in the Daly River catchment.

8.3 Methods

8.3.1 Acoustic receiver array

An array of 35 acoustic receivers (VR2W-180 kHz, Vemco, Halifax, Canada) was deployed along the main channel of the Daly River (Figure 8-1) from January 2017 to May 2019. Receivers were attached to bankside trees by 4 mm plastic-coated stainless steel cable, weighted with a short length of anchor chain, and held upright in the water column by SHE-10 net floats. The acoustic array consisted of two sections: (i) a 37.7 km downstream section of 20 receivers accessed from Oolloo Crossing (‘Oolloo Reach’, numbered 24–43), and (ii) a 26.3 km upstream section of 15 receivers (‘Mentabie Reach’, numbered 5–18) accessed from a site adjacent to Theyona gauging station on Black Bull Station and a site on Mentabie Station (Figure 8-1 and Figure 8-2). Receivers were deployed at ~2 km intervals, except for receiver 9a, which was located between receivers 9 and 10 downstream of a large spring inflow. The intervening reach between these two sections could not be accessed to deploy receivers. Receivers in the downstream section were deployed in mid-July 2017, with two additional receivers (#42 and #43) deployed in mid-July 2018 to extend the downstream limit of the array; receivers in the upstream section were deployed in late June 2018 and removed 25–28 September 2019.

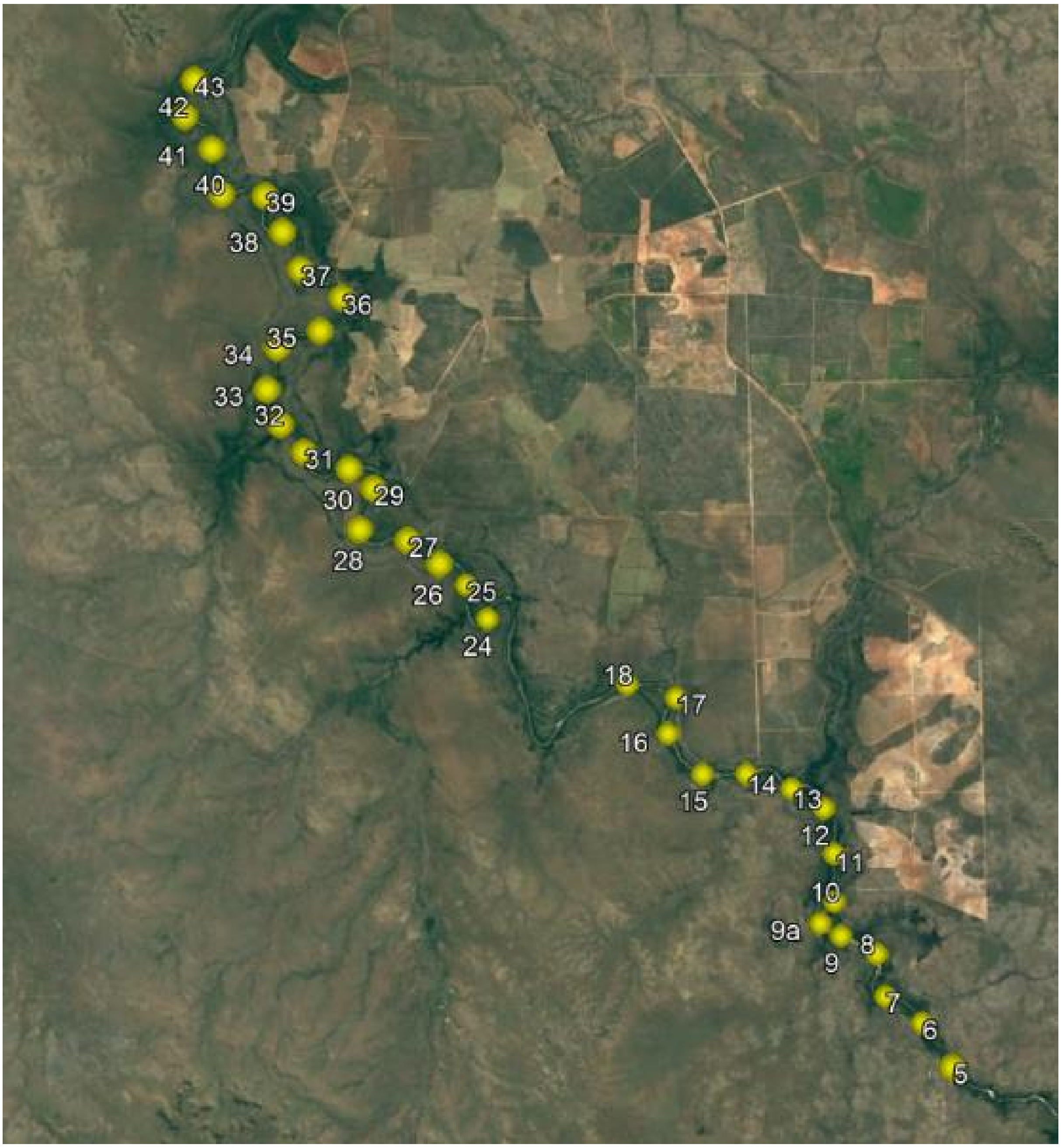


Figure 8-1. Google Earth image showing the study area in the Daly River and the distribution of the acoustic receiver array (yellow dots).

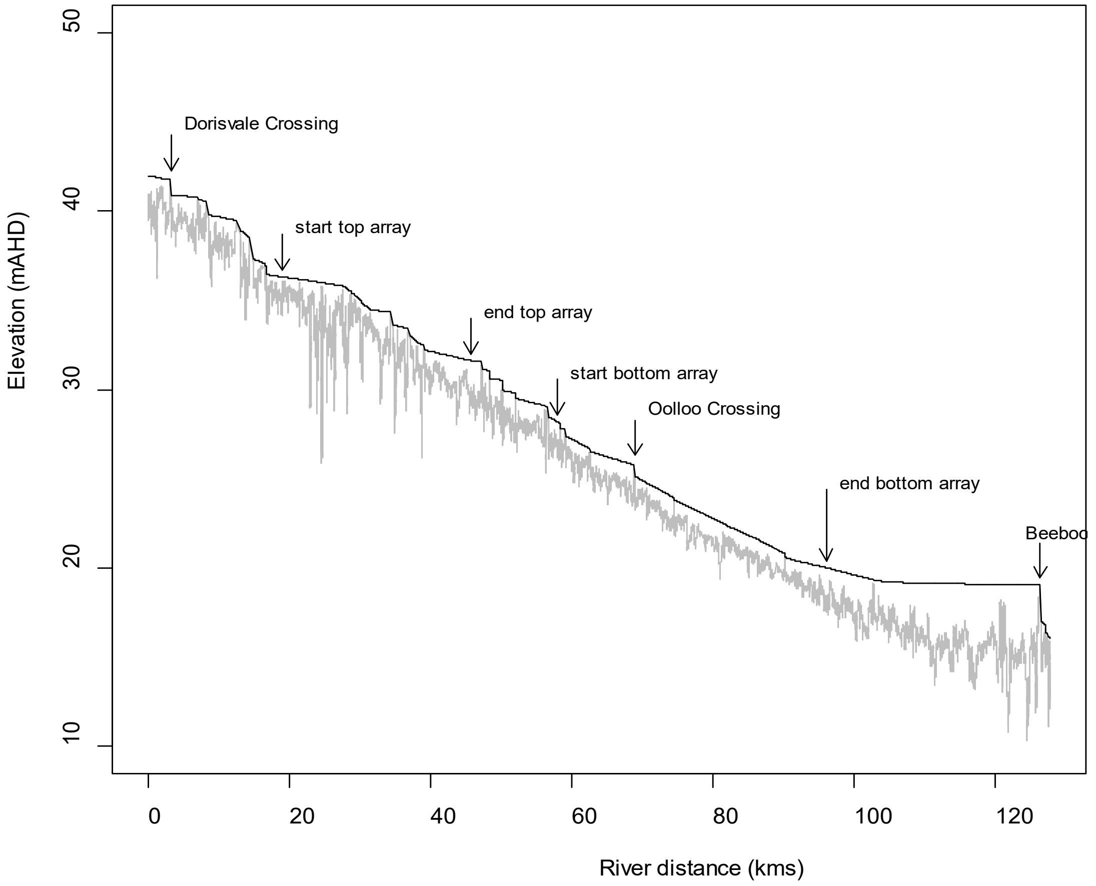


Figure 8-2. Longitudinal profile of water level and bed elevation (metres above Australian Height Datum) of the study region from bathymetric surveys conducted in June 2016.

8.3.2 Fish collection and tagging

Fish for tagging with acoustic transmitters were collected by angling using baited barbless hooks. SL of all fish was measured to the nearest 1 mm and weight measured to the nearest 1 g. Transmitters (V7-1L, Vemco, Halifax, Canada) were surgically implanted into the peritoneal cavities of 31 sooty grunter on 10–13 July 2017 and 11–17 July 2018 (Table 8-1). Collected fish were anaesthetised with Aqui-S and placed in a V-shaped foam holding cradle lined with wetted absorbent cloth (Figure 8-3). The transmitters were disinfected by soaking in Betadine and then Hibitane, and rinsed with sterile saline prior to implantation. Five to six scales were removed from the ventral surface ~10 cm anterior to the anal vent and slightly offset from the midline. An incision of ~25 mm length was made in an anterior–posterior orientation into the peritoneal cavity using a sterilised scalpel. The transmitters were inserted into the peritoneal cavity through the incision, which was then closed with a single layer closure using 2–3 interrupted sutures placed into the musculature 3–4 mm beneath the skin (2.0 metric, absorbable monofilament, 26 mm swaged needle) (Figure 8-3). Betadine was then applied to the area. An assistant irrigated the gills using fresh river water throughout the procedure (~4 min). After the procedure, fish were held in fresh river water until normal posture and gill movement resumed and were then released at the site of collection.

Figure 8-3. Surgical implantation of acoustic transmitters into sooty grunter showing V-shaped foam holding cradle lined with wetted absorbent cloth used for surgery (top) and fish with sutures used to close the incision (bottom).

Table 8-1. Details of individual fish tracked during the study.

Tagging date	Tagging reach	Fish ID	Weight (g)	FL (mm)	SL (mm)
12/7/17	Oolloo	630	101	174	146
12/7/17	Oolloo	631	187	213	186
10/7/17	Oolloo	632	670	320	268
10/7/17	Oolloo	633	160	200	169
12/7/17	Oolloo	634	155	208	172
12/7/17	Oolloo	635	140	200	168
12/7/17	Oolloo	636	530	284	240
12/7/17	Oolloo	637	265	234	196
12/7/17	Oolloo	638	171	203	173
12/7/17	Oolloo	639	433	284	236
12/7/17	Oolloo	640	161	205	173
12/7/17	Oolloo	641	422	275	235
12/7/17	Oolloo	642	156	209	175
12/7/17	Oolloo	643	81	164	137
13/7/17	Oolloo	644	402	276	233
13/7/17	Oolloo	645	148	205	175
17/7/18	Mentabie	9879	295	250	211
17/7/18	Mentabie	9880	295	249	211
17/7/18	Mentabie	9881	185	223	189
11/7/18	Oolloo	9882	95	173	144
16/7/18	Mentabie	9883	390	274	230
16/7/18	Mentabie	9884	160	205	172
17/7/18	Mentabie	9885	270	245	206
17/7/18	Mentabie	9886	230	232	196
17/7/18	Mentabie	9887	230	232	194
17/7/18	Mentabie	9888	390	271	228
17/7/18	Mentabie	9889	230	226	190
11/7/18	Oolloo	9890	100	180	150
11/7/18	Oolloo	9891	80	163	135
11/7/18	Oolloo	9892	160	203	172
11/7/18	Oolloo	9893	330	261	220

FL = fork length, SL = standard length

8.4 Results and discussion

8.4.1 General movement patterns

Detections were recorded for 29 of the 31 sooty grunter tagged with acoustic transmitters over the course of the study (Table 8-2, Figure 8-4). A total of 328,219 detections was recorded, with individual fish being detected from 1 to 54,624 times (average detections = 10,588). Aside from a single fish that was detected only once on the day it was tagged (Fish ID 9890), the minimum tracking duration was 93 days, and the maximum tracking duration was 382 days.

Table 8-2. Summary of tracking results for sooty grunter in the Daly River.

Tagging date	Tagging reach	Fish ID	No. detections	Final detection	Tracking duration (d)	Cumulative distance (km)	Extent (kms)
12/7/17	Oolloo	630	12,512	31/12/17	173	0	0
12/7/17	Oolloo	631	665	26/7/18	379	43.4	21.7
10/7/17	Oolloo	632	3,246	15/11/17	128	45.6	25.9
10/7/17	Oolloo	633	251	31/12/17	175	28.3	28.3
12/7/17	Oolloo	634	10,890	18/11/17	129	6.1	2.0
12/7/17	Oolloo	635	436	11/5/18	304	31.6	12.1
12/7/17	Oolloo	636	958	11/12/17	153	16.2	2.0
12/7/17	Oolloo	637	38,691	4/1/18	177	0	0
12/7/17	Oolloo	638	6,519	7/7/18	360	0	0
12/7/17	Oolloo	639	78	12/10/17	93	0	0
12/7/17	Oolloo	640	28,185	28/7/18	381	71.5	7.5
12/7/17	Oolloo	641	7,883	28/7/18	382	7.6	3.8
12/7/17	Oolloo	642	26,027	10/12/17	151	0	0
12/7/17	Oolloo	643	17,084	28/7/18	382	31.9	16.0
13/7/17	Oolloo	644	5,685	2/1/18	174	35.3	13.5
13/7/17	Oolloo	645	140	11/1/18	182	14.2	9.7
17/7/18	Mentabie	9879	3,740	20/12/18	156	0	0
17/7/18	Mentabie	9880	22,383	23/6/19	342	0	0
17/7/18	Mentabie	9881	132	19/11/18	126	9.1	9.1
11/7/18	Oolloo	9882	0	–	–	–	–
16/7/18	Mentabie	9883	54,624	1/8/19	382	64.5	9.1
16/7/18	Mentabie	9884	28,314	12/2/19	212	6.8	6.9
17/7/18	Mentabie	9885	6,473	1/8/19	380	36.7	8.1
17/7/18	Mentabie	9886	1,853	30/4/19	287	2.2	1.1
17/7/18	Mentabie	9887	47	30/4/19	287	0	0
17/7/18	Mentabie	9888	10,036	23/11/18	129	9.0	6.9
17/7/18	Mentabie	9889	32,533	2/8/19	382	0	0
11/7/18	Oolloo	9890	1	11/7/18	–	0	0
11/7/18	Oolloo	9891	4,611	26/11/18	139	12.0	6.0
11/7/18	Oolloo	9892	0	–	–	–	–
11/7/18	Oolloo	9893	4,222	21/11/18	134	57.6	57.6

A diversity of movement behaviours was exhibited by the tagged fish (Figure 8-4). The majority of fish exhibited limited movement over the study period, with 14 fish (48%) moving over longitudinal ranges of <5 km and an additional eight (28%) moving <10 km (Table 8-2, Figure 8-5). The remaining seven fish (25%) moved over extents >10 km, and of these, only one fish moved >30 km. This fish (9893, Figure 8-4) was recorded more than 4,000 times at the same location between July and November 2017, before undertaking a rapid downstream migration of >57 km out of the study reach on 18 November 2017. Two other fish (9881 and 9888, Figure 8-4) also made rapid downstream migrations out of the study reach at around the same time in late November 2018.

The cumulative distance moved by tagged fish (i.e. the sum of distances between detections from different receivers) ranged from 0 (i.e. fish only detected on a single receiver, n=10) to 71.5 km (Table 8-2). The fish with the highest cumulative movement of 71.5 km (640, Figure 8-4) made a series of return movements among three receivers in April 2018, but exhibited restricted movement at other times over the study period. Other fish with high cumulative movement distances were those that undertook large-scale movements over relatively short periods of time, most commonly during the early wet season (e.g. 632, 633, Figure 8-4). No fish exhibited wide-ranging behaviour for extended periods of time. The number of non-residence events (i.e. detections on a different receiver from the previous detection) was highest during increasing flows in the early wet season (November and December), although there were smaller peaks in non-residency on lower flows in April and August (Figure 8-6).

Of the 16 fish that were tagged in the Oolloo Reach in July 2017, seven (44%) exhibited clear homing behaviour: that is, they moved away from established home ranges for a period of time before returning to their previous locations (631, 632, 635, 640, 641, 643, 644, Figure 8-4). Interestingly, only two (13%) of the 15 fish tagged in July 2018 in the Oolloo and Mentabie reaches exhibited evidence of homing behaviour (9883, 9885, Figure 8-4), despite these fish being tracked over similar lengths of time as the 2017 fish. The lack of movement away from established home ranges and subsequent homing behaviour is potentially related to the much lower river discharge in the 2018/2019 wet season than the previous year. As mentioned, non-residence events occurred most commonly during increasing flows in the early wet season, and it is possible that the lower flows in 2018/2019 provided less cues for large-scale movement by sooty grunter.

Our findings of strong site fidelity, increased movement during high flows, and homing behaviour by sooty grunter are consistent with a concurrent acoustic tracking study of this species in Magela Creek on the East Alligator River system (Crook et al. 2021). In that study, ~20% of sooty grunter tagged during the dry season in a main channel billabong in the upper reaches of Magela Creek migrated 20 km downstream into the sand channels within the Ranger Uranium Mine lease during the wet season. As flows began to decline towards the end of the wet season, these fish moved back upstream to their previous home ranges, where they spent the dry season. This pattern of large-scale movement followed by directed homing behaviour was repeated in consecutive years. The strong site fidelity, increased movement during high flows, and homing behaviour exhibited by sooty grunter are also consistent with previous studies of other species of riverine fish elsewhere in Australia (e.g. Golden perch, *Macquaria ambigua*, O'Connor et al. 2005; Murray cod, *Maccullochella peeli peeli*, Koehn et al. 2009; barramundi, *Lates calcarifer*, Crook et al. 2017) and internationally (channel catfish, *Ictalurus punctatus*, Pellet et al. 1998; striped bass, *Morone saxatilis*, Wingate & Secor 2007).

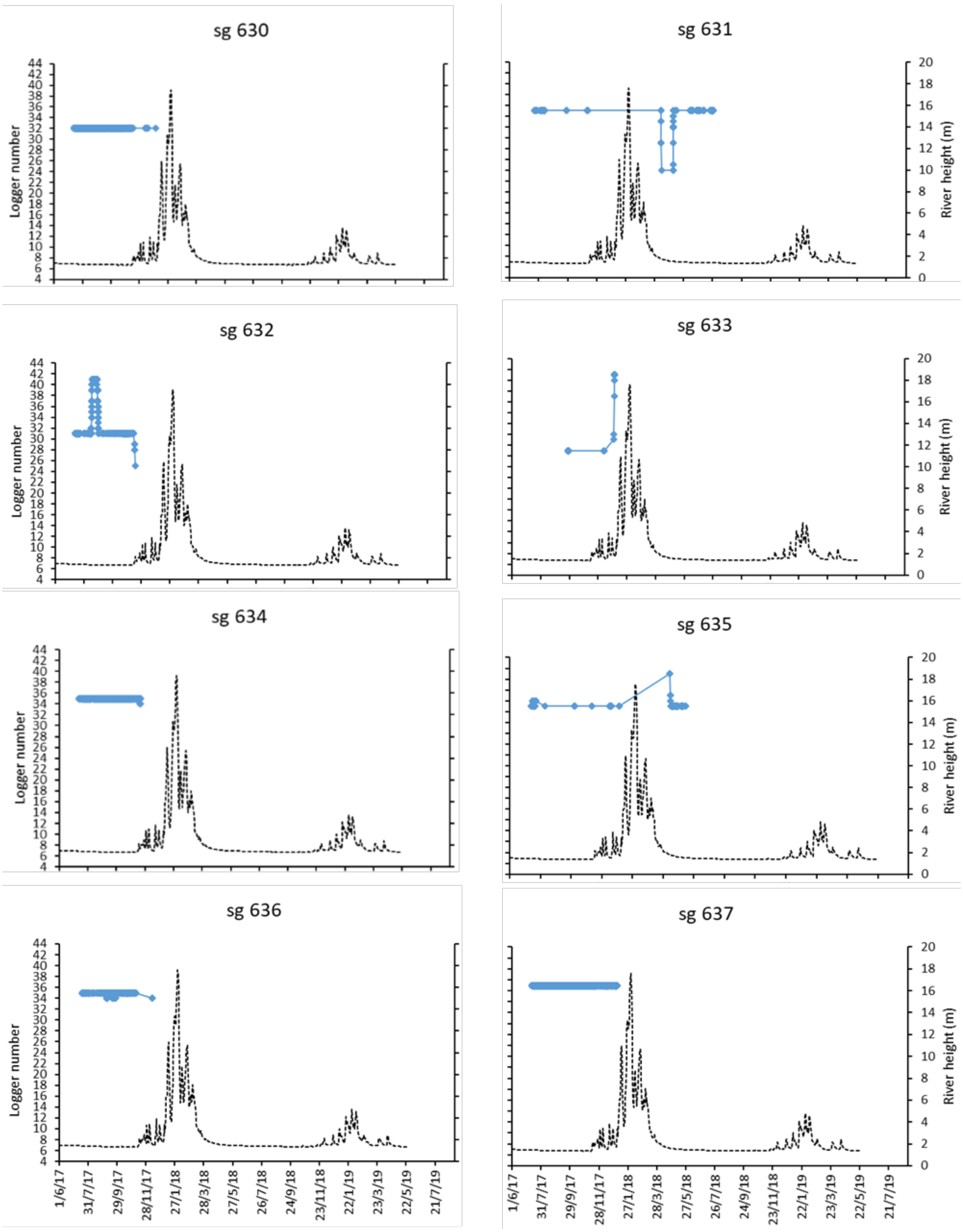


Figure 8-4. Movements of individual sooty grunter over time and in relation to river height (continues on following pages).

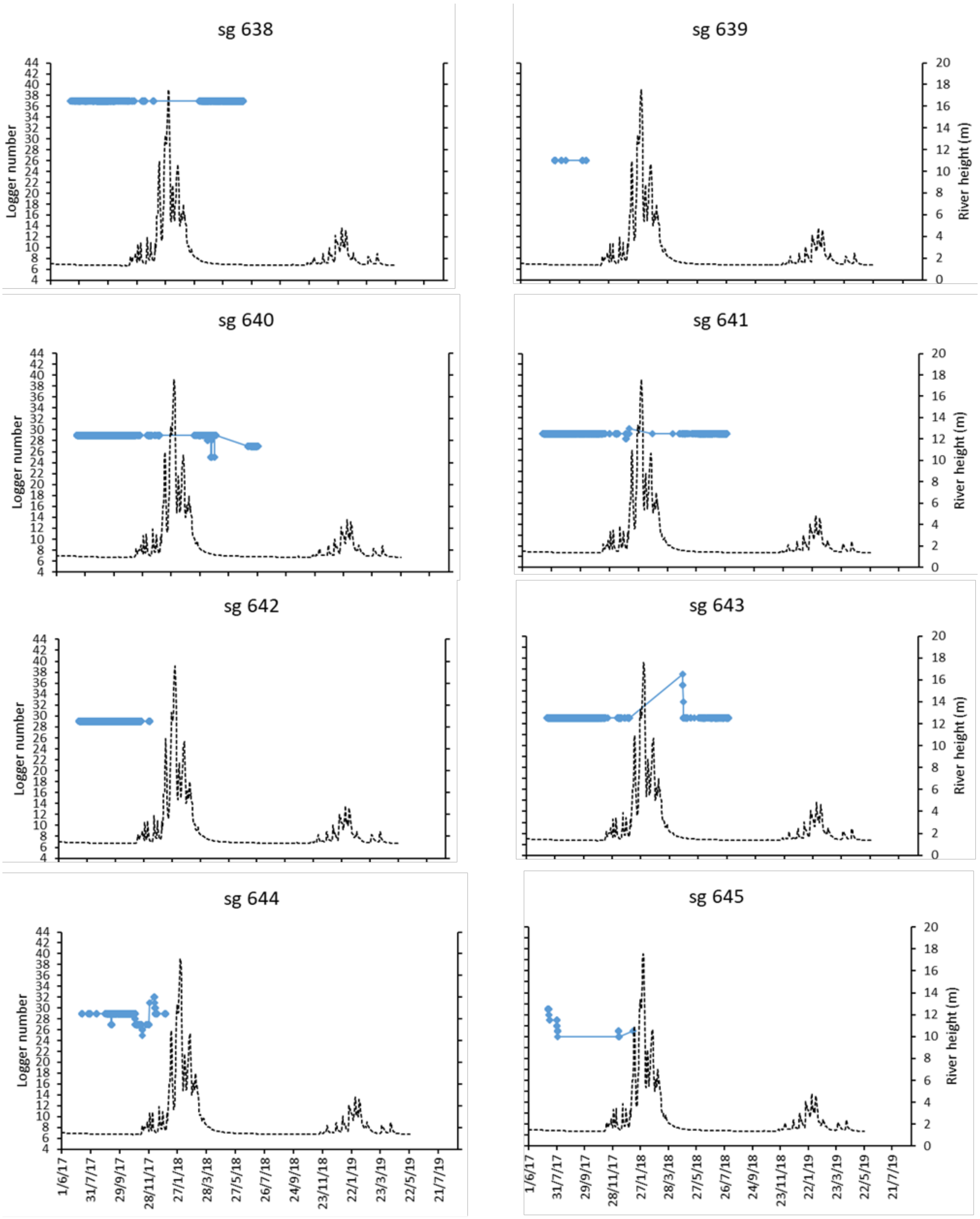
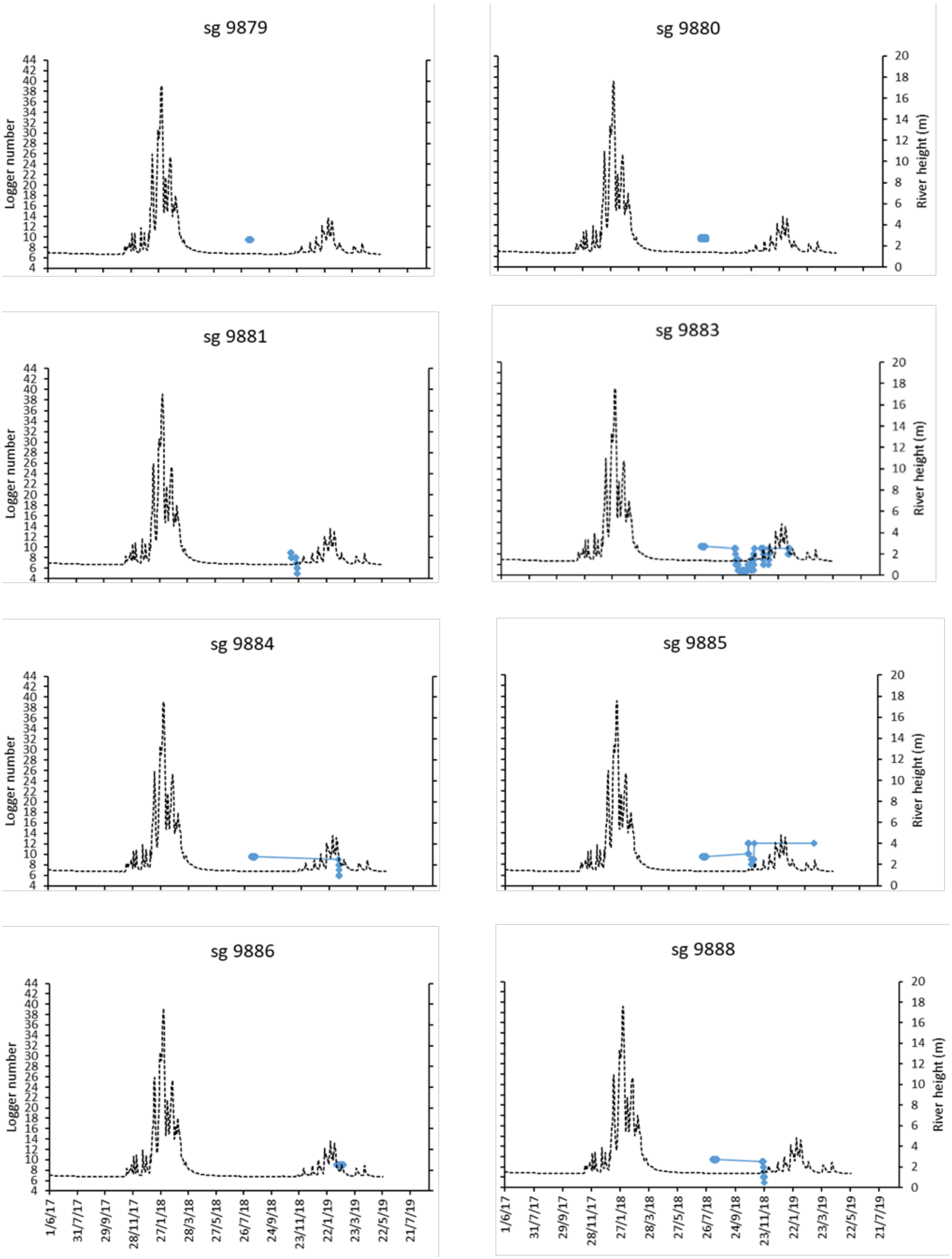


Figure 8-4 cont.



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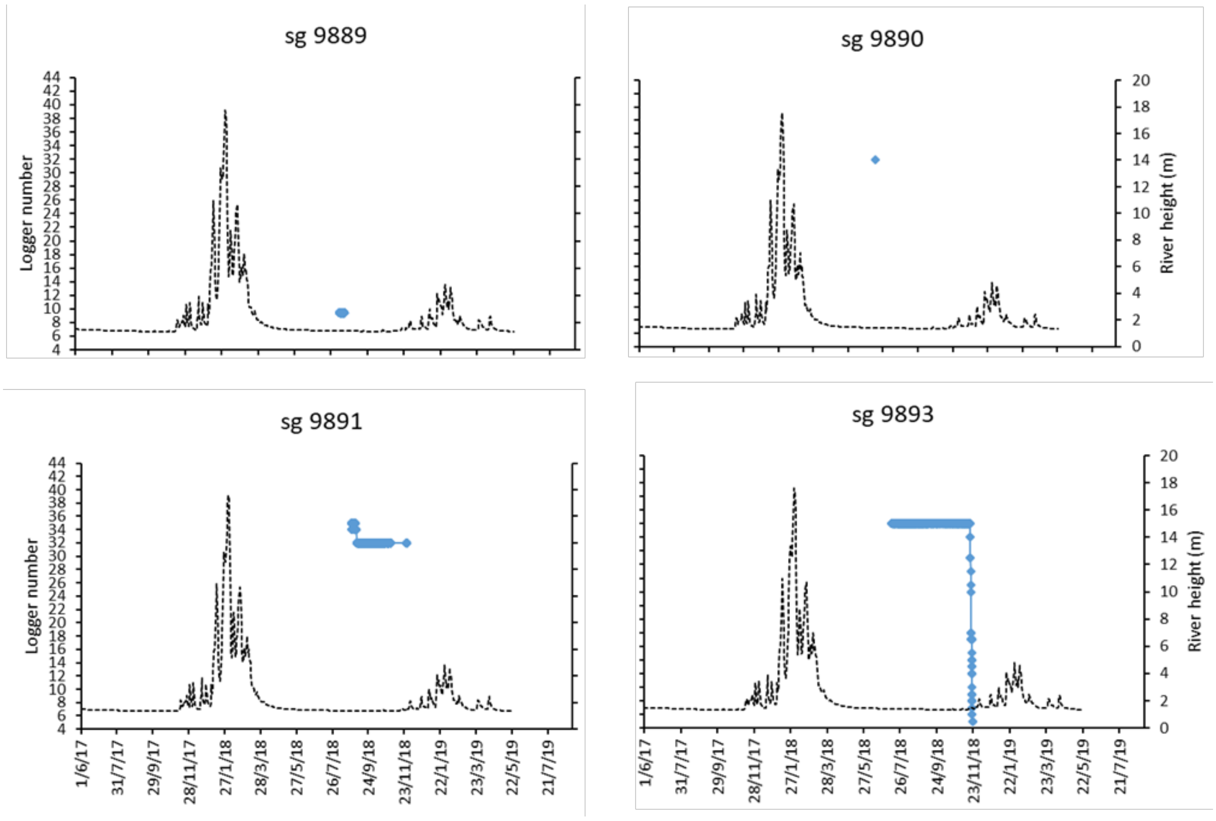

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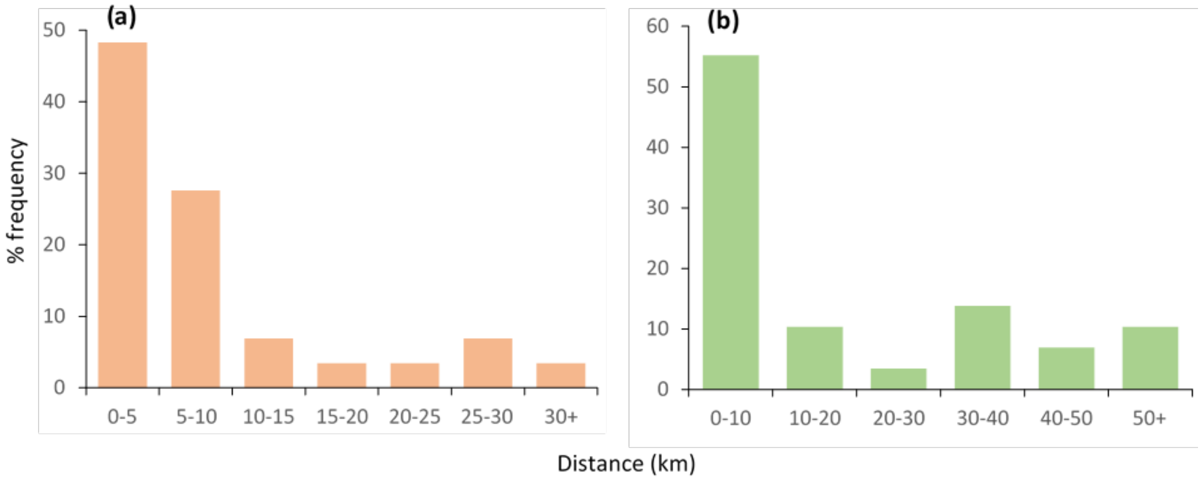

Figure 8-5. Frequency histograms showing (a) the longitudinal extent of movement and (b) cumulative movement by tagged sooty grunter.

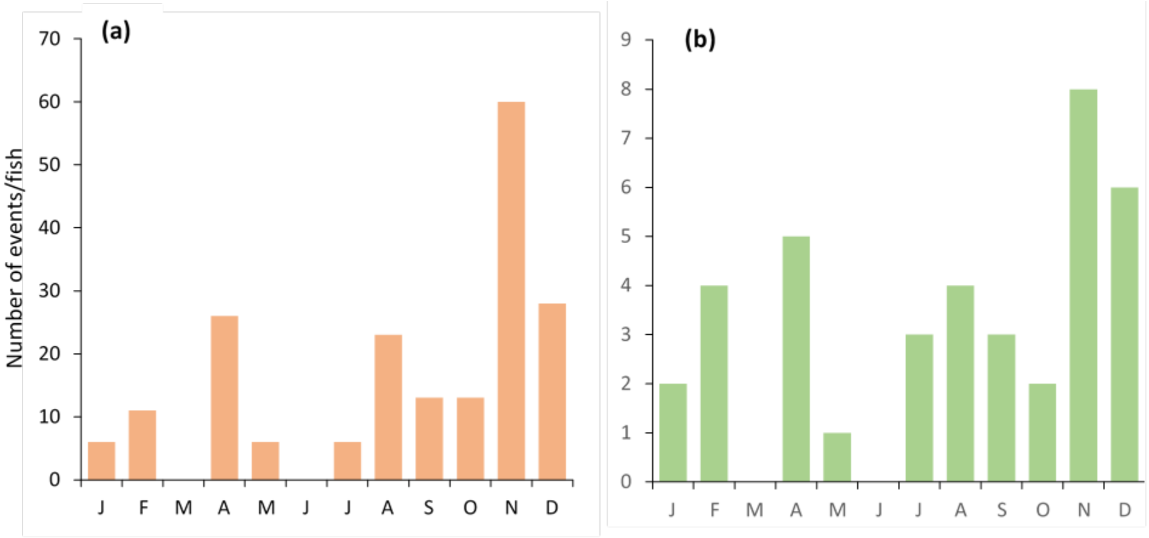

Figure 8-6. Frequency histograms showing (a) the total number of non-residence events and (b) number of fish exhibiting non-residency across months.

8.4.2 Movement past shallow areas and low-flow barriers

A primary aim of the current study was to determine the potential vulnerability of sooty grunter to reduced connectivity that may result from future increases in consumptive water use in the Daly River catchment. Although the tagged sooty grunter exhibited long periods of restricted movement and site fidelity, the acoustic tracking data also show that this species can exhibit high mobility at times, especially during the wet season. Previous studies of riverine fish with similar movement behaviours have shown that periods of high mobility serve important ecological functions by facilitating dispersal and colonisation of habitat at the river-catchment scale (Bond et al. 2015). To preserve these ecological functions, it is necessary to maintain sufficient flow across natural shallow parts of the channel (e.g. riffles) and low-flow barriers (e.g. road crossings) to provide connectivity for fish movement along the river channel (Rolls et al. 2012).

To examine this issue, we identified the major shallow areas and low-flow barriers (i.e. control points) within the study reach and used the acoustic tracking data to determine the river discharge at the time that fish crossed each point (Table 8-3, Figure 8-7). This analysis showed that fish crossed four control points 19 times during the study. A major riffle between receivers 7 and 8 was crossed six times during the study at flows of 14.2 to 139.0 m^3/s (Claravale gauge). CP12 between receivers 9a and 10 was crossed five times during the study at flows of 12.8 to 56.5 m^3/s (Claravale gauge) and CP13 was crossed once at a discharge of 13.5 m^3/s (Claravale gauge). CP25 (Oolloo Crossing) between receivers 29 and 30 was crossed seven times during the study at flows of 41.1 to 362.5 m^3/s (estimate of flow at Oolloo Crossing, Table 8-3). These river discharges do not provide a conclusive estimate of the discharge necessary to maintain connectivity for sooty grunter in the Daly River; for example, it is possible that fish can cross the points at lower discharges than those we observed, or that movement was hampered (but not completely blocked) at the observed discharges. Nonetheless, the minimum discharges at which movement across potential low-flow barriers occurred provides a starting point for developing flow criteria to maintain connectivity for fish. For instance, flow spells analysis could be conducted using recorded hydrologic time-series to examine the relative impact of modelled flow scenarios on connectivity for fish migration using the criteria presented in Table 8-3.

Table 8-3. Mean daily flow (m^3/s) at Claravale gauging station (GS8140067) and Theyona gauging station (GS8140098) during passage of sooty grunter across control points. Records with minimum flow values for each control point shown in bold. Flow at Oolloo predicted from the relationship between flow at Oolloo and Theyona.

