Water abstraction impacts on flow dependent fisheries species of the Northern Territory, Australia

- a synthesis of current knowledge and future research needs

Final Report 2023

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Abbreviations

AROWS	Adelaide River Offstream Water Storage (AROWS)
FB	Flow-biota relationship
FHB	Flow-habitat-biota relationship
FL	Fork length
IFB	Inferred flow-biota relationship
II	Inferred impact
MI	Measured impact
MDB	Murray Darling Basin
NPF	Northern Prawn Fishery
NT	Northern Territory
NT RAC	Northern Territory Research Advisory committee
PI	Predicted impact
QLD	Queensland
SST	Sea Surface Temperature
SOI	Southern Oscillation Index
TL	Total length
UN	United Nations
WA	Western Australia

Executive summary

This project was funded to provide the Northern Territory Research Advisory committee (NT RAC) with synthesised information that could be used to help guide decision making around the protection of fisheries species that may be impacted by water abstraction. This review was led by Griffith University and conducted in collaboration with the University of Western Australia, Charles Darwin University, and the Northern Territory Fisheries.

Firstly, we conducted a global systematic literature review on the impacts of water abstraction on tropical aquatic species in general. Fewer studies measuring impacts have been conducted in northern Australia compared to many other tropical regions, which is consistent with the lower number of developments in northern Australia compared to many other regions. However, we found that Australia (along with South America) leads the research effort for tropical flow-ecology studies, with many of the Australian flow-ecology studies using quantified flow-biota relationships to predict impacts of water abstraction on aquatic species. Secondly, we reviewed grey and published flow related literature on NT fisheries species, most of which are found across northern Australia. This information was then synthesised to provide expert opinion on the likely impacts on these species of various environmental changes arising from water abstraction, including from wet season water abstraction, in-channel dams, and dry season groundwater extraction/direct pumping from river channels. Some of these impacts are described briefly here with more information available in Section 3. There is also an Excel attachment made available that lists the flow related research collected on these species and provides a table of information on the location, type of study, scale, and results of each study.

We found that research effort was skewed towards Barramundi, Banana Prawns, and Giant Mud Crabs, with few flow related studies found for Spangled Perch, Cherabin, Black Catfish, King Threadfin, Golden Snapper, and Black Jewfish. More research is needed on the flow dependence of the life cycle of less well studied species including Black Jewfish, Golden Snapper, and forktail catfish species. Available evidence suggests that the timing and magnitude of river flows is important for spawning and recruitment migrations for some freshwater (Black Catfish, Sooty Grunter, and Spangled Perch), euryhaline (Barramundi, Mullet, Cherabin), and coastal species (Giant Mud Crabs, Northern Prawn Fishery (NPF) prawn species). Flow in northern Australia is influenced by monsoonal climate cycles and catch and recruitment of Giant Mud Crabs, NPF prawns, and Barramundi has been linked to climate cycles such as the Australian Monsoon Index and Southern Oscillation Index.

Wet season flood flows were found to be important for lateral connectivity, with species such as Barramundi, Cherabin, forktail catfish species, and Spangled Perch utilising floodplain inundation to access productive floodplain habitats to feed. Wet season water abstraction would reduce wetland flushing, impacting water quality in wetlands which serve as dry season aquatic refugia and productivity hotspots. Wet season water abstraction would also reduce lateral connectivity via reduced floodplain inundation, limiting the opportunity for movement between the river channel and floodplain (Fig. 1).

Lateral connectivity is also important for the transfer of nutrients from the floodplain to the estuary, a nutrient poor environment, fueling food web productivity and providing food for the growth and survival of coastal species such as NPF prawns and Giant Mud Crabs. In-channel dams would likely impact estuarine habitat for these coastal species through changes to sediment transport and reduced salinity via artificial flow releases in the dry season (Fig. 2). Reduced estuarine salinity has been shown to reduce benthic meiofauna abundance and diversity and cause seaward emigration of prawns to areas of higher salinity.

Longitudinal connectivity is particularly important for euryhaline species (including threatened sawfish) to migrate between the estuary and freshwater to fulfill important life history stages and for freshwater species to move through freshwater reaches to forage, find refuge in the dry season, and find suitable spawning habitat. Altered water volume will influence longitudinal connectivity, the size, quality, and persistence of dry season refuge pools, and availability of habitat. Interannual variability in flow is important for the life history diversity of fisheries species, with wet years increasing connectivity and supporting higher life history diversity through contributions to the fishery of reproducing individuals that move between freshwater and the coast.

Freshwater habitat will be impacted by reduced water volume as water is taken from the river, particularly by in-channel dams and dry season water abstraction (Fig. 2 & 3). Many freshwater and euryhaline species show strong habitat affinity, with Barramundi, adult Sooty Grunter, Spangled Perch, and forktail catfish species distribution associated with pool depth and size, and shallow riffle habitat critical for juvenile Sooty Grunter. Some studies have modelled changes to the area and persistence of habitat characteristics under water development scenarios and found even low levels of water extraction could have severe impacts on habitat availability and persistence.

Additional to impacts caused by changes to water volume are infrastructure and water quality impacts. Infrastructure impacts can be acute to many of the freshwater and euryhaline fisheries species, including entrainment in pumps, entrapment in reservoirs and irrigation channels, and even small road crossings can severely impede movement to refuge pools critical for survival through the dry season. However, the severity of many infrastructure impacts can be reduced through design measures such as fishways, pump positioning, and irrigation screens. Mining and agricultural activities can contaminate aquatic ecosystems, which can be compounded by lower flushing rates due to water abstraction, causing additional stress to organisms.

Other factors such as climate change and the cumulative impacts of multiple, small water developments also need to be considered but there is little research on these topics for northern Australian rivers, warranting further investigation.

This review highlighted the need for future studies that measure the impacts of existing water developments, to determine if impacts differ from subtropical and temperate regions in Australia for which there is more available evidence of existing impacts, and to determine if rules set to limit water take for environmental protection measures are adequately protecting species that face additional pressures from fishing activities. Managers will benefit from studies that quantify relationships between flow and critical components of survival for these fisheries species, including growth, condition, reproduction, and movement, so that various scenarios can be run in optimisation models to find lowest impact solutions. Environmental Impact Statements and long-term monitoring programs are useful tools that if implemented properly will help to better understand current and future impacts.

In summary, our synthesis of existing information on the impacts of water abstraction found substantial evidence for impacts on some species and large gaps in the research literature for others. The reviewed studies showed that the severity of predicted impacts varies between river systems and between different modes of water abstraction, as well as with different timing, magnitude, and thresholds of water take. We conclude that the collective results of these studies modelling potential impacts of water abstraction warrant a precautionary approach to setting water takes, with particular emphasis on ensuring the continuation of high flow years which disproportionately support fishery biomass. We recommend that the flow dependencies of these species be carefully considered when implementing water policies and research be conducted to fill knowledge gaps for species where little is known about their dependency on the natural flow regime.

