Northern Australia Environmental Resources Hub

National Environmental Science Programme

Environmental water needs of Western Australia's Fitzroy River

Final report

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Cover photographs

Front cover: Yeerra Pool in the Fitzroy River, Nyikina-Mangala Country (photo Michael Douglas).

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Acronyms and abbreviations

AIC .... Akaike information criterion

DBH............... Diameter at breast height

DWER .... Western Australian Department of Water and Environmental Regulation

NAWRA......... Northern Australia Water Resource Assessment

NESP............. National Environmental Science Program

UWA.............. The University of Western Australia

Acknowledgements

We gratefully acknowledge the Traditional Owners of the Country on which this work was undertaken – the Nyikina-Mangala people of the Walalakoo region, the Yanunijarra and Gooniyandi people – and recognise their continuing connection to land, water and culture. We pay our respects to their Elders, past, present and emerging. We thank the Prescribed Bodies Corporate for the different native title groups, and representatives from Yungngora Community, for providing us with permission to undertake research on Country. We thank the Indigenous rangers and ranger coordinators who assisted us with fieldwork and acknowledge the assistance of the Kimberley Land Council in project facilitation, particularly Karen Dayman. We thank the pastoral managers of Jubilee Downs, Myroodah, Mount Anderson, Millijidee, Noonkanbah and Gogo stations for their cooperation. We thank the Western Australia Department of Biodiversity, Conservation and Attractions and the Department of Primary Industries and Regional Development for equipment storage. This project was supported through funding from the Australian Government's National Environmental Science Program through the Northern Australia Environmental Resources Hub. Fish research was carried out under Fisheries exemptions #191-2009-27 and 2974, DBCA permit FO25000288, and The University of Western Australia's Animal Ethics permits RA/3/100/884 and RA/3/100/1536 (Animal Ethics Committee, The University of Western Australia). Plant material was collected under Department of Biodiversity of Conservation and Attractions licence to take flora for scientific or prescribed other purposes #SW19087. All researchers conducting field work had a valid Permission to Use Animals (PUA) licence to use animals for scientific purposes as per the *Animal Welfare Act 2002* (Western Australia). All field procedures were performed in accordance with relevant guidelines and regulations.

Executive summary

This project was funded through the National Environmental Science Program's Northern Australia Environmental Resources Hub with the aim of determining environmental water requirements for the Fitzroy River in the Kimberley region of Western Australia. The project was part of a larger program which used a transdisciplinary research approach that included researchers from a range of disciplines, decision-makers from government agencies, Traditional Owners and Indigenous rangers.

The project was designed in three phases. The first phase used desktop knowledge to describe hydro-socio-ecological relationships to encourage more integrated and inclusive water allocation planning. The results from this first phase, namely key considerations for water planning, fed into the development of initial water-planning documents by the Western Australian Government. The first phase also sought to identify key ecological knowledge gaps, revealing there was very little ecological data on the relationships between flow and biota or habitats for the Fitzroy River. The knowledge gaps identified by the conceptual model were used to guide data collection in the second phase of the project.

The second phase involved the implementation of targeted on-ground ecological studies, with Traditional Owners and Indigenous rangers. On-ground ecological research was conducted over three and a half years (mid-2017 to late 2020), with a focus on aquatic biota and riparian vegetation. The research outputs included data supporting five flow-biota relationships and 14 habitat-biota relationships. Flow-biota relationships are particularly useful for environmental water planning because they provide a direct link between river flow and an ecological outcome – indicating the potential implications of water extraction. Outputs from this research included new evidence relating to the following.

- Links were identified between flow velocity and algal biomass, which is important for riverine productivity.
- Local food sources support fish in the main channel at the end of the dry season, as demonstrated in a food web study.
- The body condition and intramuscular fat of fork-tailed catfish were greater in years following moderate to high wet-season flow, and these reserves decreased as the dry season progressed.
- Larger wet-season flows increase the cherabin population.
- The duration of inundation from flood flows was a strong predictor of the occurrence of woody riparian plant species, which may be used to predict species response to water-take scenarios.
- There is a zonation in the composition and structure of riparian tree species from the edge of the river and across the floodplain.
- The water sources used by riparian trees reflect the local hydrology, with trees using regional groundwater sources where it is available.
- There is a relationship between some physiological traits of riparian trees and their distribution along a hydrological gradient.

The third phase of the project reviewed new evidence that had emerged since the start of the research program, either from this project or other published sources. New scientific evidence gathered during the course of this project was in broad alignment with our general theoretical understanding of how the river would function. This meant that the general structure of the conceptual model, which detailed relationships between key flow components and the habitats and biota they support, changed little between Phase 1 and Phase 3. The main change was that the model transitioned from being largely reliant on knowledge transferred from elsewhere in northern Australia and further afield to one that was populated largely by knowledge generated from the study system. This model is more defendable and creates greater certainty for management. The trade-off is that it now does not span the same ecological breadth as the original version. Therefore, some important relationships between flow and biota or flow and ecological processes such as dispersal are now no longer captured in the model. Those using the model need to be aware of this limitation. We recommend that both models be used to guide management decision-making and policy development for the river. We conclude with identified knowledge gaps that could direct future research, as well as provide considerations for the development of an effective monitoring program.

1. Management problem and context

Freshwater habitats, including rivers and their associated riparian zones, have high ecological and cultural values, however they are also some of the most threatened ecosystems on earth (Flitcroft et al. 2019; Hubble et al. 2010; Naiman et al. 1993; Vörösmarty et al. 2010). Development that alters the flow of surface and groundwater has the potential to impact the biodiversity and function of freshwater systems (Hubble et al. 2010; Naiman et al. 1993). Developing the water resources of northern Australia is a policy objective of both federal and state governments (DIIS, 2015). The Fitzroy River, in the Kimberley region of Western Australia, is one northern river identified as potentially able to support an expansion of irrigated agriculture (Petheram et al. 2018a). The Fitzroy River is the largest river in the Kimberley and possesses significant biological, conservation, geoheritage and sociocultural values, and a large section of the river is on the National Heritage list (Pusey and Arthington, 2003). Water-resource development that changes the depth to groundwater and the flow regime of the river has the potential to impact the environmental and cultural values of the river. To mitigate this risk, and ensure sustainable development, it is critical that the water requirements of important environmental assets are understood and protected by water policy. However, there is a paucity of data available to inform water management decisions for the Fitzroy River, which has prompted an increase in research effort in the catchment.

In 2018, the CSIRO published a series of studies on the Fitzroy River and other rivers in northern Australia as part of a broad water-resource assessment (Petheram et al. 2018a). To assess potential impacts on key environmental assets, a desktop study used available data and mathematical modelling to predict changes to assets under reduced flow scenarios, finding that ‘the greatest flow changes are at the end-of-system’ and that ‘changes occurred across assets’ (Pollino et al. 2018). It also noted that ‘dry seasons have the potential to be extended causing a loss of connectivity to wetlands’ and that ‘flow changes are likely to have an impact on nursery habitats’ (Pollino et al. 2018). However, the limitations of a desktop approach in a data-poor system were recognised, as was the risk of developing a suitable water plan in the absence of hydro-ecological data (Petheram et al. 2018a).

Commencing in mid-2017, this project was funded through the National Environmental Science Program’s Northern Australia Environmental Resources Hub to address key knowledge gaps and increase knowledge about the environmental water requirements of the Fitzroy River. The project was part of a larger program which used a transdisciplinary research approach that included researchers from a range of disciplines, decision-makers from government agencies, Traditional Owners and Indigenous rangers. A transdisciplinary approach is increasingly considered best practice for addressing complex ‘wicked’ problems, as there is mounting evidence that the inclusion of a diverse group of stakeholders increases the usefulness, adoption and legitimacy of scientific research (Lang et al. 2012). Several external groups were involved in the creation of the Fitzroy River environmental water needs project, including policy staff from the federal Department of Agriculture, Water and the Environment (which funded the research program) and water planning staff from Western Australia’s Department of Water and Environmental Regulation (DWER).

The project was designed in three phases (Figure 1.1). The first phase was conceptual and used desktop knowledge to describe hydro-socio-ecological relationships to enable more integrated and inclusive water allocation planning. The first phase also sought to identify key ecological knowledge gaps. The results from this first phase, namely key considerations for water planning, fed into the development of initial water planning documents by the Western Australia government. The second phase involved the implementation of targeted on-ground ecological studies, with the assistance of Traditional Owners and Indigenous rangers, to fill knowledge gaps identified in the first phase. The third phase was to review new evidence that has emerged since the start of the research program, either from this project or other published sources, and use this knowledge to revise our conceptual understanding of the system and to incorporate the associated principles and considerations. This report summarises these three phases and finishes by presenting advice about future environmental flow monitoring and management in the Fitzroy River.

	Phase 1 *(1-2 years)*	Phase 2 *(3-5 years)*	Phase 3 *(5-10 years)*	Monitoring *(on-going)*
Ecological research	Literature review, conceptual models	Data gathering and analysis	Synthesis of outputs, revise model	Literature review, conceptual models
Outputs	*NESP conceptual model, NAWRA ecology reports*	*Scientific papers and technical reports*	*Final report and communication workshops and products; targeted baseline data collection*	*Monitoring by proponents at local scales; Monitoring by Government at catchment scale to detect impacts*
Water allocation planning	Water allocation statement	Water allocation discussion paper	Water allocation plan	Water plan, license conditions, monitoring of catchment

Figure 1.1. Outline of the research program for the environmental water needs of the Fitzroy River. The project did not investigate monitoring but research outputs highlighted the need for an effective monitoring program to support water allocation decisions.

2. The study system

The Fitzroy River is situated within the wet–dry tropics of the Kimberley region of Western Australia (see Figure 2.1), with a catchment that spans ~ 94,000 km^2. The river's flow regime is strongly seasonal with pronounced 'wet' and 'dry' seasons and has a mean annual discharge of 6,600 GL (Petheram et al. 2018b). The timing of the wet season (November to April) is predictable but varies markedly in magnitude from year to year (Kennard et al. 2010). During the dry season (May to October), high temperatures create an annual evaporative demand that exceeds 1.9 metres and in the late dry season, the river ceases to flow in some years (Kennard et al. 2010; Petheram et al. 2018b).

The current project focused on the lowland area of the Fitzroy River, downstream of Fitzroy Crossing (Figure 2.1). This area is the region likely to be targeted for water extraction, and modelling by the Northern Australia Water Resource Assessment (NAWRA) indicates that changes to river flow will be most marked at the end-of-system (Pollino et al. 2018). In this region the river displays a sinuous planform and contains alternating deep and shallow reaches (Taylor, 1998). The floodplain is dominated by cracking clays and dissected by distributary creeks that distribute water from the main channel during elevated within-bank flows (Taylor, 1998). Larger overbank flood flows inundate the floodplain proper and its wetlands. During dry periods, the main channel contracts to an alternating string of pools and sandbar habitats. Pool persistence is linked to channel shape and the influx of alluvial or deep groundwater (Harrington et al. 2014; Taylor, 1998). The influx of deep groundwater is greatest in the middle reaches of the study region, between Noonkanbah and Fitzroy Crossing. Pools sustained by deep groundwater change little in depth through time, whereas those that receive little groundwater or receive alluvial groundwater undergo marked shrinkage (Harrington et al. 2014; Karim et al. 2018). Water extraction from the river is likely to involve flow diversion during the wet season but may also involve groundwater pumping (DWER, 2020; Petheram et al. 2018b).

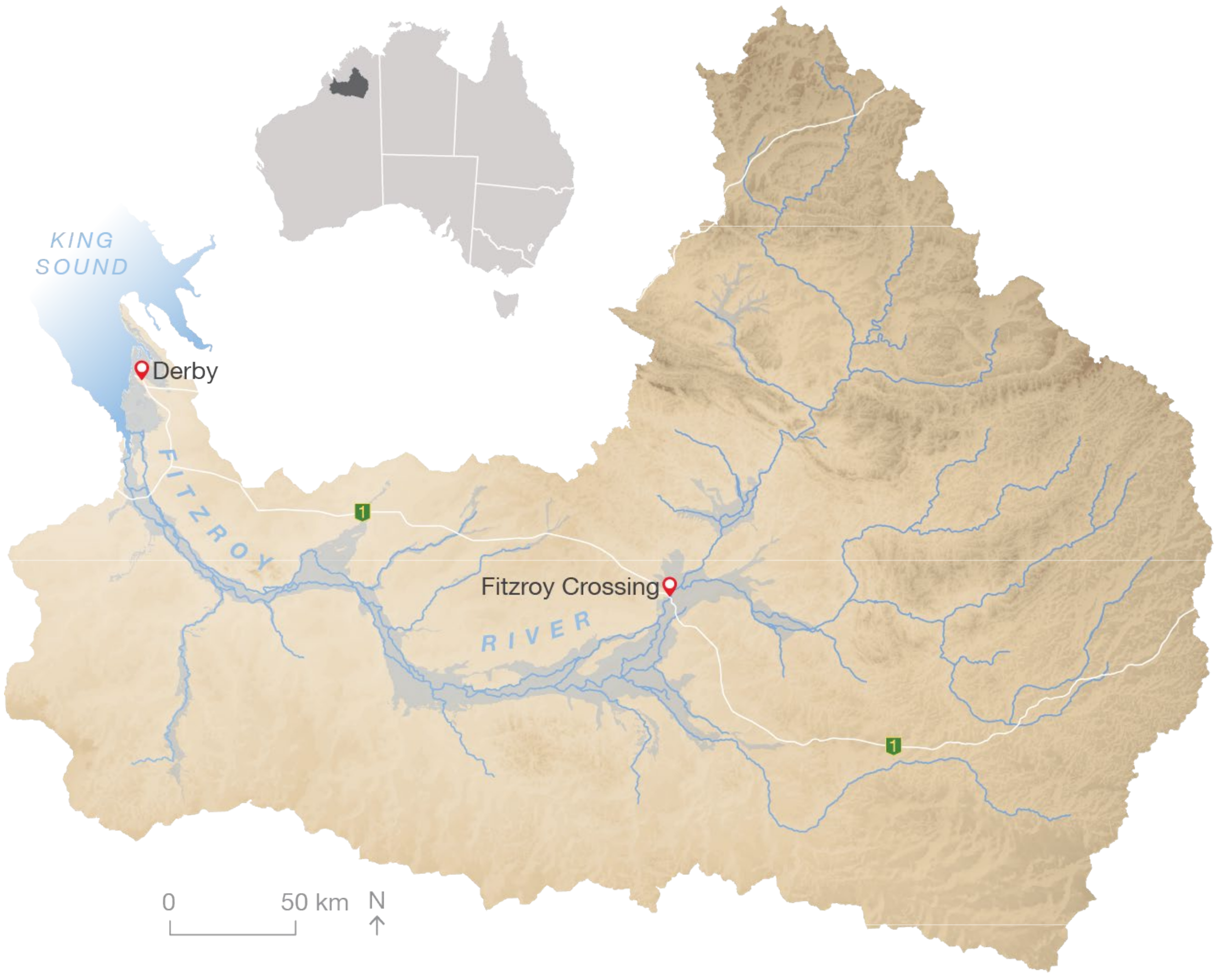

Figure 2.1. The Fitzroy River in the Kimberley region of Western Australia. The major towns of Fitzroy Crossing and Derby are shown, as is the Great Northern Highway.

3. Phase 1: Conceptualising hydro-socio-ecological relationships in the Fitzroy River to enable more integrated and inclusive water allocation planning

The first phase was collaboratively undertaken by this project and another Hub project titled ‘Indigenous water needs for the Fitzroy River’. A desktop review of the literature was used to conceptualise hydro-socio-ecological relationships in the lower Fitzroy River and identify the risks posed by water extraction. The inclusion of Indigenous values in this appraisal was considered critical in a system where there is a history of power imbalance and distrust of government exists (Douglas et al. 2019). The broad aims were to:

- identify the major flow components of the river that underpinned ecological functioning
- describe the ecological roles or functions delivered by the different flow components in different habitats and the Indigenous values fulfilled
- identify key ecological knowledge gaps
- create considerations for water planning.

The approach, outlined below, is presented in detail in the publication: Douglas MM, Jackson S, Canham C, Laborde S, Beesley L, Kennard MJ, Pusey BJ and Setterfield SA (2019) ‘Conceptualising hydro-socio-ecological relationships to enable more integrated and inclusive water allocation planning’. *One Earth,* 22:361–373.

This phase began identifying the major flow components of the river and the habitats that these flow components sustain. This process is commonly used by ecologists in the creation of environmental-flow recommendations (see Richter et al. 2006). Five key flow components and their key ecological roles were identified: (1) within-bank flows, (2) overbank flood flows, (3) recessional flows, (4) groundwater or low flows, and (5) antecedent flows. These five flow types are shown schematically in Figure 3.1.

Once flow components were identified, we then reviewed the published literature to identify the ecological roles or functions delivered by the different flow components in different riverine habitats and the associated Indigenous values. Our conceptual model is shown in Figure 3.2 and is supported by evidence in Douglas et al. (2019) Supplementary Table S1. Supporting literature was classified as either local (i.e. pertaining to the Fitzroy catchment), regional (i.e. from tropical northern Australia) or as remote (i.e. from elsewhere in Australia or the world). Our desktop review revealed that while considerable local knowledge existed about the importance of flows and habitats for Indigenous values in the Fitzroy River, there was very little ecological knowledge. The main exceptions being a study on habitat use by sawfish (Whitty et al. 2017) and studies on fish diet and the aquatic food web (Fellman et al. 2013; Jardine et al. 2012; Thorburn et al. 2014), and a study on nutrient bioavailability (Fellman et al. 2014). Thus, knowledge gaps existed for most flow components and most habitats, with a particular lack of knowledge for riparian vegetation.