Control point	Receiver pair	Fish ID	Direction	Date	Claravale m^3/s	Theyona m^3/s	Oolloo m^3/s
Riffle	8_7	9893	US	21/11/18	14.5	26.1	29.2
Riffle	**8_7**	**9888**	**US**	**21/11/18**	**14.2**	**27.1**	**30.1**
Riffle	7_8	9883	DS	1/12/18	54.3	60.8	61.6
Riffle	8_7	9883	US	21/12/18	92.9	132.7	129.0
Riffle	7_8	9883	DS	2/1/19	139.0	88.7	87.8
Riffle	8_7	9884	US	12/2/19	83.3	111.1	108.7
CP12	9a_10	9885	DS	17/11/18	13.4	27.9	30.8
CP12	**10_9a**	**9885**	**US**	**19/11/18**	**12.8**	**31.7**	**34.4**
CP12	10_9a	9893	US	21/11/18	14.9	25.6	28.7
CP12	9a_11	9885	DS	1/12/18	55.9	61.7	62.5
CP12	11_9a	9885	US	11/4/19	56.5	35	37.5
CP13	**13_12**	**9893**	**US**	**20/11/18**	**13.5**	**27.6**	**30.6**
CP25 (Oolloo)	30_29	644	US	11/12/17	23.8	35.7	38.1
CP25 (Oolloo)	29_30	633	DS	30/12/17	50.6	68.9	69.2
CP25 (Oolloo)	29_30	641	DS	7/1/18	452.8	382.1	362.5
CP25 (Oolloo)	33_29	631	US	10/4/18	42.9	53.6	54.9
CP25 (Oolloo)	32_29	643	US	25/4/18	26.6	37.8	40.1
CP25 (Oolloo)	29_32	631	DS	5/5/18	22.1	33.7	36.3
CP25 (Oolloo)	**32_29**	**9893**	**US**	**18/11/18**	**17.3**	**38.9**	**41.1**

DS = downstream, US = upstream

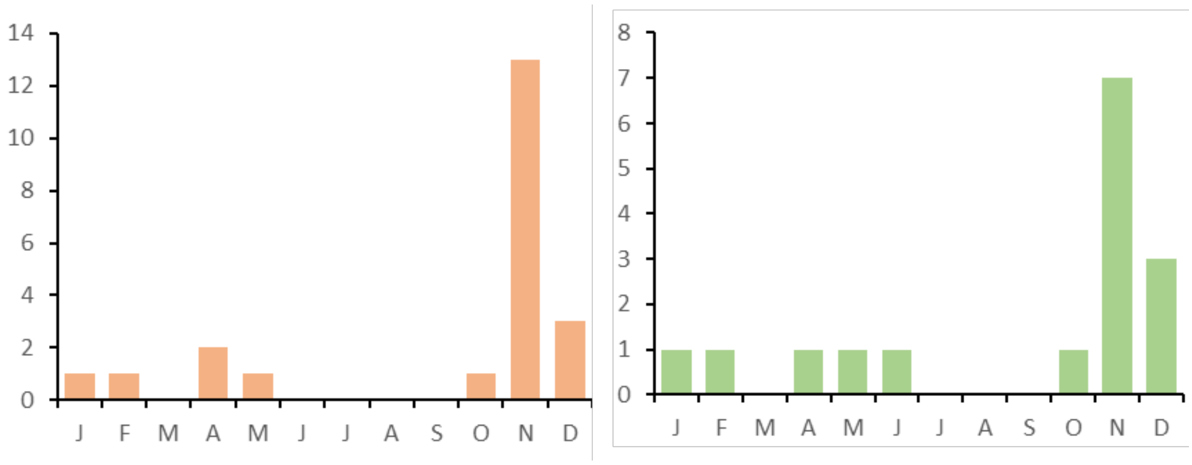

Figure 8-7. Frequency histogram showing (a) the total number of times control points were crossed by tagged fish and (b) number of tagged fish crossing control points across months.

8.5 Conclusions

This study demonstrates that adult sooty grunter in the Daly River exhibit long periods of restricted movement and site fidelity. However, ecologically important large-scale movements are undertaken by a substantial proportion of the population over the scale of 10s of kms, especially during the wet season. To preserve the ecological functions provided by these movements into the future, it will be necessary to maintain sufficient flow across natural shallow parts of the channel (e.g. riffles) and low-flow barriers (e.g. road crossings) to provide connectivity along the river channel. The criteria presented in this report have the potential to be used as a starting point to examine the impact of future flow scenarios on connectivity for fish migration, thus supporting the development of environmental flow recommendations to protect fish populations in the Daly River.

9. Flow requirements for spawning of freshwater fish

Contributors: Kyle Tyler, Alison King, David Crook, Mark Kennard, Dion Wedd

This component was conducted as part of a PhD program by Kyle Tyler (CDU).

Aim 1 of this research has been published: Tyler, K. J., Wedd, D., Crook, D. A., Kennard, M. J., & King, A. J. (2021). Hydrology drives variation in spawning phenologies and diversity of larval assemblages of Australian wet–dry tropical fish. *Freshwater Biology* 66(10), 1949-1967. https://doi.org/10.1111/fwb.13802

Aim 2 of this research is currently submitted to a peer-reviewed journal: Tyler, K. J., Wedd, D., Crook, D. A., Kennard, M. J., & King, A. J. (submitted). Predicting drivers of tropical riverine larval fish abundance and diversity.

9.1 Background

Tropical northern Australia has >110 freshwater fish species from a variety of taxonomic and life history strategy groups; however, the reproductive and early life history of most species in this region is poorly studied (King et al. 2013; Pusey et al. 2017). Several studies have highlighted the importance of both wet-season (high-discharge flows) and dry-season (low-discharge flows) periods for spawning and recruitment of many fish species in tropical Australia (Bishop et al. 2001; Pusey & Kennard 2009; Warfe et al. 2011; King et al. 2020). However, descriptions of the timing of reproduction of freshwater fishes in this region are often transferred from other regions (Pusey et al. 2004) or use non-direct lines of evidence, such as length-frequency analysis, gonad staging and gonadosomatic indices (Bishop et al. 2001; Pusey et al. 2018) to make inferences regarding spawning times and recruitment processes.

King et al. (2020) conducted a preliminary study investigating spawning phenologies (calendar showing start, duration and end of spawning season) of freshwater fishes in the lower Daly River system; however, the sampling design was temporally limited (1 year) and restricted to only one perennially flowing reach (Daly River Crossing). Hydrological requirements for spawning, larval development and recruitment of the fish assemblage are crucial information needs for supporting future science-based water and species management, particularly in regions facing ongoing pressure for increased water extraction, which may alter river flows and groundwater dynamics (e.g. King et al. 2015; Pusey et al. 2020). Therefore, the lack of knowledge on the variability of timing, peak abundance and hydrological, biotic and environmental determinants of reproduction, larval productivity, growth and recruitment for most freshwater fish species is a key barrier to informing ecologically sound development in the wet-dry tropical region (Stewart-Koster et al. 2011; King et al. 2013, 2015).

9.2 Aims and objectives

This project component consisted of three studies:

1. **Spawning phenologies and larval assemblages**
   The first study investigated the temporal and spatial dynamics of fish spawning timing (phenologies) and larval fish assemblages at multiple perennially and intermittently

flowing sites across the Daly River catchment. We aimed to identify (i) key periods for fish spawning throughout the annual wet–dry cycle; (ii) whether within-species (intraspecific) variation in spawning phenologies occurred in response to contrasting hydrological flow classes (i.e. perennial vs intermittently flowing reaches); and (iii) whether larval fish assemblages varied in response to hydrological conditions across both space and time.

2. **Larval fish productivity models**
   The second study investigated larval fish abundance and diversity in the Daly River catchment as a function of primary and secondary production, structural habitat complexity, and physicochemical and hydrological variables. Specifically, we aimed to determine what is the relative importance and contribution of key hydrological, environmental and food productivity variables to total larval fish abundance and diversity.
3. **Comparison of larval fish growth rates**
   The third study investigated whether there were spatial and temporal differences in the growth rates of larval fish in the Daly River catchment, and whether any growth differences may occur as the result of groundwater inputs to the river. We aimed to identify (i) whether larval growth rates differed between sites upstream and downstream of a region of groundwater outwelling (riverbed and channel-bank thermal springs) in the dry season; and (ii) whether any relationships identified in the dry season persisted in the wet season, when it was hypothesised that groundwater inputs would be less important due to the homogenisation of water quality during high flows.

9.3 Methods

Methods are described in detail in Tyler et al. (2021) but are briefly described here. Larval and juvenile fish were collected using electrofishing, light traps and drift nets from eight sampling sites (night samples were also collected at three sites) distributed between perennial (four sites) and intermittent (four sites) reaches of the Daly River catchment (Figure 9-1, Figure 9-2). Samples were collected on a monthly (nine samples) to bi-monthly (two samples) basis over a 12-month period (September 2016 – September 2017) to cover one full hydrological cycle (dry season, dry–wet transition season, wet season and wet–dry transition season).

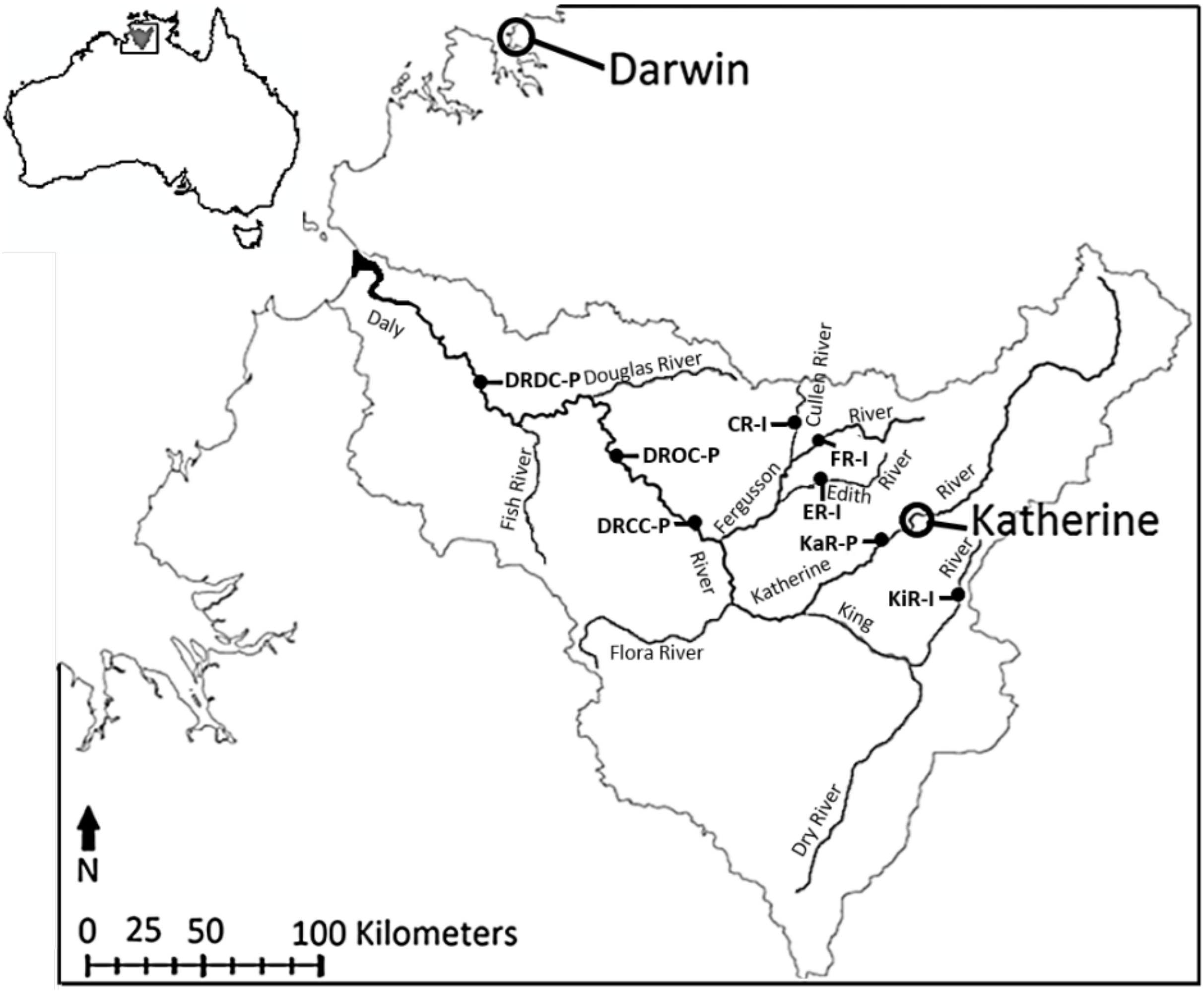

Figure 9-1. Map of the Daly River catchment, Northern Territory, showing rivers, sampling locations and nearby cities. DRDC-P = Daly River, Daly Crossing (perennial); DROC-P = Daly River, Oolloo Crossing (perennial); DRCC-P = Daly River, Claravale Crossing (perennial); KaR-P = Katherine River (perennial); CR-I = Cullen River (intermittent); FR-I = Fergusson River (intermittent); ER-I = Edith River (intermittent), and KiR-I = King River (intermittent).

Figure 9-2. Photos of three of the four perennial sites – Daly River, Daly Crossing (a), Daly River, Oolloo Crossing (b) and Daly River, Claravale Crossing (c) – and three of the four intermittent sites – Fergusson River (d), Edith River and Cullen River (f) – during low/cease-to-flow conditions (i) and high-flow conditions (ii).

9.3.1 Spawning phenologies and larval assemblages

Spawning phenologies were produced using back-estimated spawning occurrence data from both larval (*t-0*:*t*-30 days) and juvenile (*t-30*:*t*-60 days) fish from all sampling methods and periods. Phenologies were then assessed as to whether taxa appeared to reproduce more during wet or dry periods and if taxa had differing phenologies between hydrological classifications (flow classes). Hill numbers were used to investigate larval taxonomic richness (Hill with q=0) and taxa diversity (Hill with q=1) (Chao et al. 2014) using daytime sweep net electrofishing (SNE) data only, so that sampling effort between sites and seasons was comparable. Larval richness and diversity were compared between flow classes and seasons using two-way analysis of variance (ANOVA) after log(x+1)-transforming values to conform with the ANOVA assumption of normality. Post-hoc tests (Tukey HSD) were performed on ANOVA models to identify which seasons had different mean values of taxonomic richness and diversity.

Instantaneous multivariate larval assemblages and univariate larval abundances were compared across seasons and flow classes (perennial and intermittent) using multivariate generalised linear models (R package ‘mvabund’; Wang et al. 2012) with a negative binomial error distribution and an offset for variable sampling effort, performed on SNE data only. Models consisted of a full-data model to determine if larval abundances and assemblages differed between seasons (categorical factor = Season) or between flow classes (categorical factor = Flow-Class), and then models to conduct planned contrasts using data from each flow-class only to investigate variation between seasons within each flow-class, and data from each season only to investigate variation between flow classes. Pairwise testing was conducted to determine differences between seasons for models where that factor was significant ($P \leq 0.05$). Respective univariate models were constructed and pairwise testing was performed for taxa with a significant Season result to determine how differences in their univariate abundance had influenced differences in the multivariate assemblage across seasons.

9.3.2 Larval fish productivity models

In conjunction with the fish sampling by electrofishing mentioned above, aquatic microfauna and phytoplankton were also sampled and were spatially and temporally coupled with quantitative measurements of habitat, and hydrological and water quality variables. Chlorophyll-*a* was used as a surrogate measure of phytoplankton abundance and was extracted from phytoplankton samples and quantified using methods adapted from the United States Environmental Protection Agency Method 445.0 (Arar & Collins 1997), which is a standard method for measuring extracted chlorophyll-*a* in marine and freshwater algae by fluorescence. Aquatic microfauna were screened (size range 75–1,000 µm) and quantified. Boosted regression trees (R packages ‘gbm’ and ‘dismo’; Hijmans et al. 2017; Greenwell et al. 2020) were used to identify which variables, from a pool of up to eight candidates (microfauna, chlorophyll-*a*, water depth, flow velocity, water temperature, habitat complexity, proportion of Q_{Max}.(maximum discharge) and *River Wave* Stage by Flow-Class [categorical variable ‘Wave_Stage_Type’]), were the most important for predicting total larval abundance and diversity (number of effective taxa; Hill number with q=1; Chao et al. 2014). Larval fish abundance was modelled with a Poisson loss function and included an offset to account for variable sampling effort, and larval diversity was converted to a rate per metre and then modelled with a Gaussian loss function. Model hyperparameters were selected after performing grid-searches of potential values to identify the combination that maximised the predictive ability of each model. Relative variable importance was compared for each model, and the effects of important variables (variables which contributed to >10% of decision splits) were interpreted using accumulated local effects (ALE) plots. Important variables that had important two-way interactions (interactions with a Friedman’s H-statistic >0.2) were interpreted using bivariate second-order ALE plots.

9.3.3 Comparison of larval fish growth rates

Larval *C. stramineus* (development stages flexion through to metalarvae) were sub-sampled from the fish larval collection retained for this project component. Samples were taken from larvae captured in November and March, which were allocated as being spawned in the late dry or late wet seasons, respectively. Only fish collected at Daly Crossing, Oolloo Crossing and Claravale Crossing (Figure 9-1) were used, as these sites corresponded to the location of groundwater ‘Outwelling’, and sites ‘Downstream’ and ‘Upstream’ thereof, respectively. Both sagittal otoliths were removed from each larva, flat-mounted sulcus-side down on a microscope slide with thermoplastic cement and photographed under light microscopy. Both otoliths of each fish were aged (in days) by counting the number of daily growth increments deposited after the hatch-check. The two-dimensional area of each otolith was determined by calibrating the length of the image scale in pixels and then calculating the number of pixels contained within the outline of the otolith in each image, as identified and enumerated through image processing routines in imageJ (Schindelin et al. 2012). Rates of daily increase in otolith area (growth rate; μm^2/day) of fish were compared between sites in each season using two separate one-way ANOVAs after determining that the assumptions of ANOVA were met. Post-hoc tests (Tukey HSD) were performed on each ANOVA model to identify which sites had different mean larval growth rates.

9.4 Results

9.4.1 Spawning phenologies and larval assemblages

A total of 27 species from 13 families were recorded as reproducing during the study. However, difficulty in identifying some larval life stages lead to some species being pooled together (see Figure 9-3 for examples of variation between adult and larval morphologies), resulting in 12 taxonomic groups of larvae available for statistical modelling. Spawning phenologies for 28 taxa groups and life stages were constructed when these data were combined with back-calculated spawning times from juveniles (Figure 9-4). Fish reproduction occurred year-round at every site (Figure 9-4). Both larval and juvenile abundances mostly comprised *C. stramineus* (62.47% and 43.34%, respectively) and *Melanotaenia* spp. (rainbowfish; 31.56% and 18.85%, respectively), with no other individual taxon contributing >2% or >5% to the larval or juvenile catches, respectively (Figure 9-5).

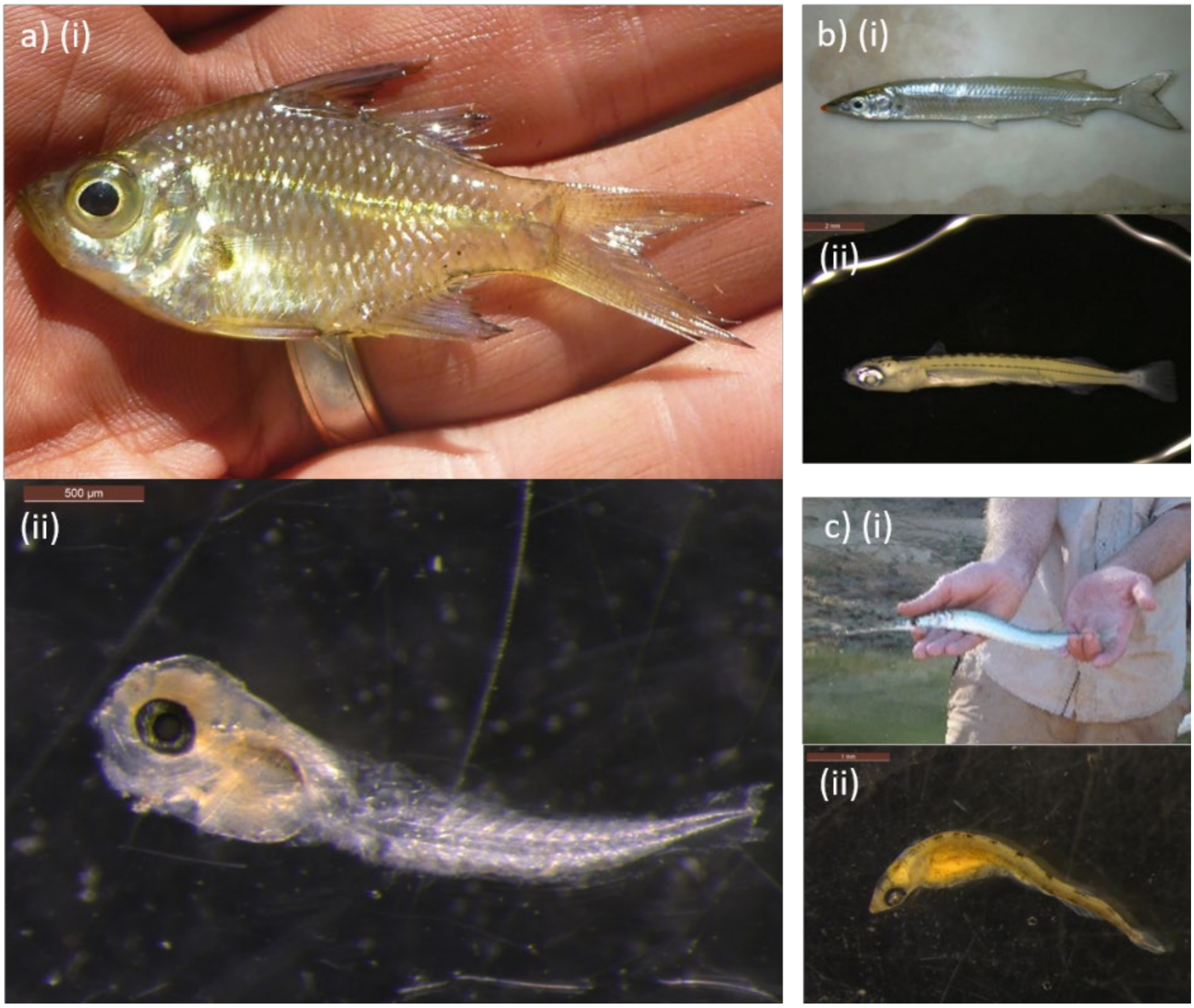

Figure 9-3. Example photos of some of the Daly River fish species showing how adult and larval morphologies may differ: Ambassis spp. (a), Arrhamphus sclerolepis (b) and Strongylura krefftii (c) as adults (i) and larvae (ii).

Thirteen taxa (*Ambassis* spp., *Ambassis* sp. NW, *Amniataba percoides, C. stercusmuscarum, C. stramineus, Glossamia aprion, Glossogobius* spp., *Hypseleotris* spp., *Oxyeleotris lineolata, Melanotaenia* spp., *Neosilurus hyrtlii, Strongylura krefftii and Syncomistes butleri*) reproduced aseasonally (reproduction occurred in every season), and the remaining 15 taxa reproduced within wet periods (late dry, wet and wet transition seasons; Figure 9-4). Twelve taxa predominantly spawned in perennial reaches, seven of them exclusively (*C. stramineus, Nematolosa erebi, Neosilurus ater, S. krefftii* and *Toxotes chatareus*, and *Ambassis interrupta, Ambassis macleayi, Arrhamphus sclerolepis, Hypseleotris* spp., *Neoarius graeffei, Neoarius leptaspis* and *S. butleri* exclusively), compared with eight taxa predominantly spawning in intermittent reaches, three exclusively (*A. percoides, Mogurnda mogurnda, Oxyeleotris selheimi, N. hyrtlii* and *Neosilurus* spp., and *Glossogobius* spp., *Leiopotherapon unicolor* and *Hephaestus* spp. exclusively; Figure 9-4).

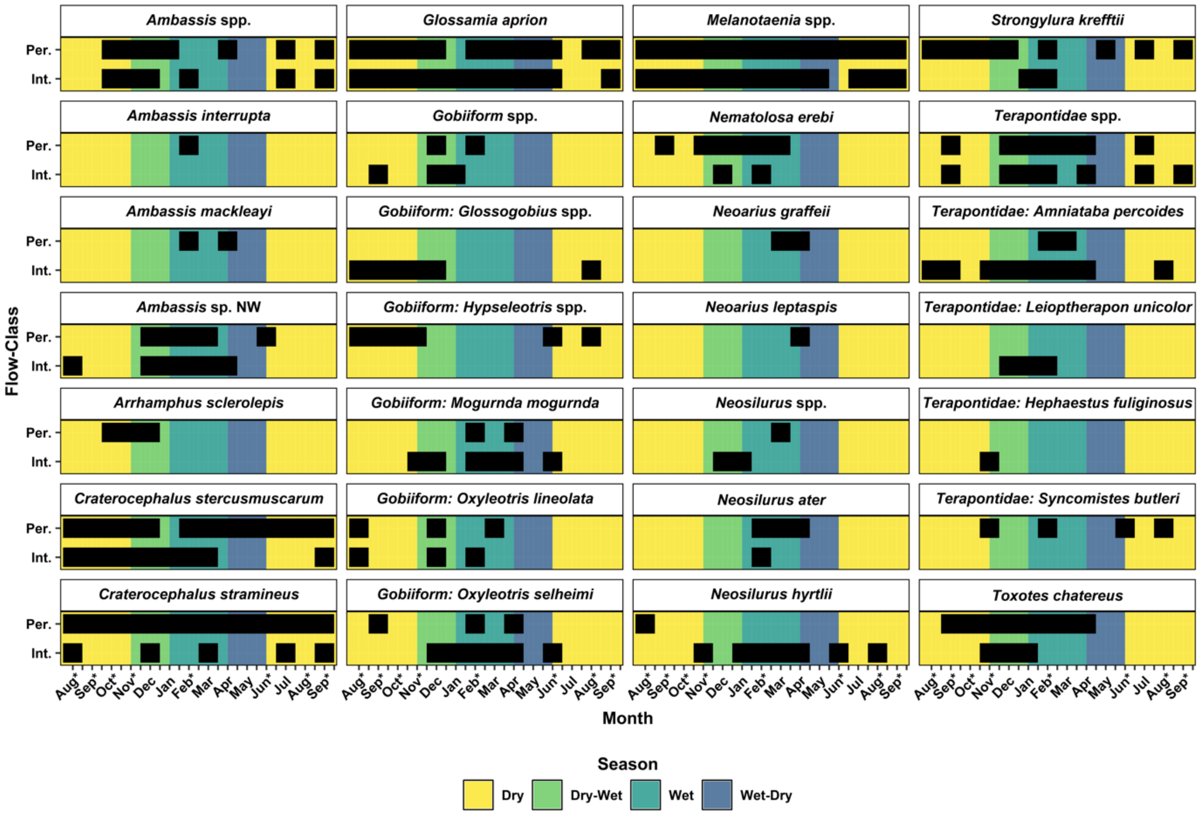

*Figure 9-4. Spawning phenologies of fish taxa estimated from backdated larval (t-0:t-30 days) and juvenile (t-30:t-60 days) occurrences for perennial (Per.) and intermittent (Int.) flow classes. *Denotes incomplete sampling; therefore, non-detections linked to these time-points should be treated with caution: no sampling occurred in August 2016, and June and August 2017; Cullen River was not sampled in September, October and November 2016 and September 2017; and Daly River, Oolloo Crossing was not sampled in February 2017.*

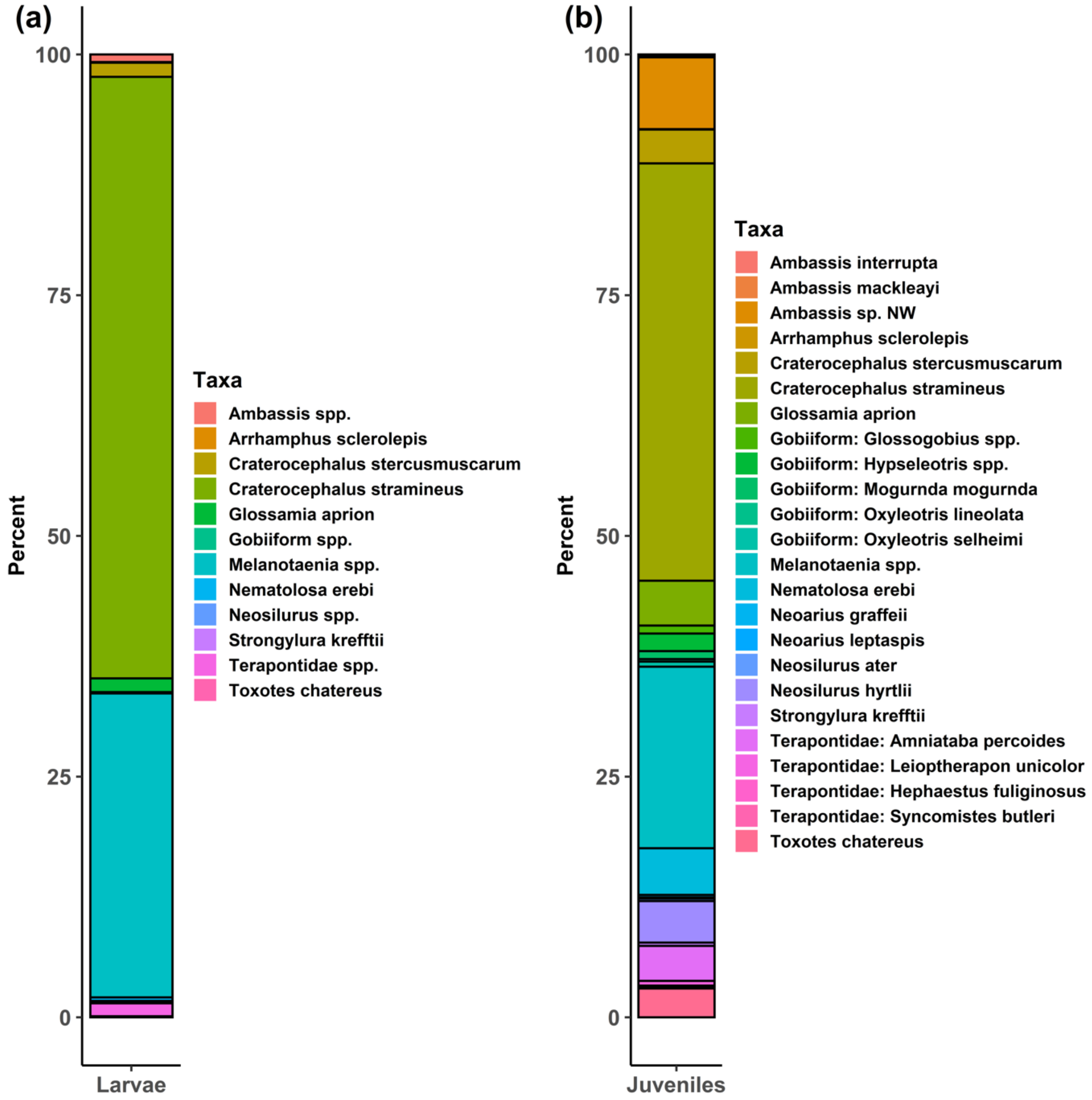

Figure 9-5. Percent contribution of taxa to total (all methods combined) larval (a) and juvenile (b) catch.

Taxonomic richness and diversity differed significantly between seasons (*F*=4.861, *p*=0.004 and *F*=5.986, *p*=0.001, respectively), with the wet–dry season having lower species richness than all other seasons, and the wet season being more diverse than the dry and dry–wet seasons (Figure 9-6). Perennial sites were significantly more diverse than intermittent sites (*F*=5.986, *p*=0.001; Figure 9-6b).

Seasonal larval assemblages differed significantly, as did assemblages in each flow-class. Differences in season and flow-class assemblages were the result of significant differences in univariate abundances: *C. stramineus* was more abundant in perennial reaches in all seasons, and more abundant in the dry and dry–wet seasons than in the wet and wet–dry seasons, both overall and within perennial reaches alone; *Melanotaenia* spp. were more abundant in the dry and dry–wet seasons in intermittent reaches, more abundant in the dry and dry–wet than in the wet and more abundant in the dry than in the wet–dry seasons overall, and more abundant in the dry and dry–wet than in the wet season in intermittent reaches alone; *Terapontidae* spp. were more abundant in intermittent reaches in the wet season, more abundant in the wet than any other season in perennial reaches, and more abundant in the dry–wet and wet than in the dry, wet and wet–dry seasons in intermittent reaches; and *Ambassis* spp. were more abundant in intermittent reaches in the dry–wet season.

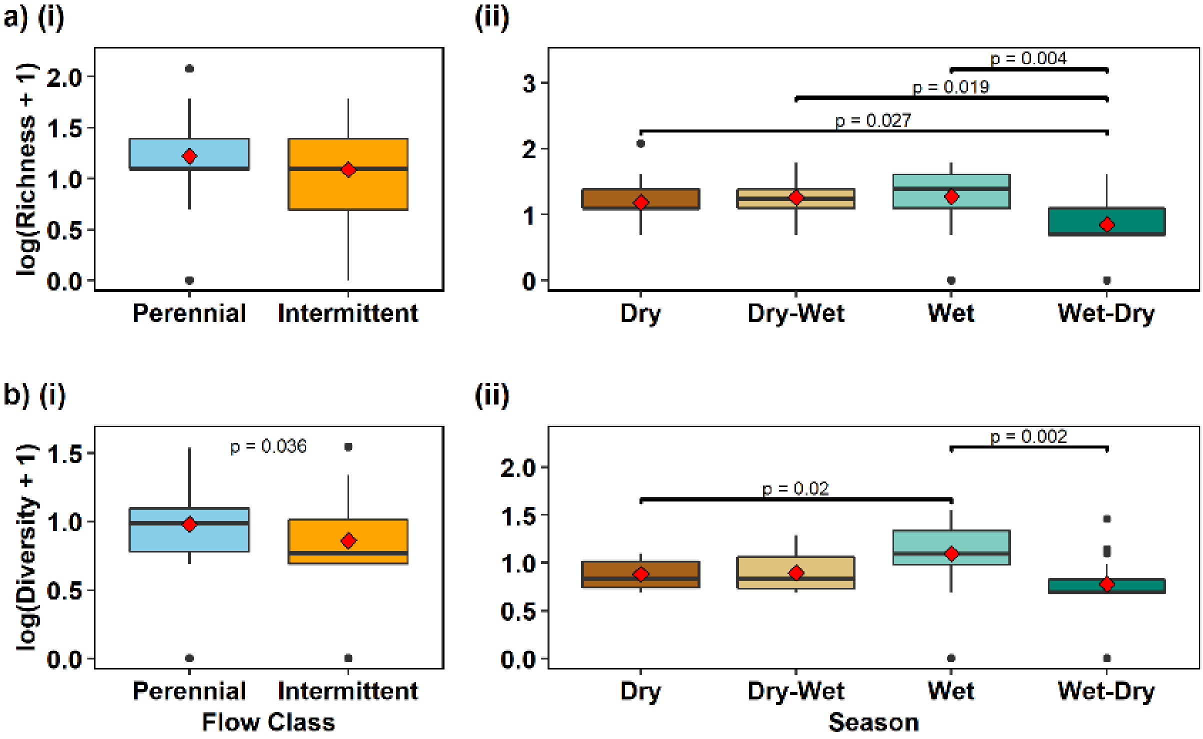

Figure 9-6. Boxplots of larval fish richness (a) and diversity (b) in each flow-class (i) and season (ii). Diamonds indicate the locations of mean values. Pairwise Tukey HSD comparisons are shown only when significant at the α = 0.05 level.

9.4.2 Larval fish productivity models

The model of larval abundance explained 57.59% of deviance in the cross-validation dataset, with three variables being >10% important and one important two-way interaction with an important variable (Figure 9-7a and Figure 9-8). Plots of ALE indicated that larval abundances were highest in warm (>30°C), moderate–highly complex (complexity index >0.35) habitats with abundant microfauna (>50/mL; Figure 9-8a). However, the effect of the abundance of microfauna on larval abundance was mediated by the proportion of Q_{Max}, whereby positive additive effects on larval abundance predictions occurred when microfauna were ~200–250/mL, irrespective of the proportion of $Q_{Max.}$, and negative additive effects occurred irrespective of microfauna abundance when the proportion of $Q_{Max.}$ was close to zero (Figure 9-8c).

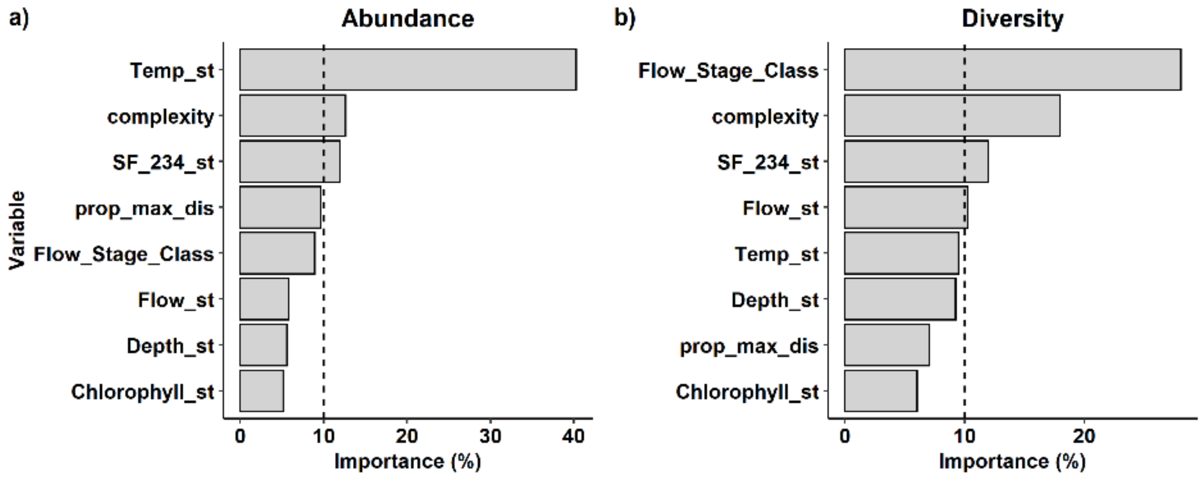

Figure 9-7. Ranked variable importance for fish larval abundance (a) and diversity (b), with 'important' variables indicated where importance exceeded 10% (dashed line).

The model of larval fish diversity explained 20.52% of deviance in the cross-validation dataset, with four variables being >10% important in the model (Figure 9-7). Plots of ALE indicated that larval diversity was highest during the Crest and then the Ascending Limb of the *River Wave* in perennial sites, and during the Ascending Limb, Crest and then the Trough stages in intermittent sites (Figure 9-8b). Larval diversity was also highest in moderate–highly complex habitats (complexity index >0.35) and those with abundant microfauna (>50/mL) and slow flow velocities (<10 cm/s; Figure 9-8b).

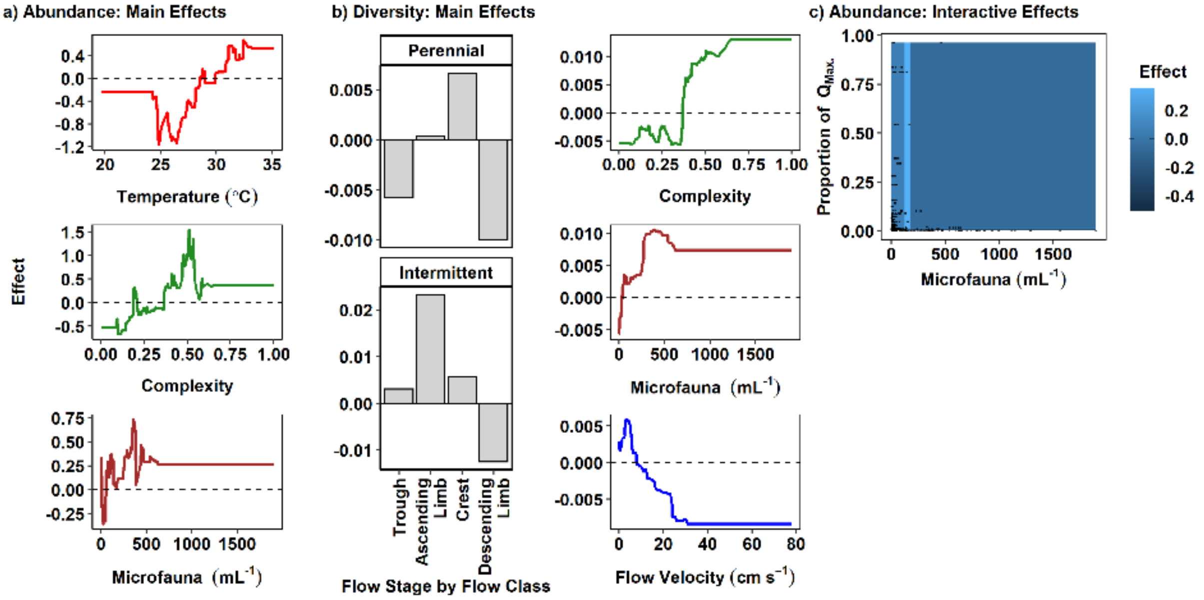

Figure 9-8. Accumulated local effects (ALE) of important variables for predicting larval fish abundance (a) and diversity (b), and second-order ALE for an important variable interaction for predicting larval abundance (c).