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1. Introduction

This project aimed to synthesise available information on the impacts of water abstraction on fisheries species in the Northern Territory (NT) that are commonly harvested and have components of their life history that are dependent on the natural flow regime. We achieved this by synthesising current information, providing expert opinion for species with little available information, and identifying future research needs. Firstly, we report the results of a global literature review conducted to understand how research is carried out on the impacts of water abstraction on tropical aquatic species in general. We then conducted a directed search of grey and published literature for flow related research for the focal NT fisheries species. The table in this report presents the collected flow related literature synthesised into likely responses of these species to environmental changes incurred due to water abstraction. Following the table, descriptions of impacts to each species or species group are presented, with expert opinion used to discuss likely impacts for species with little available information. Later sections of the report then discuss other factors influencing species responses (e.g. cumulative impacts and multiple stressors) and provide an assessment of knowledge gaps and future research needs.

1.1 River flow and water resource development

The timing, magnitude, frequency, duration, and rate of change of river flows are critical components of the natural flow regime that support river ecology (Poff *et al.*, 1997). Highly seasonal precipitation in the wet-dry tropics of northern Australia causes high river flow in summer that progressively recedes throughout the winter, and in some rivers, flow ceases prior to the next wet season (McJannet *et al.*, 2014). In free-flowing tropical rivers, the flow regime provides lateral connectivity to seasonally inundated habitats, including creeks, floodplains, and floodplain wetlands, and longitudinal connectivity of in-channel riverine habitats with downstream estuarine and coastal zones (Pettit *et al.*, 2017; Stoffels *et al.*, 2014). This connectivity supports ecosystem processes through the transfer of energy across habitats and delivery of nutrients to the coast which drives estuarine productivity (Burford *et al.*, 2011; Jardine *et al.*, 2015; Saboret *et al.*, 2021). Tropical floodplain wetlands can be highly productive habitats and may serve as aquatic refuges for organisms during the dry season and drought (Pettit *et al.*, 2011; Waltham *et al.*, 2014). Fish use seasonal flood pulses to move to and from floodplain wetlands, facilitating the transfer of energy between floodplain and in-channel/estuarine environments (Jardine *et al.*, 2012; O'Mara *et al.*, 2021a). The reconnection of in-channel habitats with wet season flows is also important for riverine ecology as it provides opportunities for local and large-scale movements by aquatic organisms for different aspects of their life history, such as refuge migrations to areas with permanent water, catadromous movements to the sea for spawning, and drift of eggs and larvae of amphidromous organisms to the estuary (Benitez *et al.*, 2018; Bond *et al.*, 2015; Novak *et al.*, 2016).

Climate change and water resource developments (e.g. dams, weirs, water extraction) affect the natural flow regime through changes to the timing and magnitude of seasonal flow pulses. They may also alter the connectivity of river networks which causes river fragmentation (Ward & Stanford, 1995). River regulation can change the temporal variability of flows by altering the seasonality of low to moderate flows, and reducing flood pulses (Humphries *et al.*, 1999). Water resource developments are a global threat to river connectivity, with less than half of the world's large river systems remaining free flowing (Grill *et al.*, 2019). Biodiversity loss increases when multiple barriers to flow (such as dams) are present along a river (Grill *et al.*, 2019). These barriers inhibit access to habitats used for spawning, foraging, and refuge, and trap sediment and nutrients needed to fuel downstream primary productivity, which has cascading effects to higher trophic levels (Liermann *et al.*, 2012). River fragmentation consequences extend beyond environmental impacts, since free-flowing rivers also provide important economic and societal ecosystem services, including productive fisheries (Grill *et al.*, 2019; Vörösmarty *et al.*, 2010).

1.2 Types of water abstraction and development in the Northern Territory

Rivers of the Northern Territory, Australia, are globally unique in that most remain largely free-flowing with intact longitudinal (within channel), lateral (river channel to floodplain) and vertical (surface to ground water) connectivity (Grill *et al.*, 2020). Water resource development in the region is less intensive than many other tropical regions around the globe and has historically focused on the extraction of groundwater resources with approximately 90% of the annual water supply in the Northern Territory provided by ground water and 10% from surface water environments (NT Government, 2023a). New proposals (Beaumont *et al.*, 2022) and policies (NT Government., 2022) are being developed to expand surface water abstraction in the Northern Territory for various uses, including agriculture and drinking water.

Pumping from groundwater bores currently represents the largest source of freshwater abstraction in the NT. The Northern Territory government lists 603 current groundwater licenses with maximum entitlements exceeding 320.5 GL/year extending from arid zones in the Alice Springs and Western Davenport Plains regions up through tropical systems near Darwin (NT Government., 2016). Surface water flows in some of the large free-flowing northern rivers, such as the Daly and Roper, are heavily dependent on groundwater inputs particularly during the dry season and during wet seasons with low rainfall when groundwater inputs maintain flow in perennial reaches (Petheram *et al.*, 2008). For example, groundwater inputs represent approximately 45% of base flow (Smerdon *et al.*, 2012) in the Daly River, and a diverse range of spring ecosystems in the Roper catchment are supported almost exclusively by groundwater recharge (Lamontagne *et al.*, 2021). Most rivers in the wet-dry tropics of Australia are intermittent (Petheram *et al.*, 2008). However, perennial rivers are also present and have a distinct ecology, highlighting the importance of maintaining their flowing status (Leigh & Sheldon, 2009; Pusey *et al.*, 2011). For example, the majority of fish reproduction in the Mitchell River (QLD) occurs in the perennially flowing main channel (Stewart-Koster *et al.*, 2021). Over-extraction of groundwater resources has potential to alter vertical connectivity and low-flow hydrology (King *et al.*, 2015) of northern Australian wet-dry rivers with potential effects on fish populations and fisheries due to reductions in connectivity, saltwater intrusion and reduced water quality, reduced availability of in-channel habitat, altered persistence of refuge habitat, and the loss of groundwater dependent ecosystems. Furthermore, groundwater environments of the Northern Territory themselves host newly discovered stygofauna communities of Crustaceans (Oberprieler *et al.*, 2021) which merit conservation management and scientific attention.

Surface water ecosystems including rivers, creeks, floodplain wetlands, and impoundments directly supply approximately 50 GL of water per year in the Northern Territory, and most of this is currently used for urban or remote community water supply (80%) followed by agriculture and pastoral uses (18%) and other uses (2%) (NT Government, 2023b). There are two major reservoirs in the NT including the Darwin River (303 GL) and Manton (14 GL) reservoirs, several smaller (e.g. Mary Anne reservoir (0.45 GL)), and one 255 GL drinking water reservoir proposed to be built near the Adelaide River as part of the Adelaide River Offstream Water Storage (AROWS) project (NT Government Water Security, 2022). The AROWS development proposes to utilise a natural geological basin in the Adelaide River catchment as an off-channel storage and will pump water from the river into it during the wet season for distribution to the Darwin regional water supply system (NT Government Water Security, 2022).