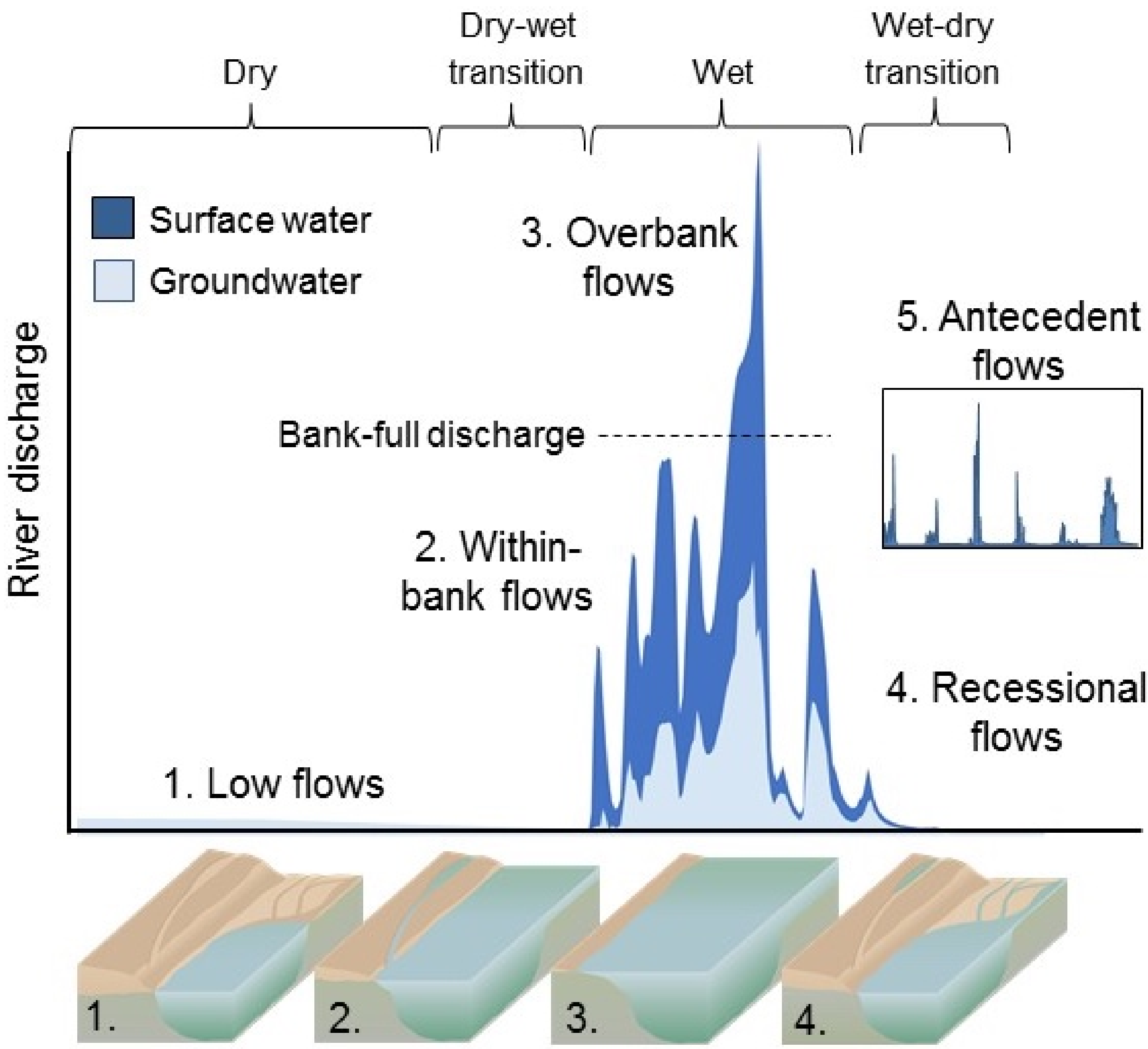

Figure 3.1. A stylised depiction of an annual hydrograph of the Fitzroy River, showing the four seasonal flow components and associated aquatic habitats present in the river's lower reaches. A fifth flow component describing inter-annual variation in flow (i.e. antecedent flows) is shown in the inset. The general contribution of surface and groundwater to river flow is illustrative only. Taken from Douglas et al. (2019).

The socio-ecological impact of water extraction in the Fitzroy River was distilled into 10 key principles and associated considerations for water planning, which are presented in Douglas et al. (2019). The first five principles pertained to Indigenous peoples and include the rights of Indigenous peoples to water governance. The latter five principles identified key flow components and the habitats they support, with management considerations to protect ecological assets and processes. The rapid delivery of this initial phase was important to government water planners, who were developing draft flow rules for water allocation with very little supporting knowledge on the flow-ecology relationships of the Fitzroy River. This conceptual model informed a discussion paper produced by state government water planners (see DWER, 2020), which was a prerequisite step to the construction of a water allocation plan. Our desktop study also identified key knowledge gaps, which guided the data collection in the second phase of the research project.

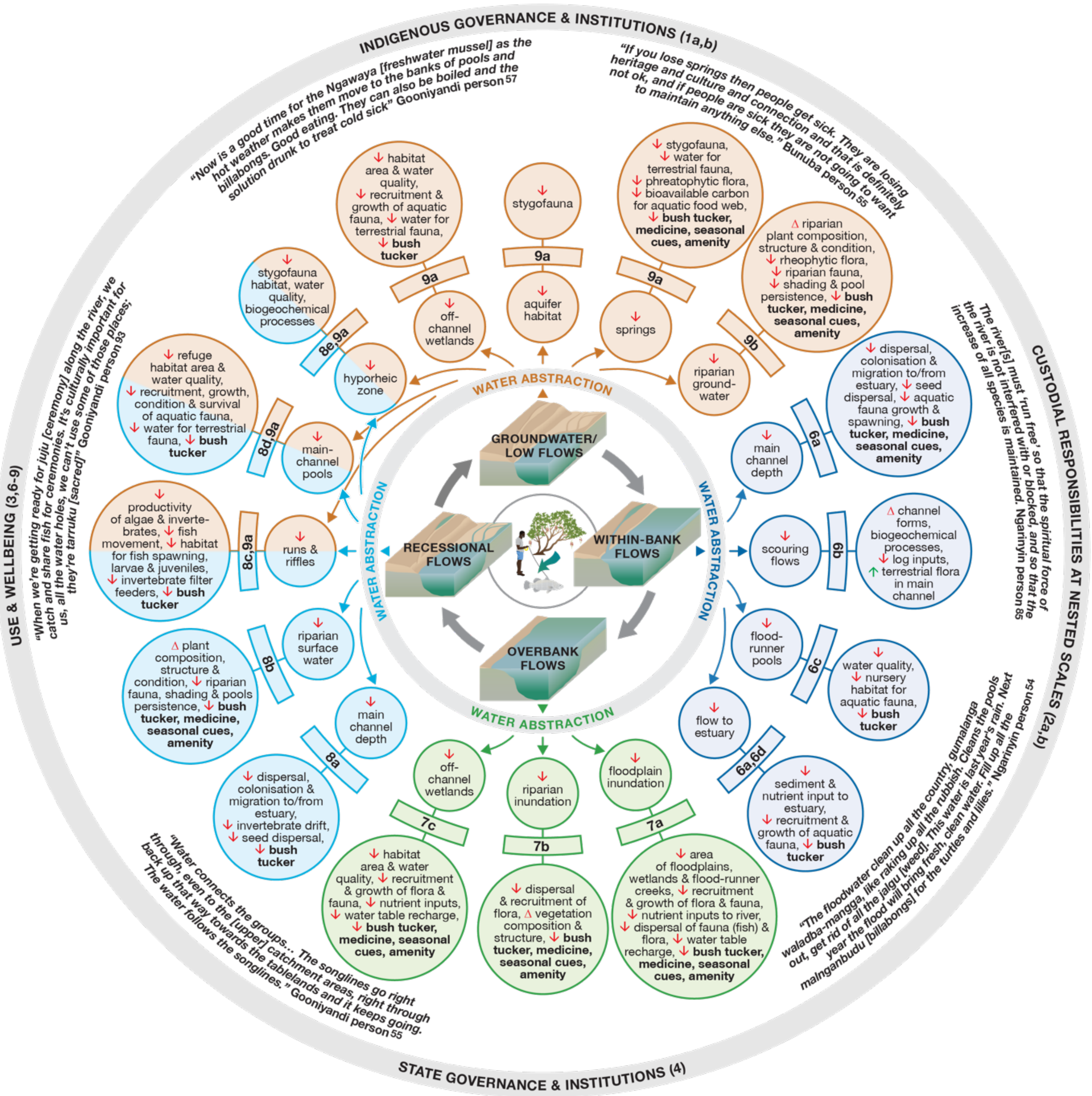

Figure 3.2. Hydro-socio-ecological conceptual model of the impacts of water abstraction in the Fitzroy River, northern Australia. The model is centred on four flow phases (depicted with three-dimensional river cross-sections) and potential impacts of abstraction during each flow phase are colour coded: low flows (orange), within-bank flows (dark blue), overbank flows (green) and recessional flows (light blue). Small inner circles describe impacts on hydrology and physical habitats, large outer circles describe impacts on habitat availability and quality, and water-dependent biota and ecological processes. Impacts of particular interest to Indigenous people are in bold type. Dual coloration indicates that a habitat may be affected by changes during two flow phases. Predicted hydro-socio-ecological responses to water abstraction are depicted with red downward arrow or delta symbol (indicating a decrease or change, respectively). The quotes illustrate Indigenous perspectives on hydro-socio-ecological relationships. The outer circle encompasses the key social factors and conditions that affect water allocation planning. Taken from Douglas et al. (2019).

4. Phase 2: Targeted on-ground ecological research

Prior to the start of this project, no flow-biota relationships had been published for the Fitzroy River, and very few studies had examined habitat-biota relationships, but see Whitty et al. (2017) for an exception. The aquatic food web was the area best studied, with three published papers available (Fellman et al. 2013; Jardine et al. 2012; Thorburn et al. 2014); however, much of the data were collected in upland sites and its representativeness to the Fitzroy valley required testing. We set about describing the aquatic food web in the lower river and gathering information on flow-biota or habitat-biota relationships from across the Fitzroy valley. As the NAWRA report highlighted that water extraction posed a threat to dry-season habitats we focussed our research effort on increasing our understanding of water availability during this time.

On-ground ecological research was conducted over three and a half years (mid-2017 to late 2020) to address the key knowledge gaps identified in Phase 1. Research focussed on aquatic biota and riparian vegetation. To learn about the importance of water availability for plants and animals in the Fitzroy River, it was necessary to survey when and where water was both plentiful and scarce. Sampling repeatedly across years with contrasting wet-season flow is an ideal way to achieve this but is not well suited to relatively short-term research projects such as ours. Thus, we chose to learn by using 'space for time' substitution, which entails sampling sites that span a gradient of water availability and letting spatial differences act as a proxy for temporal patterns. The aquatic team did this by sampling shallow and deep pools in main-channel and floodplain habitats (Figure 4.1). The riparian vegetation team did this by sampling sites close to water (riverbank, adjacent to a wetland) and sites further from water (top of bank, floodplain). Our survey years also included years with moderate and very low wet-season flow, which assisted our learning about the impact of low water availability on biota.

Figure 4.1. An example of a deep and shallow pool in main-channel habitats in the Fitzroy River.

Engaging with Indigenous rangers and Traditional Owners

Research was conducted on four native title areas: Nyikina-Mangala; Noonkanbah; Yi-martuwarra, and Gooniyandi (Figure 4.2). Prior to research activity, research agreements were negotiated and agreed upon with each relevant Prescribed Body Corporate. Researchers met with Traditional Owners and Indigenous rangers to discuss data collection; and study site locations were selected after discussion with the people who spoke for that part of the Country. Data collection was conducted with a total of 61 Aboriginal people who accompanied researchers on-Country, with many people assisting on multiple occasions.

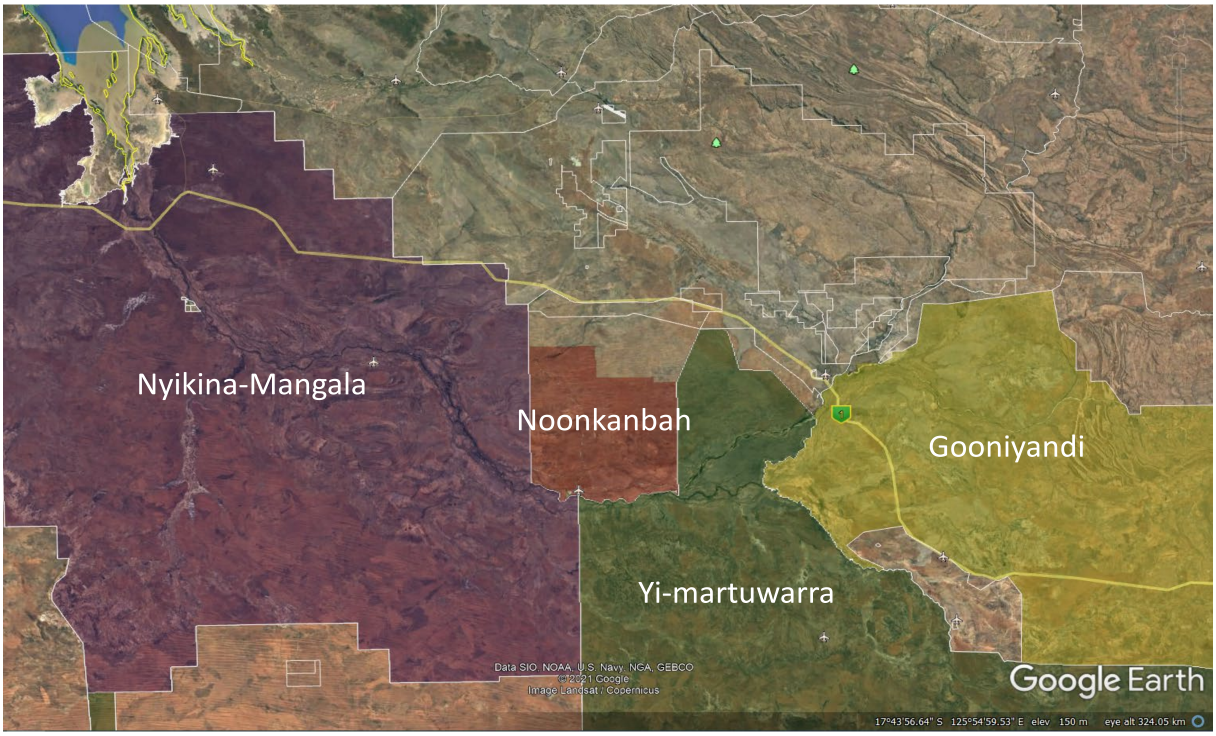

Figure 4.2. Map of native title areas and groups that the project worked with to collect data along the lower Fitzroy River.

4.1 Aquatic biota

4.1.1 Aims and approach

The desktop literature review in Phase 1 revealed that no flow-biota relationships had been documented for aquatic fauna in the Fitzroy River. There was also very little information on habitat-biota associations. Thus, our broad aim was to learn about flow-biota or flow-ecology relationships, or to learn about habitat-biota relationships where flow is an important factor shaping the habitat. Specifically, we sought to:

1. reveal the importance of flow velocity and other factors regulating the biomass of algal biofilm in shallow run habitats in the main channel
2. improve our knowledge of the food webs in floodplain and main-channel habitats and seek evidence that large-bodied fish were moving energy around the system either from the floodplain or from the estuary

3. investigate the importance of flow and habitat to the energy reserves of fork-tailed catfish
4. describe the size-related distribution of cherabin across two years to reveal habitat associations, the influence of wet-season flow, and highlight distributional patterns suggestive of an amphidromous life history
5. describe how reduced depth of main-channel and floodplain pools affect the ecological functions and cultural values delivered by the fish assemblage.

To investigate the first aim, we measured the density of algal biofilms and associated environmental factors during the late dry season (August 2017). To investigate the second aim, we used stable isotopes to describe the food web late in the dry season (October 2017) and during the wet season (March 2018). To investigate aims 2–4, we undertook system-wide surveys of fish and cherabin in main-channel and floodplain pools using a range of gear types (boat electrofishing, trapping, seine netting) during 2018 and 2019 (see Figure 4.3, Figure 4.4, Figure 4.5).

The next section provides a brief summary of each research sub-project, including its key findings and their ecological implications in relation to changes in water availability. A detailed description of the methodology and results for aims 1–4 can be found in the accompanying published journal articles. A description for aim 5 is not available as the research is not yet published.

Aim 1

Burrows RM, Beesley L, Douglas MM, Pusey BJ and Kennard MJ (2020) 'Water velocity and groundwater upwelling control benthic algal biomass in a sandy tropical river during base flow: implications for water resource development'. *Hydrobiologia,* 847:1207–1219.

Aim 2

Beesley LS, Pusey BJ, Douglas MM, Canham CA, Keogh CS, Pratt OP, Kennard MJ and Setterfield SA (2020) 'New insights into the food web of an Australian tropical river to inform water resources management'. *Scientific Reports,* 10*,* Article number 14294.

Aim 3

Beesley LS, Pusey BJ, Douglas MM, Keogh CS, Kennard MJ, Canham CA, Close PG, Dobbs RJ and Setterfield SA (2021) 'When and where are catfish fat fish? Hydro-ecological determinants of energy reserves in the fork-tailed catfish, *Neoarius graeffei,* in an intermittent tropical river'. *Freshwater Biology*. https://doi.org/10.1111/fwb.13711

Aim 4

Beesley LS, Killerby-Smith S, Gwinn DC, Pusey BJ, Douglas MM, Canham CA, Keogh CS, Pratt OP, Kennard MJ and Setterfield SA (in preparation) 'Describing the habitat use and distribution of the giant freshwater prawn (*Macrobrachium spinipes*) in an intermittent tropical river to guide water resource policy'. *Freshwater Biology*.