9.4.3 Comparison of larval fish growth rates

Larval *C. stramineus* growth rates differed significantly between sites in the dry season (F=18.11, p<0.001), with mean growth in the Outwelling and Downstream sites significantly greater than in the Upstream site (Table 9-1). In the wet season, there was also a significant difference between sites (F=16.3, p<0.001), due to mean larval *C. stramineus* growth rates in the Downstream site being significantly greater than in the Upstream and Outwelling sites (Table 9-1).

Table 9-1. Significance levels from pairwise comparisons of otolith growth rates between sites in the dry season and between sites in the wet season using Tukey HSD. Mean otolith growth rates (μm^2/day) and standard deviations (SD) of the first and second site in each comparison are also reported to determine the direction of differences. Bold p-values indicate significance at the α = 0.05 level.

Comparison	Adjusted *p*-value	Mean growth rate (first site; ± SD)	Mean growth rate (second site; ± SD)
Dry season			
Outwelling vs Upstream	**<0.001**	780.3 ± 78.8	653.9 ± 68.7
Downstream vs Upstream	**<0.001**	799.7 ± 69.7	653.9 ± 68.7
Downstream vs Outwelling	0.84	799.7 ± 69.7	780.3 ± 78.8
Wet season			
Outwelling vs Upstream	0.47	571.2 ± 78.4	681.1 ± 206.1
Downstream vs Upstream	**<0.001**	1035.4 ± 159.6	681.1 ± 206.1
Downstream vs Outwelling	**<0.001**	1035.4 ± 159.6	571.2 ± 78.4

9.5 Discussion

This study demonstrated that the majority of freshwater fish in the region have spawning periods spanning multiple hydrological seasons (aseasonal), while other taxa have discrete spawning windows aligning with the onset of wet-season flow conditions. Indeed, some taxa may have spatially/hydrologically discrete spawning preferences, resulting in variations in spawning phenologies and larval assemblages, richness, diversity, productivity and growth between perennial and intermittent hydrological conditions.

Increased river discharge is often implicated as an important cue to initiate spawning and to support successful recruitment for fish in wet-dry tropical rivers (e.g. Bishop et al. 2001; Pusey & Kennard 2009; Warfe et al. 2011; King et al. 2020). We found evidence of the potential importance of discharge increases in triggering spawning of 15 taxa. Similar findings have also been found in other tropical systems where there is a tendency for fish reproductive activity to precede or peak during the wet season (e.g. Paugy 2002). Periods of increased discharge in the wet season are assumed to facilitate rapid growth, development and dispersal of fish early life stages by providing the opportunity for increased food uptake and habitat availability and connectivity (Welcomme 1985; Bishop et al. 2001; Warfe et al. 2011).

While periods of increased discharge were important for many taxa, 17 taxa utilised low-discharge periods for spawning, and for some taxa, low-discharge periods were utilised more than high-discharge periods. *C. stramineus* and *Melanotaenia* spp. had the most abundant larvae in all seasons, but their abundances were highest during periods of low or no flow, which concurs with the findings of King et al. (2020) for these taxa within the same catchment, as well as elsewhere for *Melanotaenia* spp. (Milton & Arthington 1984; Pusey et al. 2001). Low-flow periods allow some species to take advantage of shallow, slack-water habitats that are abundant and which seemingly provide conditions that enhance concentrations of suitable prey, and provide suitable hydraulic conditions for larvae with low swimming abilities, refuge from predators, and optimal water physicochemistry, all of which is conducive to facilitating the rapid development and maximal survival of their larvae (Humphries et al. 1999, 2020).

Potential preferences for spawning in different hydrological classes were found for at least 19 taxa in this study, with differences in larval assemblages between these classes being mostly driven by *C. stramineus and Melanotaenia* spp*., Ambassis* spp. and *Terapontidae* spp. Larvae of *C. stramineus* were almost exclusively detected, and were more abundant, in perennially flowing sites, potentially indicating a flow requirement for this species' reproduction. In contrast, larvae of both *Melanotaenia* spp*. and Terapontidae* spp. were detected at all sites and *Ambassis* spp. at most sites, but all were more abundant in intermittent sites. Small-bodied species, such as *Melanotaenia* spp., have been suggested to reproduce more intensely in upstream reaches of wet tropical river systems, where food is potentially more abundant during low-flow periods (Pusey et al. 2002); this concurs with the findings of this study, whereby high food abundance was correlated with high larval abundances.

Climate change scenarios indicate the potential for the intensity of storm events to increase in the wet-dry tropics (Narsey et al. 2020), but for the duration of the wet season to be reduced (thus lengthening the dry season). Therefore, care should be taken not to compound climate change effects on stream flow, and subsequently the effects of altered stream flow on fish reproduction, by water extraction at rates such that river perenniality may be put at risk. Seven taxa were found to spawn only in perennially flowing sites (*A. interrupta, A. macleayi, A. sclerolepis, Hypseleotris* spp*., N. graeffei, N. leptaspis* and *S. butleri*). If perennial reaches of the Daly River were to begin to flow intermittently due to decreased water availability, either through climatic conditions or water extraction (King et al. 2015), reproductive outcomes for these seven taxa may be impacted. If perennial reaches are pushed into intermittency, it is possible that species that rely on flowing waters for reproduction may find it difficult to persist across the spatial extent and in the numbers that they do currently (Morrongiello et al. 2011). Indeed, we could predict that larval assemblages in perennial systems could shift towards those more reflective of intermittent reaches, resulting in less species-diverse adult assemblages (Pusey et al. 2020). Furthermore, reduced groundwater storage (i.e. reduced hydraulic head, potentially through groundwater extraction or reduced recharge) and associated declines in base flows in the river could also lessen the magnitude and duration of peak wet-season flows catchment-wide (King et al. 2015; Pusey et al. 2020). Such dramatic changes to the hydrograph could reduce the time-window available for access to essential habitats (i.e. floodplains or upstream nurseries) that are likely to be essential for high recruitment of wet-period spawners, such as *A. interrupta*, *A. macleayi*, *A. sclerolepis*, *N. ater, N. graeffei and N. leptaspis, S. butleri* and *T. chatareus (*see Section 10*).*

Further evidence of the importance of protecting water levels during the late dry season came from our larval growth study, which found that growth of larval *C. stramineus* was significantly higher in areas of, or downstream of, groundwater discharge during this time period. Increased growth rates in areas of high groundwater connectivity, but not in other areas, suggests that groundwater discharge has an influence on larval growth, with the effect potentially persisting for at least 60 km downstream. This outcome provides evidence that groundwater outwelling zones not only support increased primary productivity (Townsend & Padovan 2005; Burrows et al. 2020), but also secondary productivity (fish growth, in this study). Protecting groundwater-derived flows during the late dry season is also likely to be important for maximising not only larval growth, but also the survival and recruitment of various species during the late dry season. During the wet season, the importance of groundwater appears to diminish. During the wet season, fish at the downstream Daly River Crossing site had the highest rates of larval growth, which is likely to be driven by either (i) connectivity with local floodplains allowing fish and water connections to areas with high rates of primary and secondary productivity (Araujo-Lima & Oliveira 1998; Jardine et al. 2012a,b; Crook et al. 2020), or (ii) increased residence time of the water in the catchment by the time it has been transported this far downstream, therefore having ample time to develop a sufficient nutrient pool to support elevated primary and secondary productivity (Vannote et al. 1980) at levels that support higher rates of larval growth. In any case, high larval productivity coincided in space and/or time with periods of high larval growth, and so these key periods need to be considered when designing water extraction rules so as to minimise any disturbance at these key periods and places.

Fish larvae were most abundant where food was abundant, and the habitat was structurally complex and warm. Larval fish diversity was highest during periods of high flow and in complex habitats, and where food was abundant and the flow velocity was slow. These results indicate that the biotic (i.e. high food availability) and environmental mechanisms (i.e. warm and hydraulically benign conditions) predicted by both the low-flow recruitment hypothesis (Humphries et al. 1999) and flood pulse concept (Junk et al. 1989) to drive riverine larval productivity were important within this catchment. Interactions between larval food resources and river discharge indicates that, within rivers, larval productivity cannot be predicted or maximised through simple match-mismatch processes (Cushing 1975) between larvae and their food resources alone. More complex fundamental triad (Bakun 1996, 1998) and riverscape recruitment (Humphries et al. 2020) mechanisms may better predict riverine larval fish productivity. This study furthers our understanding of these complex relationships and supports calls for the adoption of a holistic riverscape approach, considerate of structural, environmental and biological processes, in any action of preservation or restoration of riverine fish productivity.

This study provides new, and builds on existing, knowledge of how freshwater fish spawning phenologies and larval assemblages vary across seasons, and perennial and intermittent hydrological regimes of the Daly River catchment. Spawning occurred for many taxa throughout the annual wet–dry cycle, with clear periods of peak reproductive activity that varied among taxa. This highlights the diverse range of hydrological conditions utilised for fish reproduction in the catchment. This study also supports and reiterates the previous findings of King et al. (2020), highlighting the importance of the dry season as a spawning period for many fish taxa, and hence emphasising the importance of maintaining dry-season water levels. Larval assemblages also varied in response to contrasting hydrological regime classes, supporting the importance of obtaining local information and subsequently managing fishes and water resources at the catchment to sub-catchment scale, especially in the face of potentially additive effects of water-resource and climate change.

10. Flow requirements for successful recruitment of freshwater fish

Contributors: Alison King, John Morrongiello (University of Melbourne), David Crook, Bradley Pusey, Michael Douglas, Quentin Allsop, Duncan Buckle, Dion Wedd, Thor Saunders

10.1 Background

The annual monsoonal rainfall pattern in northern Australia characterises the wet-dry hydrology cycle of the region's rivers (Warfe et al. 2011; King et al. 2015). River flow is highly seasonal and annually predictable, but considerable inter-annual variability occurs in the timing, magnitude, duration and frequency of key hydrological events. The resulting wet-dry hydrological cycle is a dominant influence on the region's aquatic ecology, with the wet season regarded as an important period of ecosystem productivity, dispersal and connectivity, and reproduction for many taxa (Warfe et al. 2011; Pusey et al. 2001, 2002, 2011).

The rivers of the wet-dry tropical region of northern Australia contain >110 species of freshwater fishes, from a variety of taxonomic groups and life history strategies (Pusey et al. 2017). While the reproductive biology of most freshwater spawning species is poorly understood (King et al. 2013; Pusey et al. 2017), several studies have highlighted the likely importance of both high- and low-discharge periods for spawning and recruitment (e.g. Bishop et al. 2001; Pusey & Kennard 2009; Warfe et al. 2011; Pusey et al. 2020). Recent research has strengthened our understanding of spawning times of fishes in the region (King et al. 2020; Tyler et al. 2021), and has highlighted the predominance of both aseasonal spawners (spawn all year round) and taxa that spawn in the wet season only. However, except for barramundi (see for example Stewart-Koster et al. 2011; Turschwell et al. 2019; Crook et al. submitted), little is known about what influence wet-season or dry-season hydrological conditions have on recruitment of many fish species. Given the increasing focus on expanding water developments in the region, understanding hydrological factors that promote strong recruitment outcomes, and therefore being able to predict the likely effects of water extraction, is of critical importance.

10.2 Aims

The aim of this study was to describe the influence of wet-season and dry-season hydrological characteristics on the abundance of juvenile freshwater fishes in the Daly River. This was achieved by relating the abundance of juvenile fish catches of 12 species from 13 years of standardised survey data to various wet-season and dry-season hydrological characteristics. In addition, we used these models to explore the effects of hypothetical water extraction scenarios on the abundance of juvenile fish.

10.3 Methods

Fish assemblages were sampled from 2006 to 2018, in the early dry season (June) and late dry season (October), at nine sites in the Daly and Katherine rivers. Sites were sampled in a stratified random design throughout the perennial mainstem of the Daly River (eight sites) and Katherine River (one site). Some sites were not consistently surveyed throughout the entire sampling period due to constraints on site access and changes in overall sampling program design. In total, we collated and analysed 167 sampling observations. River flows were variable both within and among years (Figure 1-3), and included years with both high (2011, 2016) and low (2015, 2017) wet-season discharge.

Fish assemblages were sampled at multiple discrete locations (shots or replicates) at each site using a boat or backpack electrofishing, or a combination of both (Kennard et al. 2011; Stewart-Koster et al. 2011; Turschwell et al. 2019; Pusey et al. 2020). We selected electrofisher gear type based on depth and safety considerations, as the river contains estuarine crocodiles, and assume similar catchability among methods (Pusey et al. 2020). Between 10 and 20 electrofishing shots (generally 15 shots) of 5 minutes duration (i.e. constant effort across shots) were conducted at each site. Replicate samples within a site were taken to target the full range of habitats present (e.g. riffles, runs, pools, macrophyte beds, stretches of mid-channel open water, undercut banks and woody debris piles). Stunned fish were netted, removed from the water, and placed into an onboard recovery tank (boat) or aerated bucket (backpack electrofisher). All fish were subsequently identified, counted and measured (SL in mm) and then returned alive to the point of capture. The total number of fish from each species observed and reliably identified but not caught during each electrofishing shot was also recorded and included in the catch data.

Twelve abundant species (Table 10-1) that were able to be designated as juveniles (assumed <1 year old) using SL or were species that only live for 1–2 years were used in the subsequent recruitment analysis.

Table 10-1. Species used in recruitment analyses, noting the standard length (SL) used to designate juvenile status and spawning phenology (from Tyler et al. 2021).

Scientific name	Common name	Juvenile designation used in this study	Spawning phenology
Craterocephalus stramineus	Blackmast	All individuals	Aseasonal
Melanotaenia australis	Rainbowfish	All individuals	Aseasonal
Oxyeleotris lineolata	Sleepy cod	SL <150 mm	Aseasonal
Strongylura krefftii	Longtom	SL <150 mm	Aseasonal
Syncomistes butleri	Butler’s grunter	SL <150 mm	Aseasonal
Ambassis spp.	Glassfish	All individuals	Wet season
Hephaestus fuliginosus	Sooty grunter	SL <150 mm	Wet season
Lates calcarifer	Barramundi	SL <300 mm	Wet season
Neoarius spp.	Forktailed catfish	SL <150 mm	Wet season
Neosilurus ater	Black catfish	SL <150 mm	Wet season
Oxyeleotris selheimi	Giant gudgeon	SL <150 mm	Wet season
Toxotes chatareus	Sevenspot archerfish	SL <150 mm	Wet season

Daily river discharge observations were available throughout the sampling period at four locations along the Daly River: Katherine (404 km upstream of river mouth), Dorisvale or Claravale crossing (298 km upstream), Beeboom (235 km upstream) and Mount Nancar (116 km upstream). All fish sampling sites were related to their nearest upstream river gauge and these daily flow data were used to calculate site-relevant flow variables.

10.3.1 Statistical approach: juvenile abundance–hydrology models

Counts of juvenile fish per shot were modelled across sites and years as a function of environmental variables using a mixed-effects model fitted with a Poisson distribution. Random intercepts for site, and sampling trip nested within site, were included to induce correlations among catches from the multiple individual shots at a site on a given trip. These nested random effects accounted for catch variation associated with differences in time and date of sampling and spatio-temporal variation in unmeasured local environmental conditions. A random intercept for Year allowed for river-wide fluctuations in species' abundance caused by larger-scale unmeasured environmental factors. Preliminary analyses indicated that our data were over-dispersed so we included an observation-level random effect in all models.

We fitted both linear and quadratic terms for all continuous habitat and hydrological predictor variables (see Table 10-2 for variable descriptions). The wet season was defined as the first and last time the Q30 discharge was exceeded (i.e. discharge exceeded 30% of the time, based on the 30-year daily flow average for each gauging site). The dry season started on 1 June each year and continued until the time of late-dry-season sampling. Early-dry-season catches were modelled as a function of hydrological conditions in the preceding wet. Late-dry-season catches were modelled as a function of dry-season hydrology and early-season catch per unit effort (CPUE). As total discharge was strongly correlated to distance upstream in both the wet and dry season, we calculated site-specific discharge anomalies by subtracting a site's observed annual discharge from its mean discharge across the study period. Hence, negative anomalies occurred in years with less total discharge than average and positive anomalies in wetter years than average. Some predictor variables were transformed (Table 10-2) to ensure homogeneity of variance and to reduce the influence of large outlier values.

10.3.2 Statistical approach: Predicting the effects of water extraction on juvenile fish abundance

We used the early and late juvenile abundance–hydrology models for four species to explore the potential impacts of flow abstraction on fish assemblages in the Daly River. The four species (*O. lineolata, L. calcarifer, H. fuliginosus, C. stramineus*) were chosen as they expressed different hydrological responses (see results). Water extraction scenarios were established based on discussions with water-resource managers in the NT Department of Environment, Parks and Water Security. The agreed scenarios for modelling included 10%, 20% and 40% extraction of dry-season (May to October) and wet-season (November to April) river discharge. Extraction seasons were based on calendar dates rather than discharge thresholds as this enabled a clear interpretation of predictions in light of current, date-based flow management. We also modelled a wet-season extraction scenario in which water was only removed from the receding arm of the hydrograph according to environmental flow recommendations for the Daly River developed by Erskine et al. (2003).

Three hydrologically distinct years were selected for examination, representing relatively low or dry (2014/2015), moderate or intermediate (2007/2008), and high or wet (2020/2011) annual discharge. We modified the daily hydrographs of gauges by 'extracting' the appropriate percentage (10%, 20%, 40%) from the daily flow records during the relevant seasons. The modified hydrographs per discharge extraction scenario were used to recalculate discharge and timing variables for the three focal years. DistanceUP was set to the gauge closest to where each species was most abundant, and depth was estimated as the average shot depth for early and late samples across all sites associated to the relevant gauge. CPUE for the late-sample models was the average CPUE for a given species across all samples associated with a gauge. We used these new variables to predict the catch of each focal species.

To facilitate prediction of the effects of water extraction, both early and late catch models for the four species needed to include DistanceUP and at least one hydrological variable. These variables were already present in the *L. calcarifer* early, *O. lineolata* early, *H. fuliginosus* early, and *C. stramineus* early and late models. We added DistanceUP to the *L. calcarifer* late models, and dryTotalAnom to the *O. lineolata* and *H. fuliginosus* late models.

Table 10-2. Predictor variables used in early- and late-dry-season models.

Period	Variable	New description and definition	Unit	Transformation applied
Both	DistanceUP	Distance upstream of each site from mouth	km	None
	Depth	Average depth of shot	cm	Log
Early	Wet duration	Wet-season duration (days) (wet season end – wet season start)	days	None
	Wet start	First time Q30 flow was exceeded at each site, deviation from 1 January. (Q30 defined as flow exceeded 30% of the time, from 30-year site average)	days	None
	Wet anomaly	Anomaly of annual wet-season total flow. Calculated as deviation from site-specific average wet-season total flow during study period (2006–2018)	cumecs/ season	None
	Wet CV	Coefficient of Variation of daily flow in wet season		Log
	Wet high spells	Number of annual wet-season occurrences during which the magnitude of flow remains above a higher threshold defined as 3 times Mean Daily Flow (Kennard et. al. 2010). MDF calculated over study period (2006–2018)		None
	Wet receding	Flow of maximum wet-season flow/number of days from wet maximum to end of wet season (unit is change in discharge/day)	Δ cumecs/ day	Sqrt
Late	Fish catch	Catch (juvenile or total, species-specific) of a given species from the corresponding early dry-season sample at site	Fish/metre	4th root transformed; not log as zero
	Dry anomaly	Anomaly of annual dry-season total flow (1 June to late-sample date). Calculated as deviation from site-specific average dry-season total flow during study period (2006–2018)	cumecs/ season	None
	Dry CV	CV of daily flow in dry season		Log

10.4 Results and discussion

10.4.1 The influence of flow and habitat metrics on juvenile fish abundance

Hydrological attributes are commonly described as major drivers of fish productivity and recruitment (see for synthesis Humphries et al. 2020). In our study, flow and flow timing variables were important predictors of juvenile abundance of 11 of the 12 taxa in the early-dry-season models, but flow variables were only important for predicting abundance of four of the 12 taxa in the late dry season (Table 10-3, Figure 10-1 and Figure 10-2). Juvenile *O. selheimi* was the only taxon with no detectable link between abundance and a flow metric in either the wet or dry season (Table 10-3). All taxa displayed spatial variations in catch throughout the river valley (DistanceUP) and the juvenile abundance of 11 taxa was influenced by water depth.

The relationships between wet-season flow variables and juvenile abundance in the early dry season varied considerably across the 12 taxa, with no common pattern evident among species that spawned in the same period (Table 10-3, Figure 10-1). For example, juvenile abundance of taxa that preferentially spawn in the wet season (wet-season spawners) would be hypothesised to increase during strong wet seasons (wet-season flow anomaly), as a result of increased food production and available habitat for young (e.g. Junk et al. 1989). However, our results demonstrate that all wet-season spawners do not respond in the same way to increased discharge. Wet-season total flow anomaly predicted juvenile catch of seven species, with wetter periods resulting in greater abundances of four species: *L. calcarifer, S. krefftii* and *N. ater*, with *Neoarius* spp. displaying a peak relationship around 30,000 ML/day. In contrast, abundances of juvenile *C. stramineus*, *H. fuliginosus* and *T. chatareus* were negatively related to wet-season flow anomaly, that is, greater catches occurred in drier wet seasons.

Lower variability in daily wet-season flow conditions (i.e. seasons characterised by more stable daily flow) was related to higher catches in three taxa (*M. australis*, *S. krefftii* and *H. fuliginosus*), while higher variability in daily flows increased catches of *T. chatareus*. The number of high-flow spells in the wet season was only important for three taxa, with higher catches predicted with greater number of spells for *Neoarius* spp. and *T. chatareus*, and a lower number of spells for *S. krefftii*. An early start of the wet season was related to higher juvenile catches of five taxa, and a delayed start predicted to increase the number of juvenile *L. calcarifer* only. The abundance of juvenile *L. calcarifer* peaked around 140 days wet-season duration, whereas *C. stramineus*, *M. australis*, *O. lineolata* and *T. chatareus* were all predicted to have higher abundances with wet-season durations of <120 days. Two taxa, *Ambassis* spp. and *M. australis*, were predicted to have higher catches with greater rates of wet-season flow decline, while *L. calcarifer*, *Neoarius* spp. and *N. ater* had greater catches with slower declines in wet-season flows.

The dry season is a natural period of declining and low flows in northern Australian rivers (Warfe et al. 2011). In lower-flow periods, two plausible mechanisms may influence juvenile fish abundance. Firstly, as flows decline there may be increased competition for available food and habitat resources for juvenile fish (reviewed in Magoulick & Kobza [2003]). Conversely, some taxa are able to take advantage of increased food concentrations and shallow protective habitats to enhance larval survival (Humphries et al. 1999, 2020; Pusey et al. 2001). In this study, the late-dry-season abundance of juveniles for all 12 taxa increased when there were greater catches of that same taxon in the early dry season (Table 10-3, Figure 10-2). This result highlights that wet-season conditions, and hence the abundance of juveniles early in the dry season, is a very strong predictor of end-of-dry-season outcomes for juvenile fish.

Dry-season total flow anomaly predicted the late-dry-season abundance of four species (Table 10-3), but with varying patterns. *Neoarius* spp. and *L. calcarifer* juvenile abundance was greater in wetter dry seasons, while the abundance of *S. butleri* peaked at 1,500 ML/day and declined at both higher and lower flows (Figure 10-2). *C. stramineus* was the only taxon to show greater abundances with lower dry-season flows – potentially indicating a true low-flow recruitment specialist (Figure 10-2). King et al. (2020) and Tyler et al. (2021) also both demonstrated increased abundance of larval *C. stramineus* in the dry season in the Daly River catchment. However, these studies also highlighted a similar low-flow spawning preference for *Melanotaenia* spp., which in this study of juvenile abundance showed no preference for dry-season flow characteristics. Such a discrepancy may reflect different processes operating at the larval versus juvenile life stage. No other species was influenced by dry-season flow characteristics, other than *S. butleri* which was more abundant in less variable, more stable, dry-season flow years.

Table 10-3. Summary of best model results explaining catch of juveniles of 12 species for early-dry catch, late-dry catch (without early-dry catch per unit effort [CPUE]) and late-dry catch (with early-dry CPUE). Sign indicates whether there was a positive or negative effect, Q is a quadratic effect, blank cells indicate no effect for that variable. Species grouped by spawning period (aseasonal or wet season) as described by Tyler et al. (2021 [Section 9]). CPUE = catch per unit effort, CV = coefficient of variation.

		Species	**C. stramineus**	**M. australis**	**O. lineolata**	**S. butleri**	**S. kreftii**	**Ambassis sp.**	**H. fuliginosus**	**L. calcarifer**	**Neoarius sp.**	**N. ater**	**O. selheimi**	**T. chatareus**
	Variable type	**Spawning period**	**Aseasonal**	**Aseasonal**	**Aseasonal**	**Aseasonal**	**Aseasonal**	**Wet**	**Wet**	**Wet**	**Wet**	**Wet**	**Wet**	**Wet**
Early Dry models	Habitat	DistanceUP	+ (Q)	+ (Q)	+	+(Q)		- (Q)	+ (Q)	- (Q)	-		+	-
		Depth	- (Q)	+ (Q)	+ (Q)	-	+ (Q)		- (Q)	+ (Q)	- (Q)	-		+ (Q)
	Flow	Wet Anomaly	- (Q)				+		-	+	+ (Q)	+		- (Q)
		Wet CV		- (Q)			-		- (Q)					+
		Wet High Spells					-				+ (Q)			+
	Flow timing	Wet Duration	-	-	- (Q)	-				+ (Q)				- (Q)
		Wet Receeding		+ (Q)				+		-	- (Q)	-		
		Wet Start	- (Q)	-			+ (Q)		- (Q)	+				- (Q)
Late Dry models	Catch	Early Dry CPUE	+	+	+	+	+	+	+ (Q)	+	+	+	+	+ (Q)
	Habitat	DistanceUP	+ (Q)	+ (Q)	+	+ (Q)			+ (Q)				+	
		Depth	- (Q)	+	+ (Q)				- (Q)	+ (Q)	+ (Q)			+ (Q)
	Flow	Dry Anomaly	-			+ (Q)				+	+			
		Dry CV				-								

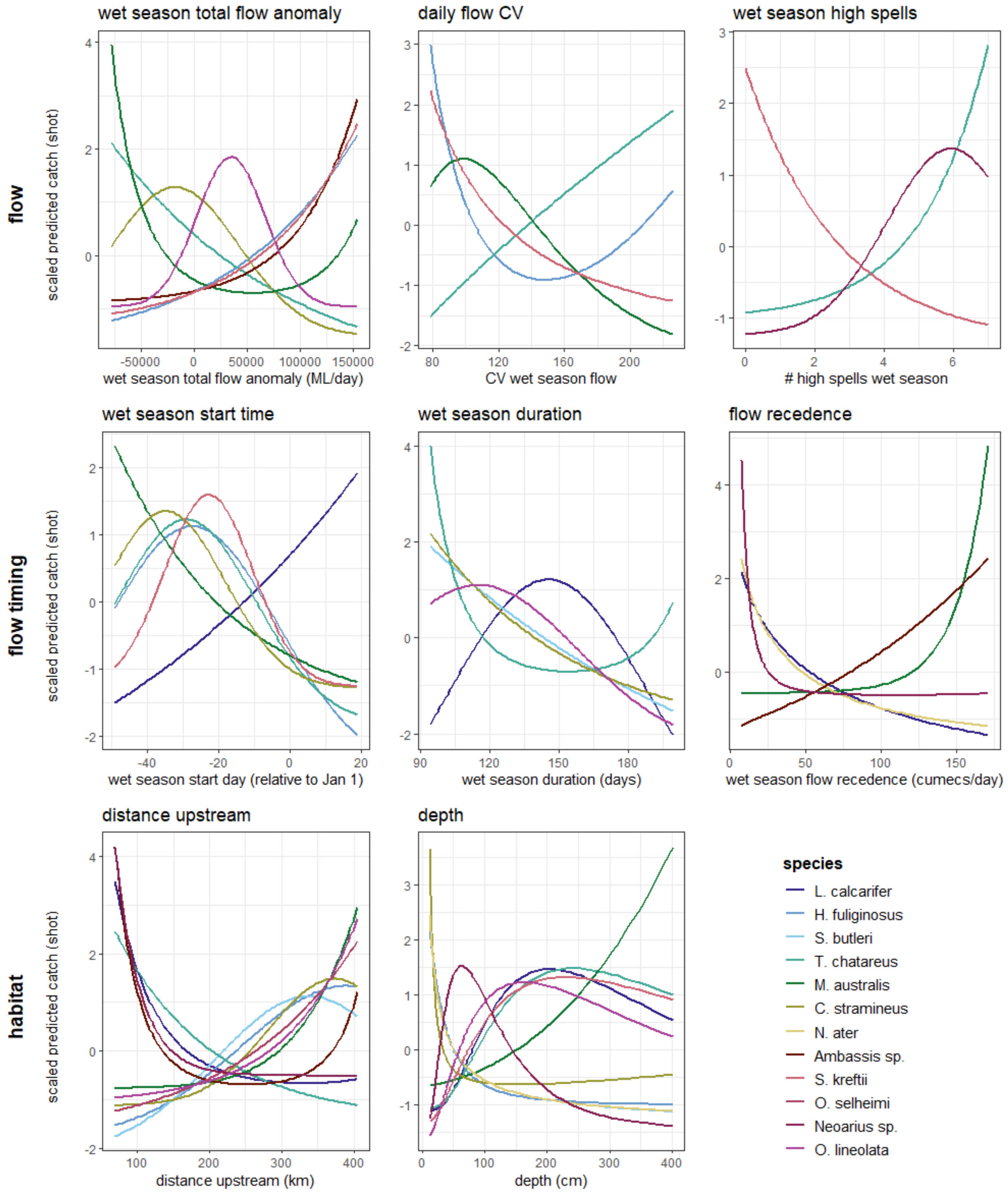

Figure 10-1. Response plots for early-dry-season catch models showing significant flow variables only for all species (see Table 10-3).

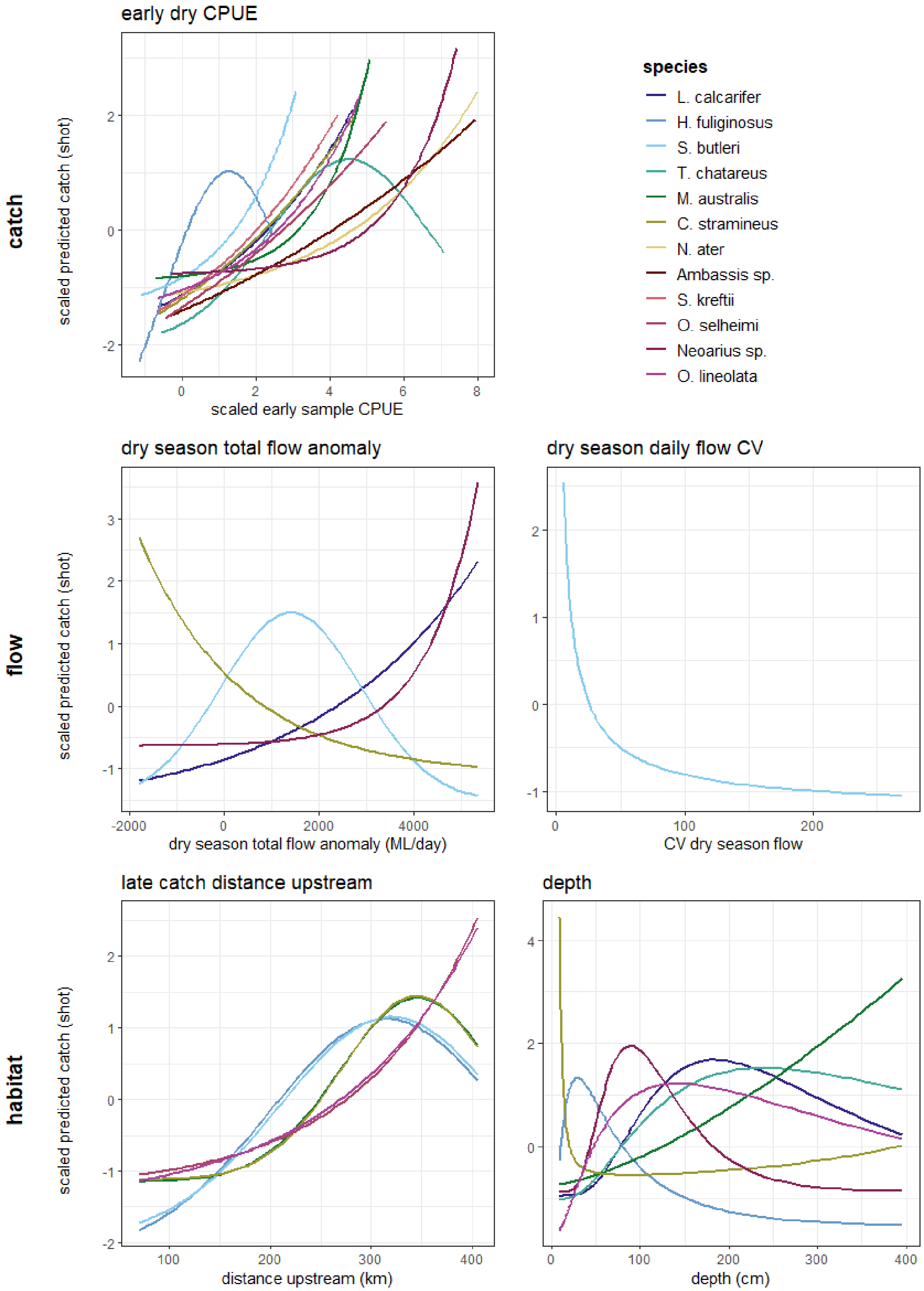

Figure 10-2. Response plots for late-dry-season catch models showing significant flow variables only for all species (see Table 10-3).

10.4.2 Predicting the effects of water extraction on juvenile fish abundance

The four focal species displayed different predicted responses to the wet-season and dry-season water extraction scenarios. In all species and scenarios, a greater percentage of flow being extracted resulted in greater predicted change in juvenile catch (Figure 10-3 – Figure 10-6). However, variation in model outcomes (95% CIs shown in plots) highlight a large range of potential outcomes for all species (indicated by wide intervals).

Abundances of juvenile *L. calcarifer* were predicted to decline in all three extraction scenarios and at the three water levels (Figure 10-3), and produced similar declines in abundance irrespective of whether the water was extracted evenly, on the receding limb of the wet season or in the dry season. Juvenile *L. calcarifer* abundance was less affected across the scenarios in the dry year than in wetter flow years, likely due to already low abundance levels. Juvenile *L. calcarifer* abundance was most affected by water extraction in the dry season, with up to 75% declines in abundance in wet years. Similar findings have also been reported in a recent study examining young-of-year catch using otolith ageing techniques (Crook et al. submitted), demonstrating the strong linkage of total discharge to juvenile barramundi abundance.

Our modelling predicted little change in the abundance of *O. lineolata* across water extraction scenarios and water levels (Figure 10-4). The early-dry-season abundance of *O. lineolata* increased in wet-season extraction scenarios in dry years relative to wet years; however, the trend was reversed in the late dry season, with wetter years displaying small declines in catch compared with dry years. This overall pattern reflects the relatively weak links between *O. lineolata* abundance and hydrology (Table 10-3).

The effect of water extraction on the abundance of *H. fuliginosus* varied depending on the year type (wetter or drier). Modelling predicted that wet-season water extraction of 20% and 40% would result in up to a 30% decline in catch of *H. fuliginosus* in dry years (Figure 10-5). However, this impact was negated if water was removed on the receding wet-season limb or in the dry season. A similar pattern of scenario sensitivity was demonstrated for *C. stramineus*. Here, wet-season water extraction in drier years had a bigger impact than wet-season water extraction in wetter years, while there was no strong abundance response to either receding-limb or dry-season water extraction (Figure 10-6).

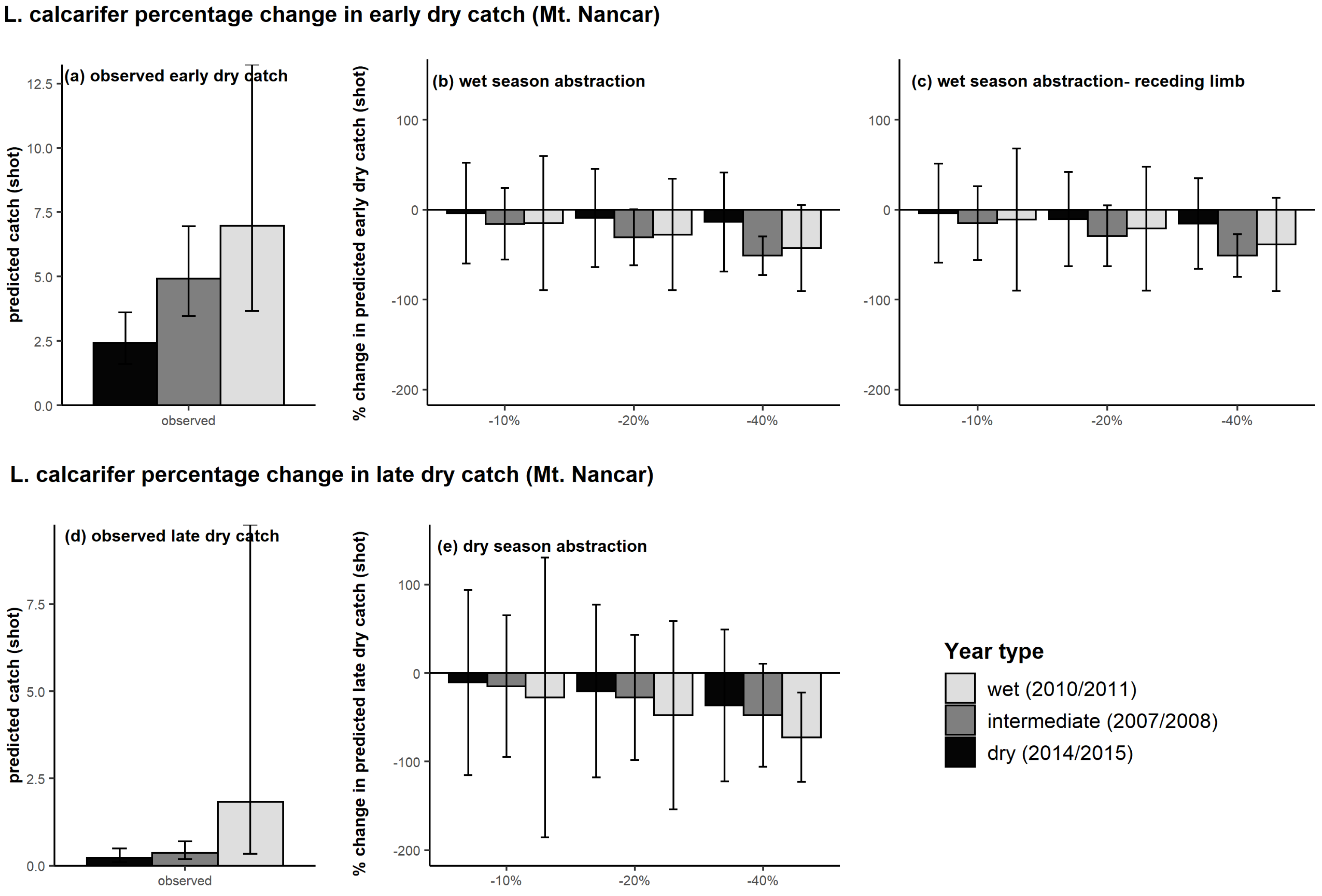

Figure 10-3. Predicted catch (+/− 95% CI; a and d) and percentage change in juvenile catch (+/− 95% CI; b, c, e) of L. calcarifer for three levels of each extraction scenario (wet-season, receding wet-season and dry-season extraction) at Mount Nancar.