Surface water abstraction will have varied impacts depending on the mode and timing of water take, and it is important to understand the ecohydrological impacts during each limb of the hydrograph (low/no flows, first wet season flows, overbank flows, and recessional flows), as well as during low, moderate, and high flow years (Douglas *et al.*, 2019). Water abstraction in the NT currently mostly occurs during the dry season when water is in demand for human uses, but this is also a time when river-floodplain ecosystems and freshwater fish populations in northern Australia can be vulnerable to changes in low-flow hydrology (King *et al.*, 2015). Similar to the effects of groundwater abstraction, surface water abstraction during the dry season may adversely affect fish populations and fisheries via reductions in connectivity, saltwater intrusion and reduced water quality, reduced availability of in-stream habitat, and loss of refuge habitat (Fig. 2). While most surface water abstraction in the NT has previously occurred during the dry season, a new 'Surface Water Take - Wet Season Flows Policy' has been drafted by the Northern Territory government (NT Government., 2022) and new developments have been proposed that will access this water. Additional new wet season water abstraction proposals are anticipated that will support contentious (Beaumont *et al.*, 2022) business cases to rapidly expand cotton production in the NT from approximately 4,500 bales in 2019 to over 400,000 bales by 2029 (Pricewaterhouse Coopers Australia, 2019). A proportion of the cotton may be produced using dry-land farming methods without irrigation. However, there is little peer-reviewed evidence available quantifying volumes of surface water abstraction required to support the expansion of the cotton industry in the NT, and therefore the potential impacts on fisheries and ecosystems are largely unknown.

While wet season water abstraction is likely to have different impacts to dry season/low flows abstraction (Figs. 1 & 2), peer-reviewed evidence does not support one of these methods having less ecological impact than the other. Wet season abstraction and off-channel storage does not pose a barrier impact to the river channel environment, however, there are other important ecological impacts that need to be acknowledged and understood. A substantial body of research shows that wet season floods maintain lateral and longitudinal connectivity in tropical river, floodplain, and wetland ecosystems (Junk *et al.*, 1989; Pettit *et al.*, 2017), influence dry season refuge habitat (Keller *et al.*, 2019; Lear *et al.*, 2021), and directly support the growth (Leahy & Robins, 2021; Pratt *et al.*, 2023; Roberts *et al.*, 2019), spawning (Tyler *et al.*, 2021) and recruitment (Broadley *et al.*, 2020; Crook *et al.*, 2022; Lear *et al.*, 2019) of a diverse range of fish and crustaceans. Floodplain water harvesting and on-farm storage in the Murray-Darling Basin has resulted in unsustainable volumes of water abstraction and contributed to blue-green algae blooms, fish kills, and other negative downstream impacts on communities and flow-dependent ecosystems (Brown *et al.*, 2022). Therefore, the potential adverse ecological and fisheries impacts of wet season water abstraction on top of pre-existing ground and surface water abstraction requires careful attention by policy makers, regulators, managers, and scientists. Furthermore, managers and policy makers should also be aware that the indirect effects associated with land-clearing to support agriculture expansion and other developments may exacerbate river flow-related fisheries and ecological changes. For example, land clearing, development of water resource development infrastructure, small dams, and agricultural pollutants adjacent to rivers typically result in wetland and floodplain habitat loss or degradation (Kingsford, 2000; Tockner *et al.*, 2008), altered sediment regimes (Wohl *et al.*, 2015), and increased pesticide and nutrient concentrations (Arthington, 1996; Blocksom *et al.*, 2010), affecting waterways and fish consumed by people.

1.3 Response of aquatic species to water resource development in the wet-dry tropics of northern Australia

The wet-dry cycle of monsoon rainfall and flood pulse (Junk *et al.*, 1989) followed by an extreme dry season and fire-prone landscape is a driver of aquatic community structure, resilience, and fisheries productivity (Douglas *et al.*, 2005; Pettit *et al.*, 2017; Robins *et al.*, 2005; Warfe *et al.*, 2011), supporting over 111 species of freshwater bony fish (excluding marine vagrants; Pusey *et al.*, 2017), 5 euryhaline shark and ray species (Grant *et al.*, 2019), and a range of marine and freshwater crustaceans in northern Australia. Aquatic species in northern Australia exhibit a variety of life history strategies that have different flow dependencies between life stages and between species. The impacts of water resource development are therefore likely to vary substantially between species with different life history strategies.

Approximately 32% of bony fishes (Pusey *et al.*, 2017) and all euryhaline rays and sharks (Grant *et al.*, 2019) in northern Australia are diadromous, relying on longitudinal connectivity to move between freshwater and marine environments. Diadromous taxa in northern Australia include species of high commercial, recreational, cultural, and conservation significance such as sawfish (*Pristis* and *Anoxypristis* species), Diamond Mullet (*Liza alata)*, Barramundi (*Lates calcarifer*), and Cherabin (*Macrobrachium spinipes*) which also have specific flow requirements (Robins *et al.*, 2005). Many of these species simultaneously rely on lateral connectivity to move between river channel and floodplain environments to gain access to food as adults or nursery habitat for growth and recruitment (Grant *et al.*, 2019; Lear *et al.*, 2019; Roberts *et al.*, 2021). Diadromous species are particularly vulnerable to water abstraction and river fragmentation because key life-stages are dependent on large-scale connectivity between marine, in-channel freshwater, and floodplain environments (Verhelst *et al.*, 2021; Winemiller *et al.*, 2016).