Figure 4.3. Some of the field methods employed during surveys of aquatic fauna. Panel (a) shows researchers working with Yimardoo-Warra Rangers Jeremiah Green and Shaquille Millindee (Nyikina-Mangala).

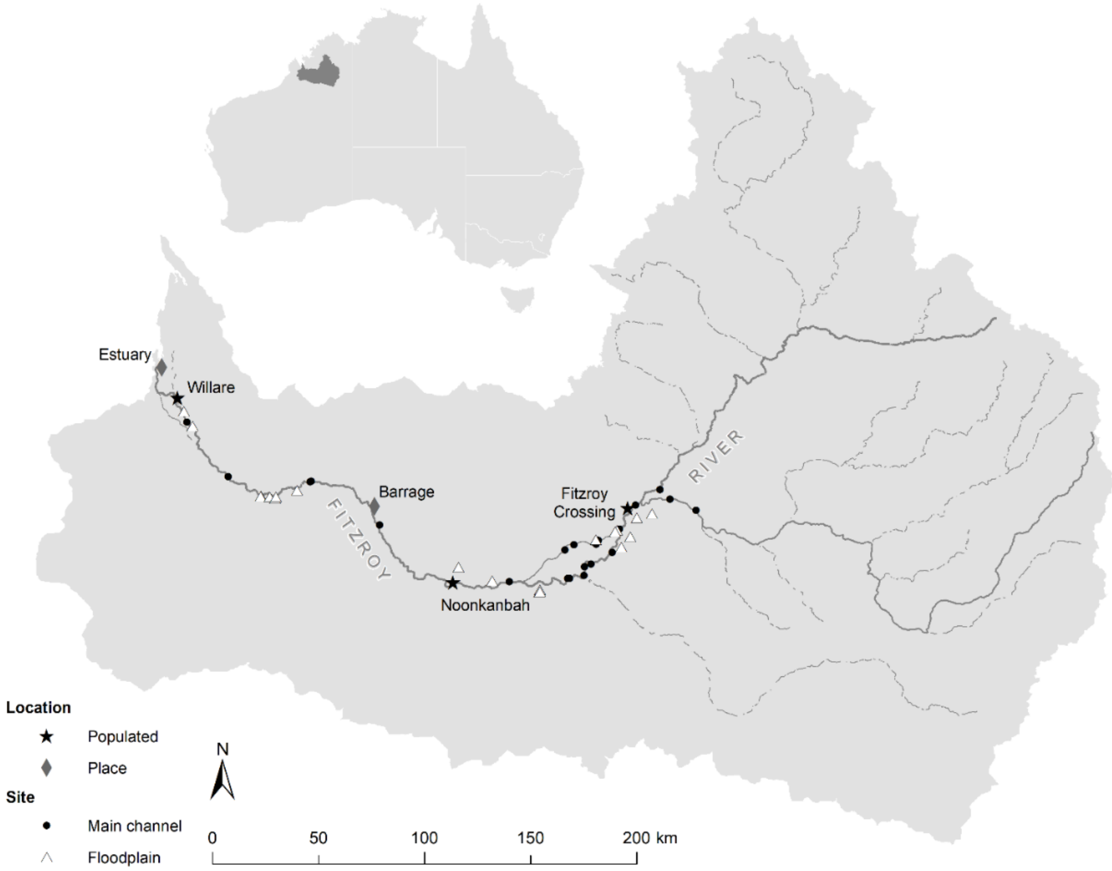

Figure 4.4. The location of main-channel and floodplain sites surveyed for fish and cherabin in the Fitzroy River, Kimberley, Western Australia. Fitzroy Crossing is located at 18.1937 °S and 125.5604 °E.

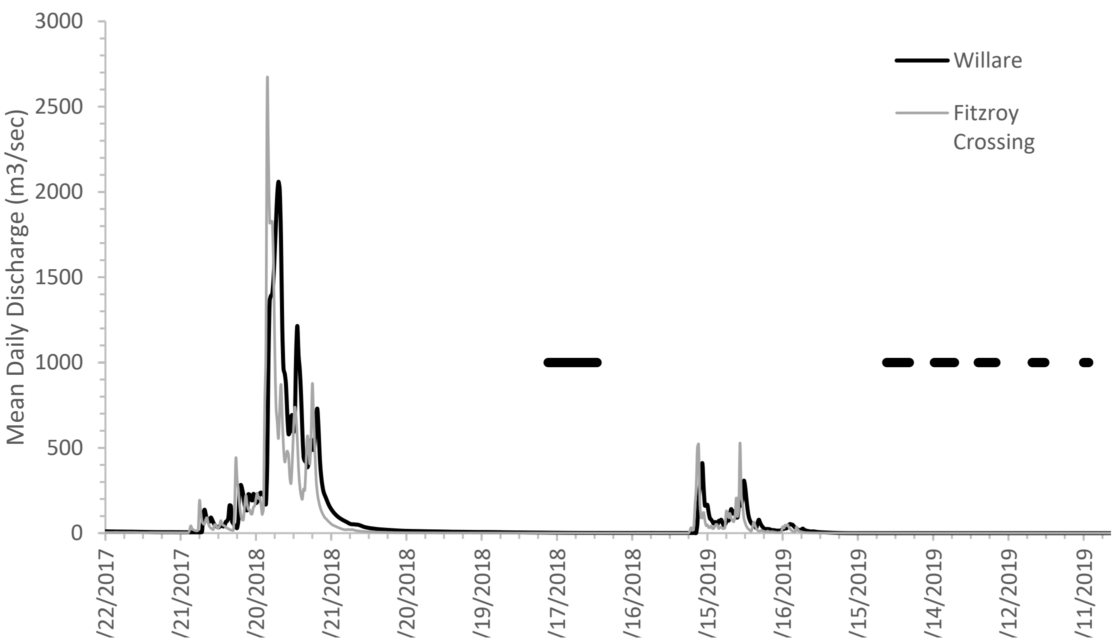

Figure 4.5 River discharge at two gauges (Willare and Fitzroy Crossing) in the lower Fitzroy River during sampling for fish and cherabin.

4.1.2 Algal biofilm biomass in main-channel sandy runs

Aim 1. To reveal the importance of flow velocity and other factors regulating the biomass of algal biofilm in main-channel shallow run habitats.

Methods. The study was conducted at two sandy run habitats in the main channel of the river during the late wet season of one year (August 2017). The run habitats were between 600 and 1,100 m in length. At each site, sampling occurred along longitudinal and lateral transects (see Figure 4.6). At each sampling point, algal biomass was measured using a benthotorch. Physico-chemical parameters including dissolved oxygen, temperature, conductivity, turbidity, nitrate, water depth, substrate size, canopy cover and active channel width were also measured. At a subset of points (n=15) in each study reach, samples were collected for nutrient analysis and to determine radon, a measure of groundwater–surface water interactivity. We investigated relationships between algal biomass and physico-chemical parameters using general linear mixed-effects models. Support for relationships was assessed using Akaike information criterion (AIC).

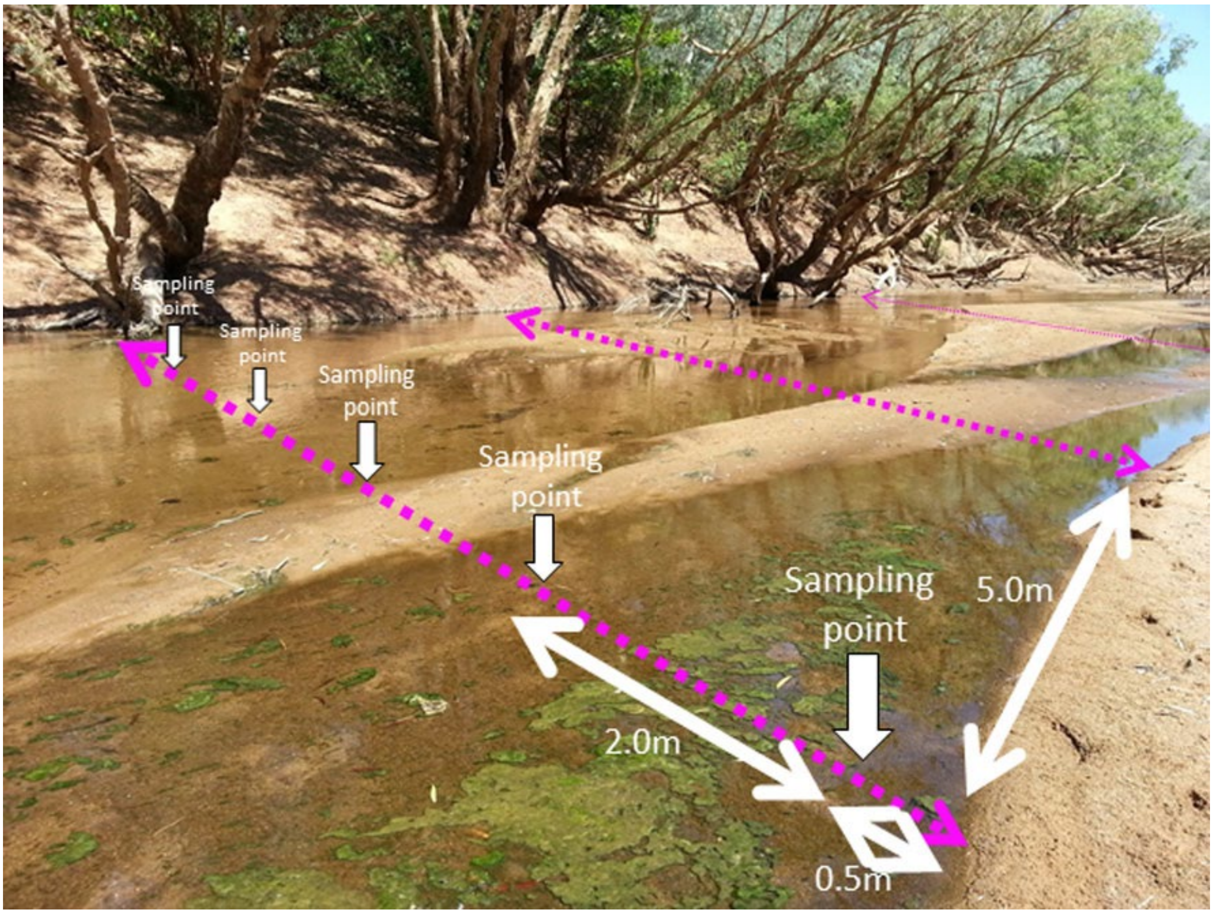

Figure 4.6. A visual representation of lateral sampling transects along a sandy run habitat.

We found:

- Water velocity was an important driver of algal biomass – algal biomass was lower at higher water velocities.
- Subsurface flow was influential – algal biomass increased in locations where groundwater upwelling occurred.

Ecological implications related to changes in water availability

- Modifications to longitudinal flow and water velocity are likely to influence the biomass of benthic algae and may have implications for the food web.
- Reductions in groundwater levels that diminish the strength of groundwater–surface water interactions will impact algal biofilm hotspots and may reduce riverine productivity.

4.1.3 Food webs in floodplain and main-channel habitats

Aim 2. To improve our knowledge of food webs in floodplain and main-channel habitats.

Methods. The study was conducted at three main-channel pools in the late dry season (October 2017) and at four floodplain sites during the wet season (March 2018). Samples were collected from all basal resources (terrestrial leaves, benthic algae, macrophytes, seston) and from consumers (macroinvertebrates including cherabin, fish). Samples were frozen in the field and processed in the laboratory where they were cleaned of contaminants, freeze-dried and analysed for stable isotopes of carbon and nitrogen. Isotope data were plotted and analysed using a mixing model (mixSIAR) which took into account trophic enrichment factors. The models estimated the relative contribution of algal biofilm to the diet of different fish species in the main-channel and floodplain habitats.

We found:

- Local algal biofilm carbon was the dominant source of energy sustaining fish in wet-season floodplain habitats, but fish in main-channel pools during the dry season were increasingly dependent on other carbon sources, such as leaf litter or phytoplankton (as per Figure 4.7).
- No evidence was found that large-bodied fish were transporting remote carbon from the floodplain or estuary into the lower main-channel of the river. However, limitations constrained our ability to detect these spatial subsidies and alternate research is needed to provide clarity.

Ecological implications related to changes in water availability

- Modifications to flow and/or groundwater that impact riparian trees could impact fish biomass in dry-season pools.
- Water harvesting that impacts water movement onto the floodplain could reduce food production on the floodplain and reduce fish productivity. Impacts are likely to be localised.

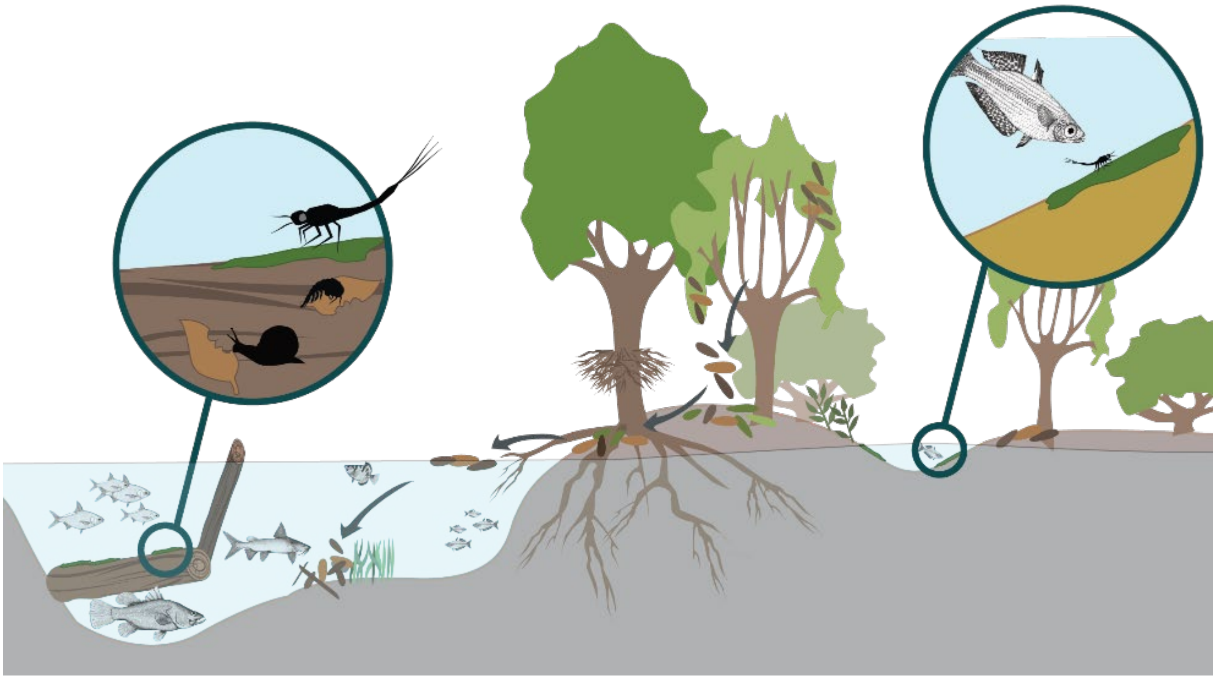

Figure 4.7. A schematic representation of the food web in main-channel and floodplain habitats.

4.1.4 Energy reserves of fork-tailed catfish

Aim 2. To investigate the importance of flow and habitat to the energy reserves of fork-tailed catfish.

Methods. Catfish were collected using a variety of techniques and were measured and weighed. Energy reserves were described using three metrics: body condition (weight for a given length), intramuscular fat (lipids stored in muscle tissue) and coelomic fat (lipids stored in the body cavity; Figure 4.8). Energy reserves were investigated using 496 fish collected from 28 sites during the dry season from three years (2009, 2018, 2019). Patterns in body fat were evaluated for all three years (332 fish), patterns in intramuscular fat were examined for fish in 2018 and 2019 only (127 fish), and patterns in coelomic fat were examined for fish in 2019 only (102 fish). Influential factors measured included mesohabitat (tributary, main-channel), pool maximum depth, year (proxy for wet-season flow), fish size and Julian day. We used general linear mixed-effects models to investigate the relationship between these factors and metrics of fish condition. Support for relationships was assessed using AIC.