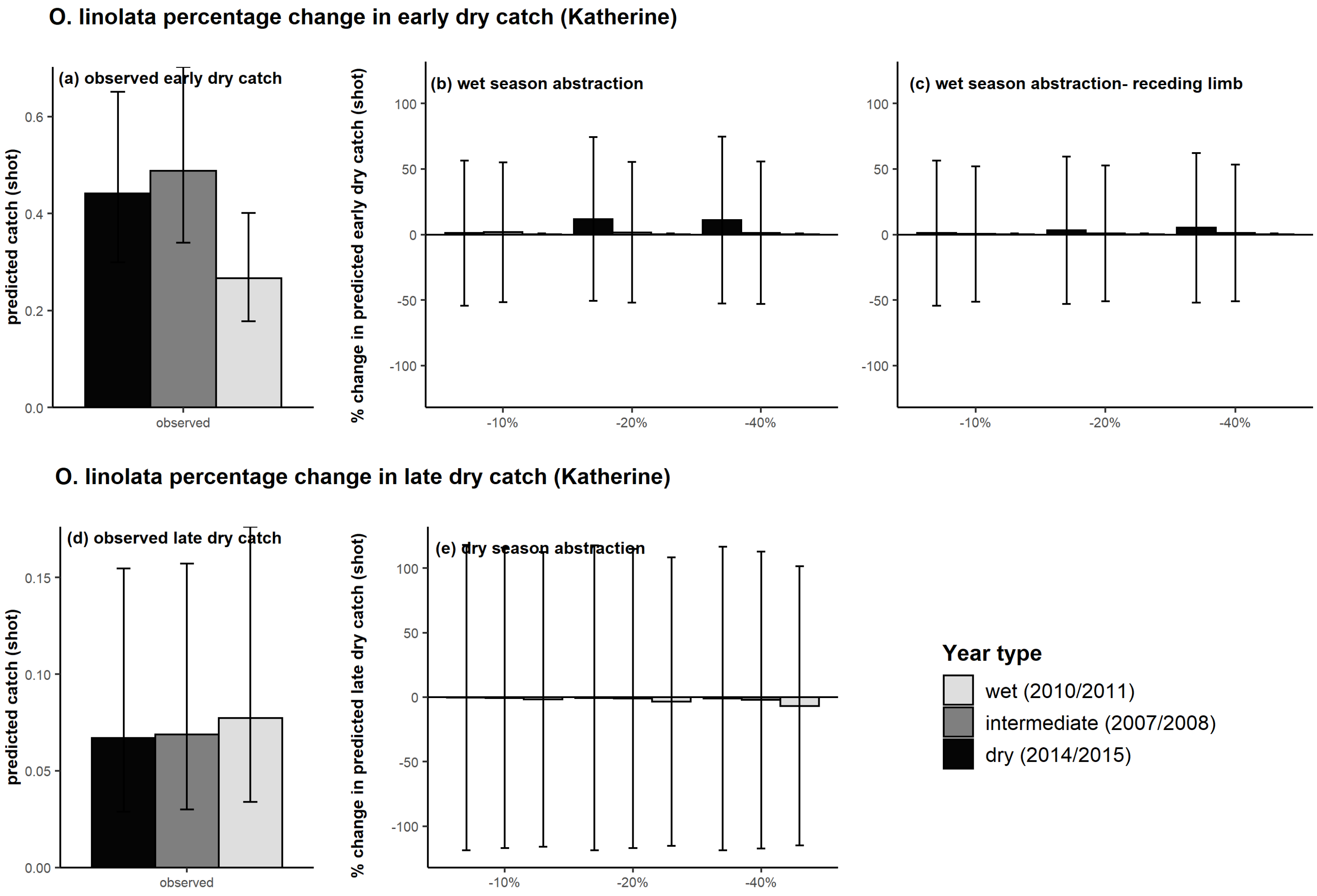

Figure 10-4. Predicted catch (+/− 95% CI; a and d) and percentage change in juvenile catch (+/− 95% CI; b, c, e) of O. lineolata for three levels of each extraction scenario (wet-season, receding wet-season and dry-season extraction) at Katherine.

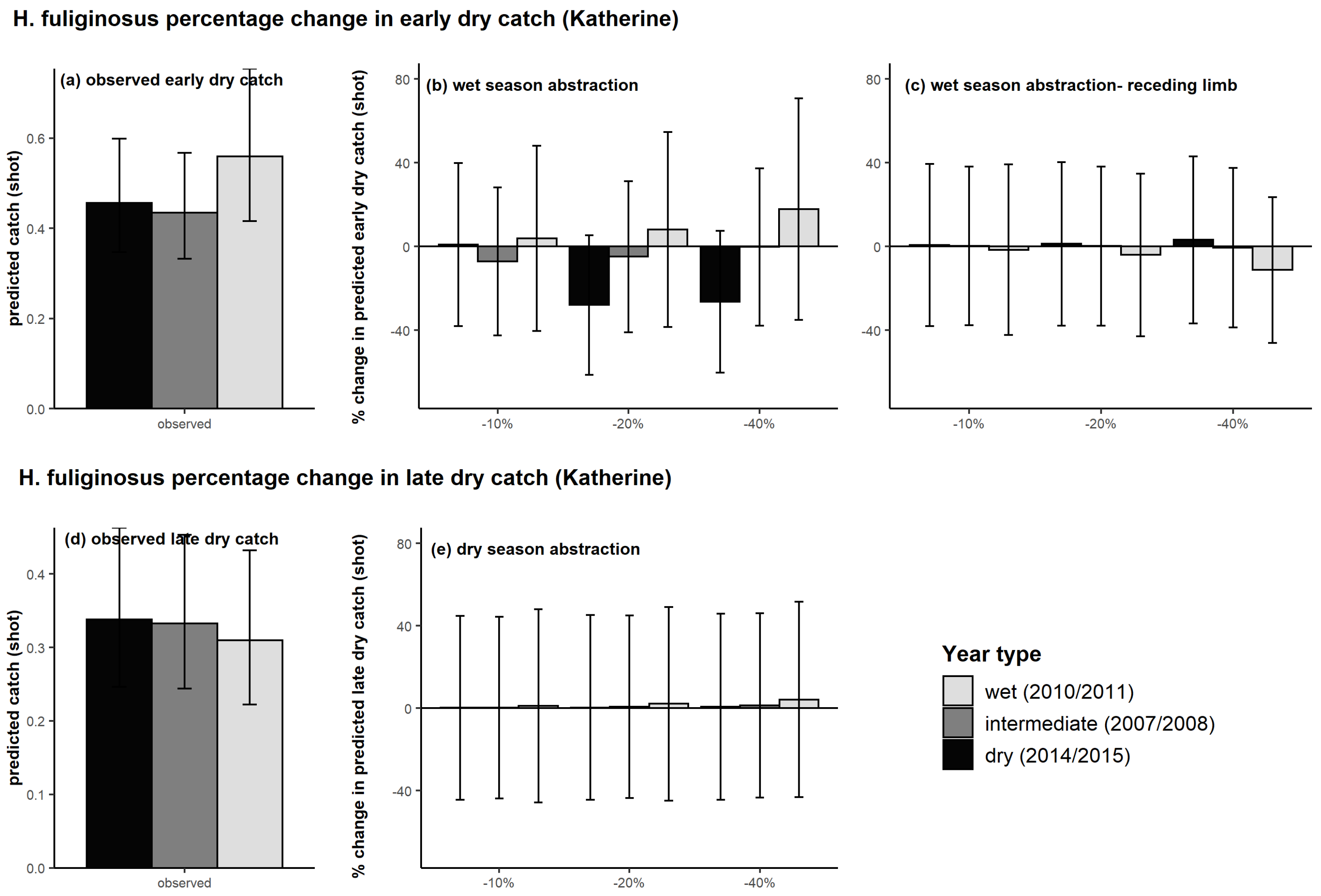

Figure 10-5. Predicted catch (+/− 95% CI; a and d) and percentage change in juvenile catch (+/− 95% CI; b, c, e) of H. fuliginosus for three levels of each extraction scenario (wet-season, receding wet-season and dry-season extraction) at Katherine.

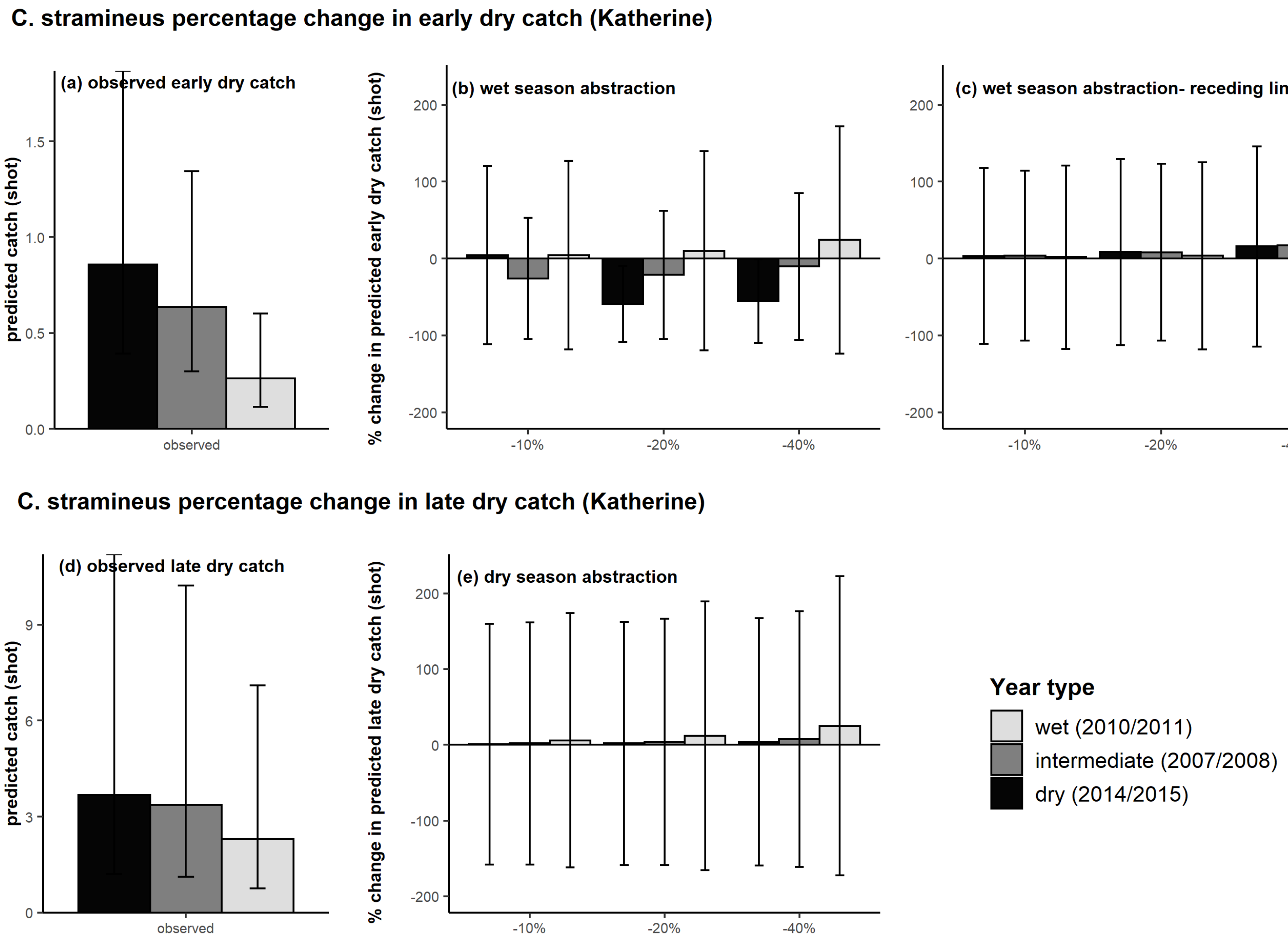

Figure 10-6. Predicted catch (+/− 95% CI; a and d) and percentage change in juvenile catch (+/− 95% CI; b, c, e) of C. stramineus for three levels of each extraction scenario (wet-season, receding wet-season and dry-season extraction) at Katherine.

10.5 Key findings

- Wet-season flow conditions were a strong predictor of both early- and late-dry-season juvenile abundance for most species (only *O. selheimi* was not clearly influenced by flows). However, there was no consistent or predictable pattern among species with similar spawning times or life history attributes.
- Wetter wet seasons resulted in a greater abundance of *L. calcarifer*, *S. krefftii*, and *N. ater*, with *Neoarius* spp. displaying a peak relationship around 30,000 ML/day. In contrast, greater abundances of juvenile *C. stramineus*, *H. fuliginosus* and *T. chatareus* occurred in drier wet seasons.
- The variability in flows, the number of high-flow spells and the timing of wet-season onset also influenced juvenile abundance for some species.
- Juvenile fish abundance at the end of the dry season was strongly predicted by wet-season conditions and early dry-season abundance.
- Abundance of juvenile *L. calcarifer* was predicted to decline in all three extraction and water-level scenarios. This outcome indicates that water extraction in either the wet season or dry season is likely to result in declines in abundance of juvenile *L. calcarifer*.
- Wet-season water extraction of 20% and 40% was predicted to decrease juvenile abundance of *H. fuliginosus* by up to 30% in dry years, but this effect was not shown if water was removed on the receding wet-season limb or in the dry season. A similar finding was observed for *C. stramineus*.

11. Migration, growth and sex change of barramundi

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This component was conducted as part of a PhD thesis by Brien Roberts (CDU).

Aims 1 and 3 of this research have been published:

Roberts, B. H., Morrongiello, J. R., King, A. J., Morgan D. L., Saunders, T. M., Woodhead, J., & Crook D. A. (2019). Migration to freshwater increases growth rates in a facultatively catadromous tropical fish. *Oecologia* 191, 253-260. https://doi.org/10.1007/s00442-019-04460-7

Roberts, B. H., Morrongiello, J. R., Morgan, D. L., King, A. J., Saunders, T. M., & Crook, D. A. (2021). Faster juvenile growth promotes earlier sex change in a protandrous hermaphrodite (barramundi *Lates calcarifer*). *Scientific Reports* 11, 2276. https://doi.org/10.1038/s41598-021-81727-1

11.1 Background

Migration is a fundamental aspect of the life history of many riverine fishes and enables individuals to exploit habitats and resources that are geographically separated from breeding grounds. However, a consistent theme of recent ecological research is that individual migratory behaviour is often highly variable within fish populations. This characteristic is frequently linked to enhanced fishery productivity and resilience, as life history diversity can result in bet-hedging in breeding success across time and space (e.g. Schindler et al. 2010). Such behavioural flexibility among individuals is often described as ‘partial migration’, where only a fraction of individuals migrate while the remainder spend their entire lives residing within breeding habitats (see Chapman et al. 2012). Importantly, migrants and residents may exhibit different growth rates, and hence differences in key fitness parameters such as size-at-age, age-at-maturity, fecundity and survival rates. Understanding the causes and consequences of migration is therefore essential for managing populations of migratory fishes, particularly for species that support important fisheries.

There is a growing appreciation that the productivity of many riverine and coastal fish populations is inextricably linked to hydrology. In a diverse array of fishes, years with high flows are associated with increased growth rates and recruitment success (e.g. Staunton-Smith et al. 2004; Morrongiello et al. 2014; Barrow et al. 2017; Crook et al. submitted). Recent evidence suggests that flow regimes may also influence the proportion of migratory phenotypes within populations. An extreme example of this occurs with the construction of dams or weirs that completely prevent fish passage, effectively eliminating migratory contingents within populations (Beechie et al. 2006). However, even minor barriers or changes to flow regimes may influence the proportion of migrants within fish populations (Branco et al. 2017). Given the increasing demand for freshwater resources in northern Australia, there is a pressing need to better understand the role of migration in shaping individual fitness and population dynamics, as well as how migration behaviour in fishes may be affected by changes to river hydrology.

The barramundi (*Lates calcarifer*) is iconic to northern Australia, and represents the most commercially and culturally significant fishery in the region (Grey 1987). Barramundi lifecycles are both complex and variable among individuals. Barramundi are sequential, protandrous hermaphrodites, with most individuals spawning as males (3–5 years) prior to transitioning to females (6–8 years; Davis 1982); however, some are known to skip spawning as males and reproduce for the first time as females (Crook et al. 2017). Spawning occurs in the saline, lower reaches of estuaries and associated coastal areas during the monsoonal wet season, where larvae hatch and are thought to spend the first few months of life. In northern Australian populations, an unknown but significant proportion of young-of-year juveniles migrate upstream into the freshwater reaches of rivers and floodplain billabongs. Juveniles that forgo migration to freshwater at this time may occasionally do so in subsequent years, but usually spend their entire lives residing within saline habitats. Of those that undertake upstream migration, the duration of freshwater residency ranges from 1 to 11 years before return migration to the saline spawning grounds (Crook et al. 2017).

Given the species' reliance on connectivity between floodplains, rivers and estuaries to complete their lifecycle, barramundi are likely to be highly vulnerable to hydrological disturbance. The present study was undertaken to explore how hydrological disturbances may impact key individual fitness parameters (e.g. growth, age at female maturity), and assess subsequent effects on population dynamics.

11.2 Aims and objectives

Broadly, the current project aimed to address the causes and consequences of migration in barramundi.

Specifically, we aimed to:

1. quantify the influence of migration to freshwater on barramundi growth rates across five geographically and hydrologically distinct river systems
2. explore relationships between individual growth rates and female maturation schedules
3. investigate relationships between environmental factors and the likelihood of juvenile barramundi migrating to freshwater.

11.3 Methods

11.3.1 Growth and salinity proxies

We explored migration and growth in individual barramundi by analysing the microchemistry and microstructure, respectively, of sagittal otoliths (ear bones). Calcareous material is deposited incrementally on the otolith surface, a process that occurs continually throughout life at a rate that is correlated with somatic growth (Campana & Thorrold 2001). Analogous to growth rings in trees, the distances between annual growth rings ('annuli') laid down within otoliths may be measured to infer favourable years, and hence conditions, for growth (Morrongiello & Thresher 2015). Additionally, trace elements from ambient water are incorporated into the calcium carbonate matrix of otoliths. As this material is not physiologically reworked, otolith microchemistry may be analysed to infer the ambient water chemistry (in this case, salinity) experienced at different stages of fish life histories and thus the timing of migrations (Elsdon et al. 2008). While a variety of chemical constituents have successfully been employed to infer movements between chemically distinct habitats, the current study analysed strontium stable isotope ($^{87}Sr/^{86}Sr$) ratios within otoliths to reconstruct the salinity histories for individual barramundi. Otolith $^{87}Sr/^{86}Sr$ were measured from the otolith core (representing the early life history), along the axis of growth, to the outer edge of the otolith (representing the end of life); see Figure 11-1 and Figure 11-2)

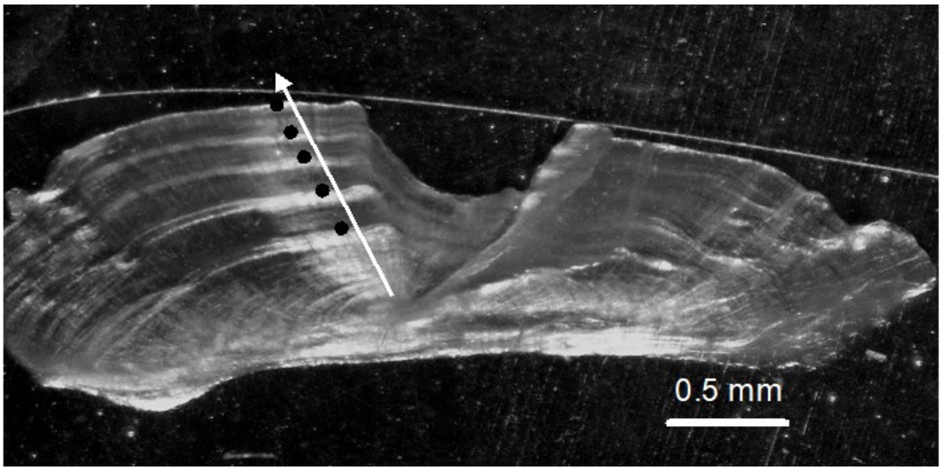

Figure 11-1. Transverse otolith section from a >5-year-old barramundi, illustrating location of ablated laser transect and annual growth increments.

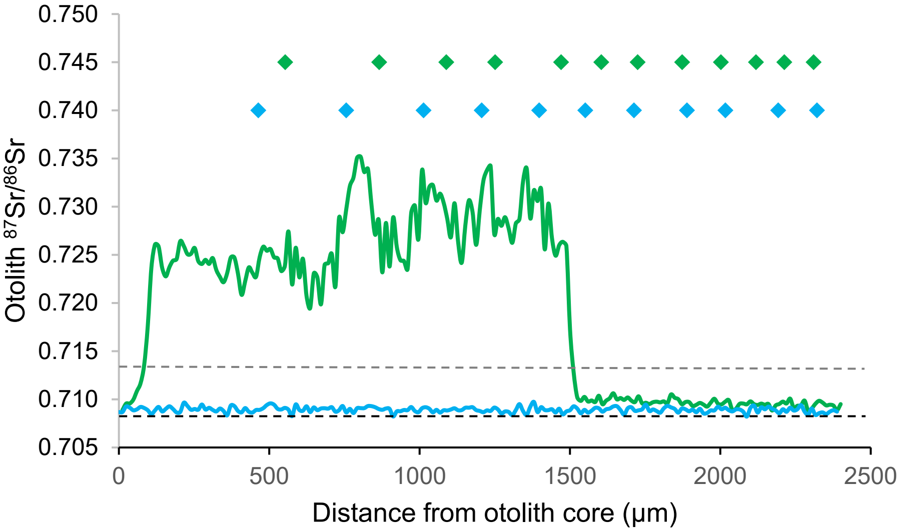

Figure 11-2. Examples of core-to-edge transects of otolith $^{87}Sr/^{86}Sr$ ratios for an estuarine resident (blue unbroken line) and a freshwater migrant barramundi that entered freshwater in its first year and returned to the estuary/marine environment at age 5 (green unbroken line). Grey broken line represents salinity of 1 part per thousand (ppt) and the black broken line represents salinity of 35 ppt (i.e. sea water) based on water $^{87}Sr/^{86}Sr$ mixing models. Values of otolith $^{87}Sr/^{86}Sr$ above grey broken line infer freshwater residency and those below estuarine or marine residency. Corresponding diamonds indicate the location of annual growth increments along the ablated transect for each fish.

11.3.2 Study sites

The study was conducted in Australia’s wet-dry tropical region in the NT and Western Australia. Barramundi otoliths were obtained from samples collected between 2001 and 2017 from the estuarine and freshwater reaches of the Fitzroy, Daly, Mary and Roper rivers. Smaller numbers of samples were also collected from the South Alligator and McArthur rivers.

11.3.3 Otolith preparation and analysis

See Roberts et al. (2019) and Crook et al. (2017) for details on otolith $^{87}Sr/^{86}Sr$ and biochronological analysis.

11.3.4 Growth analyses

A mixed-effects modelling framework was developed to explore the effect of habitat type (i.e. saline vs freshwater) on growth. Otoliths from 131 individuals were analysed, and a proxy for annual growth was obtained by measuring otolith increments. Next, each growth year was assigned a categorical salinity value (based on $^{87}Sr/^{86}Sr$ values): ‘freshwater’ or ‘estuarine’ if the year was spent entirely within either habitat type, or ‘mixed’ if a portion of the year was spent in both habitats. A suite of fixed and random factors were included in the modelling framework based on *a priori* expectations that an array of intrinsic (e.g. age, age-at-capture) and extrinsic (e.g. river, cohort) effects would be expected to influence individual growth rates (see Morrongiello & Thresher 2015).

11.3.5 Sex change analyses

A significant impediment to exploring individual variation in the timing of sex change is that the precise ontogenetic timing of sex change of a captured barramundi is unknown: an individual caught as a female may have transitioned a few weeks prior to capture, or several years previously. Similarly, a fish captured as a male might have imminently switched to female if it was not captured. To address this issue, growth analyses were focused on three separate comparisons between subsets of individuals. Firstly, to compare variation in the age at which individuals transitioned, growth trajectories were compared between individuals that had matured as females before their 5th birthday (young sex-changers) and individuals that remained males beyond age 5 (old sex-changers). Next, to explore variation in the size that individuals changed sex, growth trajectories were compared between individuals captured at <850 mm (small sex-changers) and individuals captured as males >850 mm (large sex-changers).

Finally, growth rates were compared between large (>850 mm) females and small (<850 mm) males. All else being equal, these subsets of individuals are assumed to be undertaking the same life history (i.e. normal progression from male to female), but captured at different ontogenetic stages. Thus, comparisons between these groups allows inferences as to whether barramundi that ultimately become large, highly fecund females are simply ‘regular’ fish that were successful in surviving to an old age, or alternatively, whether large size is achieved via rapid juvenile growth.

11.3.6 *Environmental drivers of migration analyses*

Relationships between a suite of environmental predictor variables and the likelihood of juveniles migrating to freshwater were explored. Each fish was assigned a binary migratory status according to whether a freshwater $^{87}Sr/^{86}Sr$ signature was detected prior to deposition of the first annulus within the otolith (0 = migrated; 1 = remained within estuary). A generalised linear mixed-effects model with a binomial distribution was fitted to the likelihood of migration as a function of the environmental predictor variables associated with the year in which each fish was spawned. To account for any river-specific effects, River was included as a random factor. See Roberts (2021) for environmental parameter descriptions.

11.4 Results

11.4.1 *Effect of migration on growth rates*

The optimal random effects model structure included random intercepts for Age and FishID, and a random intercept for River*Year (see Roberts et al. 2019 for parameter descriptions and model results). The best-supported fixed effects structure included an Age*Salinity interaction (conditional R^2: 0.68). Barramundi growth was highest in freshwater, intermediate in years spent partially within both fresh and saltwater (i.e. mixed), and lowest in estuarine waters. These habitat-specific differences in growth became less pronounced as fish grew older (Figure 11-3).

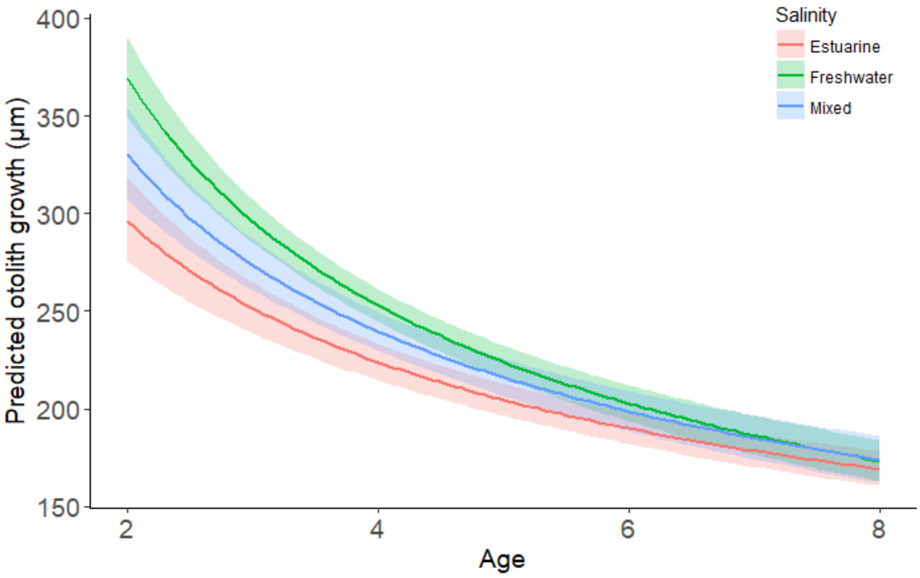

Figure 11-3. Estimated age and salinity effects on growth. Shaded areas represent 95% confidence intervals.

11.4.2 Effect of growth on timing of female maturation

Barramundi sex was more closely associated with length than age. Rapid juvenile growth was associated with decreased age of female transition, but did not appear to strongly influence the size at sex change. The largest females in the dataset had substantially faster growth rates than those that were captured as small males (Figure 11-4).

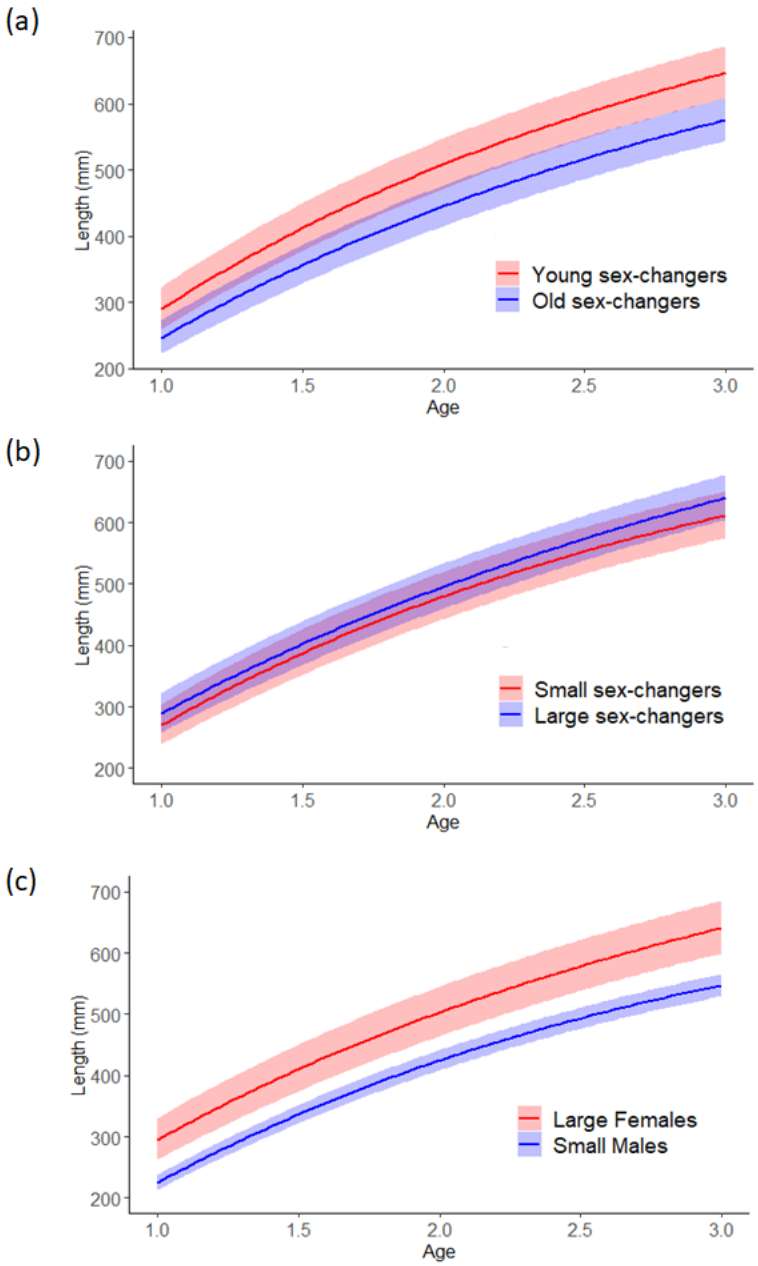

Figure 11-4. Linear mixed-effects growth curves illustrating differences in size-at-age between different life history types. Blue lines, males; red lines, females. (a) old sex-changers and young sex-changers (i.e. effect of growth rate on age of sex change); (b) large sex-changers and small sex-changers (i.e. effect of growth rate on size at sex change); (c) large females and small males. Shaded areas represent 95% confidence intervals.

11.4.3 Environmental drivers of migration analyses

Of the 168 barramundi that were subjected to microchemical analysis, 105 contained a freshwater $^{87}Sr/^{86}Sr$ signature between the otolith core and the first annulus, indicating that these individuals undertook upstream migration to freshwater during the first year of life. The optimal model structure included a random intercept for River and a fixed Australian Monsoon Index (AMI) effect. The likelihood of migrating to freshwater was negatively correlated with AMI (*P*=0.011), indicating that fish spawned in wet years were more likely to adopt resident life histories within the estuary (Figure 11-5). This effect was consistent across all of the study rivers.

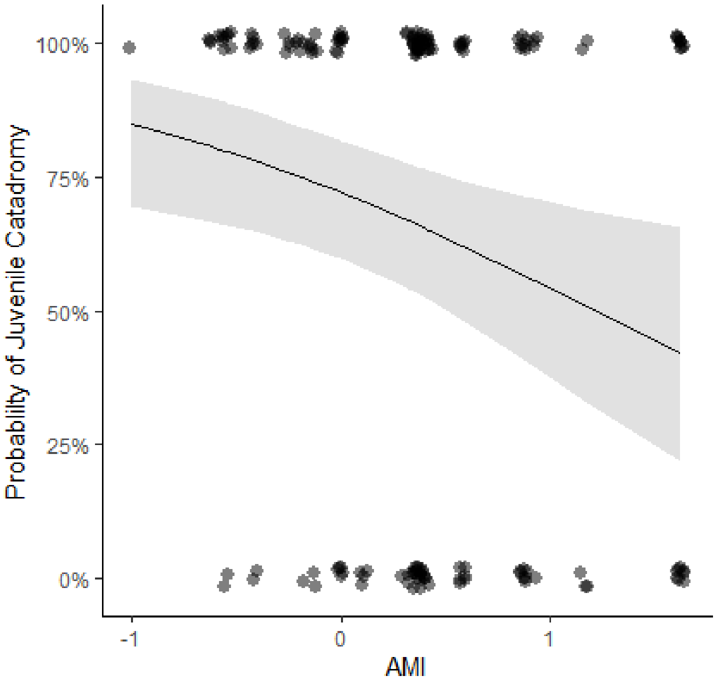

Figure 11-5. The likelihood of juvenile barramundi migrating to freshwater within the first year of life as a function of the Australian Monsoon Index.

11.5 Discussion

The results of this study demonstrate that migration to freshwater results in a growth advantage in barramundi (Roberts et al. 2019). This effect is likely driven by greater foraging success by barramundi in freshwater habitats compared with estuaries, which may in turn reflect increased access to floodplain-derived food resources. The floodplain rivers of northern Australia undergo annually predictable periods of inundation during the wet season (Douglas et al. 2005), which inject large-scale influxes of nutrients to aquatic food webs (‘flood pulse concept’, *sensu* Junk et al. 1989). Annual flooding events are thought to provide a seasonal abundance of food supplies to barramundi and other large-bodied fishes in freshwaters (Jardine et al. 2012a,b). Our results suggest that migratory barramundi that include a freshwater phase may obtain greater access to these highly productive food resources, and hence greater growth, than individuals that remain as estuarine residents.

As body size is positively correlated with a range of fitness traits of fish, our finding of increased growth in migratory barramundi suggests that migration may have important implications for individual fitness. However, although different migratory strategies may infer different growth trajectories, migrant and resident phenotypes may both represent viable reproductive strategies if lifetime reproductive output is equal among phenotypes, or if the optimal strategy depends on environmental conditions. Individual fitness may involve complex trade-offs between migration and reproduction. For example, individuals that migrate into freshwater for extended periods, delay reproduction and maximise energetic investment in growth may ultimately increase their chances of developing into large, highly fecund females (Roberts et al. 2021). However, delayed return to saline spawning habitats incurs a cost of elevated risk of mortality prior to spawning. In contrast, the adoption of more sedentary lives within estuaries may facilitate successful reproduction during the initial male phase, but may reduce the chances of developing into females later in life. Such trade-offs likely maintain the existence of diverse life histories within barramundi populations.

Analyses of relationships between growth rate and the timing of sex change revealed that female maturation was more closely related to individual size, rather than age (Roberts et al. 2021). Hence, barramundi that grew quickly achieved female status sooner than slow-growing barramundi. Individuals that were captured as large females had faster juvenile growth rates than those captured as small males, indicating that rapid growth during the early years of life promotes larger size-at-age throughout ontogeny. Growth rates did not seem to have a strong effect on the size at which individuals changed sex. Ultimately, our results suggest that rapid growth increases individual fitness by simultaneously increasing age-specific fecundity and the portion of ontogeny spent as a female.

The apparent primacy of fast growth with respect to fitness suggests that extrinsic factors, rather than individual trade-offs, may be the primary driver of individual variation in sex-change schedules. For example, individuals may achieve fast growth rates by encountering favourable environmental conditions or lower rates of competition during the early life history. Indeed, the protracted spawning season of barramundi (September–March) effectively gives early-spawned individuals a ‘head start’ of up to 6 months over late-spawned individuals within a cohort. In the first months of life, young barramundi become increasingly piscivorous as they grow, which may drive rapid increases in growth rates (Post 2003) and shape extreme size variability within cohorts. Early-spawned recruits, or recruits that encounter favourable habitats during the early life history, may therefore achieve a substantial size advantage, and in turn may attain female status at an earlier age.

Analyses of relationships between environmental variables and the frequency of juvenile migration demonstrated a clear link between AMI and migration behaviour. In high-rainfall wet seasons, young-of-year barramundi were more likely to remain in the estuary, indicating that under these conditions, abundant resources within the estuary provide an incentive for recruits to forgo migration. In contrast, low-rainfall years were linked to higher rates of juvenile migration, suggesting that a paucity of resources within the estuary in dry years encourage barramundi to migrate in search of more productive habitats.

As outlined above, variation in the proportion of barramundi migrants and residents within cohorts likely reflects temporal variation in the availability of suitable prey for juvenile barramundi within estuaries. Although floodplain-derived prey resources may generally be more readily available to barramundi residing within freshwaters than estuaries, this nutritional source also comprises a substantial portion of the diet of estuarine barramundi

(Jardine et al. 2012a). In wet years, estuaries are likely to receive a greater influx of energy from floodplains, which likely drives the higher rates of residency in these years.

This study provides new insights into the drivers of migration by riverine fishes and highlights the complex interplay between life history characteristics and fitness. The results underscore the importance of preserving highly productive and hydrologically variable tropical freshwater habitats, especially in the face of increasing demand for water resources and a changing climate. If barramundi access to high-quality freshwater habitat and floodplain-derived resources is reduced by anthropogenic disturbances, then growth rates will likely decrease. Additionally, potential future changes to hydrology are likely to reduce inter-seasonal and inter-annual variability in flow regimes, which may potentially impact current levels of life history diversity within barramundi populations. In short, deleterious impacts to connectivity of floodplain rivers of northern Australia will likely cause the productivity of barramundi populations and their associated fisheries to decline.

12. Conclusions and environmental flow considerations

12.1 Key findings and environmental flow considerations

The key findings from this study are:

- **Floodplain inundation.** The Landsat satellite record provided important context and historical trends, providing good insight into frequency of inundation patterns. However, there are some spatial and temporal resolution challenges that should be considered. We recommend a multi-sensor approach for future investigation, that integrates both Sentinel-1 (SAR) and Sentinel-2 (multi-spectral) data into an analysis framework with the Landsat archive to provide higher spatial and temporal resolution.
- **Floodplain inundation.** Floodplain inundation behaviour changes throughout the catchment. Sustained wetting of adjacent floodplains in the Katherine River only occurred with very-high-flow conditions (>1,000 cumecs, 2% exceedance probability), and similarly at Dorisvale and Oolloo Crossing reaches (5% exceedance probability). The lower catchment, however, showed evidence of floodplain inundation with both high discharge (<10% exceedance probability) and lower discharges, indicating the presence of more rainfall-driven inundation.
- **Hydrodynamic mapping.** High-resolution hydrodynamic models of both Wilden and Mentabie reaches were conducted and a series of in-stream low-flow (dry-season) scenarios were modelled for each study location to determine the impacts of reduced stream flows on preferred habitat availability for various study species. Model outputs are now retained by the NT Department of Environment, Parks and Water Security for use in future assessment work.
- **Hydrodynamic mapping.** Each output layer can be used to identify total area and spatial distribution of favourable habitat conditions for each parameter, which can be used to determine the overall area of suitable habitats of interest. By correlating available in-stream habitat within the modelled reaches with habitat requirements of indicator species, minimum flow requirements for various biota and their sensitivity to reductions in river flow can be determined.
- **Hydrodynamic mapping.** The approach taken to develop the hydrodynamic models and relate them to known eco-hydrological requirements for indicator species establishes a science-based methodology to determine ecological flow thresholds and establish environmental flow requirements for any waterway. The methodology is transferable, including the preferential habitat data for indicator fish species. Hydrodynamic modelling of representative reaches will be required for each waterway where this method is to be used.
- **Dry-season habitat use by fishes.** Fishes of the Katherine and Daly rivers can be grouped into four distinct habitat-use guilds. The guilds respond broadly to important habitat elements such as water depth, velocity, and in-stream structures and bank shape. These habitat guilds can be used to simplify habitat-use requirements and potentially extrapolated to predict requirements of similar species or systems that currently have little ecological knowledge.