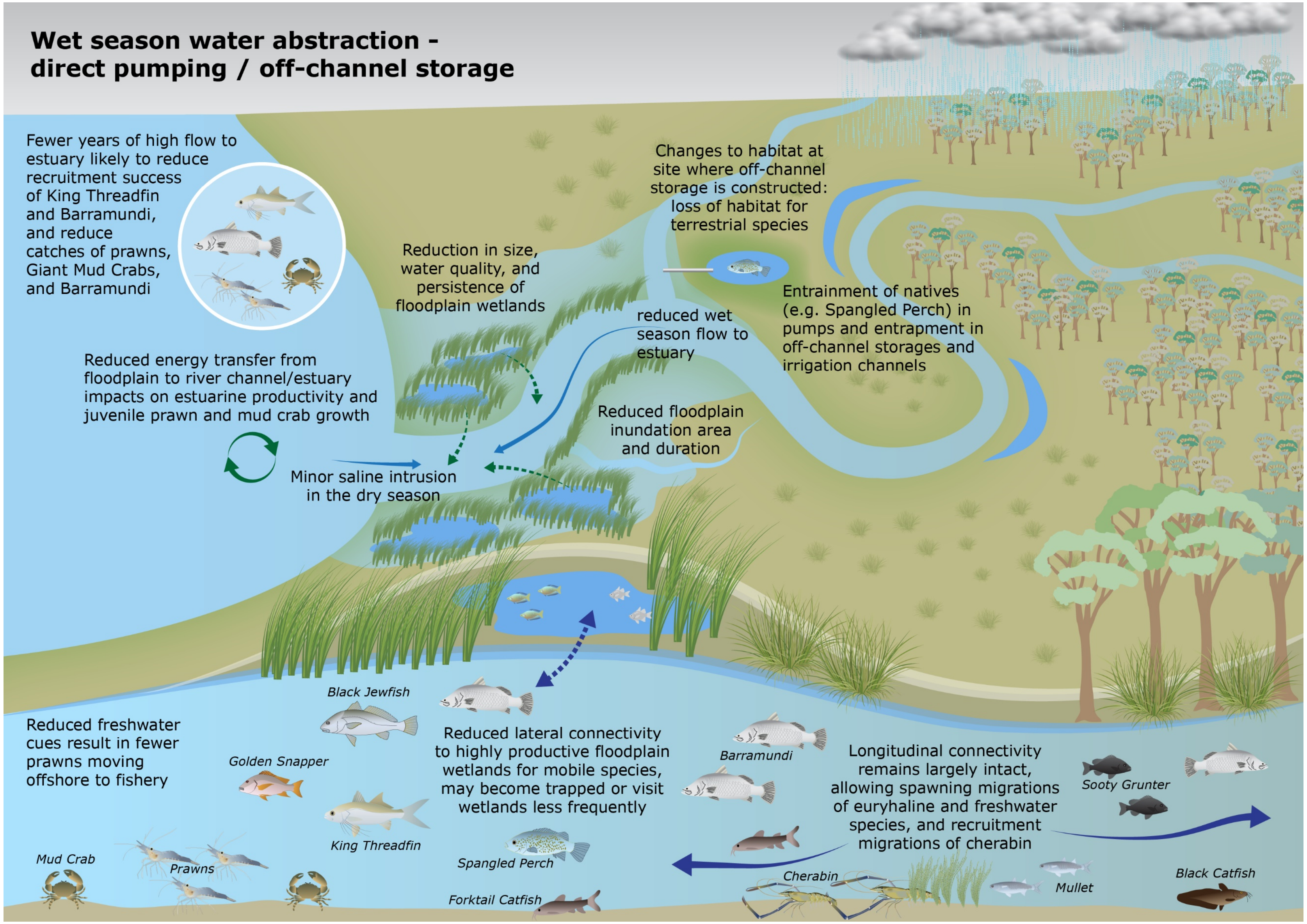
Predatory fish in northern Australia are often ‘equilibrium strategists’ (Sternberg & Kennard, 2014; Winemiller & Rose, 1992), characterised by having a relatively large body size, late maturation, low fecundity, and high juvenile survivorship which is supported by high parental care or offspring investment (e.g. large offspring size, live-bearing, nest guarding, mouth brooding, etc.). In northern Australia, this includes species such as sawfish (*Pristis* spp.), Blue Catfish (*Neoarius graeffei*), and Northern Saratoga (*Scleropages jardinii*). The vast production of food resources on the floodplain allows large predators in northern Australia to achieve a high biomass (Jardine *et al.*, 2017), and therefore predator biomass and associated fisheries may be adversely affected by flow alteration, which influences the extent, duration and/or timing of wet season floodplain inundation (Fig. 1).

The reduced variability of flows and altered seasonality, including larger than normal dry season flow and reduced magnitude, frequency or duration of wet season flood pulses is likely to impact aquatic species with ‘periodic’ life-history strategies (Arantes *et al.*, 2019; Mims & Olden, 2013; Winemiller & Rose, 1992), particularly medium to large-bodied species that produce large clutches of small eggs (sensu ‘Periodic’ Winemiller & Rose, 1992). These species are abundant in tropical river systems globally (Arantes *et al.*, 2019), including the monsoonal tropics of Australia (Sternberg & Kennard, 2013). Species such as Barramundi and Spangled Perch (*Leiopotherapon unicolor*) take advantage of seasonal flood pulses by producing large numbers of small eggs, often resulting in boom–bust recruitment cycles that follow large flood events. Recruitment of periodic strategists will likely be susceptible to wet season water abstraction and climate change effects (e.g. changes to the Southern Oscillation Index (SOI)) that alter flood magnitude, frequency or flood timing (Crook *et al.*, 2020; Staunton-Smith *et al.*, 2004).

Species with other life-history strategies rely on in-channel riverine habitats or permanent freshwater wetlands during the dry season. For example, species such as Sooty Grunter (*Hephaestus fuliginosus*) rely on shallow riffle habitats for various developmental stages during the dry season (Crook *et al.*, 2021a; Keller *et al.*, 2019). Dry season water abstraction and groundwater abstraction can increase intermittent flows and increase the number of no flow days (King *et al.*, 2015), which may reduce the area of shallow (e.g. riffle) habitat, and affect species and developmental stages that rely on flowing water (Fig. 2; Chan *et al.*, 2012). Small and fast-growing opportunistic fishes (sensu 'Opportunistic' Winemiller & Rose, 1992) are the most species-rich group in northern Australia and include taxa such as Macleay's Glassfish (*Ambassis macleaya*) and Blackmast (*Craterocephalus stramineus*). Some opportunistic fish species may benefit from altered low to moderate river channel flow environments, and pools created by river regulation (Arantes *et al.*, 2019; Mims & Olden, 2013). However, the loss of floodplain habitat (Tockner *et al.*, 2008) and floodplain food resources, combined with altered flow velocity and loss of longitudinal connectivity created by dams and water abstraction, is a threat to many small-bodied floodplain-dependent species.

Life history diversity within populations is important because higher diversity supports resilience and species population stability (Schindler *et al.*, 2010). Reduced movement opportunity through entrapment in wetlands and reservoirs, infrastructure barriers that block migrations, and changes to inter-annual variability in the flow regime (e.g. reduced number of strong wet seasons across years), can reduce the life history diversity of species populations and influence fishery productivity (Fig. 3; Schindler *et al.*, 2010). For example, fast-growing freshwater migrating Barramundi rely on seasonal and interannual variations in flow to cue migrations to freshwater as juveniles and to the coastal fishery as adults (Crook *et al.*, 2022; Halliday *et al.*, 2010; Roberts *et al.*, 2019). Changes to migrations between freshwater and the coast may reduce the life history diversity of populations of coastal diadromous species (Beechie *et al.*, 2006).

Changes to interannual variability in flow can also alter the composition of communities through decreases in the relative abundance of species for which the altered conditions are unfavourable (Gido *et al.*, 2013). For example, changes to the length of spawning season is likely to impact species differently depending on their reproductive life history strategies (Winemiller & Rose, 1992). Changes in relative abundance can eventually lead to local extinction of species and loss of biodiversity within river systems, reducing community stability and resilience (Grill *et al.*, 2020; Hooper *et al.*, 2005).