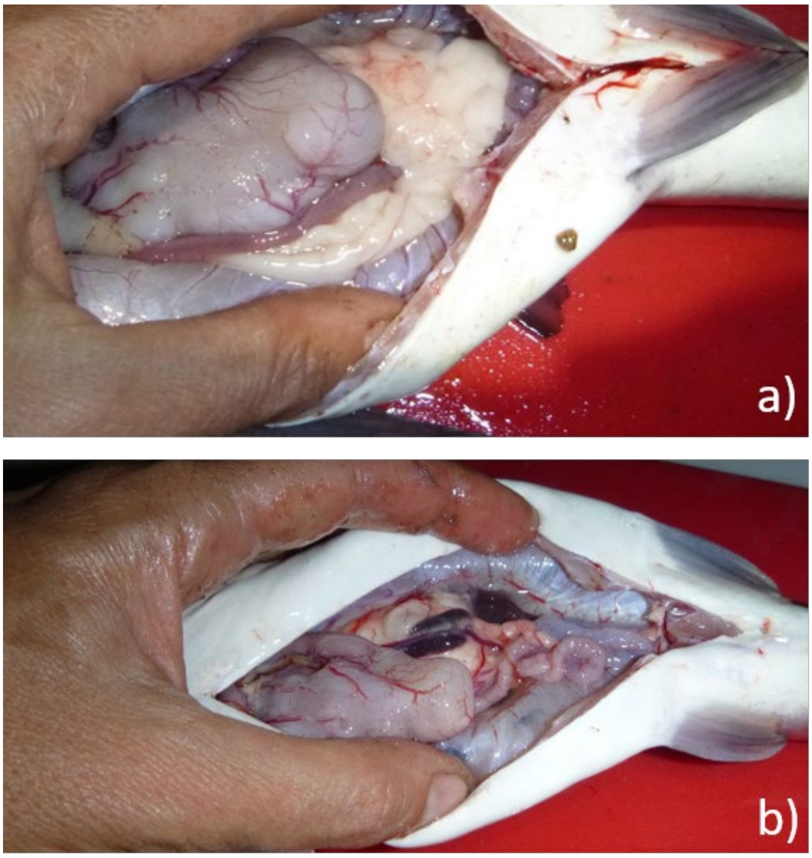

Figure 4.8. Fork-tailed catfish with (a) moderate and (b) negligible fat in the body cavity.

We found:

- Body condition and intramuscular fat were greater in years following moderate to high wet season flow and smallest in a year following very low flows, and these reserves decreased as the dry season progressed.
- Coelomic and intramuscular fat were lower in smaller pools.
- There was no association between mesohabitat and energy stores.

Ecological implications related to changes in water availability

- Fish in dry season pools will be more vulnerable in years following poor wet-season flows.
- Groundwater that sustains dry-season pools will keep fish in better condition and will be particularly important late in the dry season.

4.1.5 Cherabin distribution along the river

Aim 3. To describe the size-related distribution of cherabin across two years to reveal habitat associations, the influence of wet-season flow, and highlight distributional patterns suggestive of an amphidromous life history.

Methods. We sampled cherabin in main-channel and floodplain pools spanning a gradient of depth along a 350 km reach of the river during the dry season of two years with contrasting wet-season flow (2018, 2019). Cherabin were collected in main-channel pools using opera and bait traps and were collected in floodplain pools using a beach seine (Figure 4.9).

Individuals were measured and released. Influential factors including pool maximum depth, mesohabitat (main-channel, floodplain) and Julian date were recorded. Size-specific occupancy models were used to estimate abundance at the site scale and accounted for variable detection among gears and environmental conditions. We coupled habitat mapping with model outputs to generate landscape-level predictions of abundance.

Figure 4.9. Collecting and measuring cherabin in the river.

We found:

- Juveniles were most abundant in main-channel pools in the lower river and adults were most abundant in floodplain pools higher in the river.
- There was no association between water availability (year, pool depth) and cherabin abundance at the site scale. However, when estimates were scaled up to the landscape, there was a strong positive impact of wet-season flow on juvenile and adult abundance.
- The predominance of small-size classes low in the river is indirect support for an estuarine nursery and an amphidromous life history, but the collection of small individuals late in the dry season suggests that some level of within-river recruitment may occur. Targeted research is needed to provide certainty about the species life history in the river.

Ecological implications related to changes in water availability

- Larger wet-season flows increase the cherabin population through provision of habitat.
- Cherabin may be vulnerable to water-resource development that affects the connectivity of recessional flows during the late wet season as their larvae likely migrate up from an estuarine nursery.

4.2 Riparian vegetation

4.2.1 Aims and approach

The desktop literature review Douglas et al. (2019) showed that there is a very little data available for the riparian vegetation of the Fitzroy River, with no data on the water requirements of riparian vegetation. To address this significant knowledge gap, we identified the following aims, which were investigated in the corresponding outputs:

1. Determine the relationship between the distribution of riparian woody plant species and surface water flow.
    - Canham CA, Beesley LS, Gwinn DC, Douglas MM, Setterfield SA, Freestone FL, Pusey BJ and Loomes RC (2021a) 'Predicting the occurrence of riparian woody species to inform environmental water policies in an Australian tropical river'. *Freshwater Biology*, DOI: 10.1111/fwb.13829
    - Freestone, FL, Canham CA, Setterfield SA, Pusey BJ, Douglas MM, Loomes RC (in preparation) 'Characterising zones within riparian vegetation along the lower Fitzroy River, WA'. *Australian Journal of Botany*.
    - Freestone, FL, Canham CA, Setterfield SA, Douglas MM, Loomes RC (2021) 'Characterising vegetation zones along the lower Fitzroy River, Western Australia'. University of Western Australia, Perth.
2. Determine the water sources used by riparian trees at the end of the dry season.
    - Canham CA, Duvert C, Beesley LS, Douglas MM, Setterfield SA, Freestone FL, Clohessy S and Loomes RC (2021b) 'The use of regional and alluvial groundwater by riparian trees in the wet-dry tropics of northern Australia'. *Hydrological Processes*, 35:e14180
3. Investigate the relationship between plant functional traits and the distribution of riparian trees.
    - Canham CA, Woods C, Setterfield A, Veneklaas E, Freestone FL, Beesley LS, Douglas MM (in preparation) 'Functional traits reflect the distribution of riparian trees in the lower Fitzroy River, northern Australia'. *Tree Physiology*.

A series of studies were completed to address these aims, collecting data along the Fitzroy River, including its floodplain (Figure 4.10). A summary of each study is provided below, with the journal articles attached in the appendices.

Figure 4.10. Examples of data collection methods for investigating riparian vegetation. Top panel shows Robyn Loomes (WA Department of Water and Environmental Regulation) Jeremiah Green (Yimardoo-warra Rangers) and Fi Freestone (The University of Western Australia) measuring stomatal conductance with a fluorometer. Bottom panel shows Sumayah Surprise and Elton Smiler (Ngurrara Rangers) assessing canopy and ground cover.

4.2.2 Predicting the distribution of riparian woody species along the Fitzroy River

Aim: Determine the relationship between the distribution of riparian woody plant species and surface water flow.

Methods: Woody vegetation was surveyed at 58 sites along the Fitzroy River between Willare and Fitzroy Crossing, with sites spanning the edge of the river to the floodplain. At each site, the species present within a 10 x 40 m transect were recorded. We developed and applied a joint species distribution model to determine the likelihood of occurrence for 26 woody riparian plant species according to the duration of flood inundation in small and larger flood events. We assessed the distribution of each species under a baseline and two water-take scenarios which removed 300 GL and 600 GL of water from the system.

We found:

- The duration of inundation from flood flows was a strong predictor of species occurrence.
- We identified species associated with wetter environments, as indicated by their effect size for the inundation metric. Species associated with the higher duration of inundation include *Melaleuca argentea, M. leucadendra, Nauclea orientalis* and *Barringtonia acutangula*.
- Under the 300 GL water-take scenario, we found little change (< 2%) in species occurrence, but under the 600 GL scenario a decline between 5.0% and 7.4% was predicted for eight species associated with wetter habitats. This decline was generally confined to a localised area (Figure 4.11).

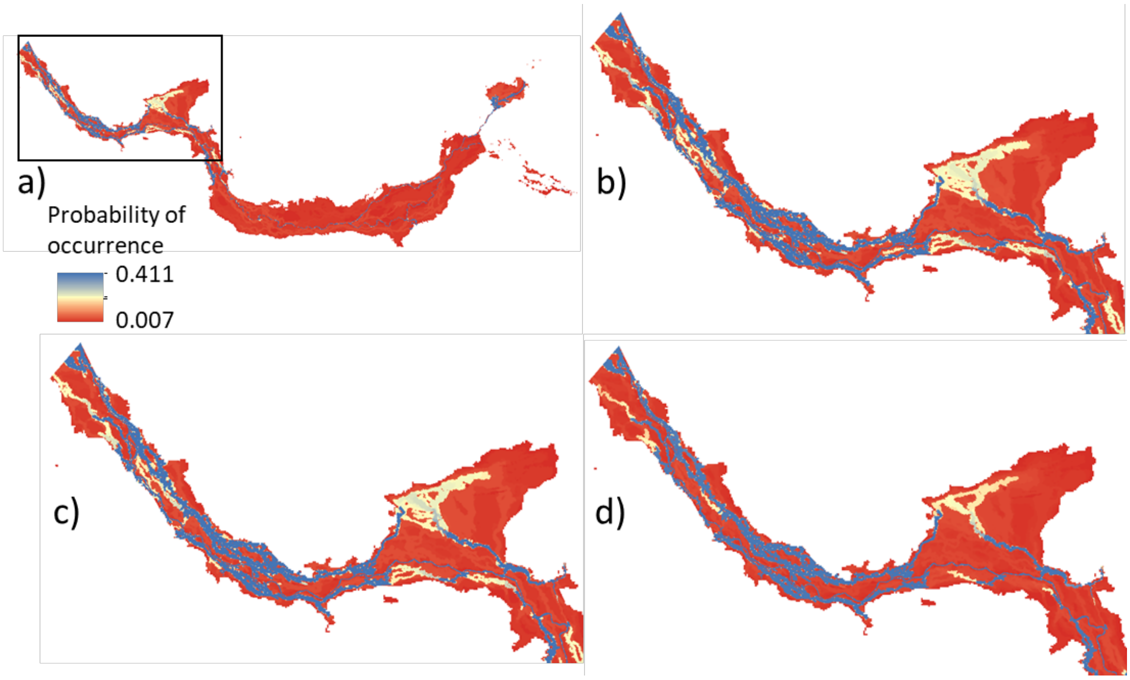

Figure 4.11. The probability of occurrence for Melaleuca argentea *under different scenarios. Panel (a) shows the whole study area under the baseline scenario. The area most impacted by water-take is highlighted showing predicted* M. argentea *occurrence under the baseline (b), 300 GL (c) and 600 GL (d) water-take scenarios. Area shown is most impacted by water-take, with the whole study area shown as inset.*

Ecological implications related to changes in water availability

- The distribution of woody riparian plant species is related to regular flood flows.
- Changes to flood flows will potentially impact the distribution of riparian plants, reducing the total area of species associated with wetter environments.

4.2.3 Characterising zones within riparian and floodplain vegetation along the Fitzroy River

Aim: Determine the relationship between the distribution of riparian woody plant species and surface water flow.

Methods: Vegetation was surveyed at the same sites sampled in the previous study, with a total of 58 sites along the lower Fitzroy River. At each site, we determined the species present and their abundance, and assessed vegetation structure. Canopy cover was assessed using a densitometer, with the presence or absence of canopy recorded at one-metre increments at 100 points around the perimeter of the 10 x 40 m transect. The health and the diameter at breast height (DBH) were recorded for each tree greater than 1.5 m tall. Recruitment of woody vegetation was assessed by counting individual tree seedlings, suckers or resprouts shorter than 1.5 m. The height of the tallest individual tree was recorded at each site. Species composition at each of the sites was analysed using multivariate analysis, visualised as nMDS ordinations. The relationship between species composition and environmental variables at each zone was evaluated using permutational analysis of variance.

We found:

- There is a zonation in the distribution of woody riparian plant species along a gradient from the edge of the main river channel to the floodplain.
- Trees on the riverbank had the greatest DBH and canopy cover, with *M. argentea*, *M. leucadendra* and *B. acutangula* the most common species in this zone.
- Trees on the floodplain were shorter and had a smaller canopy than those growing closer to the main river channel, with *Eucalyptus microtheca* the most common floodplain species.
- Floodplain wetlands and flood-runners had a greater diversity of species, with *Corymbia bella*, *E. camaldulensis*, *Terminalia platyphylla* and *Ficus coronulata* common in these habitats.
- Recruitment, as indicated by presence of seedlings, was more common in the wetland and flood-runner habitats.

Ecological implications related to changes in water availability

- Species composition and the structure of vegetation differs across a hydrological gradient from the main river channel to the floodplain, including floodplain wetlands (Figure 4.12).
- Changes to hydrology may alter the distribution of these zones, which can reduce the complexity of vegetation of the Fitzroy River.

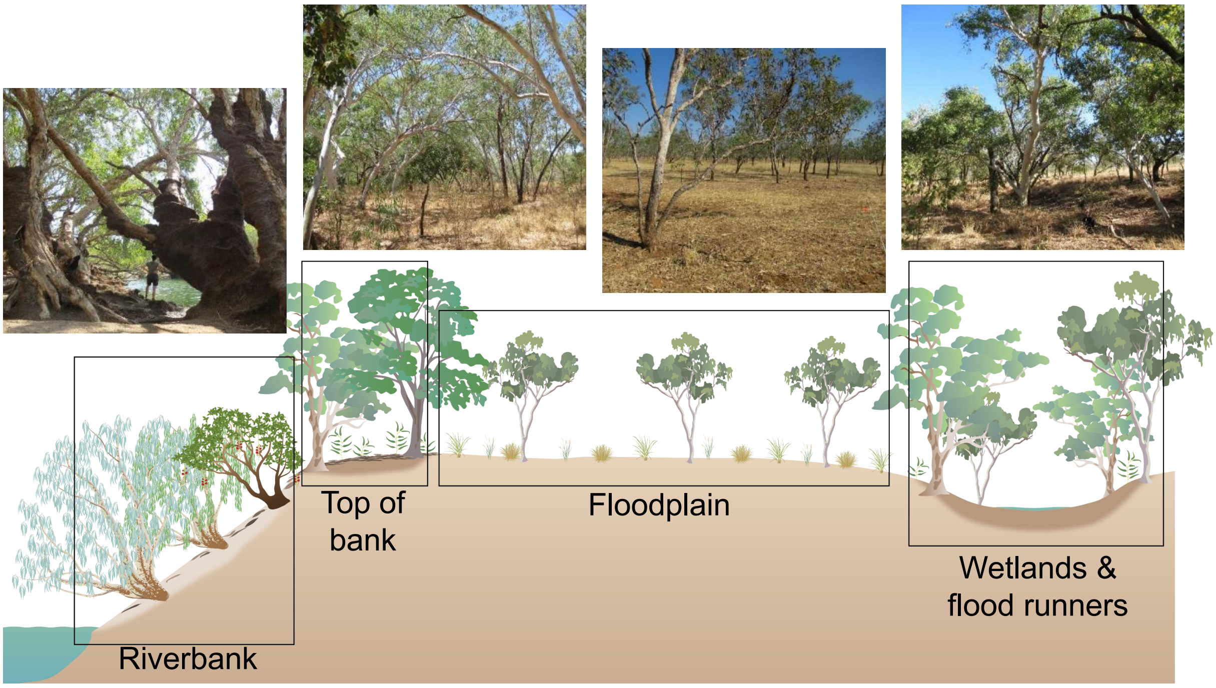

Figure 4.12. A representation of the zonation of riparian woody plants, including photographs representative of each zone.

4.2.4 The use of regional and alluvial groundwater by riparian trees

Aim: Determine the water sources used by riparian trees at the end of the dry season, including a comparison between sites with different hydrogeological processes.

Methods: We used isotopic analysis complemented by measurements of plant water relations to assess water sources for riparian trees at two sites with contrasting hydrogeological processes – one with an alluvial aquifer overlaying an aquitard, and one where fault-induced preferential pathways in the aquitard allowed the flow of deeper, older groundwater from a regional aquifer to the alluvium. At both sites, plant water potential, stomatal conductance, and plant water isotope composition in the xylem sap of riparian trees were collected from two landscape positions – the riverbank and the floodplain. A Bayesian mixing model (MixSIAR) was used to assess the proportion of water sources for sites and landscape positions.

We found:

- Xylem water isotope values differed between the two sites in line with their hydrogeological characteristics, with trees using regional groundwater at the site where the deeper aquifer is connected to alluvial aquifer and river (Figure 4.13).
- At the site where only alluvial groundwater is present, trees used a mixture of water sources, with no dominant water source identified.
- Trees closer to the river had higher isotope values, indicative of shallower water sources such as shallow soil water and river water.

Ecological implications related to changes in water availability

- The water sources used by riparian trees along the Fitzroy River reflect local hydrogeology and resource availability.
- Established trees that use the regional aquifer may be impacted if water-take alters the depth of the water table, particularly in the dry season.
- However, if regional groundwater is not available, riparian trees are likely to use other water sources including soil water and alluvial groundwater.