- **Dry-season habitat use by fishes and vulnerability to water extraction.** Reduced dry-season water levels are predicted to reduce the amount of available suitable habitat for some species. Three taxa – *Neoarius* spp., and juvenile *S. butleri* and juvenile *H. fuliginosus* – are predicted to undergo significant declines in suitable habitat with decreasing water discharge in both study reaches. A >20% loss of available suitable habitat occurred for these three species and for *C. stercusmuscarum* with discharge of <2 cumecs (at Wilden gauge, Katherine River) and <5 cumecs (at Claravale gauge, Daly River). Other species either had no change, or marginal increases or declines with changed water levels.
- **Dry-season food web.** Stable isotope analysis showed that a mixture of basal resources supports dry-season food webs in the Daly River, with a strong reliance on both internal (e.g. in-stream algae) and external (floodplain and marine) primary production. The flow of energy from external food sources into the riverine food web (i.e. energetic subsidy) highlights the importance of maintaining connectivity throughout the system to sustain a healthy ecosystem.
- **Dry-season food web.** Dry-season flow is likely to have a significant effect on the riverine food web through its effect on resource availability, due to high contributions of benthic macroalgae and macrophytes in the diets of macroinvertebrates. For example, reductions in flow of 1 m^3/s at Claravale Crossing will reduce available area for *Spirogyra* spp. and *Vallisneria* spp. by ~14%.
- **Dry-season food web.** Invertebrates are generally more reliant on internal resources than fish. Fish generally had a higher reliance on external resources in the Katherine River compared with the Daly River at Oolloo Crossing, while the proportions of internal and external resources were similar for macroinvertebrates. Site differences may be related to differences in internal resource availability with potential links to flow.
- **Dry-season habitat preference for juvenile sooty grunter.** Radio-tracking of juvenile sooty grunter and mapping their habitat preferences demonstrated a strong preference for shallow, fast-flowing hydraulic habitat during the dry season. This broadly confirms previous studies using indirect measures of habitat in the Daly River and is consistent with observations in other parts of the species' range.
- **Vulnerability of juvenile sooty grunter habitat to water extraction.** Preferred habitat for juvenile sooty grunter declined sharply as dry-season river discharge reduced. For example, at flows of 0.5 m^3/s, habitat availability was reduced by ~61% compared with the flows experienced during the study (2.8 m^3/s), while flows of <2 m^3/s are predicted to reduce preferred habitat area by ~12%.
- **Movement of pig-nosed turtles.** Broadscale acoustic tracking showed that most pig-nosed turtles of both sexes underwent limited movements within their home ranges, with a few individuals ranging widely (maximum 23.5 km linear home range).
- **Movement of pig-nosed turtles.** There were considerable sex-based differences in movements throughout the study reach. Male pig-nosed turtles exhibited a consistent pattern of movement, with intense activity during the dry-season months of April to August, and relatively low activity from September to March, with the cessation of activity seemingly coinciding with increased water temperatures that reduce the need for thermal basking on hot springs, and the commencement of female nesting. Most large-scale

movements by female pig-nosed turtles occurred in the late dry season and the wet season.

- **Use of thermal springs by pig-nosed turtles.** Pig-nosed turtles use riverbed springs during dry-season months to assist in thermoregulation. In this study, turtles were more active in the early dry-season period, when the water temperature is colder, compared with the late dry season. Access to thermal hot springs is therefore a critical requirement for this species.
- **Core habitat of pig-nosed turtles.** The core habitat of pig-nosed turtles in the Daly River encompasses the region between Claravale and Oolloo crossings, where high spring inflows, warmer river temperature and extensive, dense ribbonweed meadows occur. This region is a critical reach to be managed sensitively.
- **Habitat and movement requirements of pig-nosed turtles related to flow conditions.** The risk of functional disconnection is highest in upper reaches of the study area (i.e. from Dorisvale to Oolloo Crossings). Hydrodynamic modelling suggested that minimum flows for passage may exceed current flow recommendations. The minimum discharges at which movement by pig-nosed turtles was observed across potential low-flow barriers provide a starting point for developing flow criteria to maintain connectivity for pig-nosed turtles.
- **Habitat and movement of adult sooty grunter.** Broadscale acoustic tracking showed that adult sooty grunter in the Daly River exhibit long periods of restricted movement and site fidelity. However, ecologically important large-scale movements are undertaken by a substantial proportion of the population over the scale of tens of kilometres (maximum >53 km), especially during the wet season.
- **Habitat and movement of adult sooty grunter.** To preserve the ecological functions provided by large-scale movements, it will be necessary to maintain sufficient flow across natural shallow parts of the channel (e.g. riffles) and low-flow barriers (e.g. road crossings) to provide connectivity along the river channel. The minimum discharges at which movement by sooty grunter was observed across potential low-flow barriers provide a starting point for developing flow criteria to maintain connectivity for fish.
- **Freshwater fish spawning.** Spawning calendars for ~26 species were described in the Daly River catchment. Most taxa had spawning periods spanning multiple hydrological seasons (aseasonal), while other taxa had discrete spawning windows aligning with the onset of the wet season.
- **Freshwater fish spawning.** Fish utilised perennial and intermittently flowing reaches differently for spawning, with perennially flowing reaches supporting a more diverse larval assemblage. Therefore, a loss of fish species diversity may result if perennial-flow regimes were to be shifted more towards intermittency.
- **Larval fish abundance and diversity.** Larval fish abundance was high during both high-flow and low-flow periods, emphasising the importance of all hydrological seasons for fish reproduction. Larval fish diversity was highest during periods of high flow when wet-period spawning taxa reproduced. Larval fish abundance and diversity was highest in structurally complex habitats, suggesting the importance of a diversity of in-stream and riparian habitat structures (i.e. macrophytes, wood, riparian trees and vegetation etc.) to support fish reproduction.

- **Larval fish growth.** Larval growth (indicator species *C. stramineus*) was fastest in, and downstream of, a groundwater discharge zone compared with upstream, highlighting the potential importance of maintaining groundwater-derived flows to the river channel during the late dry season to maintain fish productivity and growth.
- **Freshwater fish recruitment.** Modelling of a range of hydrological variables to juvenile fish abundance demonstrated that wet-season flow variables were strong predictors of juvenile fish abundance for most species in the early dry season. However, the late-dry-season juvenile abundance was related to both wet-season conditions and early-dry-season abundance, and very minimally related to dry-season flow conditions.
- **Freshwater fish recruitment.** Wetter wet seasons result in greater abundances *of L. calcarifer, S. krefftii* and *N. ater*, with *Neoarius* spp. displaying a peak relationship around 30,000 ML/day. In contrast, greater abundances of juvenile *C. stramineus*, *H. fuliginosus* and *T. chatareus* occurred in drier wet seasons.
- **Freshwater fish recruitment.** Abundance of juvenile *L. calcarifer* was predicted to decline in all three extraction (wet season, wet receding limb and dry season) and water-level (10%, 20% and 40%) scenarios. This indicates that water extraction in either the wet season or dry season is likely to result in declines in abundance of juvenile *L. calcarifer*.
- **Freshwater fish recruitment.** Wet-season water extraction of 20% and 40% was predicted to decrease juvenile abundance of *H. fuliginosus* by up to 30% in dry years only, but the effect did not occur if water was removed on the receding wet-season limb or in the dry season. A similar finding was observed for *C. stramineus*.
- **Migration of barramundi.** Otolith (ear bone) chemistry and microstructure analysis showed that migration to freshwaters results in a growth advantage in barramundi, highlighting the importance of maintaining open longitudinal and lateral connectivity for barramundi, and allowing access to floodplain and channel freshwater-derived food resources.
- **Migration of barramundi.** Juvenile barramundi were more likely to remain in estuarine habitats during high-rainfall wet seasons; however, in low-rainfall years, juvenile barramundi were more likely to migrate into freshwaters in search of more productive growth habitats. This finding shows that changes to flow regimes have profound implications for growth and migration rates in barramundi and the productivity of the fisheries they support.

This study has resulted in several new and important environmental flow considerations for the Daly and Katherine rivers that should be considered in future environmental flow studies and recommendations (Table 12-1). Where possible, the flow considerations have been developed to be specific to reaches and discharge thresholds, where there is suitable evidence to provide this. In other cases, flow considerations are more general statements.

Importantly, while this study provides new evidence of the importance of flows for a number of key values of the Daly and Katherine rivers, it is not an environmental flows study, in which all values and threats would be considered and final environmental flow recommendations would consider all aspects of the river’s ecological functions.

Table 12-1. Daly River environmental flow considerations as outcomes from this study.

Flow period/ component	Relevant Daly River reach	Environmental flow consideration	Key function	Line of evidence	Confidence of evidence (high, medium, low)	Risk considerations
Early wet season	Dorisvale Crossing to Douglas River confluence	Protect early flows of wet season	Large-scale movements of female pig-nosed turtles and sooty grunter commence in early wet season	Acoustic tracking data and coincident discharge data	Medium	Disruption of normal movement responses
Early wet season	Dorisvale Crossing to Douglas River confluence	Protect early flows of wet season	Initiate hatching of pig-nosed turtles	Doody et al. (2001)	High	Later emergence of hatchlings during higher flows
Wet season	Katherine River	~ >1,000 cumecs (Katherine Railway Bridge) required for sustained inundation of floodplain	Main channel and floodplain connectivity Maintains wetlands through surface water connection and allows exchange of material and biota into main channel	Water Observations from Space (WOfS) imagery analysis	Medium	Reduction of food and energy into main channel from floodplain resources Failure to connect and top-up wetland habitats
Wet season	Daly River	~ >1,000 cumecs (Claravale and Oolloo crossings) required for sustained inundation of floodplain	Main channel and floodplain connectivity Maintains wetlands through surface water connection and allows exchange of material and biota into main channel	WOfS imagery analysis	Medium	Reduction of food and energy into main channel from floodplain resources Failure to connect and top-up wetland habitats

Flow period/ component	Relevant Daly River reach	Environmental flow consideration	Key function	Line of evidence	Confidence of evidence (high, medium, low)	Risk considerations
Wet season	Katherine and Daly rivers	Ensure preservation of peak wet-season flows and recession	Maximise access of fish to food resources of floodplains and return to main channel habitats	In the dry season a high proportion of food sources for fish originates from previous wet-season resources (floodplain and marine derived)	Medium	If access to rich wet-season food sources is restricted, fish that rely heavily on external resources may have poorer survival over the dry season
Wet season	Daly catchment	Minimise changes to the slope of rising and receding limbs	Supports high larval productivity when these flows coincide with high primary and secondary productivity	Larval fish productivity was highest in intermediate- to high-flow periods when flows coincided with intermediate to high levels of primary and secondary productivity	Medium	Reduction in larval productivity could result in lower numbers of functional species having strong recruitment
Wet season	Dorisvale Crossing to Douglas River confluence	Maintain period of duration of overbank flows and access to off-stream resources	Allows access to accumulate food resources for growth and to support reproduction for pig-nosed turtles	Inferred from acoustic tracking data, supported by previous observations	Low	Low reproductive output, potentially reproductive failure
Wet season	Daly and Katherine rivers	In drier wet seasons (e.g. similar to 2014/2015), protection of wet-season flows is important to maintain recruitment of *H. fuliginosus*	Supports breeding and recruitment of *H. fuliginosus*	Wet-season water extraction of 20% and 40% was predicted to decrease juvenile abundance of *H. fuliginosus* by up to 30% in dry years, with the effect not shown if water was removed on the receding wet-season limb or in the dry season A similar finding was observed for *C. stramineus*	Medium	Reduced recruitment of key freshwater fish species

Flow period/ component	Relevant Daly River reach	Environmental flow consideration	Key function	Line of evidence	Confidence of evidence (high, medium, low)	Risk considerations
Wet season and receding limb	Daly and Katherine rivers	Decreased wet-season discharge increases risk of reduced recruitment of some fish species, including *L. calcarifer*	Wet-season discharge supports greater abundances of juvenile *L. calcarifer, S. krefftii*, and *N. ater*, with *Neoarius* spp.	Juvenile abundance of these species was highest in wetter years Abundance of *L. calcarifer* was strongly influenced by scenarios of wet-season extraction rates at 10%, 20% and 40% levels	Medium	Reduced recruitment of key freshwater fish species
Dry season	Katherine River	Maintain >2.0 cumecs at Wilden gauge during dry season	Protection of critical riffle habitat for juvenile sooty grunter (e.g. available habitat declines by 30% from 2 to 1 cumecs, and by 55% from 2 to 0.5 cumecs)	Targeted radio-tracking study of juvenile sooty grunter showed habitat is specifically linked to hydraulic features of the reach	High	Less available habitat and poor recruitment in low-water years Increased risk of population-level consequences with consecutive years of low flows
Dry season	Katherine River	Maintain >2.0 cumecs at Wilden gauge during dry season	Protection of a diversity of habitats suitable for diversity of fish species Critical velocity and shallow habitat (riffles) for juvenile sooty grunter, Butler's grunter and *Neoarius* spp. declines significantly with discharge <2.0 cumecs	Depth and velocity habitat use calculated for a variety of species, linked to hydrodynamic model of habitat area under various water scenarios	Medium	Less available habitat, poor survival rates and poor recruitment in low-water years Increased risk of population-level consequences with consecutive years of low flows

Flow period/ component	Relevant Daly River reach	Environmental flow consideration	Key function	Line of evidence	Confidence of evidence (high, medium, low)	Risk considerations
Dry season	Daly River	Maintain >5 cumecs at Claravale gauge during dry season	Protection of a diversity of habitats suitable for diversity of fish species Critical velocity and shallow habitat (riffles) for juvenile sooty grunter, Butler's grunter and *Neoarius* spp. declines significantly with discharge <5.0 cumecs	Depth and velocity habitat use calculated for a variety of species, linked to hydrodynamic model of habitat area under various water scenarios	Medium	Less available habitat, poor survival rates and poor recruitment in low-water years Increased risk of population-level consequences with consecutive years of low flows
Dry season	Katherine and Daly rivers	Decreased dry-season flows reduce high-velocity habitat for *Vallisneria* spp. and filamentous algal growth	Protect dry-season sources of productivity that support food webs during dry-season low flows	High proportion of in-stream algal sources were present in many taxa in the dry season (especially invertebrates) (e.g. 1 cumec decline = 14% loss in suitable habitat for filamentous algae and *Vallisneria* spp.)	Medium–low	Less available habitat for dry-season production in low-water years could lead to decreased resources to support food webs Potentially poor growth and survival of some taxa over dry season
Dry season	Dorisvale Crossing to Douglas River confluence	Maintain high levels of thermal spring/ aquifer inflow to river	Maintain thermal springs for basking by pig-nosed turtles, and maintain base flow levels for connectivity	Inferred from acoustic tracking data, and supported by previous studies on basking behaviour	Medium	Reduced activity and body condition during cool dry-season months, potentially effects on timing of reproduction and overall body condition
Dry season	Dorisvale Crossing to Douglas River confluence	>6 cumecs at Dorisvale gauge, >12 cumecs at Oolloo Crossing	Maintain river connectivity for pig-nosed turtles	Hydrodynamic modelling of flow scenarios, with assumptions of critical depth for pig-nosed turtle passage across riffles	Medium	Failure to access critical resources in some reaches, especially upper reaches

Flow period/ component	Relevant Daly River reach	Environmental flow consideration	Key function	Line of evidence	Confidence of evidence (high, medium, low)	Risk considerations
Dry season	Dorisvale Crossing to Douglas River confluence	Minimum Oolloo flows ~12–15 cumecs	Protect critical habitat of ribbonweed beds on Oolloo dolostone pavements	Rea et al. (2002)	Medium	Loss or degradation of critical food resource
Dry season	Dorisvale Crossing to Douglas River confluence	Minimum 19 cumecs at Oolloo Crossing to maintain river connectivity	Minimum flow for movement of pig-nosed turtles	Acoustic tracking data and coincident discharge data	High	Connectivity across Oolloo Crossing restricted to wet season
Late dry season	Perennial reaches of Daly catchment	Ensure perennial connected flow	Supports reproduction of a higher number of species than intermittent reaches	Larval sampling at multiple sites in both perennial and intermittent reaches revealed lower taxa diversity of larval assemblages in intermittent reaches	Medium	Loss of taxa within some river reaches due to reduction of suitable spawning environments
Late dry season	Intermittent reaches of Daly catchment	Maintain presence of water in late dry season	Supports intermediate levels of larval productivity when low water levels support high rates of primary production in the late dry season	Intermediate rates of larval fish production occurred in the late dry season when rates of primary productivity were also high	Medium	Reduction in larval productivity could result in lower numbers of functional species having strong recruitment prior to, or during, the wet season
Late dry season	Perennial reaches of Daly catchment	Ensure persistence of groundwater inputs to Oolloo Reach	Supports high larval growth rates at Oolloo Reach, and downstream thereof in the late dry season	Comparison of growth rates of larval *C. stramineus* using otolith microstructure analyses between sites upstream and downstream of the Oolloo Reach	Medium	Lower growth rates could translate into reduced survival and recruitment of a potentially important food resource for piscivores

12.2 Future research priorities

This research project has provided considerable new knowledge; however, it has also highlighted a number of priorities for future research:

- A multi-sensor approach should be used for future investigations of floodplain inundation in the region. Analysis should integrate both Sentinel-1 (SAR) and Sentinel-2 (multi-spectral) data into a framework with the Landsat archive to provide higher spatial and temporal resolution.
- Satellite image analysis can provide reliable estimates of surface water areal extent, but has limited ability to infer depth and volume without the use of a high-quality digital terrain model. We recommend the prioritisation of high-resolution airborne LiDAR surveying of the river channels and floodplains for future research, to make these linkages explicit.
- This study provided important correlative evidence of the importance of wet-season and dry-season flows for freshwater fish movement, spawning and recruitment in the Daly River catchment. Further research on the mechanisms, such as food and habitat availability, and predator control would be important future research avenues.
- Fish populations were annually monitored in the Daly River over 2006–2019. These data have provided critical baseline information on the status and variability of populations over varying flow conditions. Future monitoring should be reinstated in the coming years to assess and ensure that current and future water developments in the region do not affect the fish population viability.
- While the study detected movements of turtles during the wet season in the main channel, further research should be conducted on understanding the importance of floodplain habitat use by turtles during the wet season.
- There has been limited research on the general ecology (e.g. habitat use, diet movements) of hatchling and juvenile pig-nosed turtles. Given the lack of evidence of recruitment of turtles, research on drivers of recruitment success and failure should be a particular focus.
- The ecological importance of riverbed thermal springs in the Daly River requires urgent further investigation. This study has suggested these areas are likely to be important for growth and metabolism for fish and pig-nosed turtles. The location and extent of influence of these areas also needs to be determined.

References

Abrahams, M. & Kattenfeld, M. (1997). The role of turbidity as a constraint on predator-prey interactions in aquatic environments. *Behavioural Ecology and Sociobiology*, 40, 169-174.

Allen, G. R., Midgley, S. H., & Allen, M. (2002). Field guide to Freshwater Fishes of Australia. Western Australian Museum, Perth.

Arar, E. J. & Collins, G. B. (1997) *In Vitro Determination of Chlorophyll a and Pheophytin a in Marine and Freshwater Algae by Fluorescence*. Method 445.0. National Exposure Research Laboratory Office of Research and Development U.S. Environmental Protection Agency. Cincinnati, Ohio 45268.

Araujo-Lima, C. A. R. M. & Oliveira, E. C. (1998) Transport of larval fish in the Amazon. *Journal of Fish Biology,* 53, 297-306. https://doi.org/10.1111/j.1095-8649.1998.tb01033.x

Arthington, A., Naiman R. J., McClain M. E., & Nilsson C. (2010). Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. *Freshwater Biology* 55(1), 1-16.

Bach, C.S. (2002). Phenological patterns in monsoon rainforests in the Northern Territory, Australia. *Austral Ecology* 27, 477-489.

Bakun, A. (1996). *Patterns in the ocean*. California Sea Grant College System, National Oceanic and Atmospheric Administration, in cooperation with Centro de Investigaciones Biologicas del Noroeste, La Paz, BCS Mexico.

Bakun, A. (1998). Ocean triads and radical interdecadal variation: bane and boon to scientific fisheries management. In: *Reinventing Fisheries Management*. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-94-011-4433-9_25

Balston, J. (2009) Short-term climate variability and the commercial barramundi (*Lates calcarifer*) fishery of north-east Queensland, Australia. Marine and Freshwater Research 60, 912-923. https://doi.org/10.1071/MF08283.

Barrow, J., Ford J., Day R., & Morrongiello J. (2017). Environmental drivers of growth and predicted effects of climate change on a commercially important fish, *Platycephalus laevigatus*. *Marine Ecology Progress Series*, 598, 201-212. https://doi.org/10.3354/meps12234

Bayliss, P., Bartolo, R., & van Dam, R. (2008). Quantitative ecological risk assessments for the Daly River. In R. Bartolo, P. Bayliss, & R. van Dam (Eds.), *Ecological risk assessment for Australia's northern tropical rivers*. Sub-project 2 of Australia's tropical rivers – an integrated data assessment and analysis (DET18), a report to Land & Water Australia, Darwin. Australia: Environmental Research Institute of the Supervising Scientist.

Bayliss, P., van Dam, R.A., & Bartolo, R.E. (2012). Quantitative Ecological Risk Assessment of the Magela Creek Floodplain in Kakadu National Park, Australia: Comparing Point Source Risks from the Ranger Uranium Mine to Diffuse Landscape-Scale Risks. *Human Ecological Risk Assessments*. https://doi.org/10.1080/10807039.2012.632290

Beechie, T., Buhle, E., Ruckelshaus, M., Fullerton, A., & Holsinger, L. (2006). Hydrologic regime and the conservation of salmon life history diversity. *Biological Conservation* 130:560-572.

Bermudes, M., Glencross, B., Austen K., & Hawkins, W. (2010). The effects of temperature and size on the growth, energy budget and waste outputs of barramundi (*Lates calcarifer*). Aquaculture, 306, 1-4,160-166.

Bishop, K.A. (1980). Fish kills in relation to physical and chemical changes in Magela Creek (East Alligator Rivers system, Northern Territory) at the beginning of the tropical Wet season. Australian Zoologist 20, 484-500.

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

Bishop, K. A., Allen, S. A., Pollard, D. A., & Cook, M. G. (2001). *Ecological studies on the freshwater fishes of the Alligator Rivers region, Northern Territory: Autecology*.

Blanch, S., Rea, N., Scott, G., (2005). Aquatic Conservation Values of the Daly River Catchment, Northern Territory, Australia. World Wildlife Fund-Australia, Charles Darwin University and the Environment Centre NT, Darwin.

Bond, N.R., Balcombe, S.R., Crook, D.A., Marshall, J.C., Menke, N. & Lobegeiger, J.S., (2015). Fish population persistence in hydrologically variable landscapes. *Ecological Applications*, 25(4), 901-913.

Branco, P., Amaral, S. D., Ferreira, M. T., & Santos, J. M. (2017). Do small barriers affect the movement of freshwater fish by increasing residency? *Science of the Total Environment* 581-582:486-494.

Burrows, R. M., Beesley, L., Douglas, M. M., Pusey, B. J. & Kennard, M. J. (2020) Water velocity and groundwater upwelling influence benthic algal biomass in a sandy tropical river: implications for water-resource development. *Hydrobiologia* 847, 1207–1219. https://doi.org/10.1007/s10750-020-04176-3

Calenge, C. (2018). Analysis of habitat selection by animals. Package ‘adehabitat’, version 1.8.3. Available at: http://cran.r-project.org/web/packages/adehabitat/index.html

Campana, S. E., & Thorrold, S. R. (2001). Otoliths, increments, and elements: keys to a comprehensive understanding of fish populations? *Canadian Journal of Fisheries and Aquatic Sciences,* 58:30-38.

Campbell, H.A., Watts, M.E., Dwyer, R.G., and Franklin, C.E. (2012). V-Track: software for analysing and visualising animal movement from acoustic telemetry detections. *Marine and Freshwater Research* 63: 815-820.

Chan, T.U., Hart, B.T., Kennard, M.J., Pusey, B.J., Shenton, W., Douglas, M.M., Valentine, E. & Patel, S. (2012). Bayesian network models for environmental flow decision making in the Daly River, Northern Territory, Australia. *River Research & Applications*, 28: 283-301 https://doi.org/10.1002/rra.1456

Chao, A., Chiu, C.-H. & Jost, L. (2014). Unifying Species Diversity, Phylogenetic Diversity, Functional Diversity, and Related Similarity and Differentiation Measures Through Hill

Numbers. *Annual Review of Ecology, Evolution, and Systematics*, 45, 297-324. https://doi.org/10.1146/annurev-ecolsys-120213-091540

Chapman, B. B., Hulthén, K., Brodersen, J., Nilsson, P. A., Skov, C., Hansson, L. A. & Brönmark, C. (2012). Partial migration in fishes: causes and consequences. *Journal of Fish Biology* 81:456-478.

Commonwealth of Australia. (2015). Our North, Our Future: White Paper on Developing Northern Australia. Australian Government, Canberra. (Available from https://www.infrastructure.gov.au/territories-regions-cities/regions/northern-australia)

Crook, D. A., Lowe, W. H., Allendorf, F. W., Erős, T., Finn, D. S., Gillanders, B. M., Hadwen, . L., Harrod, C., Hermoso, V., Jennings, S., Kilada, R. W., Nagelkerken, I., Hansen, M. M., Page, T. J., Riginos, C., Fry, B., & Hughes, J. M. (2015). Human effects on ecological connectivity in aquatic ecosystems: Integrating scientific approaches to support management and mitigation. Science of The Total Environment, 534: 52-64.

Crook D. A., Buckle D. J., Allsop Q., Baldwin W., Saunders T. M., Kyne P. M., Woodhead J. D., Maas, R., Roberts, B., & Douglas M. M. (2016) Use of otolith chemistry and acoustic telemetry to elucidate migratory contingents in barramundi Lates calcarifer. Marine and Freshwater Research 68, 1554-1566. https://doi.org/10.1071/MF16177

Crook, D. A., Buckle, D. J., Allsop, Q., Baldwin, W., Saunders, T. M., Kyne, P. M., Woodhead, J. D., Maas, R., Roberts, B. & Douglas M. M. (2017). Use of otolith chemistry and acoustic telemetry to elucidate migratory contingents in barramundi *Lates calcarifer*. *Marine and Freshwater Research* 68:1554-1566.

Crook, D. A., Buckle, D. J., Morrongiello, J. R., Allsop, Q. A., Baldwin, W., Saunders, T. M. & Douglas, M. M. (2020) Tracking the resource pulse: Movement responses of fish to dynamic floodplain habitat in a tropical river. *Journal of Animal Ecology,* 89, 795-807. https://doi.org/10.1111/1365-2656.13146

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

Crook, D.A., Morrongiello, J.R., King, A.J., Adair, B. J., Grubert, M.A., Roberts, B.H., Douglas, M.M., & Saunders, T.M. (submitted). Environmental drivers of Barramundi (*Lates calcarifer*) recruitment in four tropical estuaries: monsoonal effects and vulnerability to water resource development.

Cushing, D. H. (1975) *Marine Ecology and Fisheries*. Cambridge University Press, Cambridge.

Davies, C-L. (2005). Thermoregulation, activity and energetics of the pig-nosed turtle (*Carettochelys insculpta*) in the Daly River, Northern Territory. Honours Thesis, University of Canberra, Canberra.

Davis, T. (1982). Maturity and sexuality in Barramundi, *Lates calcarifer* (Bloch), in the Northern Territory and south-eastern Gulf of Carpentaria. *Marine and Freshwater Research* 33:529-545.

Davis, T.L.O. (1985a), The food of barramundi, *Lates calcarifer* (Bloch), in coastal and inland waters of Van Diemen Gulf and the Gulf of Carpentaria, Australia. Journal of Fish Biology, 26: 669-682. https://doi.org/10.1111/j.1095-8649.1985.tb04307.x

Davis TLO (1985b) Seasonal changes in gonad maturity, and abundance of larvae and early juveniles of barramundi, *Lates calcarifer* (Bloch), in Van Diemen Gulf and the Gulf of Carpentaria. Marine and Freshwater Research 36, 177-190. https://doi.org/10.1071/MF9850177

Davis, A. M., Pearson, R. G., Pusey, B. J., Perna, C., Morgan, D. L. & Burrows, D. (2011). Trophic ecology of northern Australia's terapontids: ontogenetic dietary shifts and feeding classification. Journal of Fish Biology 78: 265-286.

Davis, A. M., Pusey, B. J. & Pearson, R. G. (2012). Contrasting intraspecific dietary shifts in two terapontid assemblages from Australia's wet-dry tropics. Ecology of Freshwater Fish. 21: 42-56. https://doi.org/10.1111/j.1600-0633.2011.00521.x

Doody, J.S., Georges, A., & Young, J. E. (2000). Monitoring plan for the pig-nosed turtle in the Daly River, Northern Territory. Unpublished report prepared by the Applied Ecology Research Group, University of Canberra for the Parks and Wildlife Commission of the Northern Territory.

Doody, J.S. (2002). *The ecology and sex determination of the pig-nosed turtle, Carettochelys insculpta, in the wet-dry tropics of Australia*. PhD thesis. University of Canberra.

Doody, J.S., Sims, R.A., & Georges, A. (2001). Use of thermal springs for aquatic basking by the pig-nosed turtle, *Carettochelys insculpta*. *Chelonian Conservation and Biology* 4: 81-87.

Doody, J.S., Young, J.E., & Georges, A. (2002). Sex differences in activity and movements in the pig-nosed turtle, *Carettochelys insculpta*, in the wet-dry tropics of Australia. Copeia 2002: 93-103.

Doody, J.S., Georges, A., & Young, J.E. (2003a). Twice every second year: reproduction in the pig-nosed turtle, *Carettochelys insculpta*, in the wet-dry tropics of Australia. *Journal of Zoology* 259: 179-188.

Doody, J.S., West, P., & Georges, A. (2003b). Beach selection in nesting pig-nosed turtles, *Carettochelys insculpta*. *Journal of Herpetology* 37: 178-182.

Doody, J.S., Green, B., Sims, R., Rhind, D., West, P., & Steer, D. (2006). Indirect impacts of invasive cane toads (Bufo marinus) on nest predation in pig-nosed turtles (*Carettochelys insculpta*). *Wildlife Research* 33: 349-354.

Doody, J.S., Pauza, M., Stewart, B., & Camacho, C. (2009a). Nesting behaviour of the pig-nosed turtle, *Carettochelys insculpta*, in Australia. *Chelonian Conservation and Biology* 8: 185-191.

Doody, J.S., Roe, J., Mayes, P., & Ishiyama, L. (2009b). Telemetry tagging methods for some freshwater reptiles. *Marine and Freshwater Research* 60: 293-298.

Douglas, M.M., Bunn, S.E., & Davies, P.M. (2005) River and wetland food webs in Australia's wet–dry tropics: general principles and implications for management. Mar Freshw Res 56:329–342. https://doi.org/10.1071/MF04084

Douglas, M., Jackson, S., Pusey, B., Kennard, M., & Burrows, D. (2011). Northern futures: Threats and opportunities for freshwater ecosystems. In B. J. Pusey (Ed.), Aquatic biodiversity of the wet–dry tropics of northern Australia: Patterns, threats and future (pp. 203–220). Darwin, Australia: Charles Darwin University Press.

Eisemberg, C.C., Rose, M., Yaru, B., Amepou, Y., & Georges, A. (2015). Salinity of the coastal nesting environment and its association with body size in the estuarine pig-nosed turtle. *Journal of Zoology* 295: 65-74.

Eisemberg, C., van Dijk, P.P., Georges, A., & Amepou, Y. (2018). *Carettochelys insculpta*. The IUCN Red List of Threatened Species 2018.

Elsdon, T. S., Wells, B. K., Campana, S. E., Gillanders, B. M., Jones, C. M., Limburg, K. E., Secor, D. H., Thorrold, S. R. & Walther, B. D. (2008). Otolith chemistry to describe movements and life-history parameters of fishes: hypotheses, assumptions, limitations and inferences. *Oceanography and marine biology: an annual review* 46:297-330.

Erskine, W. D., G. W. Begg, P. Jolly, A. Georges, A. O'Grady, D. Eamus, N. Rea, P. Dostine, S. A. Townsend and A. Padovan (2003). *Recommended environmental water requirements for the Daly River, Northern Territory, based on ecological, hydrological and biological principles*. Supervising Scientist Report 175 (National River Health Program, Environmental Flows Initiative, Technical Report 4). Darwin, N.T.

Erskine, W. D., Jolly, P., & Smith, I. (2004) Environmental Water Requirements of the Daly River: Revision of Recommendations of Erskine et al. (2003), based on Daly Regional Water Allocation Workshop held in Darwin on 5 May 2004, Report 30/2004D, Department of Infrastructure, Planning and Environment, Natural Resources Division, Palmerston NT

Erskine, W.D., Saynor, M. & Lowry, J. (2017). Application of a new river classification scheme to Australia's tropical rivers. *Singapore Journal of Tropical Geography* **38**, 167–184, https://doi.org/10.1111/sjtg.12196

Feyisa, G.L., Meilby, H., Fensholt, R., & Proud, S.R. (2014) Automated Water Extraction Index: A new technique for surface water mapping using Landsat imagery. *Remote Sens. Environ.* https://doi.org/10.1016/j.rse.2013.08.029

Finn, M., & Jackson, S. (2011). Protecting Indigenous values in water management: a challenge to conventional environmental flow assessments. *Ecosystems*, 14, 1232-1248.

Garcia, E. A., Dostine, P., Humphrey, C., Douglas, M. M., Pusey, B. J. & Cook, B. (2011). Chapter 5: Aquatic Invertebrates. Aquatic biodiversity in Northern Australia: patterns, threats and future. B. J. Pusey. Darwin, CDU Press: 51-70.

Gebhard, A.E., Paine, R.T., Hix, L.A., Johnson, T.C., Wells, W.G., Ferrell, H.N., & Perkin, J.S. (2017). Testing cross-system transferability of fish habitat associations using *Cottus carolinae* (banded Sculpin). *Southeastern Naturalist*, 16, 70-86.

Georges, A. (1992). Thermal characteristics and sex determination in field nests of the pig-nosed turtle, *Carettochelys insculpta* (Chelonia: Carettochelydidae), from northern Australia. *Australian Journal of Zoology* 40: 511-521.

Georges, A., & Kennett, R. (1989). Dry-season distribution and ecology of *Carettochelys insculpta* (Chelonia: Carettochelydidae) in Kakadu National Park, northern Australia. *Australian Wildlife Research* 16: 323-335.

Georges, A., Choquenot, D., Coventry, A.J., and Wellings, P. (1989). Some observations on the pig-nosed turtle (*Carettochelys insculpta*) in northern Australia. *Northern Territory Naturalist* 11: 8-11.

Georges, A., Webster, I. T., Guarino, E., Thoms, M. C., Jolly, P., & Doody, S. (2002). Modelling dry season flows and predicting the effects of water extraction on a flagship species [Project ID: 23045]. University of Canberra, CRC for Freshwater Ecology and the Applied Ecology Research Group, University of Canberra.

Georges, A. Doody, J.S., Eisemberg, C., Alacs, E.A., and Rose, M. (2008a). *Carettochelys insculpta* Ramsay 1886 – Pig-Nosed Turtle, Fly River Turtle. Conservation Biology of Freshwater Turtles and Tortoises. *Chelonian Research Monographs*, No. 5.

Georges, A., Alacs, E., Pauza, M., Kinginapi, F., Ona, A., and Eisemberg, C. (2008b). Freshwater turtles of the Kikori drainage, Papua New Guinea, with special reference to the pig-nosed turtle, *Carettochelys insculpta*. *Wildlife Research* **35**: 700-711.

Glencross, B.D. & Felsing, M. (2006), Influence of fish size and water temperature on the metabolic demand for oxygen by barramundi, *Lates calcarifer* (Bloch), in freshwater. Aquaculture Research, 37: 1055-1062. https://doi.org/10.1111/j.1365-2109.2006.01526.x

Greenwell, B., Boehmke, B., Cunningham, J. & GBM Developers (2020). gbm: Generalized Boosted Regression Models. R package version 2.1.8. https://CRAN.R-project.org/package=gbm

Grey, D. (1987). An overview of *Lates calcarifer* in Australia and Asia. *Management of wild and cultured sea bass/barramundi*:15-21.

Griffin R. K. (1982). A survey of amateur angling for barramundi (Lates calcarifer) in the Northern Territory. Technical Report No. 2, Northern Territory Department of Primary Production, Darwin.

Gorman, O. T. & Karr, J. R. (1978). Habitat structure and stream fish communities. *Ecology* 59, 507–515, https://doi.org/10.2307/1936581.

Groshens, T.G., & Orth, D.L. (1994). Transferability of habitat suitability criteria for smallmouth bass *Micropterus dolomieu*. *Rivers*, 4, 194–212.

Grossman, G. D., Ratajczak, R. E., Crawford, M. & Freeman, M. C. (1998). Assemblage organization in stream fishes: effects of environmental variation and interspecific interactions. *Ecological Monographs* 68, 395–420, https://doi.org/10.1890/0012-9615

Grubert, M. A., Saunders, T. M., Martin, J. M., Lee, H. S. & Walters, C. J. (2013). Stock Assessments of Selected Northern Territory Fishes. Northern Territory Government, Australia. Fishery Report No. 110.

Halliday, I. A., Robins, J. B., Mayer, D. G., Staunton Smith, J., & Sellin, M. J. (2011). Freshwater flows affect the year-class strength of barramundi Lates calcarifer in the Fitzroy River estuary, central Queensland. Proceedings of the Royal Society of Queensland 116, 1–11.

Halliday, I. A., Saunders, T., Sellin, M. J., Allsop, Q., Robins, J. B., McLennan, M., & Kurnoth, P. (2012). Flow impacts on estuarine finfish fisheries of the Gulf of Carpentaria. FRDC Project number 2007/002, Queensland Department of Agriculture, Fisheries and Forestry, Brisbane, Qld, Australia.

Hermoso, V., Cattarino, L., Linke, S., & Kennard, M. J. (2018). Catchment zoning to enhance co-benefits and minimise trade-offs between ecosystem services and biodiversity conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 28, 1004–1014. https://doi.org/10.1002/aqc.2891

Hijmans, H. J., Phillips, S., Leathwick, J., Elith, J. (2017). dismo: Species Distribution Modeling. R package version 1.1-4. https://CRAN.R-project.org/package=dismo

Horne, A., Nathan, R., Poff, N. L., Bond, N. R., Webb, A. J., Wang, J., & John, A. (2019). Modelling flow-ecology responses in the Anthropocene: Challenges for sustainable riverine management. *Bioscience*, 69, 789–799. https://doi.org/10.1093/biosci/biz087

Humphries, P., King, A. J. & Koehn, J. D. (1999) Fish, Flows and Flood Plains: Links between Freshwater Fishes and their Environment in the Murray-Darling River System, Australia. *Environmental Biology of Fishes*, 56, 129-151. http://dx.doi.org/10.1023/a:1007536009916.

Humphries, P., King, A. J., McCasker, N., Kopf, R. K., Stoffels, R., Zampatti, B. P. & Price, A. E. (2020) Riverscape recruitment: a conceptual synthesis of drivers of fish recruitment in rivers. *Canadian Journal of Fisheries and Aquatic Sciences*, 77, 213-225. https://doi.org/10.1139/cjfas-2018-0138

Jackson, D. A., Peres-Neto, P. R. & Olden, J. D. (2001). What controls who is where in freshwater fish communities - the roles of biotic, abiotic, and spatial factors. *Canadian Journal of Fisheries and Aquatic Sciences* 58, 157–170, https://doi.org/10.1139/f00-239

Jackson, S. (2006). Compartmentalising culture: The articulation and consideration of Indigenous values in water resource management. *Australian Geographer*, 37, 19–32. https://doi.org/10.1080/00049180500511947

Jackson, S., Finn, M., and Featherston, P. (2012). Indigenous aquatic resource use in two tropical Australian river catchments: the Fitzroy River and Daly River. *Human Ecology* 40: 893–908.

Jackson, S.E., Douglas, M.M., Kennard, M.J., Pusey, B.J., Huddleston, J., Harney, B., Liddy, L., Liddy, M., Liddy, R., Sullivan, L., & Huddleston, B. (2014). We Like to Listen to Stories about Fish: Integrating Indigenous Ecological and Scientific Knowledge to Inform Environmental Flow Assessments. *Ecology and Society*, 19, 43.