Wet season water abstraction - direct pumping / off-channel storage

Fewer years of high flow to estuary likely to reduce recruitment success of King Threadfin and Barramundi, and reduce catches of prawns, Giant Mud Crabs, and Barramundi

Reduction in size, water quality, and persistence of floodplain wetlands

Changes to habitat at site where off-channel storage is constructed: loss of habitat for terrestrial species

reduced wet season flow to estuary

Entrainment of natives (e.g. Spangled Perch) in pumps and entrapment in off-channel storages and irrigation channels

Reduced energy transfer from floodplain to river channel/estuary impacts on estuarine productivity and juvenile prawn and mud crab growth

Reduced floodplain inundation area and duration

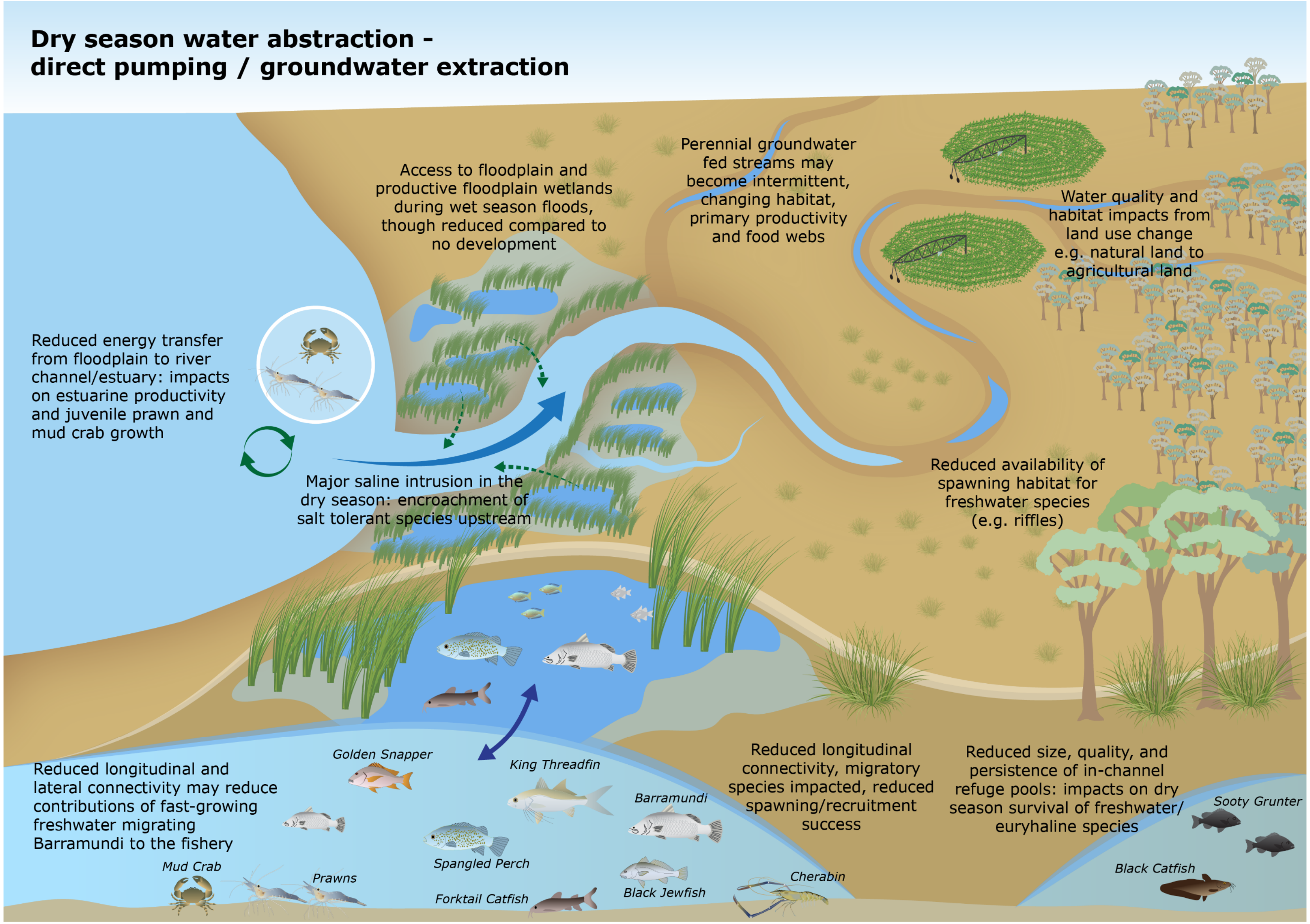
Minor saline intrusion in the dry season

Reduced freshwater cues result in fewer prawns moving offshore to fishery

Reduced lateral connectivity to highly productive floodplain wetlands for mobile species, may become trapped or visit wetlands less frequently

Longitudinal connectivity remains largely intact, allowing spawning migrations of euryhaline and freshwater species, and recruitment migrations of cherabin

Figure 1. Conceptual model of primary wet season water abstraction impacts on focal fisheries species.



Dry season water abstraction -
direct pumping / groundwater extraction

Access to floodplain and productive floodplain wetlands during wet season floods, though reduced compared to no development

Perennial groundwater fed streams may become intermittent, changing habitat, primary productivity and food webs

Water quality and habitat impacts from land use change e.g. natural land to agricultural land

Reduced energy transfer from floodplain to river channel/estuary: impacts on estuarine productivity and juvenile prawn and mud crab growth

Major saline intrusion in the dry season: encroachment of salt tolerant species upstream