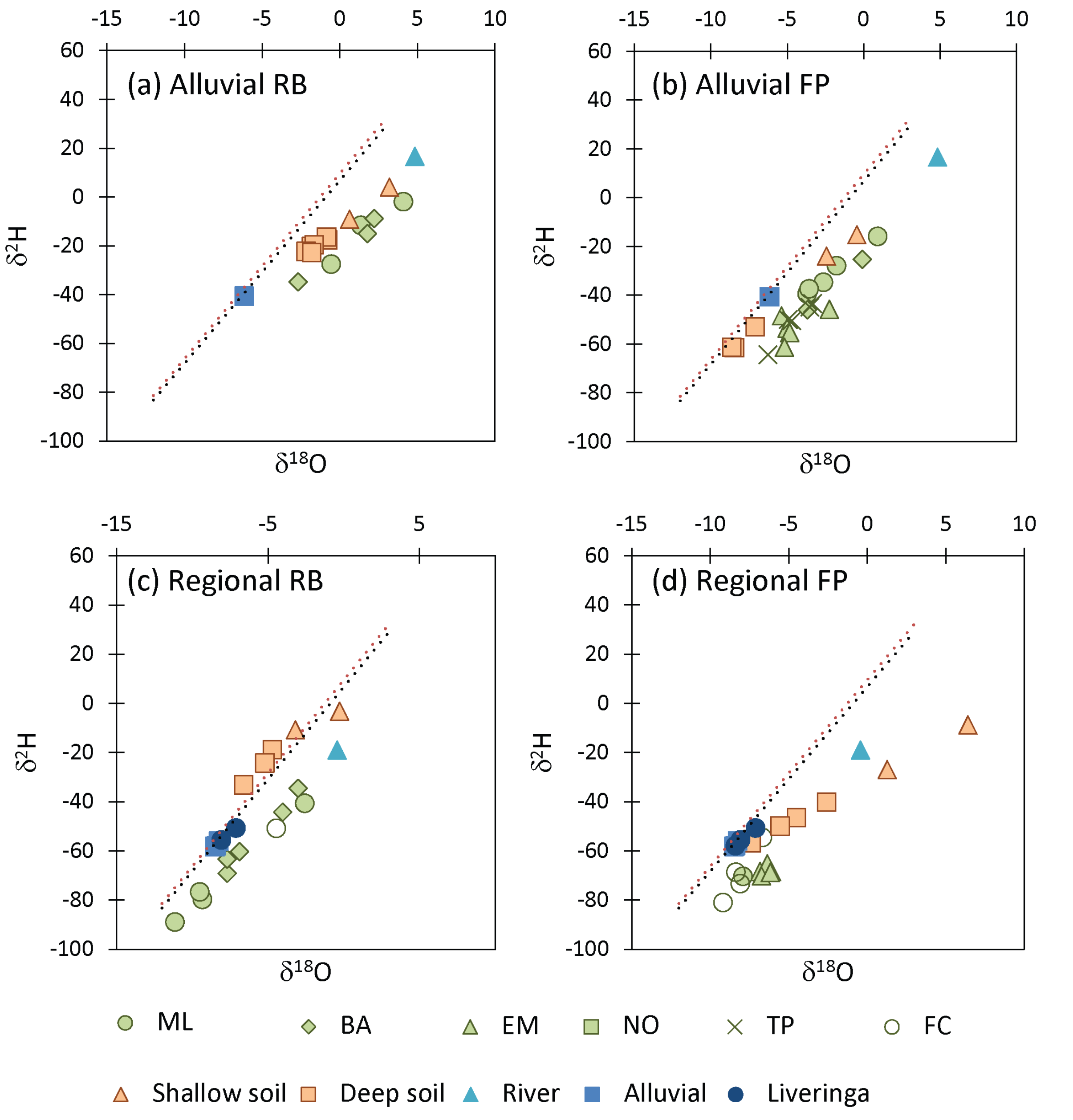

Figure 4.13. Bi-plots of $\delta^{2}H$ and $\delta^{18}O$ water isotope values for study trees (green symbols) at the alluvial and regional study sites. Tree species are Melaleuca leucadendra *(ML),* Barringtonia acutangula *(BA),* Eucalyptus microtheca *(EM),* Nauclea orientalis *(NO),* Terminalia platyphylla *(TP) and* Ficus coronulata *(FC). Sources are shallow soil water (0–0.75 m) and deep soil water (1.0–2.5 m) groundwater (alluvial and Liveringa aquifers) and river water. The black dotted line shows the meteoric water line for Halls Creek (Crosbie et al. 2012) and the red dotted line shows the meteoric water line for Dampier Peninsula (data retrieved from wir.water.wa.gov.au/Pages/Water-Information-Reporting.aspx).*

4.2.5 Plant functional traits reflect the distribution of riparian trees

Aim: Examine the relationship between key plant functional traits and the distribution of common riparian tree species of the Fitzroy River.

Methods: For nine tree species, we assessed the following plant functional traits: leaf mass per unit area, leaf dry-matter content, foliar carbon content, the ratio of carbon to nitrogen, foliar $\delta^{13}C$ which is related to water use efficiency, leaf osmotic potential, stem-specific density, mean xylem vessel diameter and xylem vessel density. Differences in trait values between species were assessed using analysis of variance (ANOVA) and we determined the correlation between trait values and a hydrological metric. Multivariate cluster analysis was used to determine grouping of species based on their trait values (see Figure 4.14).

We found:

- With increasing water availability, $\delta^{13}C$ values decreased and osmotic water potential values increased.
- Cluster analysis using trait value data showed that species grouped according to their distribution along a hydrological gradient, although this relationship was complicated by differences in deciduousness between species, as well as differences between myrtaceous and non-myrtaceous species.

Ecological implications related to changes in water availability

- The physiology of riparian tree species reflects their distribution along a hydrological gradient.
- Species with higher water-use efficiency (determined from foliar δ13C) may be better adapted to drier conditions under water-take scenarios.
- In contrast, species with low water-use efficiency may be impacted if water availability is reduced.

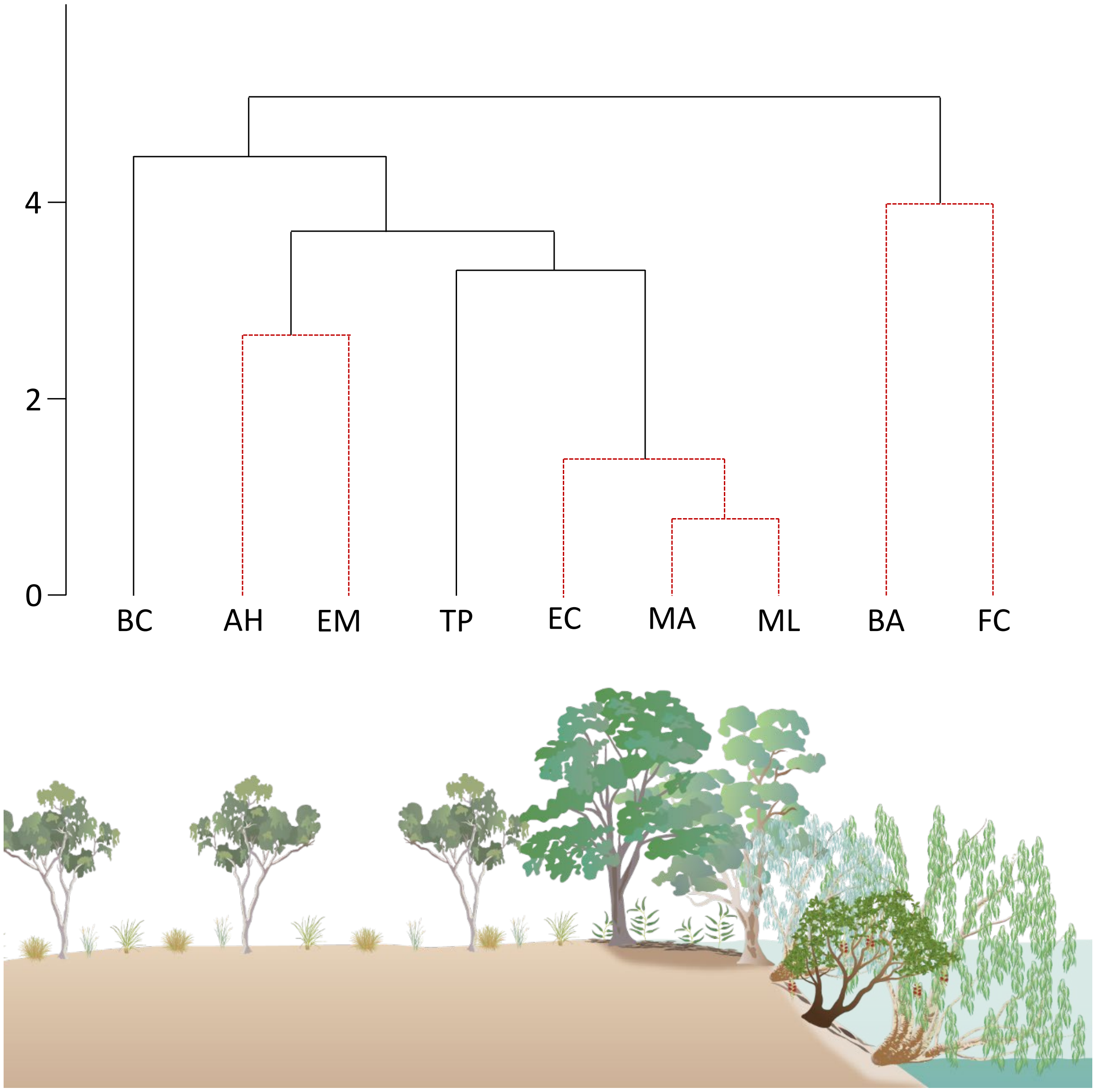

Figure 4.14. Cluster analysis based on average trait values per species for nine riparian and floodplain tree species in the Fitzroy River catchment (n *= 10 per species). Data were normalised and a Euclidean distance resemblance matrix was used to determine the placement on the dendrogram. Solid lines indicate splits supported by a SIMPROF test (nperm = 999, $p < 0.05$). Species are* Bauhinia cunninghamii *(BC),* Atalaya hemiglauca *(AH),* Eucalyptus microtheca *(EM),* Terminalia platyphylla *(TP),* E. camaldulensis *(EC),* Melaleuca argentea *(MA),* M. leucadendra *(ML*), Barringtonia acutangula *(BA), and* Ficus coronulata *(FC).*

5. Phase 3: Using new knowledge from the Fitzroy River to revise our conceptual model and principles and considerations

5.1 New knowledge

Considerable new evidence emerged about environmental water requirements in the Fitzroy River during the 4-year period of the project; the majority from Phase 2. The new knowledge details flow-biota and habitat-biota relationships, but also includes habitat-habitat and habitat-abiotic relationships, as well as more characterisation of the aquatic food web and biotic groups, such as riparian vegetation. New knowledge from this project, along with previously published knowledge, is presented in Appendix 2 and is summarised below. Research published by other groups during this project's duration is also referred to below.

This project markedly increased our knowledge about the importance of water availability for fish and cherabin in the river. Key learnings from this research include that the size of wet-season flows can affect the energy stores of fork-tailed catfish (Beesley et al. 2021), a highly valued harvest fish for Aboriginal people. We also found that the size and depth of pools (main-channel, floodplain) can affect the fish species present at a site (NESP, unpublished data) and their energy stores, as demonstrated for fork-tailed catfish (Beesley et al. 2021). Evidence also emerged that the floodplain is important for the recruitment of many fish species (NESP, unpublished data) and is associated with rapid growth of some species (i.e. bony bream (NESP, unpublished data)), probably because this mesohabitat provides warm temperatures coupled with high food density (i.e. zooplankton). We found that floodplain pools support high densities of adult cherabin (Beesley et al. in preparation), likely because they provide a refuge from predators present in the main-channel, such as barramundi and crocodiles. Research also revealed that wet-season flows influenced the dispersal of fish across the landscape, with floodplain pools supporting more diverse fish assemblages in years following larger wet-season flows (NESP, unpublished data). The size of wet-season flow also influenced the size of the cherabin meta-population via habitat provision (Beesley et al. in preparation). However, questions remain about the importance of flows for cherabin in the Fitzroy River. Although we found the greatest densities of cherabin in lowland main-channel reaches (Beesley et al. in preparation), which supports use of an estuarine nursery, this evidence is indirect. Currently, large knowledge gaps remain about the wet-season flows that transport cherabin larvae to the estuary and the recessional flows used by juveniles to migrate back up the river.

This project also generated knowledge about food webs, water chemistry, invertebrates (e.g. zooplankton) and algal production. For example, while we discovered, like others, that local algal biofilm carbon was the dominant source of energy sustaining fish in wet-season floodplain habitats, we found that fish in lowland main-channel pools during the dry season were increasingly dependent on other carbon sources such as leaf litter or phytoplankton (Beesley et al. 2020). This evidence suggests that the energetics of the river may differ somewhat from other floodplain rivers in tropical northern Australia and it highlights the potential importance of riparian vegetation, at least in lower reaches of the river. Preliminary evidence also suggests that phytoplankton and zooplankton may play an important trophic role in some of the highly turbid pools on the floodplain, as we found dense zooplankton assemblages in some pools (NESP, unpublished data). Our research also revealed that algal biofilm production in shallow sandy run or riffle habitats of the river is shaped by flow velocity and the upwelling of groundwater (Burrows et al. 2020). The latter result highlights the potential importance of surface–subsurface flow interactions in this sandy river, and is supported by preliminary carbon-14 dating which suggests that ancient carbon from regional aquifers may contribute energy to present day food webs, but that this may be limited to habitats dominated by regional groundwater, such as springs (Tayer, unpublished data).

For riparian vegetation, the knowledge base prior to the start of the project was very small, with no data available for the relationship between flow and riparian vegetation for the Fitzroy River, and very little data available from across northern Australia (Douglas et al. 2019). Our research demonstrated the relationship between surface water flows, primarily flood flows, and the distribution of riparian woody species. We also tested how the distribution of woody species may change under the same scenarios being considered by water managers as part of determining a water allocation plan (Canham et al. 2021a). This information was able to inform water planning and supported our original conceptual model that highlighted the link between surface water flow and riparian species. The conceptual model also identified the potential for groundwater to be an important water source for riparian vegetation, particularly at the end of the dry season. The hydrogeology of the Fitzroy River is complex, with localised outcropping of regional groundwater in some locations, while in other areas, groundwater is primarily the alluvial aquifer. We found that riparian trees use regional groundwater in locations where it is discharging to the alluvium and river, and trees may be dependent on this water source (Canham et al. 2021b). At locations where regional groundwater is not available, trees were found to use alluvial groundwater as well as deep stored soil moisture (Canham et al. 2021b). These outcomes highlight the importance of considering local-scale hydrology when determining the potential impact of water development on riparian trees. We also assessed some of the physiological traits of the common riparian and floodplain tree species, to learn more about how tree physiology is related to the water regime. We found that there were relationships between traits such as leaf dry-matter content, $\delta^{13}C$ and leaf osmotic water potential and our hydrological variables, although leaf traits were also strongly related to species being myrtaceous or non-myrtaceous, as well as differences in deciduousness. The studies completed as part of this project increase our knowledge of riparian vegetation on the Fitzroy River, as well as for northern Australia more broadly.

5.2 Updating the conceptual model

The new evidence acquired in this project was used to update our conceptual model. The revision was constrained to the hydro-ecological linkages of the model, as updates about Indigenous knowledge and relationships with water were revised as part of the 'Indigenous water needs for the Fitzroy River' project (Appendix 1). Our revised conceptual model highlights the ecological linkages that are supported by research conducted in the Fitzroy River (Figure 5.1 and Table 5.1). The outermost boxes in the diagram describe the impact on biota and habitats as a result of water-take. These predictions are supported by evidence for the Fitzroy River, including published studies from this project, research published by others, and unpublished findings from this project based on preliminary data (indicated by numbers and letters on arrows and summarised in Appendix 2). It is important to recognise that scientific certainty or confidence will differ for each piece of evidence. It was beyond the scope of this study to evaluate the confidence for each piece of evidence; however, confidence will be greater where studies have greater spatial and temporal coverage, the strength of the scientific relationship is strong, the causal link to flow is direct, and when it is supported by other research. Confidence will also be higher for relationships that are governed more by physical processes, e.g. a decrease in algal biofilm with increasing flow velocity, than shaped by biotic processes which can be very complex, e.g. a decrease in catfish energy stores with a decline in wet-season flow. Lastly, confidence will be higher for research published in the scientific literature than for unpublished or preliminary findings.

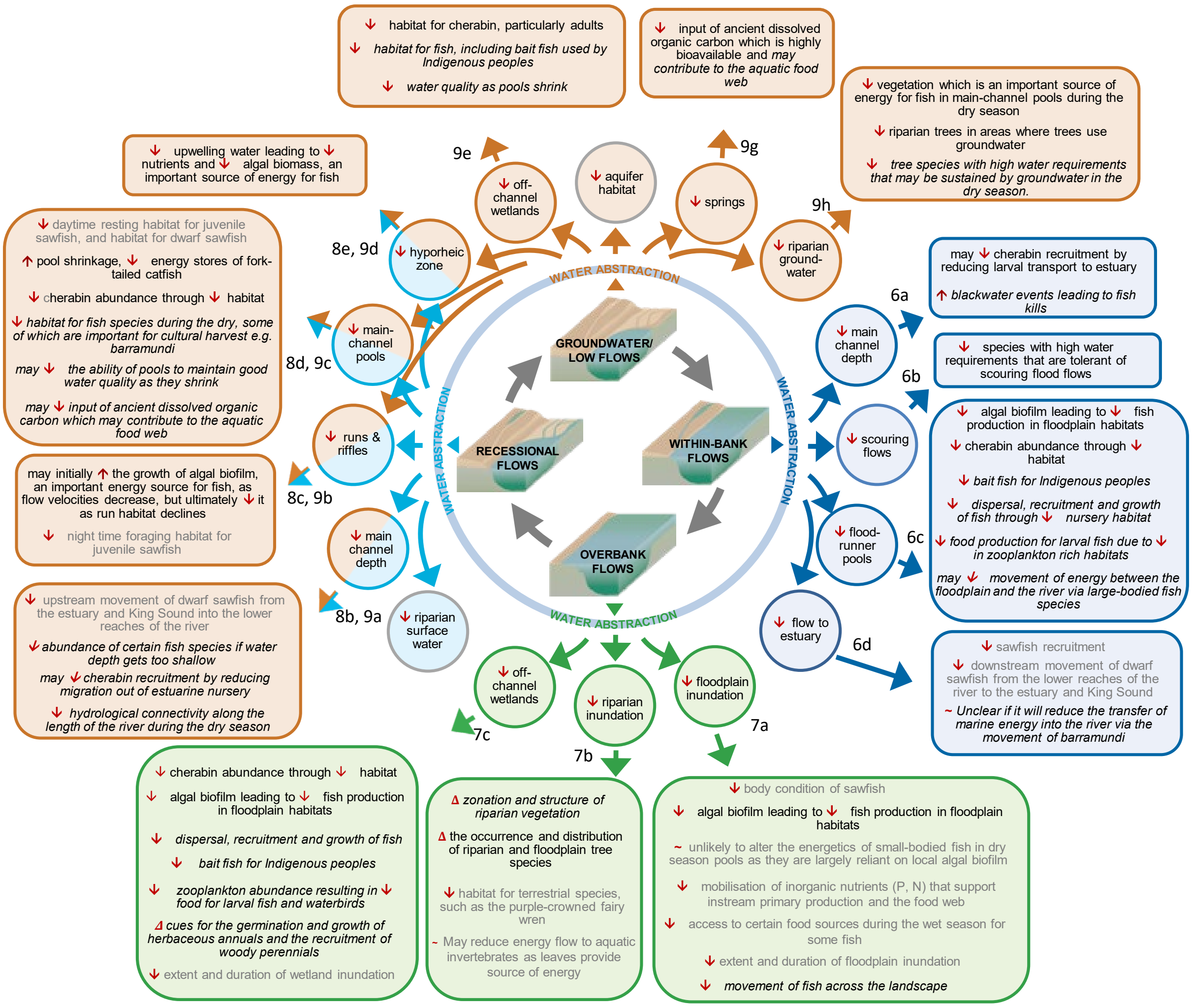

Figure 5.1. Revised conceptual model of hydro-socio-ecological linkages using research undertaken wholly, or in part, in the Fitzroy River. Black text = NESP evidence, published; black text italicised = NESP evidence, unpublished. Grey text = non-NESP evidence, published. Predicted hydro-socio-ecological responses to water abstraction are depicted with red symbols; a downward arrow indicates a decrease, an upward arrow an increase, a delta symbol a change in an unclear direction and a tilde symbol indicates little if any change. Numbers and letters next to habitats refer to the rows in the table of evidence, with the numbering corresponding to that used in the original conceptual model (Douglas et al. 2019) – see supporting information table in Appendix 2.