Jardine, T. D., Pettit, N. E., Warfe, D. M., Pusey, B. J., Ward, D. P., Douglas, M. M., Davies, P. M., & Bunn, S. E. (2012a). Consumer-resource coupling in a wet-dry tropical river. Journal of Animal Ecology, 81, 310–322. https://doi.org/10.1111/j.1365-2656.2011.01925.x

Jardine, T., Pusey, B., Hamilton, S., Pettit, N., Davies, P., Douglas, M., Sinnamon, V., Halliday, I., & Bunn, S. (2012b). Fish mediate high food web connectivity in the lower reaches of a tropical floodplain river. Oecologia, 168(3), 829-838. http://doi:10.1007/s00442-011-2148-0

Jardine, T. D., Rayner, T. S., Pettit, N. E., Valdez, D., Ward, D. P., Lindner, G., Douglas, M. M. & Bunn, S. E. (2017). Body size drives allochthony in food webs of tropical rivers. *Oecologia*, 183(2), 505-517. http://doi:10.1007/s00442-016-3786-z

Jolly, P. (1984). *Douglas-Daly groundwater resource investigations 1981–1983* (report 8/1984). Darwin, Australia: NT: Department of Transport and Works (Water Division).

Jowett, I. G. (1993). A method for objectively identifying pool, run, and riffle habitats from physical measurements. *New Zealand Journal of Marine and Freshwater Research* 27, 241–248, https://doi.org/10.1080/00288330.1993.9516563

Junk, W. J., Bayley, P. B. & Sparks, R. E. (1989) The flood pulse concept in river-floodplain systems. *Canadian Special Publication of Fisheries and Aquatic Sciences*, 106, 110-127.

Kalnach, A. & Kalnacs, J, Mutule, A., & Persis, U. (2013). Potential of the Lower Daugava for Siting Hydrokinetic Turbines / Daugavas Lejteces Enerģētiskais Potenciāls Hidrokinētisko Turbīnu Izmantošanai. *Latvian Journal of Physics and Technical Sciences.* 50. 10.2478/lpts-2013-0007.

Keller, K., Allsop, Q., Brim Box, J., Buckle, D., Crook, D.A., Douglas, M. M., Jackson, S., Kennard, M. J., Luiz, O.J., Pusey, B. J., Townsend, S. A. & King, A.J. (2019). Dry season habitat use of fishes in an Australian tropical river. *Scientific Reports* 9(1): 5677. https://doi.org/10.1038/s41598-019-41287-x

Kennard, M. J., Pusey, B. J., Olden, J. D., Mackay, S. J., Stein, J. L., & Marsh, N. (2010). Classification of natural flow regimes in Australia to support environmental flow management. Freshwater Biology, 55, 171–193. https://doi.org/10.1111/j.1365-2427.2009.02307.x

Kennard, M. J., Pusey, B. J., Perna, C., Burrows, D. & Douglas, M. M. (2011) Field manual– Including protocols for quantitative sampling of fish assemblages, habitat, water quality and sample preservation. Charles Darwin University, Northern Territory, Available at https://www.nespnorthern.edu.au/wp-content/uploads/2019/04/TRaCK-5.8-Fish-Sampling-Protocol-FINAL-Pusey.pdf

King, A. J., Humphries, P. & McCasker, N. G. (2013) Reproduction and Early Life History. Chapter 7. In: *Ecology of Australian Freshwater Fishes*. (Eds: P. Humphries & K. F. Walker). CSIRO Publishing, Victoria, Australia.

King, A. J., Townsend, S. A., Douglas, M. M. & Kennard, M. (2015). Implications of water extraction on the low-flow hydrology and ecology of tropical savannah rivers: an appraisal for northern Australia. *Freshwater Science* 34**(**2): 741–758.

King, A. J., Doidge, C., Buckle, D., & Tyler, K. J. (2020). Preliminary evidence of spawning phenologies of freshwater fish in a wet–dry tropical river: the importance of both wet and dry seasons. *Marine and Freshwater Research*, 71(2), 202-212. https://doi.org/10.1071/MF18458

King, I. P. (2006), Documentation RMA 2 – RMA2 – A Two Dimensional Finite Element Model for Flow in Estuaries and Streams, Resource Modelling Associates, Sydney Australia.

Koehn, J.D., McKenzie, J.A., O'Mahony, D.J., Nicol, S.J., O'Connor, J.P. & O'Connor, W.G., (2009). Movements of Murray cod (*Maccullochella peelii peelii*) in a large Australian lowland river. *Ecology of Freshwater Fish*, 18(4), 594-602.

Krause, C., Dunn, B., Bishop-Taylor, R., Adams, C., Burton, C., Alger, M., Chua, S., Phillips, C., Newey, V., Kouzoubov, K., Leith, A., Ayers, D., Hicks, A., & DEA Notebooks contributors. (2021). Digital Earth Australia notebooks and tools repository. Geoscience Australia, Canberra. https://doi.org/10.26186/145234

Laist, D.W, & Reynolds, J.E. (2005). Florida manatees, warm-water refuges, and an uncertain future. *Coastal Management* 33: 279-295.

Lamontagne, S., Cook, P. G., O'Grady, A. & Eamus, D. (2005). Groundwater use by vegetation in a tropical savanna riparian zone (Daly River, Australia). *Journal of Hydrology* 310, 280–293, https://doi.org/10.1016/j.jhydrol.2005.01.009

Larson, S. & Alexandridis, K. (2009). *Socio-economic profiling of tropical rivers*. Land & Water Australia.

Lear, K.O., Gleiss, A.C., Whitty, J.M., Fazeldean, T., Albert, J.R., Green, N., Ebner, B.C., Thorburn, D.C., Beatty, S.J. & Morgan, D.L. (2019). Recruitment of a critically endangered sawfish into a riverine nursery depends on natural flow. *Scientific Reports* 17071.

Magoulick, D. D. (2000) Spatial and temporal variation in fish assemblages of drying stream pools: The role of abiotic and biotic factors. *Aquatic Ecology* 34, 29–41, https://doi.org/10.1023/a:1009914619061

Magoulick D.D., & Kobza, R.M. (2003) The role of refugia for fishes during drought: a review and synthesis. *Freshwater Biology*, 48, 1186-1198.

Manly B., McDonald, L., Thomas D., McDonald T.L., & Erickson W.P. (2002). *Resource selection by animals: statistical design and analysis for field studies*. Chapman and Hall, London.

McDonald N.S. & McAlpine J. (1991) Floods and droughts: the northern climate. C.D. Haynes, M.G. Ridpath, M.A.J. Williams (Eds.), Monsoonal Australia, Landscape, Ecology and Man in the Northern Lowland, Balkema, Rotterdam (1991), pp. 19-29

McFeeters, S.K., (1996). The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *Int. J. Remote Sens.* https://doi.org/10.1080/01431169608948714

Merrick, J.R. & Schmida G.E. (1984) Australian Freshwater Fishes: Biology and management. J. R. Merrick. North Ryde, NSW. 409pp

Miller, B. (2018). *Katherine River Hydrodynamic Modelling*. Water Research Laboratory, University New South Wales School of Civil and Environmental Engineering.

Miller, B. (2020). *Daly River – Mentabie Reach Hydrodynamic Modelling*. Water Research Laboratory, University New South Wales School of Civil and Environmental Engineering.

Milton, D. & Arthington, A. (1984) Reproductive strategy and growth of the crimson-spotted rainbowfish, *Melanotaenia splendida fluviatilis* (Castelnau) (Pisces : Melanotaeniidae) in south-eastern Queensland. *Marine and Freshwater Research*, 35, 75-83. http://dx.doi.org/10.1071/MF9840075.

Moise, A., Abbs, D., Bhend, J., Chiew, F., Church, J., Ekström, M., Kirono, D., Lenton, A., Lucas, C., McInnes, K., & Monselesan, D. (2015). *Monsoonal North Cluster Report*. Climate Change in Australia Projections for Australia’s Natural Resource Management Regions. Cluster Reports. CSIRO and Bureau of Meteorology, Australia.

Morrongiello, J. R., Beatty, S. J., Bennett, J. C., Crook, D. A., Ikedife, D. N. E. N., Kennard, M. J., Kerezsy, A., Lintermans, M., McNeil, D.G., Pusey, B. J. & Rayner, T. (2011). Climate change and its implications for Australia’s freshwater fish. *Marine and Freshwater Research*, 62(9), 1082-1098. http://dx.doi.org/10.1071/MF10308

Morrongiello, J. R., Walsh, C. T., Gray, C. A., Stocks, J. R. & Crook D. A. (2014). Environmental change drives long-term recruitment and growth variation in an estuarine fish. *Global Change Biology* 20:1844-1860.

Morrongiello, J. R., & Thresher, R. E. (2015). A statistical framework to explore ontogenetic growth variation among individuals and populations: a marine fish example. *Ecological Monographs* 85:93-115.

Mueller, N., Lewis, A., Roberts, D., Ring, S., Melrose, R., Sixsmith, J., Lymburner, L., McIntyre, A., Tan, P., Curnow, S., & Ip, A., (2016). Water observations from space: Mapping surface water from 25years of Landsat imagery across Australia. *Remote Sens. Environ.* https://doi.org/10.1016/j.rse.2015.11.003

Narsey, S. Y., Brown, J. R., Colman, R. A., Delage, F., Power, S. B., Moise, A. F. & Zhang, H. (2020) Climate change projections for the Australian monsoon from CMIP6 models. *Geophysical Research Letters*, 47, e2019GL086816. https://doi.org/10.1029/2019GL086816

Newton, J. R., Smith-Keune C., & Jerry D. R. (2010). Thermal tolerance varies in tropical and sub-tropical populations of barramundi (*Lates calcarifer*) consistent with local adaptation. Aquaculture, 308, 1 S128-132.

Northern Territory Government (2019a). *Katherine Tindall Limestone Aquifer Water Allocation Plan 2019–2024*, Department of Environment and Natural Resources, Northern Territory Government, Darwin, Australia.

Northern Territory Government (2019b) *Oolloo Dolostone Aquifer Water Allocation Plan 2019-2029*, Department of Environment and Natural Resources, Northern Territory Government, Darwin, Australia.

O'Connor, J. P., O'Mahony, D. J. & O'Mahony, J. M., (2005). Movements of *Macquaria ambigua*, in the Murray River, south-eastern Australia. *Journal of Fish Biology*, 66(2), 392-403.

Paugy, D. (2002) Reproductive strategies of fishes in a tropical temporary stream of the Upper Senegal basin: Baoulé River in Mali. *Aquatic Living Resources*, 15, 25-35. https://doi.org/10.1016/S0990-7440(01)01144-5

Pellett, T.D., Van Dyck, G.J. & Adams, J.V., (1998). Seasonal migration and homing of channel catfish in the lower Wisconsin River, Wisconsin. *North American Journal of Fisheries Management*, 18(1), 85-95.

Perna, C. & Burrows, D. (2005). Improved dissolved oxygen status following removal of exotic weed mats in important fish habitat lagoons of the tropical Burdekin River floodplain, Australia. Marine Pollution Bulletin, 51,1-4, 138-148.

Pettit, N. E., Jardine, T. D., Hamilton, S. K.,Sinnamon, V., Valdez, D., Davies, P. M., Douglas, M. M., & Bunn, S. E. (2012). Seasonal changes in water quality and macrophytes and the impact of cattle on tropical floodplain waterholes. *Marine and Freshwater Research* 63(9): 788-800.

Phillips, D., Newsome, S., & Gregg, J. (2005). Combining sources in stable isotope mixing models: Alternative methods. *Oecologia*, 144, 520-527. http://doi:10.1007/s00442-004-1816-8

Poff L. N., & Zimmerman J. K. H. (2010). Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology*, 55, 194-205.

Poff, N. L., Tharme, R. E., & Arthington, A. H. (2017). Evolution of environmental flows assessment science, principles, and methodologies. In A.C. Horne, J.A. Webb, M.J. Stewardson, B. Richter & M. Acreman (Eds.), *Water for the Environment* (pp. 203-236). Academic Press.

Post, D. M. (2003). Individual variation in the timing of ontogenetic niche shifts in largemouth bass. *Ecology* 84:1298-1310.

Price, O, Milne, D., Connors, G., Harwood, B., Woinarski, J., & Butler, M. (2000). *A conservation plan for the Daly basin bioregion*. Parks and Wildlife Commission of the Northern Territory.

Pusey, B. J., Arthington, A. H., Bird, J. R. & Close, P. G. (2001) Reproduction in three species of rainbowfish (Melanotaeniidae) from rainforest streams in northern Queensland, Australia. *Ecology of Freshwater Fish*, 10, 75-87. http://dx.doi.org/10.1034/j.1600-0633.2001.100202.x

Pusey, B. J., Arthington, A. H., Close, P. G. & Bird, J. R. (2002) Larval Fishes in Rainforest Streams: Recruitment and Microhabitat Use. *Proceedings of the Royal Society of Queensland*, 110, 27-46.

Pusey, B.J., Kennard, M. J., & Arthington, A. H. (2004). *Freshwater fishes of North-eastern Australia*. CSIRO Publishing, Clayton.

Pusey, B. J. & Kennard, M. J. (2009) Aquatic ecosystems in northern Australia. Chapter 3. In: *Northern Australia Land and Water Science Review*. (Ed: P. Stone). Final report to the Northern Australia Land and Water Taskforce. CSIRO, Canberra, Australia.

Pusey, B. J., Warfe, D., Townsend, S., Douglas, M. M., Burrows, D., Kennard, M. J., & Close, P. G. (2011). Condition, impacts and threats to aquatic biodiversity. Pages 151–172 in B. J. Pusey (editor). *Aquatic biodiversity in northern Australia: patterns, threats and future*. Charles Darwin University Press, Darwin, Australia.

Pusey, B. J., Burrows, D. W., Kennard, M. J., Perna, C. N., Unmack, P. J., Allsop, Q. & Hammer, M. P. (2017) Freshwater fishes of northern Australia. *Zootaxa*, 4253, 1-104. https://doi.org/10.11646/zootaxa.4253.1.1

Pusey, B. J., Kennard, M. J., Douglas, M. & Allsop, Q. (2018) Fish assemblage dynamics in an intermittent river of the northern Australian wet–dry tropics. *Ecology of Freshwater Fish*, 27, 78-88. https://doi.org/10.1111/eff.12325

Pusey, B. J., Douglas, M.M., Olden, J. D., Jackson, S., Allsop, Q., & Kennard M.J. (2020). Connectivity, habitat, and flow regime influence fish assemblage structure: Implications for environmental water management in a perennial river of the wet–dry tropics of northern Australia. *Aquatic Conservation: Marine and Freshwater Ecosystems* 30(7): 1397-1411.

Railsback, S.F. (2016). Why it is time to put PHABSIM out to pasture? *Fisheries*, 41, 720-725.

Rayner, T. S., Pusey, B. J. & Pearson, R. G. (2008). Seasonal flooding, instream habitat structure and fish assemblages in the Mulgrave River, north-east Queensland: towards a new conceptual framework for understanding fish-habitat dynamics in small tropical rivers. *Marine and Freshwater Research* 59, 97–116, https://doi.org/10.1071/MF07129

Rea, N., Dostine, P., Cook, S., Webster, I. T., & Williams, D. (2002). *Environmental water requirements of Vallisneria nana in the Daly River, Northern Territory* (35/2002).

Reidy-Liermann, C., C. Nilsson, J. Robertson, & R. Y. Ng. 2012. Implications of dam obstruction for global freshwater fish diversity. *BioScience* 62:539–548.

Rimmer, M. A. & Russell, D. J. (1998). 14 - Aspects of the Biology and Culture of *Lates calcarifer*. Tropical Mariculture. S. S. De Silva. London, Academic Press: 449-476.

Roberts, B. H., Morrongiello, J. R. , King, A.J., Morgan, D. L., Saunders, T. M., Woodhead, J. & Crook, D.A. (2019). Migration to freshwater increases growth rates in a facultatively catadromous tropical fish. *Oecologia*, 1919, 253-260.

Roberts, B. H, Morrongiello, J. R. , King, A.J., Morgan, D. L., Saunders, T. M., Woodhead, J. & Crook, D.A. (2021). Faster juvenile growth promotes earlier sex change in a protandrous hermaphrodite (barramundi *Lates calcarifer*). *Scientific Reports* 11(1): 2276.

Roberts, B.H. (2021) Drivers of catadromous migration in barramundi (*Lates calcarifer*) in the wet/dry tropics of northern Australia. PhD thesis, Charles Darwin University.

Robins, J. B., Halliday, I. A., Staunton-Smith, J., Mayer, D. G., & Sellin, M. J. (2005) Freshwater-flow requirements of estuarine fisheries in tropical Australia: a review of the state of knowledge and application of a suggested approach. *Marine and Freshwater Research* 56, 343-360. https://doi.org/10.1071/MF04087

Robins, J., B. Mayer, D., Staunton-Smith, J., Halliday, I., Sawynok, B. & Sellin, M. J. (2006), Variable growth rates of the tropical estuarine fish barramundi *Lates calcarifer* (Bloch) under different freshwater flow conditions. *Journal of Fish Biology*, 69: 379-391. https://doi.org/10.1111/j.1095-8649.2006.01100.x

Rolls, R.J., Leigh, C. & Sheldon, F., (2012). Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. *Freshwater Science*, 31(4), 1163-1186.

Russell, D. J. & Garrett, R. N. (1983). Use by juvenile barramundi, *Lates calcarifer* (Bloch), and other fishes of temporary supralittoral habitats in a tropical estuary in northern Australia. *Australian Journal of Marine & Freshwater Research* 34(5): 805-811.

Russell, D. J. & Garrett, R. N. (1985). Early life history of barramundi, *Lates calcarifer* (Bloch), in north-eastern Queensland. *Marine and Freshwater Research* 36(2): 191-201.

Schindelin, J., Arganda-Carreras, I., Frise, E., Kaynig, V., Longair, M., Pietzsch, T., Cardona, A. (2012) Fiji: an open-source platform for biological-image analysis. *Nature Methods*, 9, 676-682. 10.1038/nmeth.2019

Schindler, D. E., Hilborn, R., Chasco, B., Boatright, C. P., Quinn, T. P., Rogers, L.A. & Webster, M.S. (2010). Population diversity and the portfolio effect in an exploited species. *Nature* 465:609-612.

Schult, J. & Townsend, S. (2012) Water quality: *A Report to the Daly River Management Advisory Committee*. *Report* Vol. Report No. 03/2012D. Department of Natural Resources, Environment, The Arts and Sport, Darwin, Northern Territory.

Showstack, R., (2014). Sentinel Satellites Initiate New Era in Earth Observation. *Eos, Trans. Am. Geophys. Union*. https://doi.org/10.1002/2014eo260003

Staunton-Smith, J., Robins, J. B., Mayer, D. G., Sellin, M. J. & Halliday, I.A. (2004). Does the quantity and timing of fresh water flowing into a dry tropical estuary affect year-class strength of barramundi (*Lates calcarifer*)? *Marine and Freshwater Research* 55:787-797.

Stewart-Koster, B., Olden, J. D., Kennard, M. J., Pusey, B. J., Boone, E. L., Douglas, M., & Jackson, S. (2011). Fish response to the temporal hierarchy of the natural flow regime in the Daly River, northern Australia. *Journal of Fish Biology*, 79, 1525–1544. https://doi.org/10.1111/j.1095-8649.2011.03072.x

Stock, B.C., Jackson, A.L., Ward, E.J., Parnell, A.C., Phillips, D.L., & Semmens, B.X. (2018). Analyzing mixing systems using a new generation of Bayesian tracer mixing models. *PeerJ* 6, e5096.

Tanimoto M., Robins J. B., O’Neill M. F., Halliday I. A., & Campbell A. B. (2012) Quantifying the effects of climate change and water abstraction on a population of barramundi (*Lates calcarifer*), a diadromous estuarine finfish. *Marine and Freshwater Research* 63, 715-726. https://doi.org/10.1071/MF11246

Tickell, S. (2002). *A Survey of Springs along the Daly River*. REPORT 06/2002. Darwin, Department of Infrastructure Planning and Environment Natural Resources Division.

Tickell, S.J. (2011) *Assessment of major spring systems in the Oolloo Dolostone, Daly River*. Northern Territory Department of Land Resource Management, Technical Report No. 22/2011D.

Torres, R., Snoeij, P., Geudtner, D., Bibby, D., Davidson, M., Attema, E., Potin, P., Rommen, B.Ö., Floury, N., Brown, M., Traver, I.N., Deghaye, P., Duesmann, B., Rosich, B., Miranda, N., Bruno, C., L’Abbate, M., Croci, R., Pietropaolo, A., Huchler, M., & Rostan, F., (2012). GMES Sentinel-1 mission. Remote Sens. Environ. https://doi.org/10.1016/j.rse.2011.05.028

Tourism NT (2018) *Tourism NT Regional Profile, Katherine Daly three year averages – year ending June 2016 – 2018*, Northern Territory Government, Darwin. http://www.tourismnt.com.au/en/research/regional-profiles

Townsend, S. A. (2003). A fish kill event, hypoxia and other limnological impacts asssociated with early wet season flow into a lake on the Mary River floodplain, tropical northern Australia. *Lakes & Reservoirs: Research and Management* 8(169-176).

Townsend, S.A. (2019). Discharge-driven seasonal pattern of ionic solutes, suspended sediment and water clarity for a tropical savanna river in northern Australia. *Marine and Freshwater Research* 70: 1585-1602.

Townsend, S. A. & Padovan, A. V. (2005) The seasonal accrual and loss of benthic algae (*Spirogyra*) in the Daly River, an oligotrophic river in tropical Australia. *Marine and Freshwater Research*, 56, 317-327. http://dx.doi.org/10.1071/MF04079

Townsend, S. A., Webster, I. T., & Schult, J. H., (2011). Metabolism in a groundwater-fed river system in the Australian wet/dry tropics: tight coupling of photosynthesis and respiration. J. N. Am. Benthol. Soc. 30, 603–620.

Townsend, S., Schult, J., Douglas, M., & Lautenschlager, A. (2017). Recovery of benthic primary producers from flood disturbance and its implications for an altered flow regime in a tropical savannah river (Australia). *Aquatic Botany*, 136, 9-20. https://doi.org/10.1016/j.aquabot.2016.08.004

Turschwell, M. P., Stewart-Koster, B., Pusey, B. J., Douglas, M., King, A., Crook, D., Boone, E., Douglas, M., Allsop, Q., Jackson, S. & Kennard, M. J. (2019). Flow-mediated predator-prey dynamics influences fish populations in a tropical river. *Freshwater Biology*, 64, 1453–1466. https://doi.org/10.1111/fwb.13318

Tyler, K. J., Wedd, D., Crook, D. A., Kennard, M. J., & King, A. J. (2021). Hydrology drives variation in spawning phenologies and diversity of larval assemblages of Australian wet–dry tropical fish. *Freshwater Biology*, 00, 1– 19. https://doi.org/10.1111/fwb.13802

Tyler, K. J., Wedd, D., Crook, D. A., Kennard, M. J., & King, A. J. (submitted). Predicting drivers of tropical riverine larval fish abundance and diversity.

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R. & Cushing, C. E. (1980) The River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Sciences,* 37, 130-137. http://dx.doi.org/10.1139/f80-017

Vilizzi, L., Copp, G.H., & Roussel, J.M. (2004). Assessing variation in suitability curves and electivity profiles in temporal studies of fish habitat use. *River Research and Applications*, 20, 605-618.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R. & Davies, P.M. (2010). Global threats to human water security and river biodiversity. *Nature* 467:555–561.

Wang, Y., Naumann, U., Wright, S. T. & Warton, D. I. (2012) mvabund– an R package for model-based analysis of multivariate abundance data. Methods in Ecology and Evolution, 3, 471-474. http://doi.org/10.1111/j.2041-210X.2012.00190.x

Warfe, D. M., Pettit, N. E., Davies, P. M., Pusey, B. J., Hamilton, S. K., Kennard, M. J., Townsend, S. A., Bayliss, P., Ward, D. P., Douglas, M. M., Burford, M. A., Finn, M., Bunn, S.E. & Halliday, I. A. (2011) The ‘wet–dry’ in the wet–dry tropics drives river ecosystem structure and processes in northern Australia. *Freshwater Biology*, 56, 2169-2195. http://dx.doi.org/10.1111/j.1365-2427.2011.02660.x

Warfe, D. M., Jardine, T. D., Pettit, N. E., Hamilton, S. K., Pusey, B. J., Bunn, S. E., Davies, P.M., Douglas, M. M. (2013). Productivity, Disturbance and Ecosystem Size Have No Influence on Food Chain Length in Seasonally Connected Rivers. PLOS ONE, 8(6), e66240. http://doi:10.1371/journal.pone.0066240

Wasson, R. J., Furlonger, L., Parry, D., Pietsche, T., Valentine, E., & Williams, D. (2010). Sediment sources and channel dynamics, Daly River, Northern Australia. *Geomorphology* 114, 161–174, http://doi.org/10.1016/j.geomorph.2009.06.022

Webb, M., Reid, M. & Thoms, M. (2011). The influence of hydrology and physical habitat character on fish assemblages at different temporal scales. *River Systems* 19, 283–299.

Webster, I. T., N. Rea, A. V. Padovan, P. Dostine, S. A. Townsend and S. Cook (2005). An analysis of primary production in the Daly River, a relatively unimpacted tropical river in northern Australia. *Marine and Freshwater Research* 56(3): 303-316.

Welcomme, R. L. (1985) *River Fisheries*. FAO Fisheries Technical Paper 262. Food and Agriculture Organisation of the United Nations, Rome, Italy.

Welsh, M. A., Doody, J. S., & Georges, A. (2017). Resource partitioning among five sympatric species of freshwater turtles from the wet-dry tropics of northern Australia. *Wildlife Research* 44: 219-229.

Westerhoff, R. S., Kleuskens, M. P. H., Winsemius, H. C., Huizinga, H. J., Brakenridge, G. R., & Bishop, C. (2013). Automated global water mapping based on wide-swath orbital synthetic-aperture radar. *Hydrol. Earth Syst. Sci*. http://doi.org/10.5194/hess-17-651-2013

Willis, S. C., Winemiller, K. O. & Lopez-Fernandez, H. (2005). Habitat structural complexity and morphological diversity of fish assemblages in a Neotropical floodplain river. *Oecologia* 142, 284–295, http://doi.org/10.1007/s00442-004-1723-z

Wingate, R. L. & Secor, D. H. (2007). Intercept telemetry of the Hudson River striped bass resident contingent: migration and homing patterns. *Transactions of the American Fisheries Society*, 136(1), 95-104.

Wood, S. N. (2017). Generalized additive models: An introduction with R. Boca Raton, FL: Chapman and Hall/CRC.

Wulder, M. A., Masek, J. G., Cohen, W. B., Loveland, T. R., & Woodcock, C. E. (2012). Opening the archive: How free data has enabled the science and monitoring promise of Landsat. *Remote Sens. Environ*. http://doi.org/10.1016/j.rse.2012.01.010

Yamazaki, D., Trigg, M. A., & Ikeshima, D. (2015). Development of a global ~90m waterbody map using multi-temporal Landsat images. *Remote Sens. Environ*. http://doi.org/10.1016/j.rse.2015.10.014

Appendix 1. Preliminary conceptual modelling of existing flow-ecology knowledge for the Daly River

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Background

Determining important flow-ecology relationships to prioritise for research and management action is difficult when working in data poor systems, since a lot of information is required and it is difficult to determine what is and should be a priority. Conceptual models are a critical first step in developing Eflows, but they require knowledge of the system. Conceptual models describe our current understanding of system processes and dynamics, as well as the linkages or relationships between activities and ecosystem responses, and can also be a means by which stakeholders develop a common understanding of the system (Gross 2003; Stewardson and Webb 2010).

Objectives

The objective of this preliminary stage of the overall study was to review and synthesise the flow-ecology relationships of four identified key ecological assets (*Vallisneria* spp., pig-nosed turtle, sooty grunter and barramundi) from the Daly River, NT, as case studies during various flow regimes and provide recommendations on environmental flows and key priorities for future research for water management.

Discrete conceptual models were developed by reviewing the literature and gaining expert opinion for each of the four hydrological periods (wet, dry, wet–dry and dry–wet transition periods). The models were developed into both box-arrow style diagrams and supporting tables describing flow-ecology relationship, measure of confidence and references used.

These models were used to refine research questions for the remainder of the project, but could also be used to explore future critical research themes. Similar to other studies (e.g. Miller et al. 2018 and McGregor et al. 2017) this information could also be used to support expert opinion in the development of environmental flow recommendations until quantitative empirical data are available. These models however, should be updated as required, with any new studies.

Outcomes

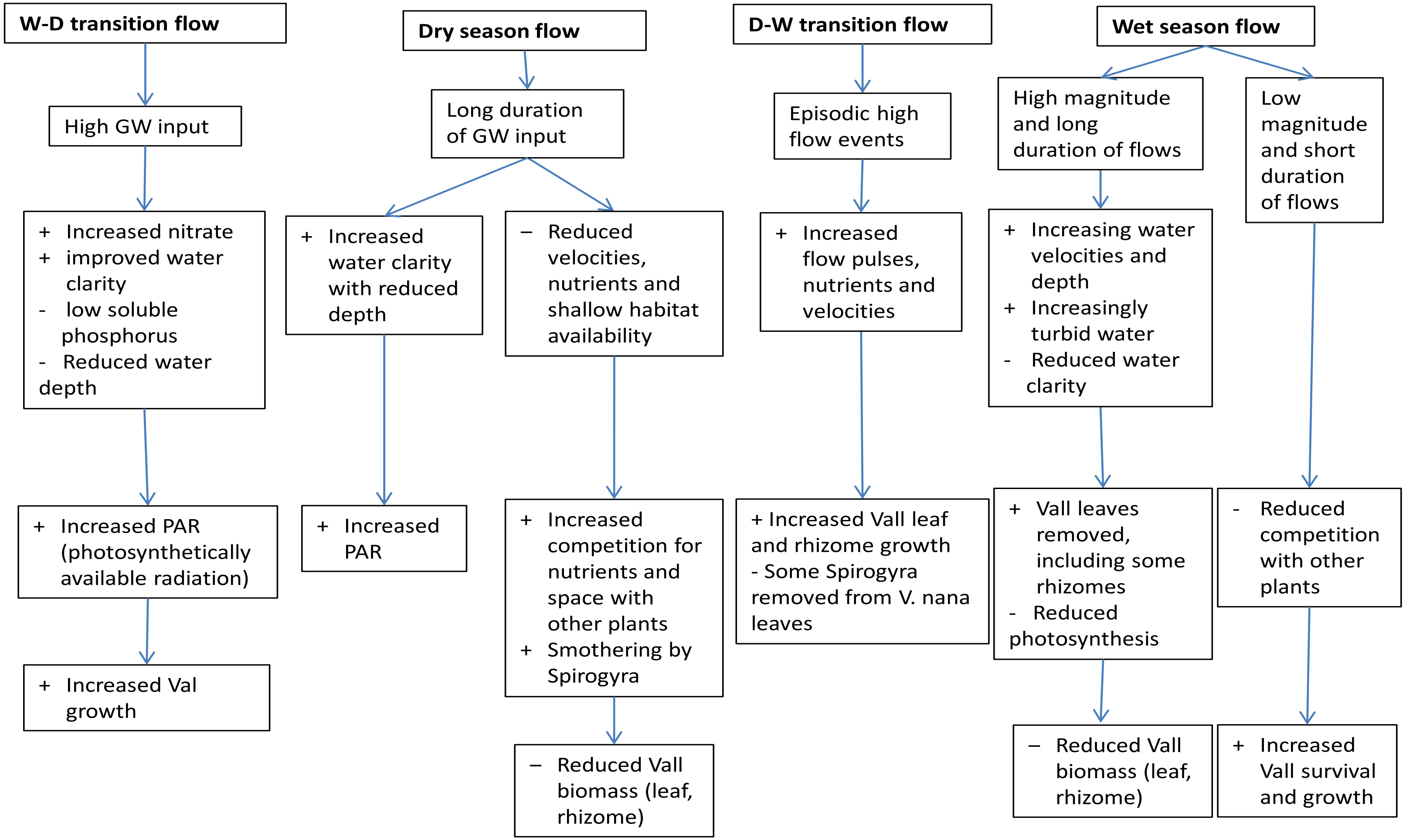

Fig. 1. Conceptual model for *Vallisneria nana* over four seasonal periods: wet–dry transition, dry season, dry–wet transition, wet season.

Table 1. Conceptual table for *Vallisneria nana*. Subjective measure of confidence: Low confidence = 1 study, 1 location. Particularly if correlative. Med = more than one study, experimental, mechanistic, High= three or more studies; experimental, mechanistic. Quality of evidence incorporates the type, amount, quality, consistency, and agreement between studies and is based on an assessment of the literature and/or authors' opinion (e.g. King et al. 2015).

Season	**Flow-ecology relationship**	**Measure of confidence**	**References**
Wet–dry transition	Riverbed PAR (photosynthetically available radiation) increases due to reduced depth and improved water clarity due to increasing groundwater content of the river. Incident seasonal PAR however declines. Riverbed PAR exceeds compensation (photosynthesis = respiration) point for initiation of plant growth. Compensation point will be reached first in shallow waters. Timing of transition (therefore *V. nana* growth start) delayed by anthropogenically lowered GW.	* Low-med (based on observations and conceptual model; possible other triggers such as temperature)	Rea et al. 2002; Erskine et al. 2003; Townsend et al. 2017; S. Townsend, pers. obs.
Wet–dry transition	Change in nutrient water quality, high nitrate concentrations and low soluble phosphorus during the transition. Nutrient limitation of plant growth.	* Low-med (Nutrient requirements for *V. nana* poorly known; relative importance of hyporheic and water column sources of nutrients not known)	Rea et al. 2002; Blanch et al. 2005; Townsend et al 2017

Dry season	Groundwater input supplies dry-season flows during the dry-season. Shallow habitat availability (<2 m) reduces with reduced flow. Dry-season flows further reduced by groundwater extraction. Water-level decline reduces habitat area (especially shallow areas along banks) and velocities, leading to potentially reduced biomass of *V. nana* during the dry season.	* Low-med (based on published/anecdotal reports and observations)	Rea et al. 2002; Erskine et al. 2003; S. Townsend, pers. obs.
Dry season	Continued increased water clarity and reduced depth increase PAR for *V. nana* photosynthesis during dry season. Growth most likely limited by nutrients.	*Low-med (based on published/anecdotal reports).	Rea et al. 2002; Erskine et al. 2003; Webster et al. 2005; Townsend et al. 2011
Dry season	Prolonged duration of low flows and low velocity increases competition of *V. nana* for nutrients and space with *Spirogyra* and charophytes.	* low (limited published/anecdotal reports)	Townsend et al. 2017
Inter-annual variation of groundwater-fed flow	Length of the growing season dependent on the period of groundwater-fed flow. Long dry seasons will permit the greater accumulation of *V. nana* biomass, especially the rhizomes for wet-season survival. Short dry season, the reverse.	* low (conceptual only)	Townsend et al. 2017; S. Townsend, pers. obs.

Dry-wet transition	Short-term flush of nutrients from episodic storm runoff events and increased velocity and magnitude enhances *V. nana* growth. Some *Spirogyra* removed from *V. nana* leaves.	* low	S. Townsend, pers. obs.
Wet season	High wet-season flows and velocity removes *V. nana* leaves including some rhizomes. Poor water clarity prevents *V. nana* photosynthesis. Known that *V. nana* persists over the wet season as rhizome with old non-photosynthetic leaves. Anecdotal reports of river remaining turbid after very big wet season.	** Low- medium (limited published reports but frequently observed)	Rea et al. 2002; Erskine et al. 2003;; Townsend et al 2017; S. Townsend, pers. obs.
Wet season-high current speeds, depth and duration	The magnitude (i.e. water depth and velocities) and duration will determine the survival of *V. nana* rhizomes and leaves to initiate dry-season growth, e.g. short duration of wet-season flows increases *V. nana* survival and growth, also removes competing plants.	* low (conceptual only-based on observations and assumptions)	Townsend et al. 2017; S. Townsend, pers. obs.

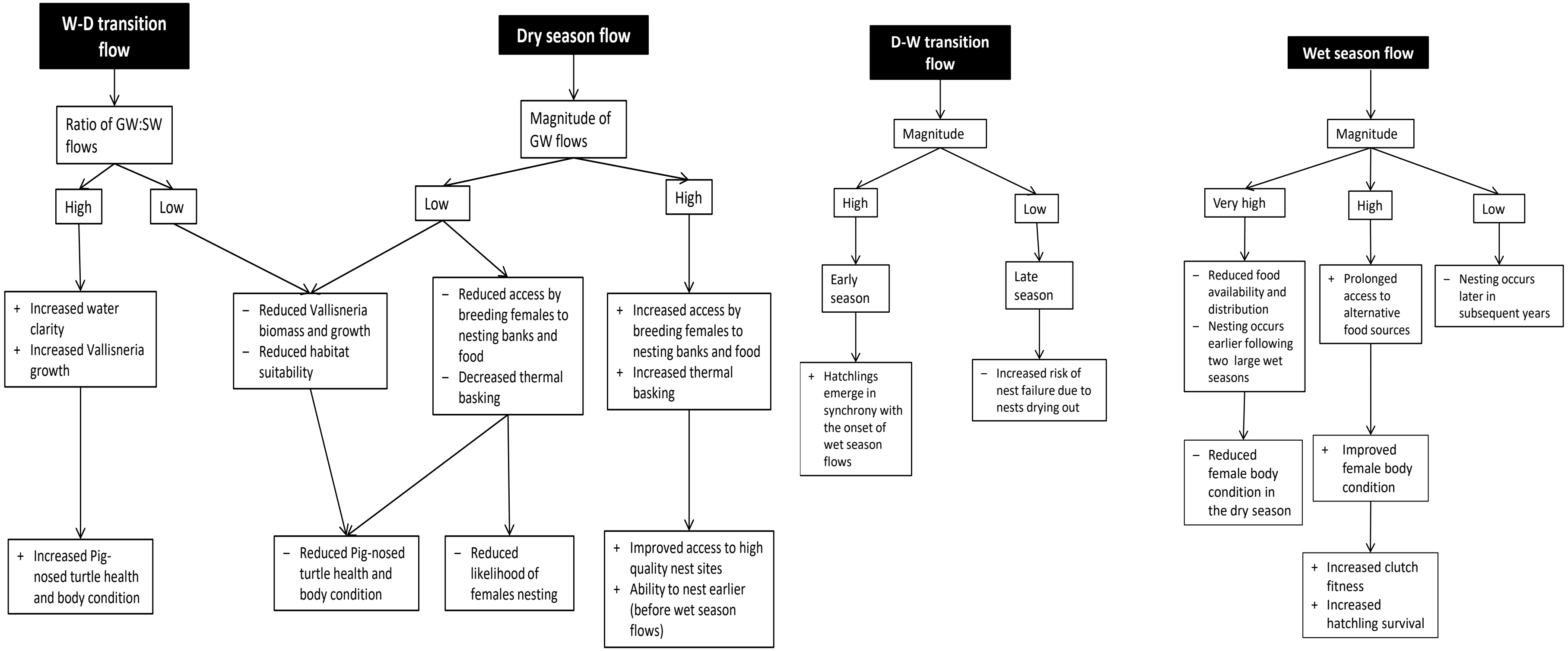

Fig. 2. Conceptual model for pig-nosed turtle over four seasonal periods: wet-dry transition, dry season, dry-wet transition, wet season.

Table 2. Conceptual table for pig-nosed turtle. Subjective measure of confidence: Low confidence = 1 study, 1 location. Particularly if correlative. Med = more than one study, experimental, mechanistic, High= three or more studies; experimental, mechanistic. Quality of evidence incorporates the type, amount, quality, consistency, and agreement between studies and is based on an assessment of the literature and/or authors' opinion (e.g. King et al. 2015).