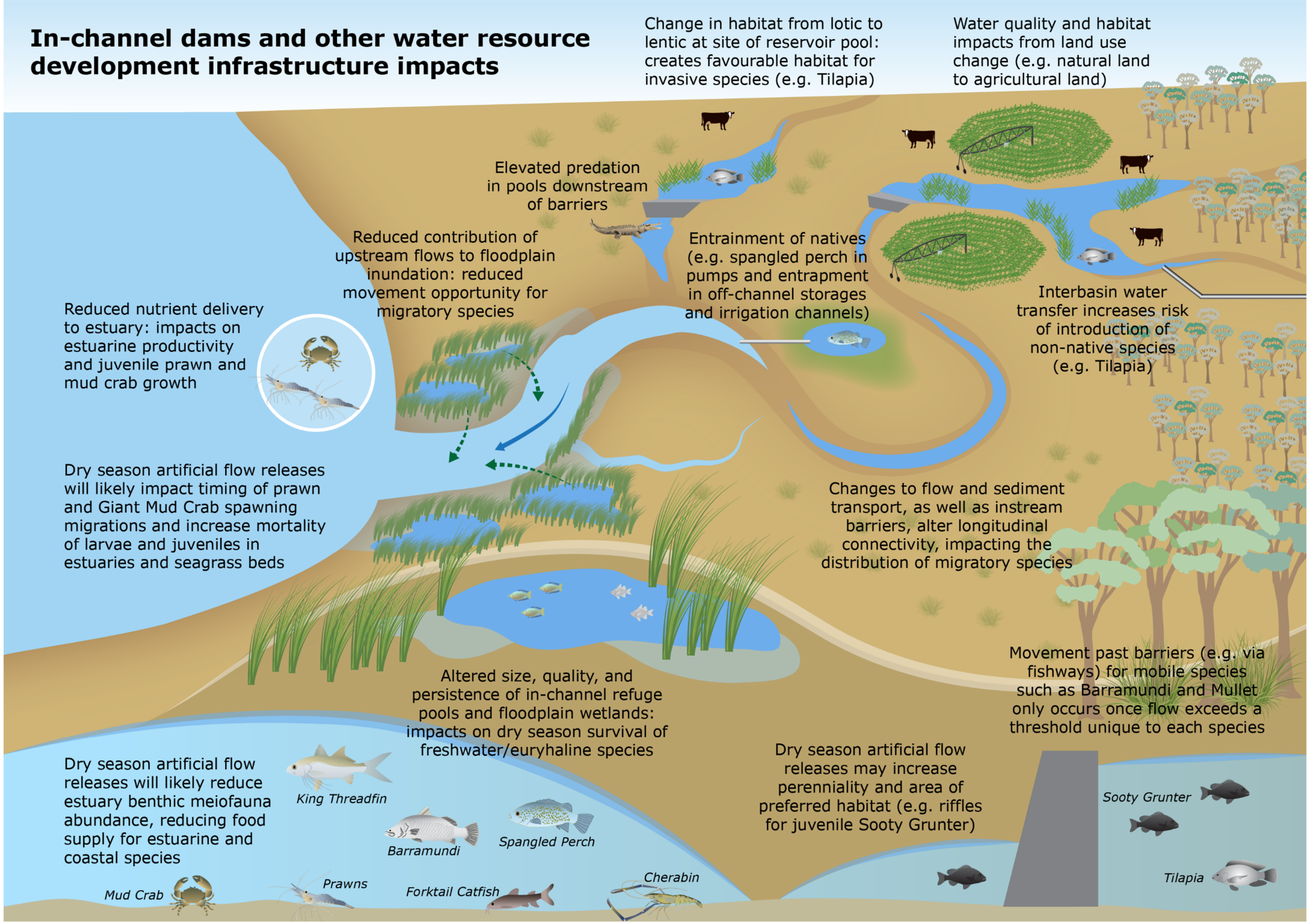
Reduced availability of spawning habitat for freshwater species (e.g. riffles)

Reduced longitudinal and lateral connectivity may reduce contributions of fast-growing freshwater migrating Barramundi to the fishery

Reduced longitudinal connectivity, migratory species impacted, reduced spawning/recruitment success

Reduced size, quality, and persistence of in-channel refuge pools: impacts on dry season survival of freshwater/ euryhaline species

Figure 2. Conceptual model of primary dry season direct pumping from channel or groundwater extraction impacts on focal fisheries species.



In-channel dams and other water resource development infrastructure impacts

Change in habitat from lotic to lentic at site of reservoir pool: creates favourable habitat for invasive species (e.g. Tilapia)

Water quality and habitat impacts from land use change (e.g. natural land to agricultural land)

Elevated predation in pools downstream of barriers

Reduced contribution of upstream flows to floodplain inundation: reduced movement opportunity for migratory species

Entrainment of natives (e.g. spangled perch in pumps and entrapment in off-channel storages and irrigation channels)

Interbasin water transfer increases risk of introduction of non-native species (e.g. Tilapia)

Reduced nutrient delivery to estuary: impacts on estuarine productivity and juvenile prawn and mud crab growth

Dry season artificial flow releases will likely impact timing of prawn and Giant Mud Crab spawning migrations and increase mortality of larvae and juveniles in estuaries and seagrass beds

Changes to flow and sediment transport, as well as instream barriers, alter longitudinal connectivity, impacting the distribution of migratory species

Altered size, quality, and persistence of in-channel refuge pools and floodplain wetlands: impacts on dry season survival of freshwater/euryhaline species

Movement past barriers (e.g. via fishways) for mobile species such as Barramundi and Mullet only occurs once flow exceeds a threshold unique to each species

Dry season artificial flow releases will likely reduce estuary benthic meiofauna abundance, reducing food supply for estuarine and coastal species

Dry season artificial flow releases may increase perenniality and area of preferred habitat (e.g. riffles for juvenile Sooty Grunter)

Figure 3. Conceptual model of primary dam and other water resource development infrastructure impacts on focal fisheries species.

2. Global systematic review of impacts of water abstraction on tropical aquatic species

2.1 Methods

To determine the different types of research that have been conducted on the impacts of water abstraction on aquatic fauna, including relationships between flow and aquatic fauna in northern Australia compared to other tropical areas around the world, we conducted a systematic review of published literature using the Scopus database search engine in November 2022. The following search terms were used:

water* or flow or hydro* or connect

AND

resource or alteration or development or abstraction or barrier or harvest or regulation or mining or withdraw* or collection or extraction or diversion or changes or dam or pump*

AND

Impact or effect* or outcome* or response or cause* or relationship*

AND

aquatic or freshwater or marine or river or stream or wetland or lake or coastal or estuar or pool or billabong or habitat or refug* or lagoon or creek or floodplain*

AND

**fish* or animal* or biota or life or invertebrate or crustacea* or fauna or crab or prawn or shrimp or ray or shark or zooplankton or turtle or crayfish*

AND

tropic or "wet-dry"*

The results were scanned for relevance to flow or water resource development and were selected as relevant if they were conducted in the tropics and fit any of the following criteria:

- Directly measured impacts on aquatic fauna, communities, or food webs
- Predicted (modelled) impacts on aquatic fauna, communities, or food webs
- Flow-biota relationships
- Flow-habitat-biota relationships (e.g. response of fauna to salinity changes)

- Lab tested impacts on aquatic fauna via changes in flow-habitat-biota relationships or flow-habitat-predator/prey relationships (e.g. response of fauna to salinity changes in the laboratory)

References were not selected if they only included:

- Habitat-biota relationships that did not examine components influenced by flow
- Food webs that did not study impacts of water abstraction or relationships to flow
- Processes not linked to fauna
- Phytoplankton and other plants
- General urbanization or land use impacts that did not specifically include dams, river fragmentation, flow alteration, or hydrological change

Relevant articles, book chapters, conference papers, and letters were reviewed, and information was recorded on the following categories for each paper:

- Type of study in relation to water abstraction impacts or flow relationships (measured impact, predicted impact, flow-biota relationship, and flow-habitat-biota relationship (including studies that manipulated flow influenced habitat characteristics (e.g. salinity, turbidity))
- UN Geoscheme region
- Environment studied (coast, estuary, river/stream, floodplain, wetland/natural lake, groundwater, reservoir)
- Type of organism studied (select species: fish, crustaceans, elasmobranchs, insects, molluscs, reptiles, mammals, or communities: fish, macroinvertebrates, zooplankton)

2.2 Results of global systematic review

The Scopus search found 5,176 document results, of which 241 were relevant articles, reviews, book chapters, conference papers, or letters fitting the criteria outlined in Section 2.1 of this report (Fig. 4).