Table 5.1. Summary of new evidence for hydro-ecological linkages and management considerations for the Fitzroy River. Evidence was derived from research undertaken as part of this project (Environmental water needs of the Fitzroy River) and is grouped by flow components identified in the original conceptual model. Management considerations were largely unchanged from Phase 1 of the project, with text from the original model italicised, with new considerations added during Phase 3 shown in bold.

Flow component	NESP evidence	Consideration
Groundwater/low flows	• Water velocity was an important driver of algal biomass – algal biomass was lower at higher water velocities. • Subsurface flow influenced algal biomass – algal biomass was greater in locations where groundwater upwelling occurred. • Fish in main-channel pools during the dry season depend increasingly on energy from leaf litter or phytoplankton. • Catfish energy stores were lower in small shallow pools than in large deep pools and decreased as the dry season progressed. • Juvenile cherabin were most abundant in main-channel pools low in the river. • Many fish species are sustained through the dry season in main-channel refuge pools, including some species not found on the floodplain during the dry (e.g. barramundi) [unpublished]. • Fish abundance declined as pool depth declined, particularly when it fell below certain levels [unpublished data]. • Water temperature increased as pools shrank but had little impact on oxygen [unpublished data]. • Hydrological connectivity in the main channel of the river during the dry season was greater in parts of the river with connections to deep groundwater [unpublished data]. • May contribute ancient dissolved organic carbon to the food web [unpublished data]. • In locations where it is available, regional (older) groundwater is used by riparian trees. • Supports tree species with higher water requirements. • Leaves from riparian trees are likely an important food source for fish in lowland main-channel pools during the dry season.	Water planning should consider how the alteration of groundwater resources will affect: • the size, persistence and quality of habitats during the dry season, including off-channel wetlands, springs, runs and riffles, main-channel pools, aquifer habitat and the hyporheic zone • the condition and composition of riparian vegetation reliant on groundwater. Water planners should take a precautionary approach to policy until sufficient food web evidence is amassed. Fish are most vulnerable late in the dry season in years where the preceding wet-season flow has been small.
Within-bank flows	• Juvenile cherabin were predominantly located in main-channel pools in the lower reaches of the river, providing indirect evidence that adults use an estuarine nursery.	Water planning should consider how the alteration of within-channel flows during the wet season will affect:

Flow component	NESP evidence	Consideration
	• Fish inhabiting floodplain habitats during the wet season were predominantly sustained by energy from local algal biofilms. • An early wet-season flow caused a blackwater event and oxygen crash at one main-channel site leading to the loss of several fish species [unpublished data]. • Fish species richness in flood-runner pools was higher in a year with short within-bank flows compared to a year with very little wet-season flow [unpublished data]. • Riparian trees that occupy the riverbank (*M. argentea, M. leucadendra* and *E. camaldulensis*) have traits that allow them to survive high-velocity flows. • Pools in floodplain habitats support fish that are used as bait fish for Indigenous harvest [unpublished data]. • No evidence was found that large-bodied fish were transporting remote carbon from the floodplain or estuary into the lower main-channel of the river. However, limitations hampered research. • Estimates of cherabin scaled up to the landscape indicate greater abundance during years following larger wet-season flows via the provision of more habitat.	• connectivity along the entire length of the main channel and the passage of animals along the length of the river, including movement to and from the estuary • the frequency and magnitude of scouring flows that clean the river, maintain within-channel geomorphic complexity (pools, bars, riffles) and prevent siltation of hyporheic sediments • the size, persistence and quality of flood-runner pools • the productivity of the estuary, as many riverine species use it as a nursery.
Overbank flows	• Local algal biofilm carbon was the dominant source of energy sustaining fish in wet-season floodplain habitats. • There was a zonation of riparian vegetation with differences in species assemblage and vegetation structure (canopy cover, basal area) over a hydrological gradient. • The likelihood of tree species occurrence was related to flood inundation duration. • Fish species richness in flood-runner pools was highest in a year with protracted overbank flows [unpublished data]. • Pools in floodplain habitats support fish that are used as bait fish for Indigenous harvest [unpublished data]. • Estimates of cherabin scaled up to the landscape scale indicate greater abundance during years following larger wet-season flows via the provision of more habitat. • Zooplankton density was higher in floodplain pools compared to main-channel pools [unpublished data].	Water planning should consider how the alteration of over-bank flows will affect: • connectivity between the river and its floodplain particularly high-value floodplain sites (biodiversity, productivity, cultural significance) • dispersal and recruitment of riparian vegetation and surface water inputs to riparian plants • the size, persistence and water quality of off-channel wetlands.

Flow component	NESP evidence	Consideration
	• The composition of herbaceous plant species differed under different inundation regimes [unpublished data].	
Recessional flows	• Juvenile cherabin were most abundant in main-channel pools low in the river, suggesting that larvae use an estuarine nursery.	Water planning should consider how the alteration of recessional flows during the dry season will affect: • connectivity along the entire length of the main channel and the passage of animals along the length of the river, including movement to and from the estuary • the condition and composition of riparian vegetation reliant on surface water from the channel • the availability and quality of shallow, fast-flowing habitats (i.e. runs/riffles) • the size, number, quality of refugial dry-season pools, particularly historically perennial pools • the extent and quality of hyporheic habitat.
Antecedent flows	• Catfish energy stores were greater in years following moderate to high wet-season flows and smallest in a year following very low flows.	Water planning should consider flows from previous years when setting water-take rules for the current year.
Monitoring	• Tree species associated with wetter habitats (i.e. *M. argentea, M. leucadendra, B. acutangula* & *N. orientalis*) were more likely to decrease under a water-take scenario, and may be effective indicators of the impact of water-take on riparian trees. • There is not a sufficient baseline data set that links aquatic biota and riparian vegetation to surface water and groundwater flows. • The fish assemblage can vary considerably among sites, particularly pools on the floodplain [unpublished data]. • The ability to detect or catch fish and cherabin varies considerably among species, among fishing gear types (nets, boat electrofishing), with effort (the time spent fishing, the size or number of nets) and with environmental conditions (e.g. pool size, water depth, water clarity, habitat etc).	Water planning should include the following considerations for effective monitoring of aquatic biota and riparian vegetation in relation to surface and groundwater flows: • selection of ecologically and culturally relevant indicators • the implementation of an appropriate sampling design and use of suitable methods to assess the status of the indicators • concomitant monitoring of other variable(s) that drive change in the indicators • consideration of both local and system-wide impacts • timely and appropriate analysis of monitoring data that reports the state of the system to trigger management intervention where needed

Flow component	NESP evidence	Consideration
	• Water quality (oxygen) is generally good in main-channel pools as the dry season progresses, but low oxygen can be a problem [unpublished data].	• establishment of a baseline data set for the system.

6. Discussion

New scientific evidence gathered during the course of this project was in broad alignment with our general theoretical understanding of how the river would function. This meant that the general structure of the conceptual model, which detailed relationships between key flow components and the habitats and biota they support, changed little between Phase 1 and Phase 3. The main change was that the model transitioned from being largely reliant on knowledge transferred from elsewhere in northern Australia and further afield to one that was populated largely by knowledge generated from the study system. This model is more defendable and creates greater certainty for management. The trade-off is that it now does not span the same ecological breadth as the original version. Therefore, some important relationships between flow and biota or flow and ecological processes, such as dispersal, are now no longer captured in the model. Those using the model need to be aware of this limitation. We recommend that both models be used to guide management decision-making and policy development for the river.

6.1 New knowledge relevant to water planning

This project generated new ecological evidence for the Fitzroy River, increasing our knowledge of riparian vegetation, fish and cherabin, the aquatic food web, the water chemistry of pools, and hydrological connectivity. The research outputs included data supporting five flow-biota relationships and 14 habitat-biota relationships. Flow-biota relationships are particularly useful for environmental water planning because they provide a direct link between river flow and an ecological outcome – indicating the potential implications of water extraction. Currently, the most direct flow-biota relationship generated by this project is the link between the duration of floodplain inundation and the probability of occurrence of different riparian tree species (Canham et al. 2021a). The relevance of this research to water policy decision-making was maximised by using the flow-biota relationship to predict tree occupancy for different water-take scenarios used in a discussion paper by state government water managers. Furthermore, spatial mapping of tree occupancy across the lower Fitzroy River highlights areas most vulnerable to water extraction. The study revealed that the species most vulnerable to wet-season water harvesting are *M. argentea*, *M. leucadendra, N. orientalis* and *B. acutangula*, which may make them good candidates for monitoring to assess environmental impacts.

Other flow-biota relationships generated by this project can also inform and support management decisions. For example, the positive link between years with high wet-season flows and the energy stores of fork-tailed catfish in dry-season pools reinforces the importance of flow and water availability as a critical force shaping the ecology of riverine biota and highlights the importance of wet-season flow and the legacy effect on the subsequent dry season. Protecting wet-season flows during years with low river discharge will be particularly important for fork-tailed catfish so that they can accumulate the energy stores needed to persist during the subsequent dry season.

Habitat-biota relationships are also useful for water planning because they can reveal the changes likely to arise if the availability and quality of habitats changes due to water extraction. For example, knowledge generated by this project about the importance of the floodplain for fish recruitment and growth indicates the importance of protecting within-bank flows that fill flood-runner channels and replenish flood-runner pools. Similarly, flood flows are important for maintaining wetlands in the floodplain, which are important habitats for the recruitment of riparian plant species (Freestone et al. in prep).

6.2 Knowledge gaps and uncertainty

Although there has been a marked increase in ecological knowledge related to flow and riverine habitats in the Fitzroy River, many knowledge gaps remain, including:

- the importance of river flows for the growth, recruitment and survival of many biota, including fish, cherabin and vegetation (woody or herbaceous)
- the ecological role of recessional flows
- the potential for off-stream water storage to trap and cause mortality for fish
- the energetics of the river system, including the role of large-bodied fish in transferring energy through space and time
- the life history of cherabin, especially their reliance on an estuarine nursery, and the wet-season flows that promote larval transport to the estuary
- the reliance of riparian trees on groundwater, especially the aquifers identified for water-take
- modelling of how groundwater take will affect water table height
- mapping and ground-truthing of groundwater-dependent ecosystems, including springs and aquifers, as well as baseline data on those identified as ‘at risk’ from pumping.

More specific questions can be framed for each of these points. For example, currently nothing is known about the timing and size of flows used by juvenile cherabin during their upstream migration. Recessional flows may also assist fish to move from floodplain habitats back to refuges in the river, but nothing is known about the timing and size of flows that are needed by fish, particularly large-bodied fish such as barramundi and fork-tailed catfish.

The certainty surrounding ecological evidence for the Fitzroy River may vary considerably. For example, some research is able to draw upon long-term data sets (e.g. Lear et al. 2021) while others are limited to short-term studies (e.g. Canham et al. 2021b). Similarly, some findings are based on data collected across a broad spatial region whereas others rely on data from one or a few sites only. The strength of causal linkages also varied between studies, with some studies having strong causal links to flow whereas others rely on indirect relationships or assumptions, or have not yet undergone peer review. The certainty around evidence should be considered when developing water-planning policy, and evidence with low certainty may require further research. Evaluating the certainty of evidence was beyond the scope of this project but information regarding the spatio-temporal nature of the research is provided in Appendix 2.

6.3 Monitoring advice

Although not a key objective of the research, our research findings and scientific expertise can inform the design of monitoring protocols to protect the ecological assets of the Fitzroy River. Key learnings from this project relevant to monitoring include:

- Some riparian tree species, including paperbarks (*Melaleuca argentea*, *M. leucadendra*), freshwater mangrove (*Barringtonia acutangula*), Leichhardt pine (*Nauclea orientalis*), and *Bridelia tomentosa*, are more likely to be impacted by water-take, as indicated from distribution model (Canham et al. 2021a) and from plant physiology (Canham et al. in prep).
- Riparian trees use groundwater where it is available, including from the regional aquifer (Canham et al. 2021b).
- Our plant surveys were not designed to detect naturally rare species nor annual herbaceous species, and there are very limited data available.
- The ability to detect or catch fish and cherabin varies considerably among species, among fishing gear types (nets, boat electrofishing), with effort (the time spent fishing, the size or number of nets) and with environmental conditions (e.g. pool size, water depth, water clarity, habitat etc) (Beesley et al in prep).
- The fish assemblage can vary considerably among sites, particularly pools on the floodplain (NESP project 1.3.3, unpublished data).
- This work has not examined groundwater-dependent ecosystems (GDEs) outside of the floodplain area.
- Water quality (oxygen) is generally good in large main-channel refuge pools as the dry season progresses but low oxygen can be a problem (NESP unpublished data).

We consider the development of an effective monitoring program to be critical to the sustainable management of water resources in the river. An effective monitoring program requires a high degree of planning and investment, particularly in the early stages.

To be effective, monitoring must:

- assess impacts at local and system-wide scales (i.e. Fitzroy valley)
- use ecologically appropriate indicators to report on the state of the system and reveal impacts. Ecological indicators should include physical (e.g. water table height, river flow, pool depth, water chemistry) and biological (e.g. species) factors. They could be structural (e.g. species richness, canopy cover) or functional (e.g. functional traits), and could target specific species and/or communities. Indicator choice needs to be justified or explained. Spot measurements of water quality are unlikely to be sufficient.
- collect data so that potential impacts can be assessed. This means collecting data on relevant ecological indicators as well as the water-related variables linked to water extraction (e.g. river discharge, water table height, pool depth). Other influential but non-target variables should also be measured so that these factors can be controlled for in analyses, increasing the statistical power to investigate the factors of interest.
- use appropriate methods for data collection (i.e. best practice methodologies should be used to measure the status of ecological indicators).

- consider how the data will be analysed. Analyses undertaken early on during monitoring, (e.g. after one or two years) will reveal limitations of data collection and inform how best to proceed so that future investment in monitoring generates the most useful data.
- generate data that is publicly available, analysed regularly and independently reviewed
- ensure that data are incorporated into management decisions (i.e. adaptive management), so that a clear link exists between monitoring outcomes and decision-making
- be able to trigger a management action. Thus, targets must be set for each ecological indicator and any monitoring that reveals that an indicator, or several indicators, have exceeded an acceptable level must trigger management intervention (i.e. reduced water take).

For monitoring to successfully assess the impacts of water extraction, a **baseline data set must be amassed** that accurately describes natural range of conditions experienced by plants and animals. The dataset collected by this project is relatively short term (i.e. one to three years only) and is insufficient as a baseline data set. Currently, there is a desire to establish a baseline data set using data collected by Indigenous ranger groups. This will allow stakeholders, such as Aboriginal Prescribed Bodies Corporate, to play a stronger role in the monitoring and management of the river. As some methods and ecological indicators used by this project are highly technical and require specialised training and custom-made, expensive equipment (such as electrofishing equipment), there is a need to compare these methods with simpler, less specialised techniques so that pre-existing NESP data can be incorporated into the baseline data set. Any limitations of taking simpler approaches also need to be made clear so that stakeholders and decision-makers can assess the pros and cons of doing so. If deemed a priority, trials could be undertaken by the Resilient Landscapes Hub (round 1) to compare simple versus complex methods. This could include studies examining the efficacy of boat electrofishing versus netting, and the ability of modified rapid vegetation assessment to describe riparian vegetation.

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Appendix 1: Table of evidence supporting the revised conceptual model

Supplementary information

Table S1. Sources of information used to construct the conceptual model of potential water-resource development impacts on ecological values in the Fitzroy River catchment and the principles and key considerations for water planning. Information has been grouped according to spatial proximity to the study river. Literature cited supports the statement. For the Fitzroy River catchment, evidence published in peer-reviewed journals is in black text if it arose from this project and is in grey if it arose from other research. Unpublished evidence from this project is in italics. Evidence from the Fitzroy River was the result of an exhaustive literature search; evidence from tropical northern Australia and elsewhere was illustrative and was only pursued in the absence of local evidence and only for ecological literature for principles 6–10.