Season	**Flow-ecology relationship**	**Measure of confidence**	**References**
Wet–dry transition/ Early dry season	Ratio of SW:GW determines timing of increased water clarity and initiation of growth of *Vallisneria*, the primary food source for pig-nosed turtle. Persistence and quality of *V. nana* depends on GW input during the dry season.	low-medium confidence	Georges et al. 2002; Rea et al. 2002; Erskine et al. 2003, Doody et al. 2003a
Wet–dry transition/ Early dry season	Low flows may reduce habitat suitability and food resources (including *Vallisneria*). Maintenance of habitat required for key resources.	low confidence	Rea et al. 2002
Mid–late dry season	Magnitude of GW determines the minimum water levels required for crossing barriers, particularly females accessing resources such as nesting banks and *Vallisneria* patches.	low-medium confidence	Georges et al. 2002; Erskine et al. 2003; Blanch et al. 2005; Georges et al. 2008a,b

Mid–late dry season	Female nesting occurs mid–late dry season. Accelerated flow reduction from water extraction may also change the physical shape of the base of nesting banks, forming a 'step' which may prevent females from accessing nesting banks.	low confidence	P. Dostine, pers. obs.
Dry season	Thermal basking in pig-nosed turtles possibly dependent on GW levels during dry season. PN turtle use riverbed springs to elevate body temperature for prolonged foraging on low nutrient diet, when spring temp is greater than river temperature. Loss of thermal basking results in constraints on foraging time, reduced body condition, and potential impacts on timing of egg laying/nesting due to water extraction.	low-medium confidence	Doody 2002 (Chapter 3); Georges et al. 2002; Erskine et al. 2003; Chapter 3 Davies thesis
Late dry season /Dry-wet transition	Females nest prior to early wet-season flows (particularly when GW levels are maintained). Embryonic diapause enables hatchlings to emerge in synchrony with the onset of wet-season flows. Extraction of flows during the late dry season increases the potential of nest failure due to nests drying out earlier and becoming hotter. Moisture/ thermal regime of the banks also change.	* low-medium confidence	Georges & Kennett 1989; Doody et al. 2001

Wet season	Magnitude of the previous wet-season flow influences nesting time and timing of hatching (e.g. turtles nested earlier after two large wet seasons and later following lower wet season flow). Larger wet seasons may allow prolonged access to resources only available during wet season including potentially critical wet-season resources e.g. fruiting riparian trees and (maybe) carrion (large wet-season flows also result in higher dry-season flows, and improved growing conditions for *Vallisneria*).	*low-medium confidence	Doody et al. 2001; Doody 2002; Georges et al. 2002; Doody et al. 2003a. Few data points.
Wet season	Magnitude of wet-season flows influences the reproductive output of individual females, larger flows produces larger clutches and heavier eggs. Increased survival of larger hatchlings.	* low confidence	Doody 2002; Doody et al. 2003b
Wet season	Extreme flood events reduce food availability and distribution (e.g. removal of *Vallisneria* beds) which reduces the female pig-nosed turtle body condition in the dry season.	* low confidence	Erskine et al. 2003; P. Dostine, pers. obs

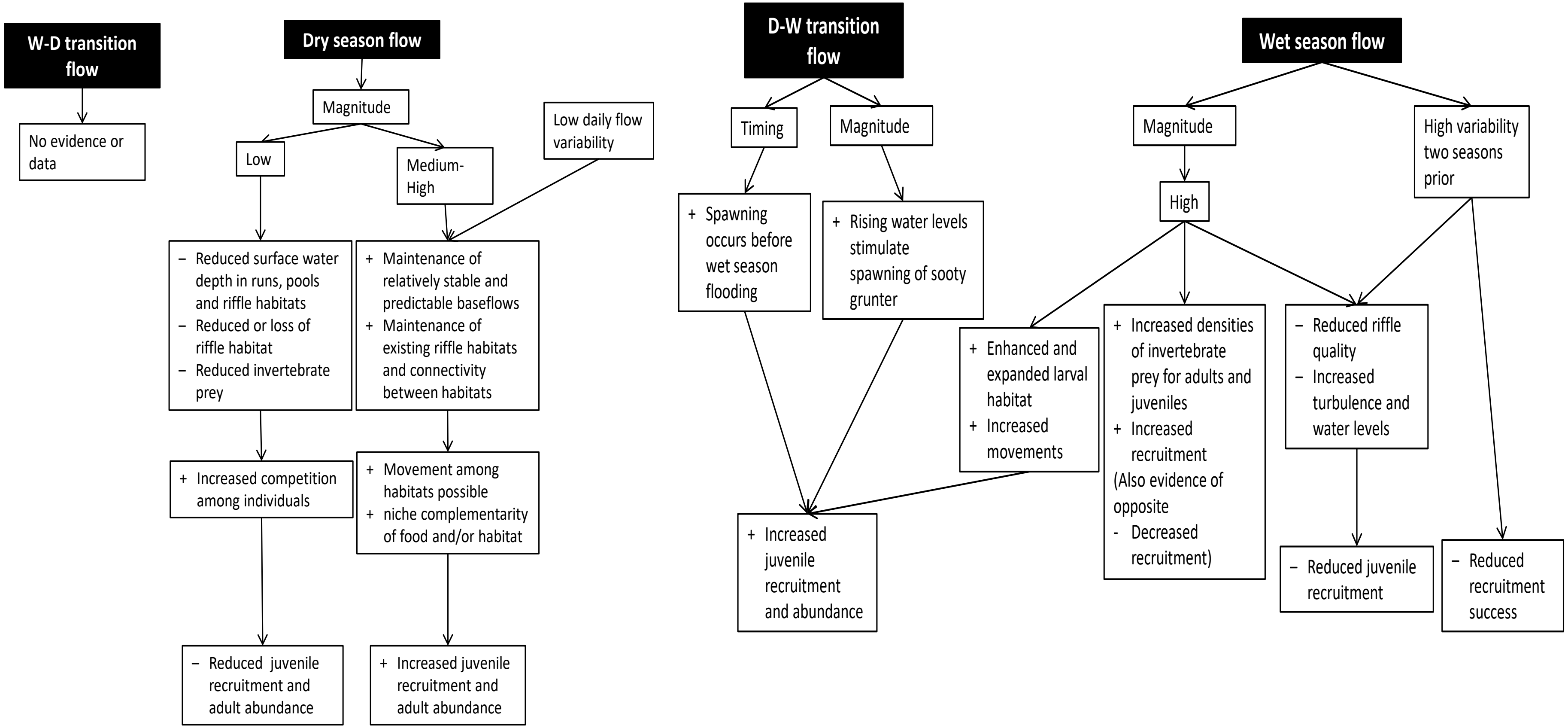

Fig. 3. Conceptual model for sooty grunter over four seasonal periods: wet–dry transition, dry season, dry–wet transition, wet season

Table 3. Conceptual table for sooty grunter. Subjective measure of confidence: Low confidence = 1 study, 1 location. Particularly if correlative. Med = more than one study, experimental, mechanistic, High= three or more studies; experimental, mechanistic. Quality of evidence incorporates the type, amount, quality, consistency, and agreement between studies and is based on an assessment of the literature and/or authors' opinion (e.g. King et al. 2015).

Season	**Flow-ecology relationship**	**Measure of confidence**	**References**
Dry season	A reduction in dry-season flow can lead to increased competition for habitat and food, which result in a reduction in fish abundance. The maintenance of relatively stable and predictable baseflow conditions in the Daly during the dry season may facilitate niche complementarity as a mechanism to avoid intense competitive interactions both between and within species.	Low-med	Pusey & Kennard, 2009; Davis et al. 2011a,b
Dry season	Low flows provide shallow, fast-flowing riffles which are critical habitats for sooty grunter and are important areas of production of invertebrate prey for the juveniles of this species. [There is an increased risk of] loss of preferred riffle habitat and impacts on fish abundances if the potentially further increased future water extraction entitlements were to occur.	Low-med	Pusey & Kennard, 2009, Chan et al. 2012
Dry season	Connectivity between suitable habitats is maintained if dry-season flows are high enough to maintain connectivity to allow adult movements.	Low	Crook, pers comm

Dry–wet transition season	Rising water levels may stimulate spawning of sooty grunter.	Low-med	Merrick & Schmida 1984; Allen et al. 2002
Dry–wet transition season	In the perennial streams and rivers of the Wet Tropics region, reproduction occurs early in the year and before wet-season flooding.	Low	Hogan 1990 in Pusey et al. 2004
Wet season	Wet-season flooding provides enhanced and expanded larval habitat.	Low	Pusey et al. 2004
Wet season	High invertebrate densities in the greatly expanded array of intermittent riffles and runs during the wet phase may provide abundant food for adult and juveniles.	Low-med	Garcia et al. 2011; Davis et al. 2011, 2012
Wet season	Increased WS magnitude results in decreased number of juveniles. This may be due to poor spawning and recruitment success during periods of highly variable wet-season flows (two wet seasons prior).	Low	Stewart-Koster et al. 2011
Wet season	Increased WS magnitude, increased number of juveniles through increased food availability for juveniles.	Low	Pusey et al. 2004
Wet season	Increased flow variability may reduce the quality of riffle spawning habitat by increasing turbulence and rapidly altering water levels which may desiccate eggs deposited in shallow marginal areas.	Low	Stewart-Koster et al. 2011

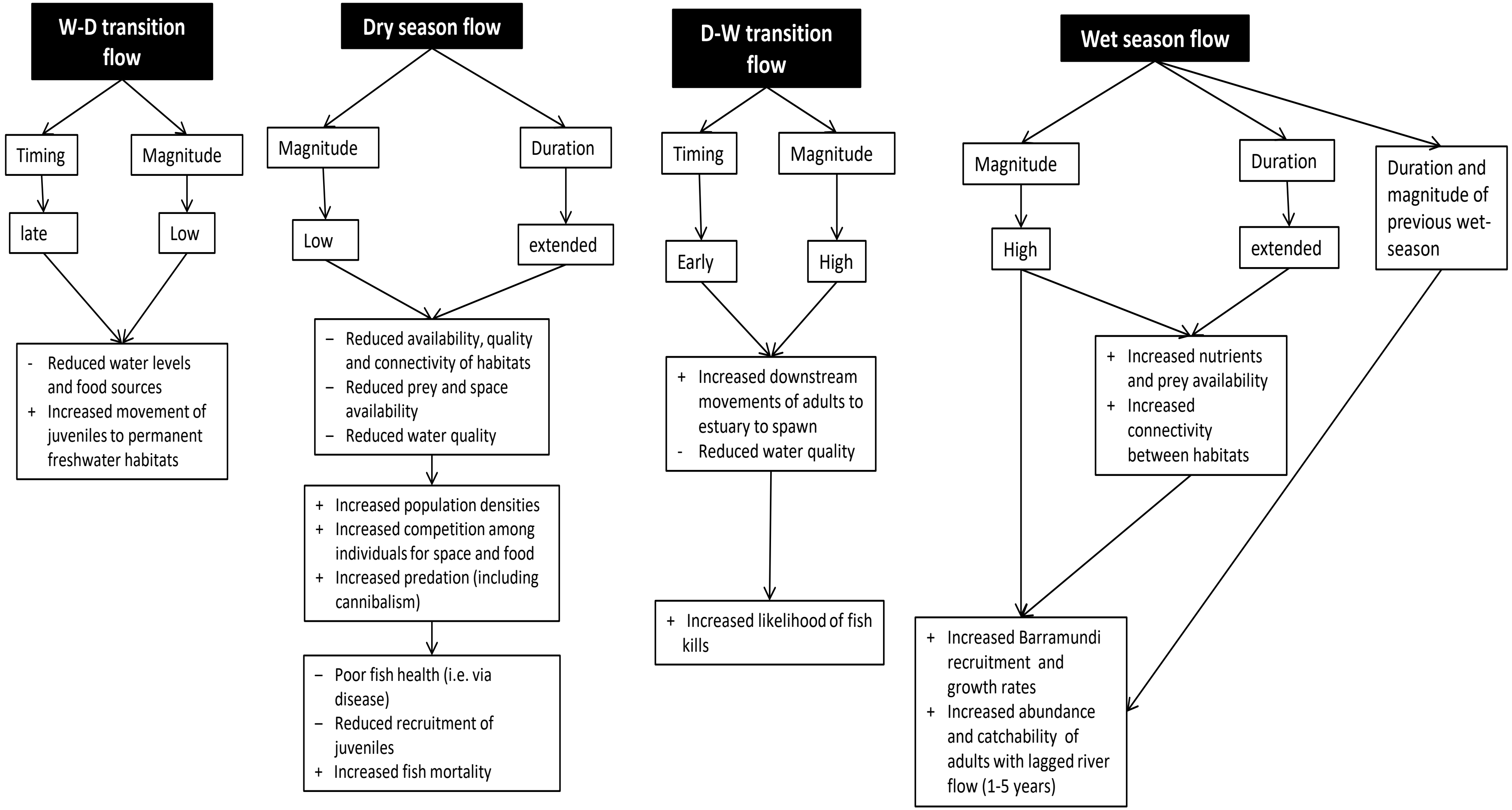

Fig. 4. Conceptual model for Barramundi over four seasonal periods: wet–dry transition, dry season, dry–wet transition, wet season

Table 4. Conceptual table for Barramundi. Subjective measure of confidence: Low confidence = 1 study, 1 location. Particularly if correlative. Med = more than one study, experimental, mechanistic, High= three or more studies; experimental, mechanistic. Quality of evidence incorporates the type, amount, quality, consistency, and agreement between studies and is based on an assessment of the literature and/or authors' opinion (e.g. King et al. 2015).

Season	**Flow-ecology relationship**	**Measure of confidence**	**References**
Wet–dry transition season	Many juvenile barramundi move to permanent freshwater habitats generally at the end of the wet season. This may be due to the lowering of water levels in these habitats, coupled with the depletion of food sources.	Low (speculative statements by studies)	Russell & Garrett 1983, 1985
Dry season	Low flows can negatively affect juvenile recruitment by reducing the availability, quality and connectivity of habitats, as well as resource availability (i.e. food and space). Timing and magnitude of water abstraction can particularly reduce the abundance of the adult sub-population. The drawdown of pools via extraction further reduces the amount of suitable habitat available for barramundi, particularly in the late dry season.	Low	Staunton-Smith et al. 2004; Chan et al. 2012
Dry season	During extended periods of low flow when longitudinal movement by barramundi is restricted, local population densities increase, and food and refuge availability	Low	Chan et al. 2012

	becomes limited. This can lead to an increase in predation (including cannibalism) and competition [among individuals], especially with reduced pool size.		
Dry season	Reduced water quality during the dry season (high temperatures, reduced dissolved oxygen concentrations) due to low flows may result in fish mortality and/or reduced fish health via transmission of disease. The timing of any abstraction is assumed to further affect the system via changes in water quality for barramundi.	High	Russell and Garrett. 1983; Rimmer & Russell, 1998; Perna & Burrows 2005; Glencross & Felsing 2006; Bermudes et al. 2010; Newton et al. 2010; Chan et al. 2012
Dry-wet transition	Initial high flows (relative to baseflow conditions) stimulate a proportion of mature adult barramundi to move downstream to spawn in the estuary. Spawning precedes the wet season and the onset of monsoonal flows i.e. before the main freshwater flows that occur after mid-December. Anthropogenic disturbance, including the extraction of flows has the potential to alter the frequency of life history contingents in barramundi populations.	Low-medium	Davis 1985a,b; Pusey & Kennard 2009; Griffin 1982 cited in Balston 2009; R. Garrett, pers. comm. 2000 in Halliday et al. 2012; R. Griffin, pers. comm. 2005 in Halliday et al. 2012; Crook et al. 2016

Dry-wet transition	Initial wet-season flows (high pulses relative to baseflow conditions) can lead to a reduction in water quality, e.g. low dissolved oxygen concentration, high organic matter, and increased likelihood of fish kills (including barramundi).	Medium-high	Bishop 1980; Pettit et al. 2012; Townsend 2003
Wet season	Duration and magnitude of freshwater flows (and/or rainfall) in rivers and across their associated flood plains delivers nutrients to the estuary, creates connectivity opportunities between habitats for adults and juveniles to access prey. Potential anthropogenic effects, such as fragmentation of floodplain habitats due to agriculture, dams and levees, and flow abstraction can also disrupt connectivity between habitats.	Low-medium	Pusey & Kennard, 2009; Jardine et al. 2012a,b; Halliday et al. 2012
Wet season	Barramundi recruitment and growth rates are positively correlated with high magnitude of river flows (or rainfall), as well as the duration and magnitude of the preceding wet-season discharge.	Med-high	Staunton-Smith et al. 2004; Robins et al. 2005, 2006; Bayliss et al. 2008; Halliday et al., , 2011, 2012; Stewart-Koster et al. 2011; Tanimoto et al. 2012; Grubert et al. 2013
Wet season	Abundance and catchability of adult barramundi is significantly correlated to the magnitude of lagged river flow (1-5 years, possibly due to enhanced growth	Low-medium	Robins et al. 2005; Bayliss et al. 2008; Balston 2009; Halliday et al. 2012

	and recruitment, see above). Both barramundi catch and population size appear highly sensitive to flow extraction; a high extraction rate correlates to negative impacts on both barramundi socio-economic and ecological assessment endpoints.		

Appendix 2. Hydrodynamic modelling report: Wilden Reach, Katherine River

Hydrodynamic modelling conducted by Water Research Laboratory, University of NSW.

UNSW
SYDNEY

Water Research
Laboratory

4th March 2020

WRL Ref: 2020008 LR20200304

COMMERCIAL IN CONFIDENCE

Assoc Prof Alison King
Research Institute for the Environment and Livelihoods
Charles Darwin University
Darwin NT 0909

By Email: Alison.King@cdu.edu.au
CC: Julia.Schult@nt.gov.au

Dear Associate Professor King,

Daly River Hydrodynamic Modelling

1. Introduction

The Research Institute for the Environment and Livelihoods together with the Department of Environment and Natural Resources (DENR) commissioned the Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney to undertake hydrodynamic modelling on the Daly River at Wilden, Northern Territory. The location of the study site and the model extent is provided in Figure 1.

Previously WRL simulated ten (10) steady state, dry weather flow conditions to develop an understanding of the hydrodynamic behaviour (depths and velocities) through the river for fish passage. Since then, WRL was provided with measurements of depth and velocity from three transects surveyed along the river. This additional information was used to refine the model parameters and before re-running the ten (10) steady state hydrodynamic scenarios. This letter report presents the methodology and results of the numerical modelling investigation.

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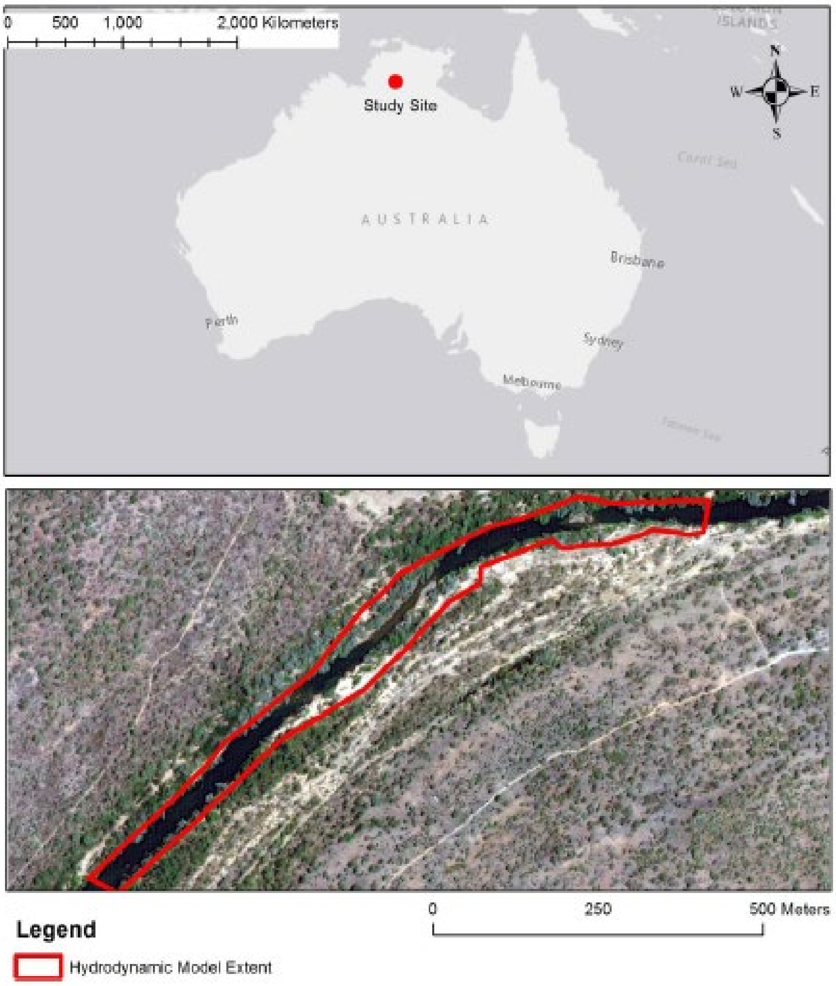


Figure 1: Location of study site and model extent

2. Numerical Modelling

Hydrodynamic modelling was completed using the RMA-2 finite element model (King, 2006). RMA-2 is a depth averaged hydrodynamic model, which computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in two-dimensional flow fields using a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows.

RMA-2 is suitable for simulation of flow in vertically well-mixed water bodies where two dimensional flow regimes exist. The RMA-2 model has been used in Australia and internationally for over 30 years, including to calculate water levels and flow distributions in several floodplain environments in the Northern Territory including the Lower Mary River, Arafura Swamp, Alligator River and the Daly River estuary.

2.1 RMA-2 Model Configuration

A fine resolution (approximately 1 m) triangular mesh was developed throughout the model domain to represent all the localised channel features and riffles in the provided bathymetric survey. The model boundary conditions consisted of a constant upstream flow boundary condition and a constant downstream water level (empirically derived from the flowrate as described in Section 2.3). The hydrodynamic model was run in steady state with wetting and drying elements. The main model parameters applied to the RMA-2 model were bed friction applied as a Manning's 'n' formulation. The Manning's 'n' parameters of the different parts of the model domain were changed to best match the velocity and depth measurements as described in Section 2.4. The RMA-2 model configuration and an example of the model geometry are shown in Figure 2.

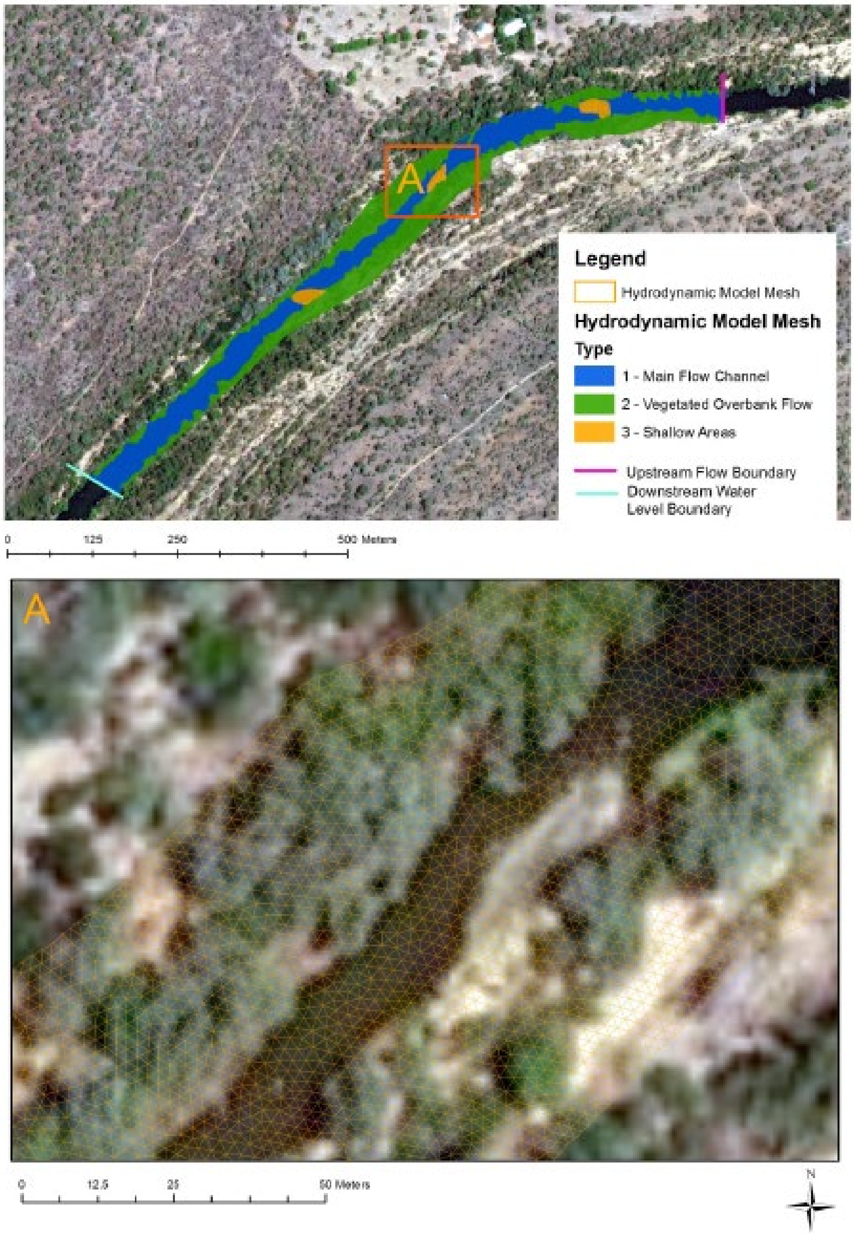


Figure 2: RMA-2 model configuration and an example of the model geometry

2.2 *Bathymetry*

Bathymetry was provided to WRL by DENR in an email dated 25th October 2018. The survey was reprocessed as a Digital Elevation Model (DEM) using ARC-GIS and has been presented in Figure 3. The DEM was applied to the geometric mesh of the hydrodynamic model to represent the channel and overbank flow areas.

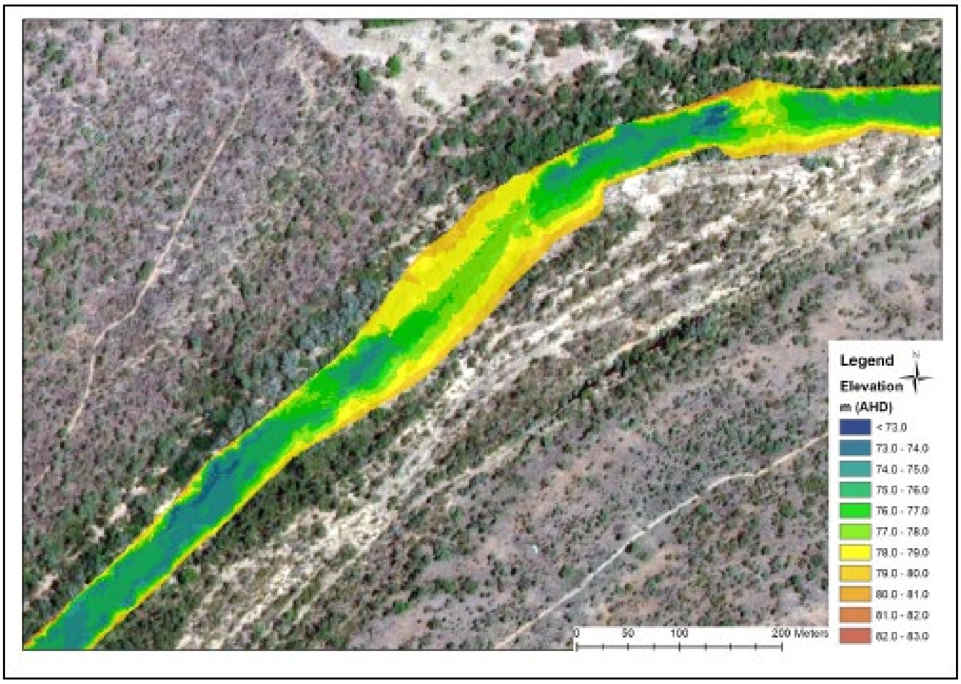


Figure 3: Bathymetry elevations in m AHD

2.3 Calculation of Downstream Water Depths

In the absence of any measurements of downstream water levels, these were assumed to be normal flow depths for the given flow scenarios. Downstream water depths were calculated based on bed slope, channel geometry, longitudinal water surface slope and upstream flow conditions for each scenario. This was calculated using the Chezy equation (Chow, 1959):

$$Q = A \times C \times R_h^{\frac{1}{2}} \times S^{\frac{1}{2}}$$

$$C = \frac{1}{n} \times R_h^{\frac{1}{6}}$$

Where:

$Q = Flow$
$A = Area\ of\ flow$
$C = Chezy's\ coefficient$
$R_h = Hydraulic\ Radius$
$S = Bed\ Slope$
$n = Manning's\ Roughness\ Coefficient$

The model dry weather inflows for the ten (10) model scenarios were provided to WRL in an email dated 3rd December 2018. A steady state flow rate of 1.7 m^3/s was used for the calibration runs, and represented the approximate river flow observed during field measurements from the 19th December 2019. The resulting downstream water level scenarios for the given flow rates are provided in Table 1.

Table 1: Model scenarios upstream flow and downstream water level

Model Reference	Upstream Inflow (m^3/s)	Downstream Water Level Boundary
Scenario 1	0.50	75.97
Scenario 2	1.00	76.06
Scenario 3	1.50	76.07
Scenario 4	2.00	76.11
Scenario 5	2.50	76.15
Scenario 6	2.76	76.18
Scenario 7	4.00	76.27
Scenario 8	6.00	76.40
Scenario 9	8.00	76.51
Scenario 10	12.00	76.70
Calibration	1.7	76.08

2.4 Selection of Bed Friction

DENR provided WRL with three depth and velocity transects to use for refining the RMA-2 model parameters. The location of these transects is shown in Figure 4. The measurements were undertaken during flow conditions of approximately 1.7 m^3/s on the 19th of December 2019. The surveys were provided to WRL as Microsoft Excel files with GPS location, measured depth, mean velocity and flow. The measurements did not record water surface elevation or bottom bed elevation at the point of the survey. As such, the previously generated DEM elevations were added to the measured depths to calculate a water surface elevation for comparison with RMA-2 model results.

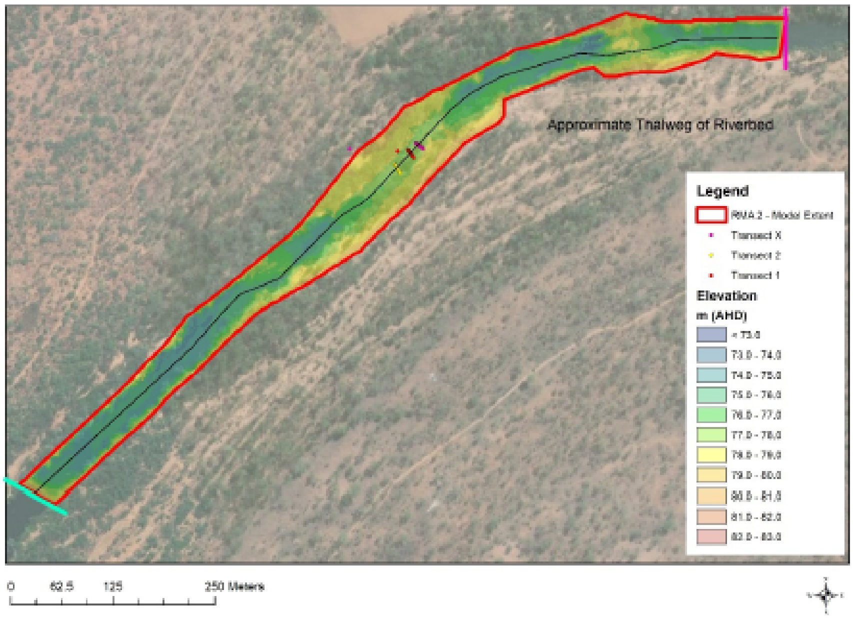


Figure 4: Location of depth and velocity transects

The parameter selection involved:

- Updating the model mesh for better representation of the measurement transects; and
- Changing the Manning's 'n' of the model to assess changes in depth and velocity.

A Manning's 'n' value of 0.038 was adopted to represent the main flow channel, a value of 0.070 was adopted for areas of overbank flow with highly vegetated landforms and a value of 0.060 was adopted for shallow rocky areas (riffles) within the model domain. The resulting depths and mean velocities for the three provided transects are shown in Figure 5 to Figure 10. The overall model water surface profile generated for the calibration scenario is shown in Figure 11.

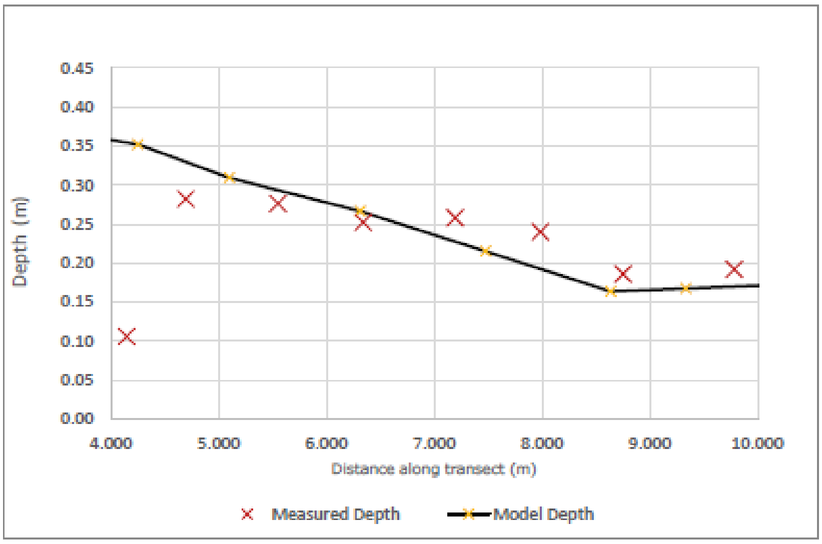


Figure 5: Transect 1 - Depth

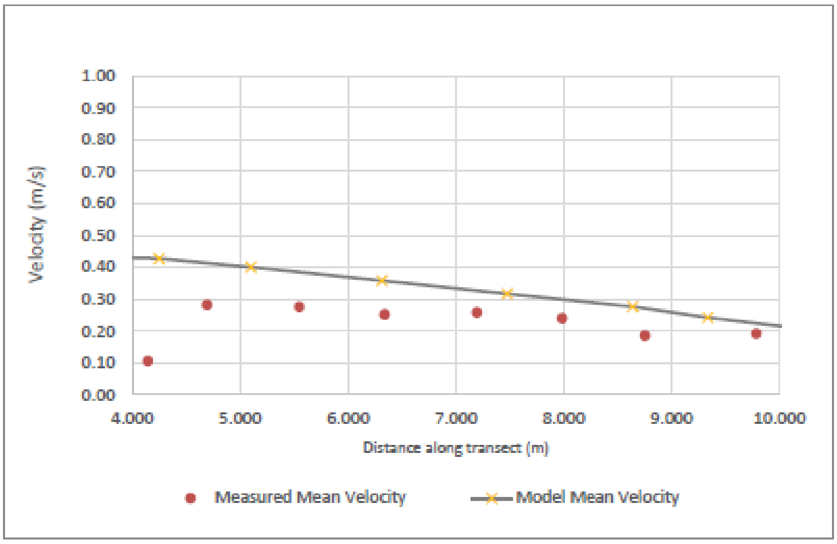


Figure 6: Transect 1 - Mean Velocity

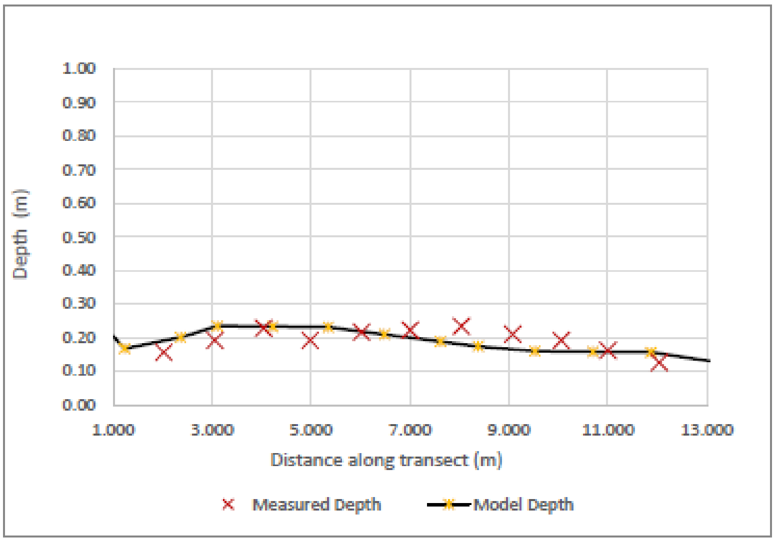


Figure 7: Transect 2 - Depth

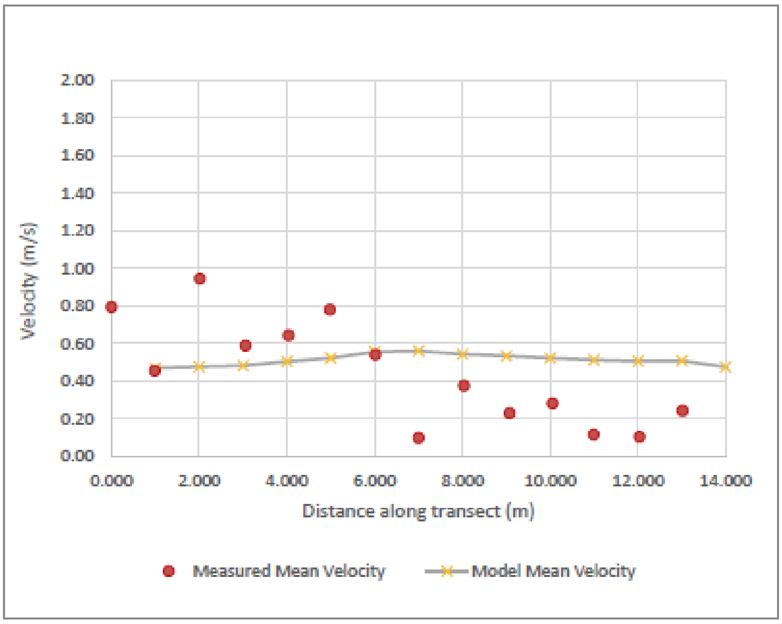


Figure 8: Transect 2 - Mean Velocity

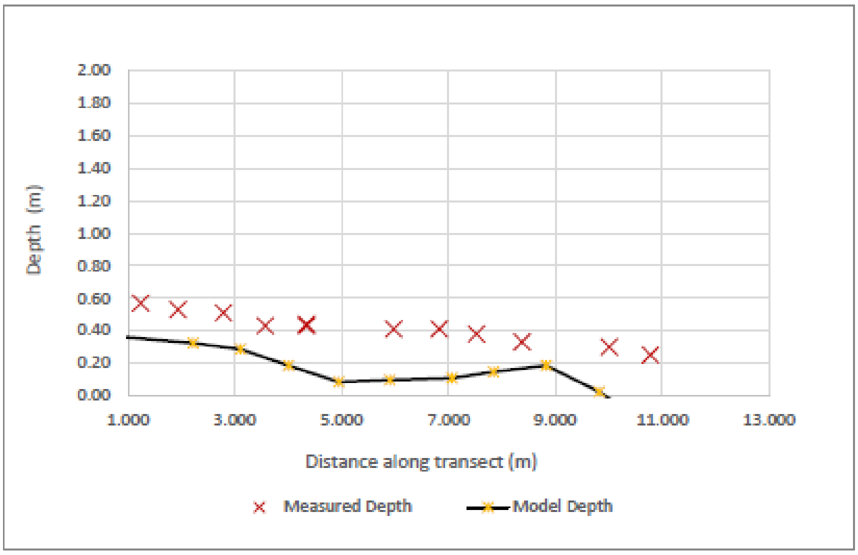


Figure 9: Transect X - Depth

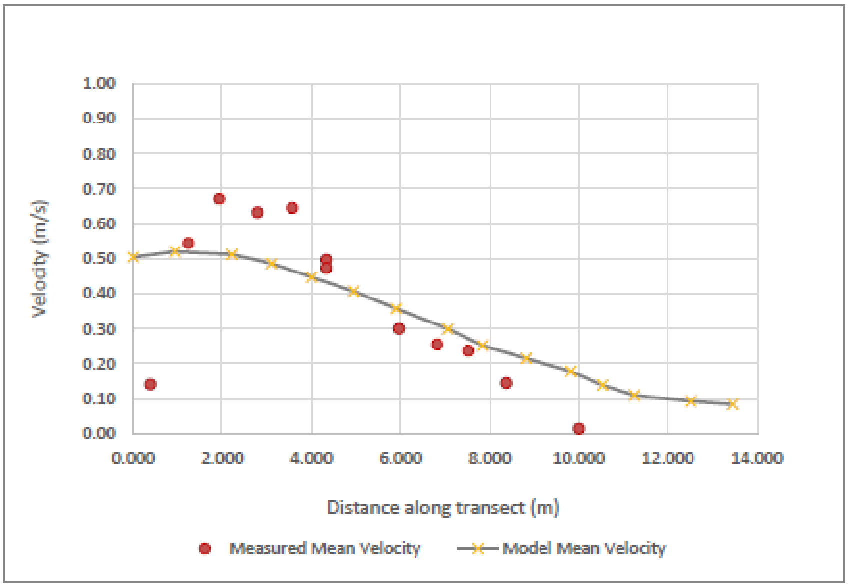


Figure 10: Transect X - Mean Velocity

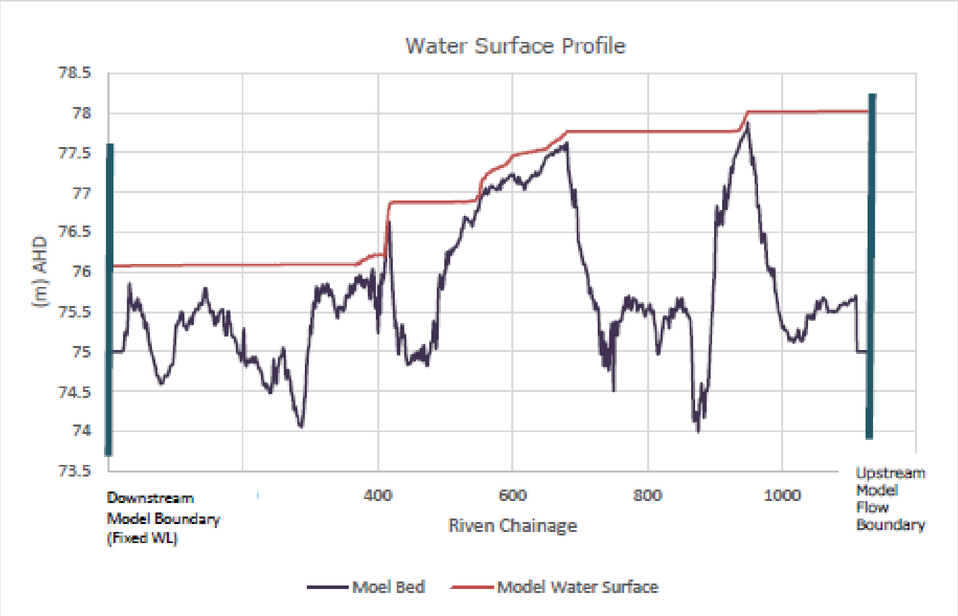


Figure 11: Water Surface Profile

The model depths could not be perfectly matched for all measured points along a transect. This was primarily because model bed elevations were previously interpolated from a DEM to a triangular mesh at a resolution of approximately 1 metre. This was often coarser than the proximity at which the depth and velocity measurements were taken (approximately 0.3-0.5 metres). As a result very localised changes to elevation were not captured in the model bathymetry and could not be perfectly matched.