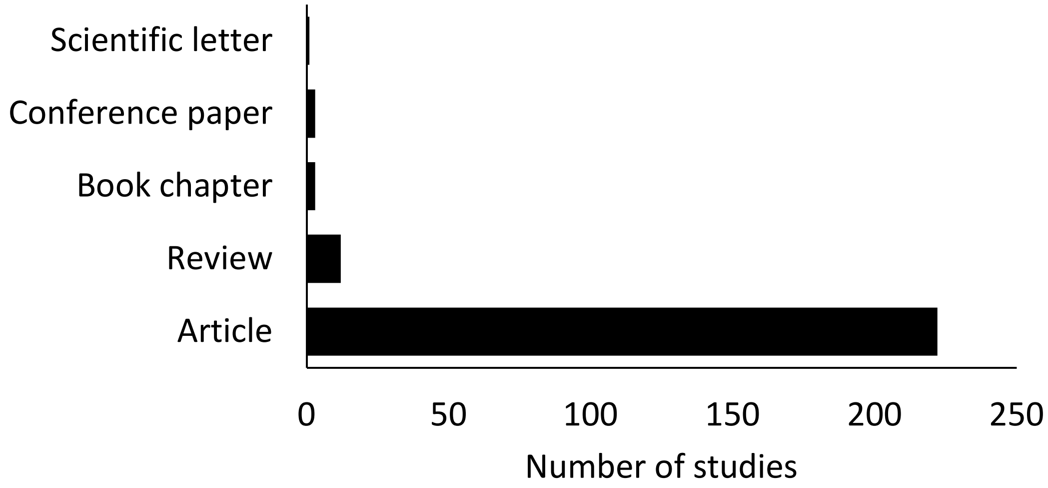


Figure 4. Types of studies comprising the 241 relevant results from the global systematic literature search.

The number of studies on flow relationships or measured impacts of water abstraction on aquatic biota have been increasing over time (Fig. 5). Of the 233 studies presenting original results (excluding reviews), there were 88 studies on measured impacts of water abstraction (including flow, barrier, or infrastructure impacts), 14 studies on predicted (modelled) impacts of water abstraction, 47 studies on flow-biota relationships, and 84 studies on flow-habitat-biota relationships (Fig. 5).

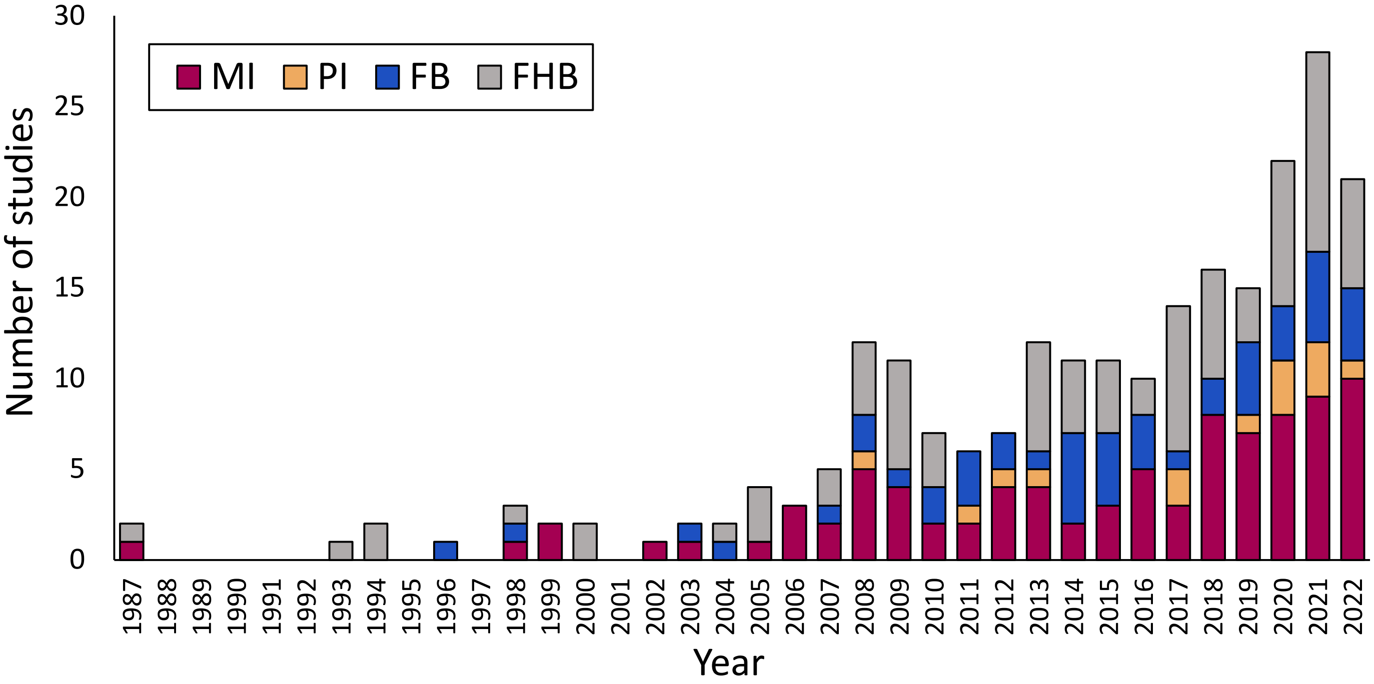


Figure 5. Categories of flow/impact focus for relevant studies selected from the global systematic literature search results. MI = measured impact, PI = predicted (modelled) impact, FB = direct flow-biota relationships studied, FHB = flow-habitat-biota (indirect flow) relationships studied.

The habitats studied differed between the categories of flow/impact focus, with rivers/creeks/streams receiving the most research attention for studies measuring impacts of water abstraction, followed by estuaries (Fig. 6). The habitats studied for predicted impacts and flow-biota relationships were somewhat similar, though unlike flow-biota studies there were no predicted impact studies in wetland/lake, groundwater, or floodplain habitats found in the literature search. The similarity between these two categories is unsurprising given flow-biota relationships are usually used as inputs to the models that predict impacts of water abstraction (e.g. O'Mara *et al.*, 2021a). There was a more even spread of studies across coastal, estuary, river/creek/stream, and wetland/lake environments in flow-habitat-biota studies than the other study types.

Fish, fish communities, crustaceans, and macroinvertebrate communities were the most frequently studied organisms across the four study types (Fig. 6). Studies that either measured or predicted impacts of water abstraction mostly focused on specific fish species or fish communities as the study organism(s). There were some flow relationship (either flow-biota or flow-habitat-biota relationship) studies on elasmobranchs, but this group of organisms was not found in measured or predicted impact studies in this literature search. While studies on crustaceans consistently represented 10-20% of flow-habitat-biota, flow-biota, and predicted impact studies, crustaceans were less of a focus compared to other organisms in measured impact studies.