Principle	Flow	Habitat	Spatial region of literature source		
			Fitzroy River catchment (local)	Tropical northern Australia (regional)	Elsewhere (remote)
6a 6b 8a	Within-bank and recessional flows	Main-channel habitat depth	• Maintain shallow run habitats that are used by sawfish [1]. • Promote fish survival by maintaining pool depth *[2].* • Promote cherabin abundance (adults, juveniles) via the provision of habitat [3]. • May facilitate cherabin recruitment [3]. • *May create a blackwater event and lead to fish kills [2].* • *Promote hydrological connectivity along the length of the main-channel [2].*	• Cue the maturation and spawning of freshwater prawns (early in the wet) [4]. • Facilitate the dispersal of potamodromous fish along the length of the river and the recolonization of within-channel and off-channel habitats [5, 6], which supports food web connectivity [7]. • Support fish passage and migration along the length of the river (longitudinal connectivity) which may be important for species to complete their life history, e.g. barramundi [8]. • Potentially important for the migration of freshwater prawns [9]. • May promote the growth of algal biomass [10]. • Contribute large woody debris (trees) into the river to provide habitat for fish [11, 12]. • May create poor water quality (low oxygen early during the wet season [13, 14]), and then improve water quality [10].	• Cue the maturation and spawning of some fish [15]. • Maintain geomorphic units (pools, bars, benches, riffles) by bed scour [16, 17]. • Push debris downstream and remove instream macrophyte beds [16]. • Remove fine sediment from the bed of the river, promoting vertical connectivity (i.e. interaction between surface and subsurface waters) in areas with course substrate (e.g. gravel) that promote biogeochemical processes [18]. • Influence the rate of nutrient processing [19].

Principle	Flow	Habitat	Spatial region of literature source		
			Fitzroy River catchment (local)	Tropical northern Australia (regional)	Elsewhere (remote)
6c	Within-bank flows	Flood-runner pools	• Sustain bait fish for Indigenous peoples [20]. • Promote cherabin abundance via the provision of habitat for adults [3]. • *Promote fish dispersal across the floodplain [2].* • *Promote the recruitment and growth of fish [2].*	• May create poor water quality (low oxygen early during the wet season [13, 14], and then improve water quality [10]).	• Support structurally complex habitats [21]. • Provide a spawning and rearing habitat for many fish species [21].
6d	Within-bank flows	Estuary	• Nursery ground for dwarf sawfish [22, 23]. • Promote sawfish recruitment [24]. • Cue the downstream movement of dwarf sawfish from the lower estuarine reaches of the river into King Sound [23]. • Remains unclear if they promote the transfer of marine energy into the riverine food web via the movement of barramundi [25].	• Deliver nutrient inputs into the estuary [26, 27]. • Increase estuarine primary and secondary productivity which in turn promotes the growth and recruitment (stock size) of marine and partially freshwater fish species, such as Barramundi [28-33]. • Drive spatial and temporal variation in estuarine fish diversity and distribution [34, 35]. • May be important for the reproduction and recruitment of freshwater prawns (e.g. cherabin) [4].	• Transport sediment and nutrients from upper catchment to the lowland section of the river and into the estuary [16].

Principle	Flow	Habitat	Spatial region of literature source		
			Fitzroy River catchment (local)	Tropical northern Australia (regional)	Elsewhere (remote)
7a	Over-bank flows	Floodplain	• Mobilise inorganic nutrients (P, N) that may support instream primary production and the food web [36]. • Provide access to certain food sources (terrestrial insects and figs) during the wet season for some fish (e.g. fork-tailed catfish, western sooty grunters) [37]. • Inundate the floodplain longer when topographic relief is low and flood magnitude and duration is longer [38]. • Increase energy stores of fork-tailed catfish during the following dry season [39]. • *May assist large-bodied fish, e.g. barramundi or fork-tailed catfish, to move energy between the floodplain and the river [2].* • *Promote the recruitment and growth of certain fish species by provision of nursery habitat [2].* • Promote the growth of algal biofilm which sustains fish production in floodplain habitats [25]. • *Assist in food production for larval fish by creating zooplankton-rich habitats [2].*	• Support rapid fish growth [40]. In some species (e.g. bony bream) energy is allocated to reproduction [7]. • Create a feeding and breeding habitat for wetland birds, including migratory species such as magpie geese [41, 42]. • Support high rates of primary productivity, i.e. floodplain vegetation biomass [43-45] which may support fish productivity [46]. • May lead to fish kills caused by poor water quality (low oxygen) associated with first flush runoff [13, 14]. • Provide habitat for frogs, turtles and other semi-aquatic species [42]. • Facilitate the dispersal of seeds across the floodplain [47, 48]. • Stimulates migration in terrestrial and aquatic snakes, inundation duration associated with increased recruitment of fishes and their predators [49]. • Inundation duration and rhythmicity correlated with increased catchment scale diversity of fish and aquatic birds [50].	• Facilitate the dispersal of fish between the main-channel and wetlands [17]. • Create hot spots of recruitment and nursery for certain fish [51]. • Promote high transpiration rates and large leaf area in riparian vegetation [52]. • Increase the incorporation of terrestrial matter into the food web [53, 54]. • Promote diversity in plant functional groups, via high velocity flows [55-57]. • Determine the distribution of water plant functional groups [58], via inundation history (hydroperiod). • Recharge the water table and return water to the river channel over the medium term [16, 21].

Principle	Flow	Habitat	Spatial region of literature source		
			Fitzroy River catchment (local)	Tropical northern Australia (regional)	Elsewhere (remote)
7b	Over-bank flows	Riparian zone	• Provide important habitat for terrestrial species, such as the purple-crowned fairy wren [59]. • Leaves provide carbon to support instream aquatic invertebrate production, particularly in headwaters [36]. • Promote zonation of riparian vegetation with distinct species assemblages along a hydrological gradient [60]. • Promote zonation of riparian vegetation with differences in vegetation structure (canopy cover, basal area) along a hydrological gradient [60]. • Influence the occurrence of riparian and floodplain tree species with different species having different flooding preferences [61]. • Support species with high water requirements and tolerant of flood flows [62]. • *Cue the germination and growth of herbaceous annuals and the recruitment of woody perennials [2].*	• Aid seed dispersal and increase the likelihood of deposition in 'safe sites' [47, 48]. • Influence the distribution of *Melaleuca* species [63]. • Shape the species richness, abundance and regeneration of rheophytic species [64]. • Provide access to riparian food sources (fruit, insects) for fishes [65].	• Influence the survival and recruitment of riparian vegetation [66-68].
7c	Over-bank flows	Off-channel wetlands	• Flood flows inundate wetlands longer when topographic relief is low and flood magnitude and duration is longer [38].	• Provide habitat for semi-aquatic species such as frogs and turtles [42, 69, 70]. • Replenish waterholes, improving water quality and the cover of aquatic plants [44].	• Provide drinking water for terrestrial fauna (e.g. kangaroos, birds) [71, 72]. • Shrinkage of wetlands is likely to reduce fish condition and recruitment [73]. • Sustain the water quality of wetlands [74, 75].

Principle	Flow	Habitat	Spatial region of literature source		
			Fitzroy River catchment (local)	Tropical northern Australia (regional)	Elsewhere (remote)
8a	Recessional flows	Riparian zone	• No peer-reviewed ecological literature found	• No peer-reviewed ecological literature found.	• Influence the abundance of riparian tree species [85].
8b 9a	Recessional flows &s low flows/groundwater	Run/riffles	• Provide nocturnal foraging habitat for sawfish and fish [76]. • Reduced water velocity in run habitats promotes the growth of algal biofilm an important energy source for fish [77]. • Maintain hydrological connectivity along the length of the main channel of the river by keeping run habitats inundated for longer [2].	• Sustain spawning habitat for some fish species (e.g. eastern sooty grunter, neosilurid catfish) [5]. • Sustain areas of high invertebrate production leading to enhanced recruitment of some fish species [78]. • Sustain movement of adult and juvenile fish from intermittent stream habitats used for reproduction to perennial dry season refugia [5]. • Provide habitat for species or life stages that prefer fast flowing or very shallow water, such as filter feeding invertebrates, juvenile or larval fish [11, 79]. • Facilitate the movement of fish along the length of the river during low flow periods [80]. • Support increased primary productivity (algae) [81] and secondary productivity (invertebrates) [82] instream.	• Promote downwelling of surface water into the hyporheic zone providing food and habitat for stygofauna [83, 84].

Principle	Flow	Habitat	Spatial region of literature source		
			Fitzroy River catchment (local)	Tropical northern Australia (regional)	Elsewhere (remote)
8c 9b	Recessional flows & low flows/groundwater	Main channel pools	• Sustain a nursery habitat and daytime resting place for sawfish [1, 76]. • Support periphyton that sustains within-pool fish production and biomass [40, 85], and fish and turtle harvesting [86]. • Provide habitat for cherabin during the dry season. Pools close to the estuary, i.e. in the lower reaches of the river, are particularly important for juveniles [3]. • Prevent pool shrinkage, improving the energy stores of fork-tailed catfish [39]. • Provide habitat for fish species during the dry season which are used for cultural harvest, e.g. barramundi [20]. • *Likely assist keeping water quality good as pools shrink [2].* • *May provide ancient dissolved organic carbon that contributes to the aquatic food web [2].*	• Sustain spawning habitat for some fish (e.g. barred grunter, rainbowfish, golden flathead goby) [5, 87]. • Provide a deep cool-water habitat that acts as a refuge (place of high survival) for aquatic biota without a drought-resistant life stage, such as fish, crocodiles and many invertebrates [88]. • Provide complex habitat (logs, macrophyte beds, undercut banks) that provide habitat for fish, cherabin and mussels [11]. • Prevent pool shrinkage and associated deterioration of water quality (e.g. temperature increases, oxygen decreases) [79]. • Limit fish mortality associated with declining water quality [13, 14].	• Limit reduced fish growth and condition associated with water quality decline [89, 90]. • Limit the loss of important habitat for fish [91-93]. • Reduce negative interactions such as competition and predation pressure, as well as reduce the risk of disease and parasite transmission [90, 94-97]. • May support intermittent stream food webs by contributing organic matter [98, 99].
8e 9c	Recessional flows & low flows	Hyporheic zone	• Upwelling water is rich in nutrients and promotes the growth of algal biomass, an important source of energy for fish [77].	No peer-reviewed literature found.	• Create critical habitat for stygofauna [100, 101]. • Cool surface water [100]. • Create a hotspot of biogeochemical transformations that alters nutrient levels and cleans the water [84, 100, 102, 103]. • Provide subsurface connectivity of flows along the river and vertical connectivity between surface water and groundwater [16].

Principle	Flow	Habitat	Spatial region of literature source		
			Fitzroy River catchment (local)	Tropical northern Australia (regional)	Elsewhere (remote)
9d	Groundwater	Off-channel wetlands/ flood-runner pools	• Provide habitat for cherabin, particularly adults [3]. • Provide habitat for fish, including bait fish used for Indigenous hunting [20].		
9e	Groundwater	Aquifer	No peer-reviewed ecological literature found.	• Sustain woodland plants during the dry season [104]. • Create critical habitat for stygofauna [105, 106].	• Groundwater level shape the water vulnerability of individual plants [107, 108].
9f	Groundwater	Springs	• Supply ancient terrestrial carbon that is bioavailable [109]. • Ancient bioavailable carbon may contribute to the aquatic food web [2].	No peer-reviewed ecological literature found	• Creates stable flow that sustains aquatic life and provides nutrients to support the aquatic food web [21, 102].
9g	Groundwater	Riparian zone	• Sustain groundwater-dependent, e.g. *Pandanus aquaticus* which provides habitat for the Endangered Purple-crowned Fairy-wren [59]. • Sustains vegetation that is likely an important source of energy for fish in main-channel pools during the dry season [25]. • In locations where it is available, regional (older) groundwater is used by riparian trees [110]. • Supports tree species with high water requirements [62].	• Sustain riparian plants during the dry season [111-113], although some species rely more heavily on groundwater than others [114].	• Maintain riparian tree species, e.g. gas exchange and canopy cover and condition [115-118]. • Influences root growth rates by riparian species [119, 120].

Principle	Flow	Habitat	Spatial region of literature source		
			Fitzroy River catchment (local)	Tropical northern Australia (regional)	Elsewhere (remote)
10	Antecedent flows	All habitats	• The size of flows during the wet season affects energy stores of fork-tailed catfish during the following dry season [39]. • The size of flows during the wet season affects the recruitment of sawfish [24].	• Exert complex effects on fish. Recent variable flows can adversely impact the abundance of some juvenile fish (e.g. *Hephaestus fuliginosus*) [121], and recent high flows can reduce abundance of juvenile barramundi [121]. Higher wet-season flow can increase the abundance of adult western rainbowfish in some areas but decrease them in others [121]. • Influence macroinvertebrate assemblage structure [79, 122]. • Prolonged flow cessation that extends the dry season may reduce resistance and resilience of macroinvertebrate assemblages [79].	• Influence fish recruitment [89, 123, 124], abundance [91, 124], and distribution across the catchment [124, 125]. • Shape the distribution of riparian plants functional types [reviewed in 66, 68]. • Can cause the loss of species, particularly sensitive species e.g. consecutive years of low flow [123, 125]. • Increased occurrence of extreme hydrologic events (floods, droughts) changing water quality, habitat availability and connectivity [126] • Can compound the effect of water withdrawal, increasing the risk of the loss of fish species [127].

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Appendix 2: Scientific evidence from the Fitzroy River

Table S2. Scientific evidence from the Fitzroy River supporting the updated conceptual model. Text in black is published, or nearly published, scientific evidence from this project. Grey text is published evidence from other research. Black italicised text is unpublished evidence from this project.

Flow component	Habitat	Link to conceptual model & principles	Biotic/abiotic element	Relationship	Evidence summary	Scientific evidence	Spatial context	Temporal context	Reference	Externally peer-reviewed
Within-bank	Main-channel depth	6a	Cherabin (*Macrobrachium spinipes*)	Habitat-biota	May promote cherabin recruitment by transporting larvae to an estuarine nursery.	Predictive modelling accounting for variable detection revealed that juvenile cherabin were predominantly located in main-channel pools in the lower reaches of the river. [Indirect evidence regarding the use of an estuarine nursery.]	HIGH n = 44 sites in main channel and floodplain habitats in the lower section of the river sampled over 70 sampling events.	LOW Dry-season sampling (Jun–Dec) for two years (2018, 2019). One year had a medium wet the other year had a very small wet.	Beesley et al. in prep. Freshwater Biology	No
Within-bank	*Main-channel depth*	*6a*	*Fish assemblage*	*Habitat-biota*	*May cause blackwater events leading to fish kills and a decline in species richness.*	*Early wet-season flow caused a blackwater event and an oxygen crash leading to the loss of several fish species.*	*V LOW* *n = 1 site low in the main channel.*	*LOW* *Longitudinal study sampling same site on 4 occasions (2019).*	*NESP 1.3.3 unpublished data*	*No*
Withinbank	Scouring flows	6b	Riparian trees	Biotic characterisation	Support species with high water requirements and tolerant of flood flows.	*Melaleuca argentea, M. leucadendra* and *Eucalyptus camaldulensis* have low water-use efficiency, making them vulnerable to drought, and their leaf and stem traits allow them to survive high-velocity flows.	LOW 1 site, 9 species, n = 10 trees/spp.	LOW sampled in one dry season.	Canham et al. in prep. Tree Physiology	No
Within-bank, overbank, recessional, groundwater	Flood-runner pools, off-channel wetlands, main-channel pools	6c, 7c, 9c	Cherabin (*Macrobrachium spinipes*)	Flow-habitat-biota	Promote cherabin abundance by the provision of habitat.	Predictive modelling accounting for variable detection coupled with habitat mapping indicated that cherabin abundance was greater in a year following larger wet season flow due to the provision of more habitat.	HIGH n = 44 sites in main channel and floodplain habitats in the lower section of the river sampled over 70 sampling events.	LOW Dry-season sampling (Jun–Dec) for two years (2018, 2019). One year had a medium wet the other year had a very small wet.	Beesley et al. in prep. Freshwater Biology	No
Within-bank, overbank	*Flood-runner pools*	*6c, 7a, 7c*	*Fish assemblage*	*Flow-biota*	*Promote fish dispersal across the landscape.*	*Fish species richness in flood-runner pools was higher in during years with short within-bank flows than a year with very little wet-season flows, and highest in a year with protracted overbank flows.*	*Work in progress*	*Work in progress*	*NESP 1.3.3 unpublished data*	*No*
Within-bank; groundwater/low flow	*Main-channel pools, flood-runner pools, off-channel wetlands*	*6c, 9c, 9e*	*Fish assemblage*	*Habitat-biota*	*Habitat for fish species during the dry season, some of which are important for Indigenous harvest or bait fish.*	*Pools in main-channel and floodplain habitats are habitat for fish, including fish used as bait by Indigenous people and fish used as harvest (e.g. barramundi, fork-tailed catfish).*	*Work in progress*	*Work in progress*	*NESP 1.3.3 unpublished data*	*No*
Within-bank	*Main-channel pools*	*6c*	*Food web*	*Habitat-biota*	*May assist large-bodied fish species to move energy between the floodplain and the river.*	*Stable isotopes of C and N indicated that muscle tissue of barramundi and fork-tailed catfish was poorly coupled to*	*MODERATE* *n= 11 sites in 2018 and 13 sites in 2019. Sites spread ~300 km along*	*LOW* *Dry-season sampling (Jun–Oct) for two years (2018, 2019).*	*NESP 1.3.3 unpublished data*	*No*