However, the trends in depth and velocities were able to be reproduced with the average velocity and depths across each section being well reproduced. Since there has only been data available for the one single flowrate, WRL considers that the model should not be called calibrated or verified.

3. Model Predictions

All model results were provided as electronic GIS layers of: water depth, velocity, Froude number and bed shear. RMA-2 predicts the water depth and velocity directly. Bed shear and Froude were calculated by post-processing results at every node using the methods detailed in Section 3.1 and Section 3.2 respectively.

3.1 *Bed Shear*

In open channel flow, shear stress (τ_b in N/m^2) is the force of moving water against the bed of a channel. Bed shear, as a function of Manning's 'n', water depth and velocity can be described by (Chow, 1959):

$$\tau_b = \frac{gn^2\rho u^2}{R_h^{\frac{1}{3}}}$$

Where:

g = acceleration due to gravity (9.81 m/s^2)
n = Manning's 'n' friction
ρ = density of fluid (water = 1000 kg/m^3)
u = depth averaged velocity (m/s)
R_h = Hydraulic Radius (approximated as the depth (m))

Bed load movement and sediment transport is a function of shear stress. Some typical values of sediment mobility due to bed sheer stress are presented in Table 2 (USGS, 2008).

Table 2: Critical shear stress by particle-size classification for determining approximate condition for sediment mobility (after Table 7 USGS 2008)

Particle Classification Name	Ranges of Particle Diameters (mm)	Critical Bed Shear Stress τ_b (N/m^2)
Coarse Cobble	128 - 256	112 - 223
Fine Cobble	64 – 128	53.8 - 112
Very Coarse Gravel	32 - 64	25.9 - 53.8
Coarse Gravel	16 - 32	12.2 - 25.9
Medium Gravel	8 – 16	5.7 – 12.2
Fine Gravel	4 – 8	2.7 – 5.7
Very Fine Gravel	2 - 4	1.3 – 2.7
Very Coarse Sand	1 - 2	0.47 – 1.3
Coarse Sand	0.5 – 1	.27 – 0.47
Medium Sand	0.25 – 0.5	0.194 – 0.27
Fine Sand	0.125 – 0.25	0.145 – 0194
Very Fine Sand	0.0625 – 0.125	0110- 0.145
Coarse Silt	0.0310 – 0.0625	0.0826 0.110
Medium Silt	0.0156 – 0.0310	0.0630 – 0.0826
Fine Silt	0.0078 – 0.0156	0.0378 - 0.0630

3.2 *Calculation of the Froude Number*

The Froude number is a dimensionless number comparing the inertial forces of the flow velocity. Sub critical flow is often characteristic of deep slow moving flow and super critical flow is characterised by shallower fast flows.

The Froude Number can be expressed as:

$$F_r = \frac{v}{\sqrt{gD}}$$

Where:

F_r = Froude number
v = velocity (m/s)
g = acceleration due to gravity (9.81 m/s^2)
D = hydraulic mean depth (m)

Flows can be categorised by the Froude number: subcritical (Fr < 1), critical (Fr = 1), or supercritical (Fr > 1). In supercritical flow (Fr > 1), waves cannot move upstream against the fluid flow (i.e. information carried by waves cannot propagate upstream of a disturbance).

3.3 *Sample Model Results*

GIS layers of modelled water depths, velocities, bed shear and Froude number following the steady state simulation for each scenario have been provided electronically to DENR as GIS rasters at 0.5 m resolution. Examples of the model results, water depths, velocities, bed shear and Froude number distributions are presented in Figure 12 – Figure 15 for Scenario 5 (flow rate of 2.50 m^3/s).

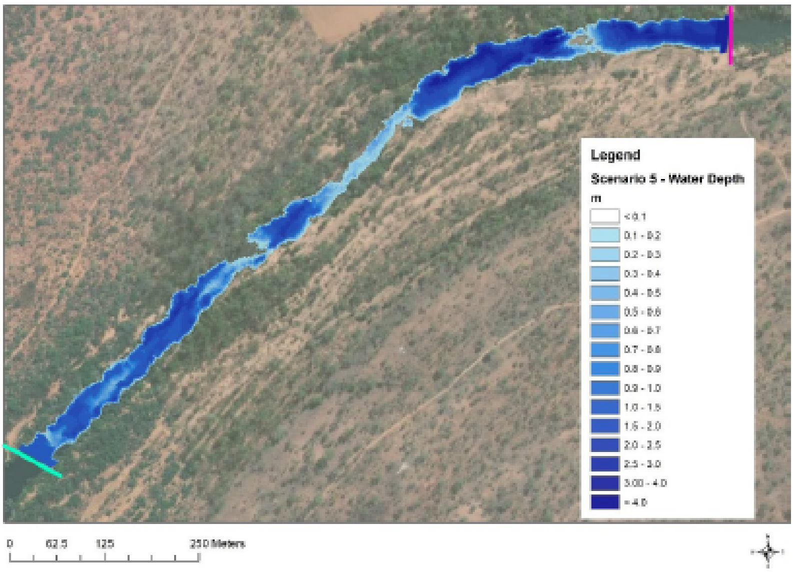


Figure 12: Scenario 5 (Q=2.5m^3/s) – water depths

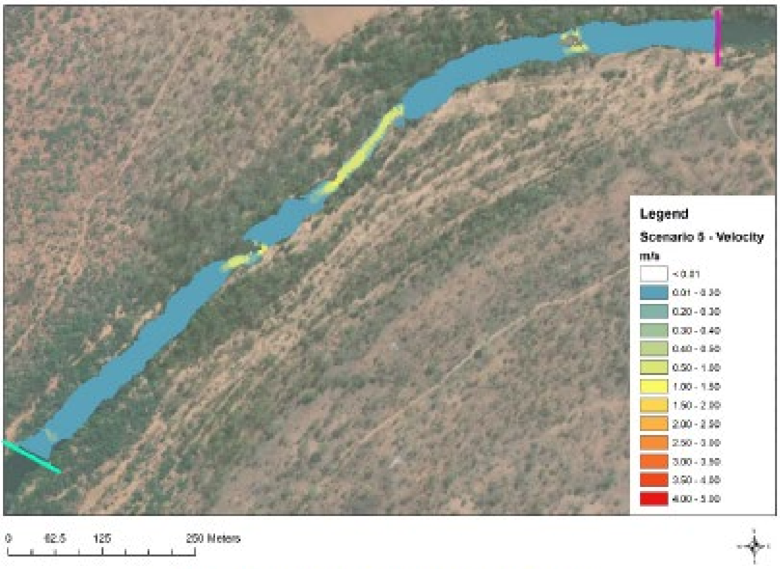


Figure 13: Scenario 5 – Velocity distributions

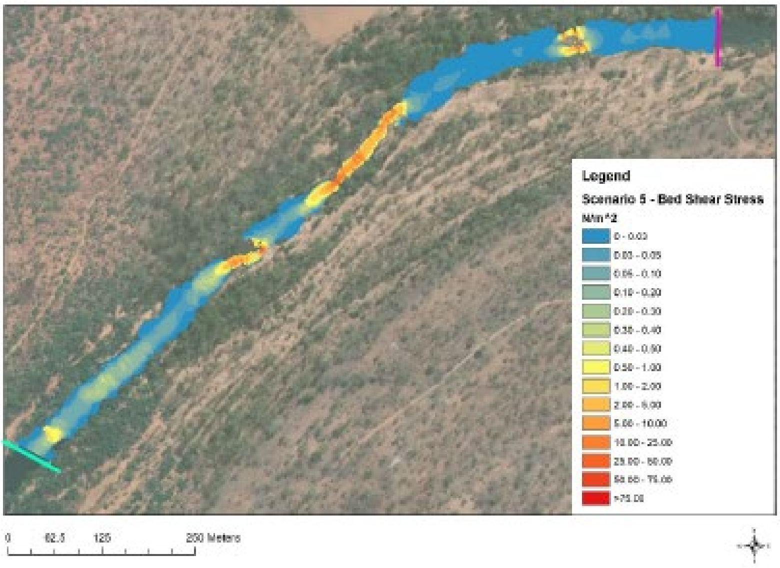


Figure 14: Scenario 5 – Bed shear stress

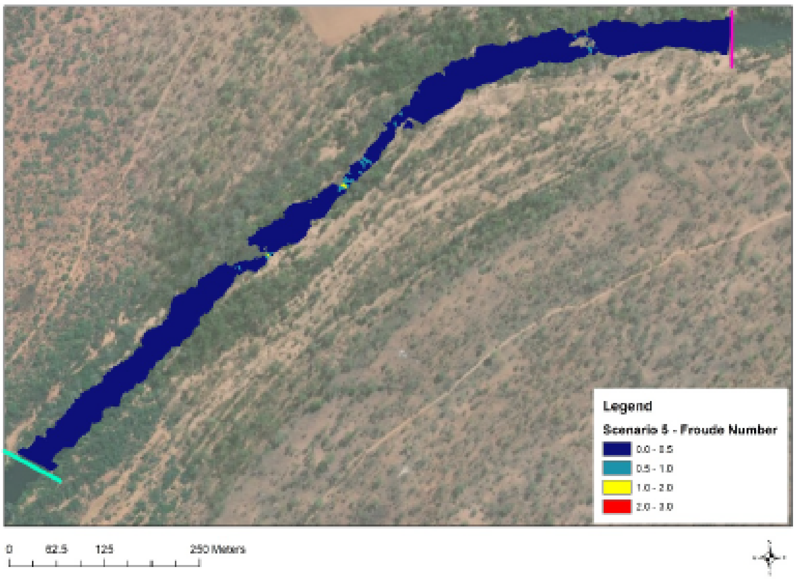


Figure 15: Scenario 5 – Froude number

3.4 *Summary Tables of Areas*

Using python scripts to analyse the GIS layers, WRL computed the following summary statistics presented in Table 3 to Table 7.

Table 3: Areas (m²) of the Wilden Reach model by depth range for each scenario

Scenario	Flowrate (m³/s)	Depth Range (m)								
		0.00 0.05	0.05 0.10	0.10 0.25	0.25 0.50	0.50 1.00	1.00 2.00	2.00 3.00	3.00 4.00	4.00 5.00
1	0.50	4301	4489	4335	3577	6193	11380	4695	621	9
2	1.00	4229	4194	4667	3797	5993	11818	5446	849	38
3	1.50	4142	3983	4692	4037	6135	11673	5741	1064	72
4	2.00	4085	3943	4532	4063	6244	11821	6067	1244	107
5	2.50	3985	3884	4399	4125	6300	11966	6330	1401	128
6	2.76	4014	3806	4328	4143	6300	12047	6467	1479	137
7	4.00	3959	3771	4157	4131	6459	12151	7038	1785	174
8	6.00	3894	3807	4013	3914	6588	12366	7833	2162	224
9	8.00	3865	4226	3867	3758	6696	12381	8527	2493	289
10	12.00	3839	4017	4085	3591	6457	12160	9805	3302	435

Table 4: Areas (m^2) of the Wilden Reach model by total velocity range for each scenario

Scenario	Flowrate (m^3/s)	Total Velocity Range (m/s)								
		0.00 0.05	0.05 0.10	0.10 0.20	0.20 0.30	0.30 0.50	0.50 0.75	0.75 1.00	1.00 2.00	2.00 5.00
1	0.50	34569	1250	1456	1034	993	209	35	11	0
2	1.00	33047	3049	1583	1094	1538	560	67	36	0
3	1.50	31453	4301	1791	1171	1687	837	145	87	0
4	2.00	27775	6800	2814	1301	1781	1133	317	103	0
5	2.50	24536	8714	4152	1274	1773	1396	467	132	0
6	2.76	23397	9720	4307	1254	1843	1439	533	153	0
7	4.00	17677	13412	6323	1430	1922	1641	838	295	3
8	6.00	13680	12084	10588	2756	2016	1712	1208	641	21
9	8.00	12363	8895	13748	4335	2365	1901	1367	1011	33
10	12.00	10767	6070	14667	6854	3859	2108	1425	1803	55

Table 5: Areas (m^2) of the Wilden Reach model by Froude Number range for each scenario

Scenario	Flowrate (m^3/s)	Froude Number							
		0.00 0.01	0.01 0.10	0.10 0.50	0.50 1.00	1.00 2.00	2.00 3.00	3.00 4.00	4.00 5.00
1	0.50	30835	5209	3208	288	16	0	0	0
2	1.00	27738	8942	3828	433	32	0	0	0
3	1.50	25426	11221	4289	479	56	0	0	0
4	2.00	20787	15762	4806	589	80	0	0	0
5	2.50	17875	18718	5092	666	91	0	0	0
6	2.76	16731	19917	5261	641	96	0	0	0
7	4.00	12076	24785	5810	750	122	0	0	0
8	6.00	8176	28904	6641	850	134	0	0	0
9	8.00	6951	30442	7480	999	146	1	0	0
10	12.00	5527	31775	9051	1120	133	2	0	0

Table 6: Areas (m²) of the Wilden Reach model by Bed Shear range for each scenario

Scenario	Flowrate (m³/s)	Bed Shear Range (N/m²)								
		0.00 **0.01**	**0.01** **0.10**	**0.10** **0.50**	**0.50** **1.00**	**1.00** **5.00**	**5.0** **10.0**	**10** **50**	**50** **100**	**100** **1000**
1	0.50	32005	3431	1632	810	1579	104	37	0	0
2	1.00	26609	8961	1896	905	2235	340	85	0	0
3	1.50	21206	13735	2363	985	2500	576	174	0	0
4	2.00	15740	17135	4302	1052	2729	846	301	1	0
5	2.50	13262	18000	5856	1045	2875	1032	444	2	0
6	2.76	12574	18464	6113	1040	2892	1115	520	3	0
7	4.00	10561	16956	9347	1497	2957	1398	887	20	0
8	6.00	9080	11753	14403	3138	3399	1465	1525	38	0
9	8.00	8495	8855	16334	4289	4373	1635	2066	56	0
10	12.00	7457	7043	14432	7034	6962	1813	2855	81	14

Table 7: Total Wet Areas (m²) of the Wilden Reach model for each scenario

Scenario	Flowrate (m³/s)	Total Wet Area (m²)
1	0.50	39598
2	1.00	41029
3	1.50	41538
4	2.00	42105
5	2.50	42517
6	2.76	42721
7	4.00	43623
8	6.00	44800
9	8.00	46102
10	12.00	47691

3.5 *Modelling Limitations*

The RMA-2 two-dimensional model assumes that velocities are the same on the surface as the bed. Whilst this is not considered to be substantial for the low flow (shallow) scenarios being modelled, velocity distributions may vary with depth for higher flow regimes. The RMA-2 hydrodynamic model does not directly solve supercritical flow, however, it does identify flow regimes approaching critical and above. Caution should be used when interpreting Froude numbers greater than 1.0 in these results.

In addition, the results presented in this letter are produced by updating the Manning's 'n' parameter of the previously developed RMA-2 model. The model friction was adjusted by comparing modelled and measured data for the three provided transects (which were collected on the 19th of December 2019 during a single river flow event of approximately 1.7m^3/s) as discussed in 2.4. As such the RMA-2 model, whilst refined, cannot be considered to be fully calibrated across all flow scenarios.

4. Conclusions

A steady state hydrodynamic numerical model of a very fine resolution, was developed to study the in bank flow regimes of ten (10) different dry weather flow scenarios on the Daly River at Wilden. Water depths, velocities, bed shear and Froude number were numerically processed for each flow scenario and have been provided electronically to DENR.

Please feel free to contact Priom Rahman in the first instance on (02) 8071 9840 if you would like to discuss the findings of this report in more detail.

Yours sincerely,

Brett Miller
Principal Engineer, CPEng

5. References

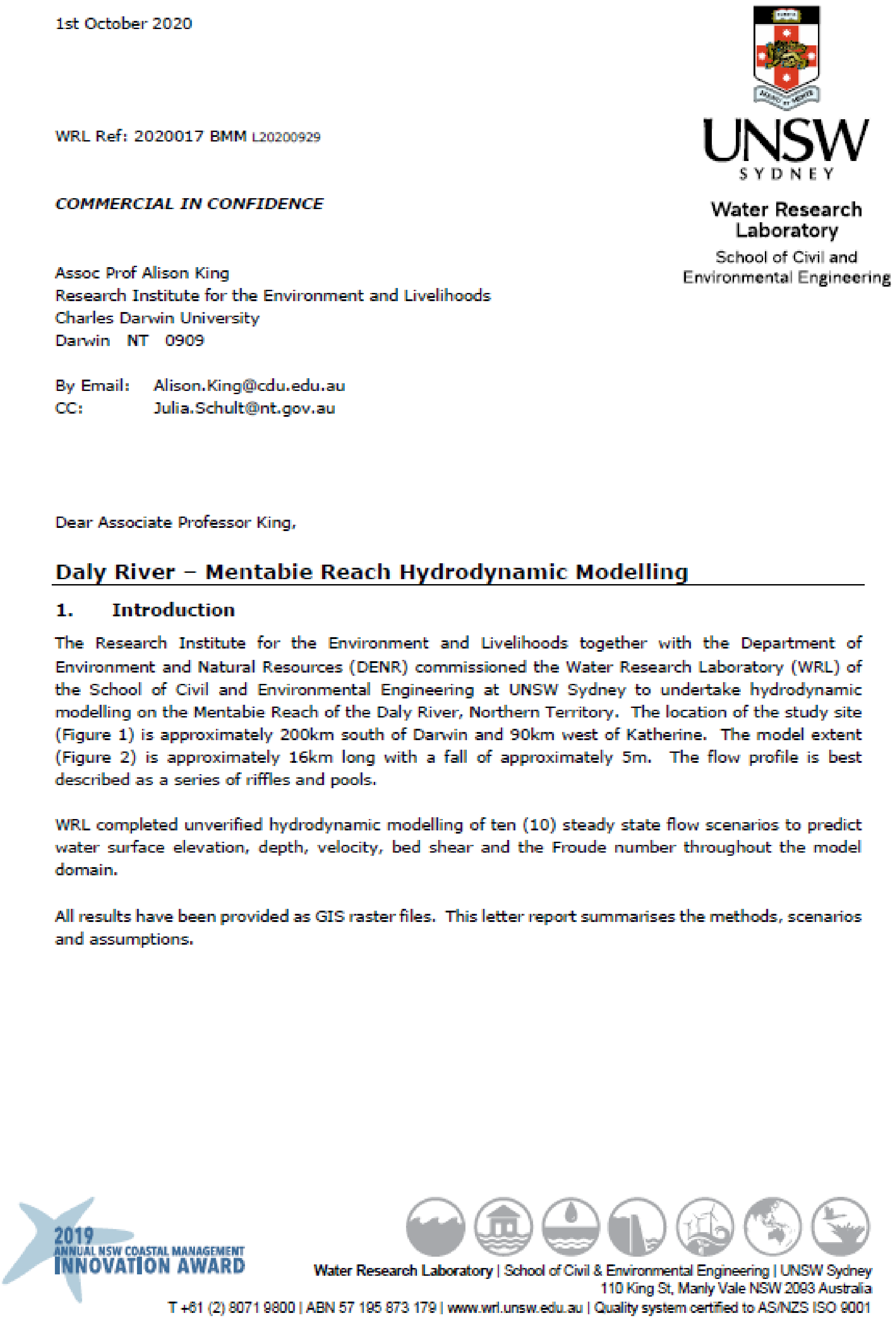
Chow V T (1959), Open-channel hydraulics. New York, McGraw-Hill, 680p.

King I P (2006), Documentation RMA 2 – RMA2 - A Two Dimensional Finite Element Model for Flow in Estuaries and Streams, Resource Modelling Associates, Sydney Australia.

USGS (2008), Simulation of Flow, Sediment Transport, and Sediment Mobility of the Lower Coeur d'Alene River, Idaho. Tech. Rep. 2008-5093.

Appendix 3. Hydrodynamic modelling report: Mentabie Reach, Daly River

Hydrodynamic modelling conducted by Water Research Laboratory, University of NSW.



1st October 2020

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UNSW
SYDNEY
Water Research Laboratory
School of Civil and Environmental Engineering

COMMERCIAL IN CONFIDENCE

Assoc Prof Alison King
Research Institute for the Environment and Livelihoods
Charles Darwin University
Darwin NT 0909

By Email: Alison.King@cdu.edu.au
CC: Julia.Schult@nt.gov.au

Dear Associate Professor King,

Daly River – Mentabie Reach Hydrodynamic Modelling

1. Introduction

The Research Institute for the Environment and Livelihoods together with the Department of Environment and Natural Resources (DENR) commissioned the Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney to undertake hydrodynamic modelling on the Mentabie Reach of the Daly River, Northern Territory. The location of the study site (Figure 1) is approximately 200km south of Darwin and 90km west of Katherine. The model extent (Figure 2) is approximately 16km long with a fall of approximately 5m. The flow profile is best described as a series of riffles and pools.

WRL completed unverified hydrodynamic modelling of ten (10) steady state flow scenarios to predict water surface elevation, depth, velocity, bed shear and the Froude number throughout the model domain.

All results have been provided as GIS raster files. This letter report summarises the methods, scenarios and assumptions.

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Figure 1: Location

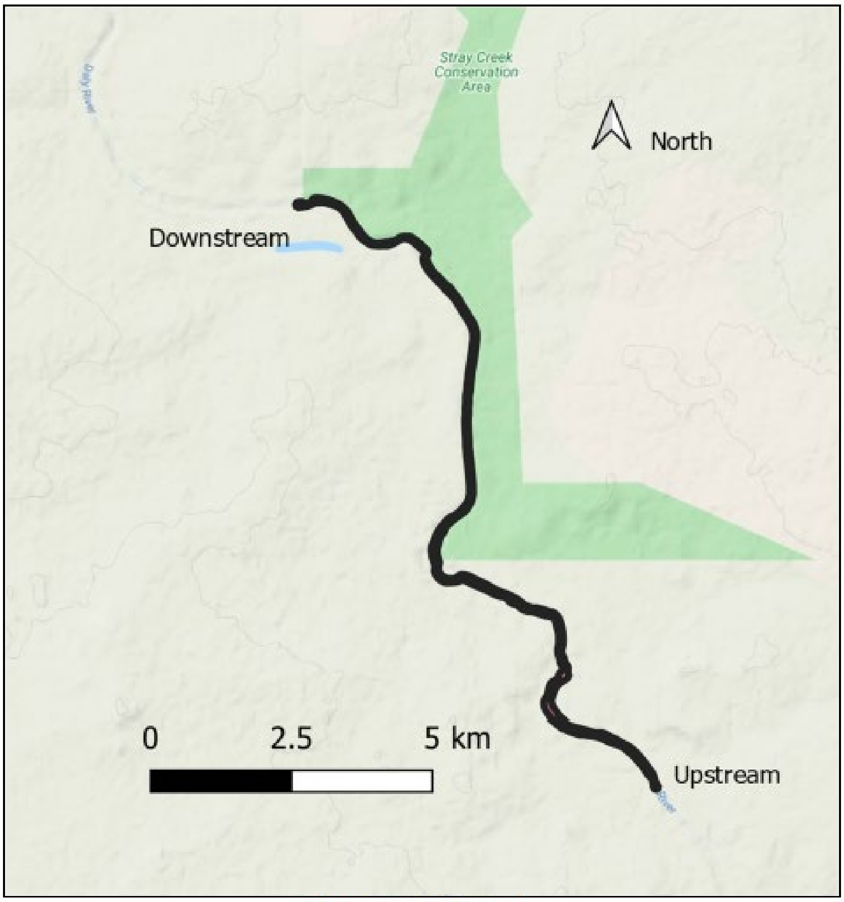

Figure 2: Mentabie Reach

2. Numerical Model

Hydrodynamic modelling was completed using the RMA-2 finite element model (King, 2006). RMA-2 is a depth averaged hydrodynamic model, which computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in two-dimensional flow fields using a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows.

RMA-2 is suitable for simulation of flow in vertically well-mixed water bodies where two dimensional flow regimes exist. The RMA-2 model has been used in Australia and internationally for over 30 years, including to calculate water levels and flow distributions in several floodplain environments in the Northern Territory including the Lower Mary River, Arafura Swamp, Alligator River and the Daly River estuary.

In this instance, RMA-2 was used to model a series of ten (10) steady state flow conditions (i.e. a constant inflow applied at the upstream model boundary).

3. Bathymetry and Topography

Survey data of the Mentabie Reach was provided to WRL by DENR. The dataset comprised of a combination of hydrographic survey points and topographic elevations (LIDAR) with an irregular distribution. An example of the spatial distribution of the survey points is shown in Figure 3.

Before this data could be applied to the numerical model, a 5m x 5m Digital Elevation Model (DEM) was developed. The irregular distribution of survey points were not suited to a regular nearest neighbor weighting interpolation scheme. The DEM was generated using the "Spline" interpolation tool in ARC-GIS which is best for generating gently varying surfaces such as elevation, water table heights, or pollution concentrations (ESRI, 2020).

It should be noted the resulting DEM is limited by the spatial distribution of the survey dataset used to generate the DEM. While there was high density of sampling points along the transects taken, interpolation was required for the areas between transects. As such, there remains some uncertainty relating to surface water flow pathways in localised, shallow areas.

Higher DEM resolutions were trialed, however no additional bathymetric features were captured by these higher resolutions.

This DEM of the bathymetry was supplied to DENR along with the model results.

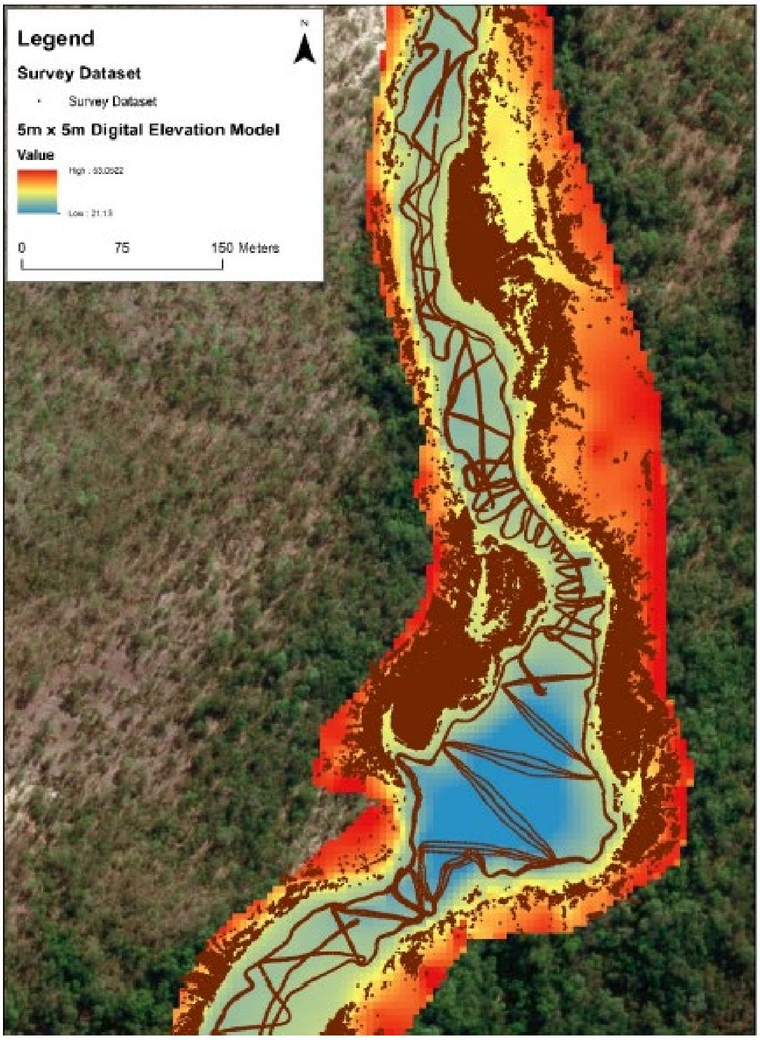

Figure 3: Example of Survey Data

4. Finite Element Mesh

A finite element mesh was generated comprising trapezoidal elements with a resolution of less than five metres laterally across the river and twenty meters longitudinally along the river. This mesh resolution was able to capture both the deeper, slow moving pools and the faster flowing, riffle structures.

Each element consists of four corner nodes and four mid-side nodes. The velocity, water surface elevation and depth are computed at every node in the model. There were a total of 5,192 elements and 16,293 nodes. An example of a section of the finite element mesh is shown in Figure 4.

Figure 4: Example of the RMA2 finite element mesh

The mesh was only generated in areas where survey data was available. Some areas, such as the sand-flat in Figure 4, have flow in larger flood events but remain dry for the relatively low flows being considered in this study. As such, this mesh is appropriate for low flow conditions, but not suitable for predicting larger flood events.

5. Bed Friction

The model scenarios predicted velocities and water depths throughout the model domain. The bed friction was prescribed as a Manning's "n" of 0.030, which was based on a mid-range value for natural slow moving channels with deeper sections. Since the range of flows being considered were all in-bank, there was no need to assign a higher friction value for vegetated areas.

The total energy loss (or drop in the water surface) is related to both the friction factor and velocity of the water. The majority of the river reach is slow moving pools and as such, the energy loss was small and reasonably insensitive to the bed friction parameter. Fast and shallow flows occur near riffles, however, these behave as control structures in the hydrodynamic model. This is often referred to as rapidly varying flow (rather than gradually varied flow) and in this instance the friction parameter is less important in determining localised head-loss.

No flow or water depth data was available to calibrate the bed friction parameter used in this model. However, as discussed above, for the low flow conditions simulated in this study, the results are expected to have limited sensitivity to bed friction.

6. Computational method for dry areas of the model

Two options exist for the modelling of dry areas. "Wetting and drying" removes elements from the model if they are dry or below depth threshold. "Marshing" leaves all elements active in the model but requires a small flow to exist below the prescribed bathymetry (essentially in a narrow "slot" through the element). "Marshing" was used for these simulations to maintain computational stability. The amount of flow through the "slots" in dry elements was minimised by using the narrowest, shallowest slot possible, whilst maintaining a stable model simulation. The amount of flow was also minimised in the slots by increasing the slot friction by a factor of 50. It was calculated that less than 5% of all flow down the channel was conveyed in these marsh slots.

7. Scenarios

The ten steady state scenarios as simulated are listed in Table 1. Note that Scenario 10 with the greatest flow is equivalent to the 90th percentile of annual minimum flow (1960-2019). As such, all scenarios are relatively dry conditions.

The groundwater inflow was assumed to be uniformly distributed over the entire model domain.

Table 1 - Scenarios

Scenario	Inflow at top of reach (m^3/s)	Groundwater inflow (m^3/s)	Outflow at the bottom reach (m^3/s)
1	1.0	9.8	10.8
2	2.0	9.8	11.8
3	3.0	9.8	12.8
4	4.0	3.2	7.2
5	4.0	9.8	13.8
6	5.0	9.8	14.8
7	6.0	3.2	9.2
8	6.1	9.8	15.9
9	8.1	9.8	17.9
10	10.2	9.8	20.0

No data was available for specifying the tailwater level in the model. The tailwater is commonly influenced by backwatering of a downstream pool. Without any field measurements or downstream bathymetry, the tailwater was set to a constant level of RL33.2 m equivalent to 1.5 m deep at the deepest point of the cross-section. The effect of the constant tailwater can be seen in Figure 5. Results in the last 900m of the model should be used with caution and the last 400m should not be used.

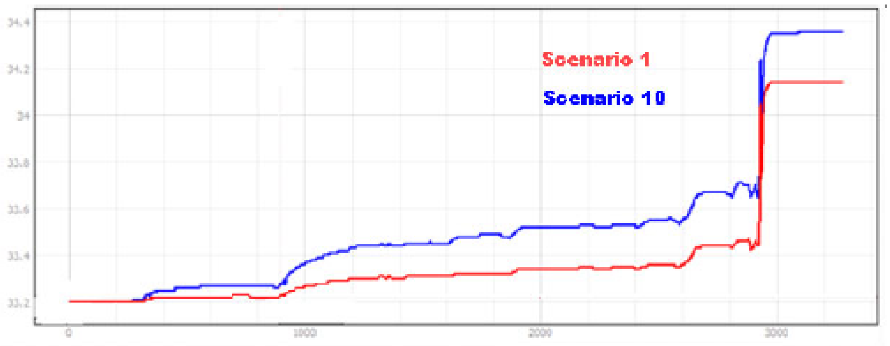

Figure 5: Influence of tailwater on water surface elevation.

8. Post processing

All model results were provided as electronic GIS layers of: water depth, water surface elevation, velocity, Froude number and bed shear. RMA-2 predicts the surface elevation, water depth and velocity directly. Bed shear and Froude number were calculated by post-processing results at every node using the methods detailed in Section 0 and Section 0 respectively.

The predictions at the nodes of the finite element mesh were interpolated onto 1m by 1m GIS layers. In total fifty (50) GIS layers were supplied.

Analysis of the GIS layers were also undertaken to calculate the total areas (m^2) within various ranges of depth, velocity, bed shear and Froude number for the model domain. These results were provided as spreadsheets.

8.1 *Bed Shear*

In open channel flow, shear stress (τ_b in N/m^2) is the force of moving water against the bed of a channel. Bed shear, as a function of Manning's 'n', water depth and velocity can be described by (Chow, 1959):

$$\tau_b = \frac{g n^2 \rho u^2}{R_h^{\frac{1}{3}}}$$

Where:

g = acceleration due to gravity (9.81 m/s^2)
n = Manning's 'n' friction
ρ = density of fluid (water = 1000 kg/m^3)
u = depth averaged velocity (m/s)
R_h = Hydraulic Radius (approximated as the depth (m))

Bed load movement and sediment transport is a function of shear stress. Some typical values of sediment mobility due to bed sheer stress are presented in Table 2 (USGS, 2008).

Table 2: Critical shear stress by particle-size classification for determining approximate condition for sediment mobility (after Table 7 USGS 2008)

Particle Classification Name	Ranges of Particle Diameters (mm)	Critical Bed Shear Stress τ_b (N/m^2)
Coarse Cobble	128 - 256	112 - 223
Fine Cobble	64 – 128	53.8 - 112
Very Coarse Gravel	32 - 64	25.9 - 53.8
Coarse Gravel	16 - 32	12.2 - 25.9
Medium Gravel	8 – 16	5.7 – 12.2
Fine Gravel	4 – 8	2.7 – 5.7
Very Fine Gravel	2 - 4	1.3 – 2.7
Very Coarse Sand	1 - 2	0.47 – 1.3
Coarse Sand	0.5 – 1	.27 – 0.47
Medium Sand	0.25 – 0.5	0.194 – 0.27
Fine Sand	0.125 – 0.25	0.145 – 0194
Very Fine Sand	0.0625 – 0.125	0110- 0.145
Coarse Silt	0.0310 – 0.0625	0.0826 0.110
Medium Silt	0.0156 – 0.0310	0.0630 – 0.0826
Fine Silt	0.0078 – 0.0156	0.0378 - 0.0630

8.2 *Calculation of the Froude Number*

The Froude number is a dimensionless number comparing the inertial forces of the flow velocity to the gravitational forces. Sub critical flow is often characteristic of deep slow moving flow and super critical flow is characterised by shallower fast flows.

The Froude Number can be expressed as:

$$F_r = \frac{v}{\sqrt{gD}}$$

Where:

F_r = Froude number
v = velocity (m/s)
g = acceleration due to gravity (9.81 m/s^2)
D = hydraulic mean depth (m)

Flows can be categorised by the Froude number: subcritical (Fr < 1), critical (Fr = 1), or supercritical (Fr > 1). In supercritical flow (Fr > 1), waves cannot move upstream against the fluid flow (i.e. information carried by waves cannot propagate upstream of a disturbance).

9. Modelling Limitations

The RMA-2 two-dimensional model assumes that velocities are the same on the surface as the bed. Whilst this is not considered to be substantial for the low flow (shallow) scenarios being modelled, velocity distributions may vary with depth for higher flow regimes.

The RMA-2 hydrodynamic model does not directly solve supercritical flow, however, it does identify flow regimes approaching critical and above. Caution should be used when interpreting Froude numbers greater than 1.0 in these results.

The bathymetry in the model was generated using a spline interpolation of the transects and LIDAR data provided. While data along the transects was closely spaced (less than 1m) there were areas between transects where the interpolated bathymetry may differ from the actual bathymetry. This is most relevant within the riffle areas.

The bed friction was not calibrated in the model. While there is some uncertainty in the flow depths, the pool-riffle nature of this reach means that this uncertainty is reduced for the low flow ranges considered. Sensitivity testing was not undertaken.

Please feel free to contact me on (02) 8071 9840 if you would like to discuss the findings of this report in more detail.

Yours sincerely,

Brett Miller
Principal Engineer, CPEng

10. References

Chow V T (1959), Open-channel hydraulics. New York, McGraw-Hill, 680p.

ESRI. 2020. How Spline Works. [ONLINE] Available at: https://pro.arcgis.com/en/pro-app/tool-reference/3d-analyst/how-spline-works.htm. [Accessed 28 September 2020].

King I P (2006), Documentation RMA 2 – RMA2 - A Two Dimensional Finite Element Model for Flow in Estuaries and Streams, Resource Modelling Associates, Sydney Australia.

USGS (2008), Simulation of Flow, Sediment Transport, and Sediment Mobility of the Lower Coeur d'Alene River, Idaho. Tech. Rep. 2008-5093.