Flow component	Habitat	Link to conceptual model & principles	Biotic/abiotic element	Relationship	Evidence summary	Scientific evidence	Spatial context	Temporal context	Reference	Externally peer-reviewed
						local algal biofilm sources, suggesting their energy came from remote sources, e.g. floodplain or estuary.	*the river from near Willare to lower Margaret River.*			
Within-bank	Estuary	6d	Dwarf sawfish (*Pristis clavata*)	Flow-biota	Cue the downstream movement of dwarf sawfish from the lower estuarine reaches of the river into King Sound.	Seventeen sawfish tagged. General additive mixed-effects models indicated that sawfish occupancy at a site was dependent on river discharge.	MODERATE 10 acoustic receivers spread across ~100 km and spanning the lower reaches of the river (estuarine and into freshwater) and King Sound.	MODERATE 1.5 years (Aug 2015 to Aug 2017)	Morgan et al 2021. Aquatic Conservation	Yes
Within-bank	*Estuary*	*6d*	*Barramundi (Lates calcarifer)*	*Food web characterisation*	*Unclear if wet-season flow to estuary will affect the movement of marine energy into the river.*	*Assessment of energy subsidies using sulphur isotopes was complicated by naturally high sulphur-34 levels high in the catchment.*	*Work in progress*	*Work in progress*	*NESP 1.3.3 unpublished data*	*No*
Within-bank, overbank	*Flood-runner pools*	*6c, 7c*	*Fish assemblage*	*Habitat-biota*	*Promote recruitment of certain fish species by provision of nursery habitat.*	*Floodplain habitats support greater abundances of young-of-year size classes of many fish species.*	*Work in progress*	*Work in progress*	*NESP 1.3.3 unpublished data*	*No*
Within-bank, overbank	*Flood-runner pools*	*6c, 7c*	*Bony bream (Nematalosa erebi)*	*Habitat-biota*	*Replenish floodplain habitats supporting the rapid growth of juvenile bony bream.*	*Juvenile bony bream grew faster in floodplain pools compared to the mainchannel pools*	*Work in progress*	*Work in progress*	*NESP 1.3.3 unpublished data*	*No*
Within-bank, antecedent	Main-channel pools, flow to estuary	6d, 10	Sawfish (*Pristis pristis*)	Flow-biota	Promote sawfish recruitment.	Positive relationship between wet-season flow and catch-per-unit-effort (CPUE) of young-of-year sawfish in freshwater pools. Flow metric that best described CPUE was the number of days that river height was >8.1 m at the Willare gauge.	MODERATE n=10 sites, four estuarine pools and six freshwater pools. Main channel lower catchment.	VERY HIGH Early dry-season sampling for 17 years (2002–2018).	Lear et al. 2019 Scientific Reports	Yes
Within-bank, overbank	*Flood-runner pools*	*6c, 7c*	*Zooplankton*	*Habitat-biota*	*Enhance zooplankton abundance, providing more food for larval fish and waterbirds.*	*Zooplankton density was higher in floodplain pools compared to main-channel pools.*	*MODERATE* *n=20 sites, five main-channel pools and 15 floodplain pools.*	*LOW* *Late dry season. One year (2020).*	*NESP 1.3.3 unpublished data*	*No*
Within-bank, overbank	Off-channel wetlands	6c, 7a, 7c	Fish assemblage	Habitat-biota	Promote the growth of algal biofilm, supporting fish production in floodplain habitats.	Stable isotope mixing models (mixSIAR) revealed that fish on the floodplain during the wet season were sustained predominantly by local algal biofilm. Specifically, 60% of fish on the floodplain obtained more than 50% of their dietary carbon from algal biofilms.	LOW n=4 sites on the floodplain.	LOW N=1 year (2018).	Beesley et al 2020 Scientific Reports	Yes
Overbank	Floodplain inundation	7a	Fish assemblage	Habitat-biota	Energy produced on floodplain plays a negligible role supporting fish biomass in dry-season pools.	Fish in dry-season pools on the floodplain and in the main channel obtain their energy primarily from local within-pool sources of energy (e.g. algal biofilm carbon).	MODERATE 19 sites in mid to upper part of the Fitzroy valley.	LOW One sampling event in July 2008 (mid dry).	Jardine et al 2012 Journal of Animal Ecology	Yes

Flow component	Habitat	Link to conceptual model & principles	Biotic/abiotic element	Relationship	Evidence summary	Scientific evidence	Spatial context	Temporal context	Reference	Externally peer-reviewed
Overbank	Floodplain inundation	7a	Water chemistry	Habitat characterisation	Mobilise inorganic nutrients (N, P) that may support instream primary production and the food web.	Leachate ammonium from floodplain sediment was high from one site (Adcock River) suggesting that floodplain sources may contribute to stream-water nutrients.	LOW n=3 sites, all sites in the headwaters of the river not in the Fitzroy valley.	V LOW One sampling occasion June 2009.	Fellman et al 2013 Freshwater Science	Yes
Overbank	Floodplain inundation	7a	Food web	Food web characterisation	Provide access to certain food sources during the wet season for some fish.	Gut content analysis revealed that ~19% of the diet of fork-tailed catfish during the wet was figs. Western sooty grunters consumed 30% figs during the wet season.	V LOW One site (Geike Gorge).	LOW TO MODERATE Three occasions: Jun 2003 (mid-dry), Nov 2003 (late dry), Mar 2004 (wet)	Thorburn et al 2014 Journal of the Royal Society of Western Australia	Yes
Overbank	Floodplain inundation	7a, 7c	Hydrology	Flow-habitat Flow-flow	Inundate the floodplain longer when topographic relief is low and flood magnitude and duration is longer.	A hydrodynamic model revealed that the duration of connection of individual wetlands to the river varied depending on flood magnitude and duration. Topographic relief, location on the floodplain and magnitude and duration of the flood were key factors controlling connectivity.	HIGH n=30 off-stream wetlands examined.	HIGH Gridded rainfall from 1890 to 2011. River discharge data from gauges from 1955 onwards.	Karim et al 2016 Hydrological Processes	Yes
Overbank	Floodplain inundation	7a	Sawfish (*Pristis pristis*)	Flow-biota	Increases food production leading to greater sawfish body condition.	Sawfish had higher body condition in years with greater wet-season flows and poorer condition with lower flows and little occurrence of overbank flooding.	V LOW Two pools in the lower main channel of the river.	V HIGH n=12 years (2008–2009).	Lear et al 2021 Science of the Total Environment	Yes
Overbank	Riparian inundation	7b	Terrestrial birds	Habitat-biota	Provide important habitat for terrestrial species such as the purple-crowned fairy wren.	The probability of occurrence of the wren increased with the crown cover of *Pandanus aquaticus.*	MODERATE n=26 sites in the Fitzroy surveyed – all site in headwaters. Another 34 sites surveyed in other Kimberley rivers.	MODERATE Surveys over three years (2007-2009) during the dry season	Skroblin and Legge 2012 Austral Ecology	Yes
Overbank	Riparian inundation	7b	Food web	Food web characterisation	Leaves provide carbon to support instream aquatic invertebrate production, particularly in headwaters.	Stable isotopes (C, N) revealed that invertebrate consumers were supported by a range of in-stream and floodplain (allochthonous leaf litter) sources.	LOW n=3 sites – all sites in the headwaters of the river not in the Fitzroy valley.	V LOW One sampling occasion (June 2009).	Fellman et al 2013 Freshwater Science	Yes
Overbank	*Riparian inundation*	*7b*	*Riparian trees*	*Habitat-biota*	*Promotes zonation of riparian vegetation with distinct species assemblage along a hydrological gradient.*	*The composition of species differed between landscape positions.*	*MODERATE* *n=58 sites, 10x40 m quadrats*	*LOW* *Tree surveys in one dry season, hydrological data from 2000 and 2013.*	*Freestone et al. in prep. Australian Journal of Botany*	*No*
Overbank	*Riparian inundation*	*7b*	*Riparian trees*	*Habitat-biota*	*Promotes differences in vegetation structure (canopy cover, basal area) along a hydrological gradient.*	*Canopy cover and basal area were greatest along the riverbanks and smallest on the floodplain. Off-channel wetlands and flood-runners also support high canopy cover.*	*MODERATE* *n=58 sites, 10x40 m quadrats*	*LOW* *Tree surveys in one dry season; hydrological data from 2000 and 2013.*	*Freestone et al. in prep. Australian Journal of Botany*	*No*

Flow component	Habitat	Link to conceptual model & principles	Biotic/abiotic element	Relationship	Evidence summary	Scientific evidence	Spatial context	Temporal context	Reference	Externally peer-reviewed
Overbank	Riparian inundation	7b	Riparian trees	Flow-biota	Influences the occurrence of riparian and floodplain tree species.	Duration of inundation is an effective predictor of occurrence for riparian tree species. Under water-take scenarios, species associated with the wettest habitats showed the greatest decrease in occupancy.	MODERATE n=58 sites, 10x40 m quadrats	LOW Tree surveys in one dry season; hydrological data from 2000 and 2013.	Canham et al. 2021a Freshwater Biology	Yes
Overbank	*Off-channel wetlands*	*7c*	*Riparian and wetland plants*	*Flow-biota*	*Cue the germination and growth of herbaceous annuals and the recruitment of woody perennials.*	Pending analysis, but preliminary results of a glasshouse seedbank experiment indicate that different watering treatments prompt the germination of different composition of species. It is also likely that there are differences in species composition between wetlands with different water regimes.	*MODERATE* *Five wetland sites, three riverbank, three top-of-bank.*	*LOW* *Sampled in one dry season (2020).*	*NESP 1.3.3 unpublished data*	*No*
Groundwater/low flow	*Main-channel depth*	*8a*	*Fish assemblage*	*Habitat-biota*	*Increase the probability of survival for certain fish species.*	*Hierarchical occupancy models accounting for variable detection reveal that the occupancy probability of certain fish species decreases below certain pool depth.*	*Work in progress.*	*Work in progress.*	*NESP 1.3.3 unpublished data*	*No*
Groundwater/low flow	Main-channel pools	8d	Fork-tailed catfish (*Neoarius graeffei*)	Habitat-biota	Mitigates pool shrinkage, improving the energy stores of fork-tailed catfish.	Catfish coelomic and intramuscular fat stores during the dry season were greater for fish living in larger or deeper pools.	MODERATE n=27 sites for body condition metrics. Sites spanned the lower section of the river and also included some upland tributary sites. Total of 17 sites for intramuscular and coelomic fat.	LOW Dry season sampling (Jun–Dec) over three years for body condition. Other energy metrics were only examined over two years (2018, 2019).	Beesley et al 2021 Freshwater Biology	Yes
Groundwater/low flow	Main-channel pools, runs and riffles	8c, 9c and 8c, 9b	Sawfish (*Pristis pristis*)	Habitat-biota	Juvenile sawfish rest during the day in deeper pools near logs and were more active during the night when they moved into shallower habitats such as pool edges and runs to forage.	32 juveniles tagged and monitored using acoustic telemetry. GAMMs and multimodel inference (AIC) used to assess strength of relationships between sawfish presence and habitat variables.	LOW Two sites in the lower river (Myroodah and Camballin).	HIGH Eight years (2008–2015).	Whitty et al 2017 Endangered Species Research	Yes
Groundwater/low flow	Main-channel depth	9a	Dwarf sawfish (*Pristis clavata*)	Flow-biota	Juvenile dwarf sawfish move upstream from the estuary and King Sound into the lower reaches of the river.	Seventeen sawfish tagged with acoustic transmitters revealed that sawfish moved from King Sound into the estuarine reaches of the river during dry-season low flows.	MODERATE 10 accoustic recievers spread across ~100 km and spanning the lower reaches of the river (estuarine and into freshwater) and King Sound.	MODERATE 1.5 years (Aug 2015 to Aug 2017).	Morgan et al 2021. Aquatic Conservation	Yes
Groundwater/low flow	*Runs and riffles, main-channel pools*	*9a*	*Hydrology*	*Hydrologic characterisation*	*Promote hydrological connectivity along the length of the river during the dry season.*	*Hydrological connectivity during the dry season was greater in parts of the river with*	*Work in progress.*	*Work in progress.*	*NESP 1.3.3 unpublished data*	*No*

Flow component	Habitat	Link to conceptual model & principles	Biotic/abiotic element	Relationship	Evidence summary	Scientific evidence	Spatial context	Temporal context	Reference	Externally peer-reviewed
						connections to deep groundwater.				
Groundwater/low flow	Runs and riffles	9b	Algal biofilm	Flow-biota	Low water velocity promotes the growth of algal biofilm, an energy source for some fish.	The biomass of algal biofilm (fish food source) was greatest in locations with low velocity.	V LOW n=2 sites, lower catchment, main channel; ~250 total sampling points.	V LOW One week in late dry season (mid-Aug 2018).	Burrows et al 2020 Hydrobiologia	Yes
Groundwater/low flow	Main-channel pools	9c	Dwarf sawfish (Pristis clavata)	Habitat-biota	Sawfish use estuarine reaches of the river as habitat during low flows.	Seventeen sawfish tagged with acoustic transmitters revealed that sawfish reside in estuarine reaches of the river.	MODERATE 10 acoustic receivers spread across ~100 km and spanning the lower reaches of the river (estuarine and into freshwater) and King Sound.	MODERATE 1.5 years (Aug 2015 to Aug 2017).	Morgan et al 2021. Aquatic Conservation	Yes
Groundwater/low flow	*Main-channel pools, off-channel wetlands*	*9c, 9e*	*Temperature, dissolved oxygen*	*Habitat-habitat*	*May assist to maintain good water quality as pools shrink.*	*Pending analysis. Pool shrinkage increased water temperature but had little impact on oxygen.*	*LOW* *n=4 main channel sites, 3 floodplain sites.*	*V LOW* *n=2–4 occasions during one very dry year (2019).*	*NESP 1.3.3 unpublished data*	*No*
Groundwater/low flow	*Main-channel pools, springs*	*9c, 9g*	*Food web*	*Food web characterisation*	*May deliver ancient dissolved organic carbon that contributes to the food web.*	*Preliminary data using C14 tracing suggests that ancient carbon is incorporated into algal biofilms in some aquatic habitats.*	*Work in progress.*	*Work in progress.*	*NESP 1.3.3 unpublished data*	*No*
Groundwater/low flow	Hyporheic zone	9d	Algal biofilm, water chemistry	Habitat-biota	Upwelling water promotes production of algal biofilm, an energy source for some fish.	The biomass of algal biofilm was greater in patches with greater groundwater upwelling.	V LOW n=2 sites; 15 sample points within each site; lower catchment, main-channel.	V LOW One week in late dry season (mid-Aug 2018).	Burrows et al 2020 Hydrobiologia	Yes
Groundwater/low flow	Springs	9g	Water chemistry	Habitat-abiotic	Provides ancient dissolved organic carbon which is highly bioavailable and may contribute to the aquatic food web.	The bioavailability of dissolved organic carbon was greatest in headwater streams that were fed more by groundwater and contained more ancient carbon than downstream sites that received more surface water and younger carbon.	HIGH n=22 streams and 1 spring (NB. only three sites in Fitzroy River, other sites in other Kimberley rivers; no springs sampled in Fitzroy, just headwater sites with high groundwater inputs).	LOW Samples collected in either May 2010 of June 2011.	Fellman et al 2014 Ecology	Yes
Groundwater/low flow	Riparian groundwater	9h	Fish assemblage	Habitat-biota	Sustains vegetation that is an important source of energy for fish in main-channel pools during the dry season.	Fish, particularly small-bodied species, living in dry-season main-channel pools are sustained by carbon originating from leaf litter and/or phytoplankton.	V LOW n=3 sites located in lower river.	V LOW One sampling event during one year (Oct 2017).	Beesley et al 2020 Scientific Reports	Yes
Groundwater/low flow	Riparian groundwater	9h	Riparian trees	Habitat-biota	In locations where it is available, regional (older) groundwater is used by riparian trees.	Dry-season groundwater use by riparian trees varies between sites.	V LOW One site with regional groundwater, one site alluvial groundwater.	V LOW Two weeks in the dry season (2019).	Canham et al 2021bHydrological Processes	Yes
Groundwater/low flow	*Riparian groundwater*	*9h*	*Riparian trees*	*Biotic characterisation*	*Support species with high water requirements*	*Species associated with high water availability (i.e. M. argentea, M. leucadendra and*	*V LOW*	*V LOW*	*Canham et al. in prep. Tree Physiology*	*No*

Flow component	Habitat	Link to conceptual model & principles	Biotic/abiotic element	Relationship	Evidence summary	Scientific evidence	Spatial context	Temporal context	Reference	Externally peer-reviewed
					and tolerant of flood flows.	*E. camaldulensis) had lower osmotic water potential and water-use efficiency (indicated by 13C).*	*One site, different landscape positions (riverbank to floodplain).*	*Two weeks in the dry season (2019).*		
Antecedent flows	Main-channel pools, flood-runner pools	10	Fork-tailed catfish (*Neoarius graeffei*)	Flow-biota	Increase energy stores of fork-tailed catfish, during the following dry season.	Catfish body condition and intramuscular fat stores during the dry season were greater in years following larger wet-season flows. Coelomic and intramuscular fat were lower in smaller pools. Total fish examined varied from 332 fish for body condition analysis to 130 for intramuscular fat and 102 fish for coelomic fat.	MODERATE n = 27 sites for body condition metric. Sites spanned the lower section of the river and also included some upland tributary sites. Total of 17 sites for intramuscular and coelomic fat.	LOW Dry season sampling (Jun–Dec) over three years for body condition. Other energy metrics were only examined over two years (2018, 2019).	Beesley et al 2021 Freshwater Biology	Yes