Most of the studies across the four flow/impact focus categories were conducted in the North, Central, and South America, and Caribbean UN Geoscheme regions (Fig. 6). More than half of the measured impact studies came from South America, particularly Brazil, where many of the rivers are regulated and have existing dams. The lower number of dams and regulated rivers in northern Australia compared to South America is represented in these results, with few measured impact studies but a larger proportion of flow-biota relationship and predicted impact studies. Unregulated rivers provide an opportunity to study relationships between flow and aquatic organism ecology that can be used as inputs into models that predict impacts of water abstraction. These figures show that South America and Australia are leading the tropical river research on flow-biota relationships and predicted impacts of water abstraction on aquatic fauna.

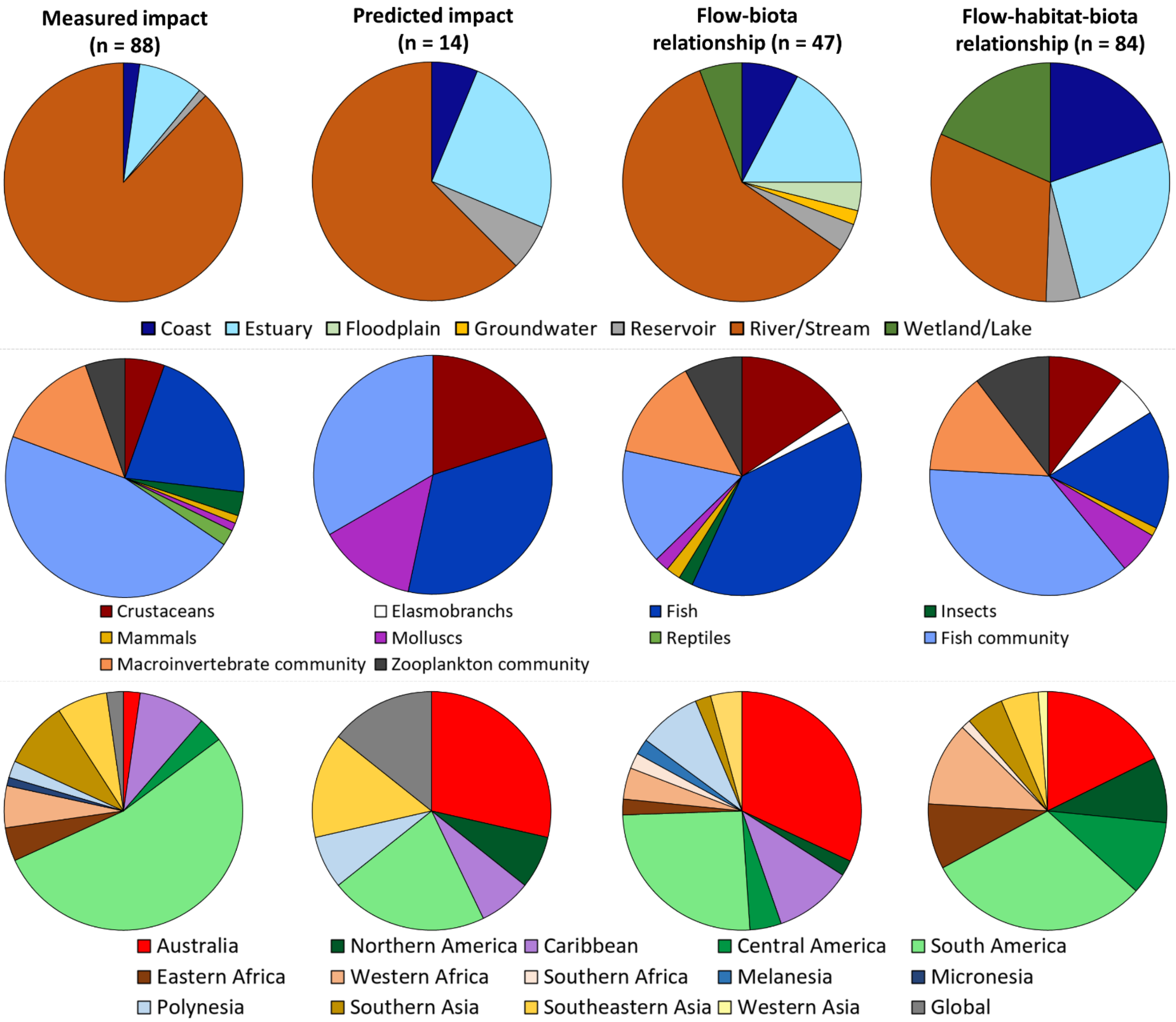


Figure 6. Environment studied (top row), organisms studied (middle row), and UN Geoscheme sub-region where study took place (bottom row) for each flow/impact type group of studies. Flow/impact types (left to right): measured impact studies, predicted (modelled) impact studies, direct flow-biota relationships studies, flow-habitat-biota (indirect flow) relationships studies.

3. Review of water abstraction impacts on focal fisheries species

3.1 Methods

Fish and crustacean species that are commonly commercially, recreationally, or culturally harvested in the Northern Territory and are likely to have an aspect of their life history that is dependent on river flow or flow-mediated connectivity were identified. Focal species to include in this study were chosen from this list if a) they were commonly recreationally or commercially harvested and information for the species was required by NT Fisheries scientists, or b) they were listed as the most harvested fish and crustacean species by Indigenous Australians in Jackson *et al*. (2011). The chosen species (referred to from here onward as the focal species) were:

Coastal species

- Penaeid prawn species caught in the Northern Prawn Fishery (NPF)
- The Giant Mud Crab *Scylla serrata*
- King Threadfin *Polydactylus macrochir*
- Golden Snapper *Lutjanus johnii*
- Black Jewfish *Protonibea diacanthus*

Euryhaline species

- Mullet (there are several mullet species that inhabit northern Australia)
- Barramundi *Lates calcarifer*
- Forktail catfish from the *Neoarius* genus
- Cherabin *Macrobrachium spinipes*

Freshwater species

- Sooty Grunter *Hephaestus fuliginosus*
- Spangled Perch *Leiopotherapon unicolor*
- Black Catfish *Neosilurus ater*

The grey and published literature was searched for documents containing information on the focal species listed above and other species with similar life histories. References that identified impacts of water abstraction, links to flow, or habitat use links to flow for the above species were reviewed in detail. Details of the study were tabulated in an Excel file according to criteria including study species, location, flow component(s), hydrodynamic predictors, relationships observed, and spatial and temporal context. The information from this table, and wider information from similar species, was used to summarise the flow dependencies of each focal species and make inferences on likely impacts of water abstraction based on the available information (Sections 3.2 & 3.3 of this report).

3.2 Results: summary of available Australian research and likely water abstraction risks to focal species

The grey and peer review literature was searched for Australian studies featuring either links to flow or impacts of water abstraction for the focal fisheries species. Barramundi and penaeid prawn species caught in the NPF have received the most research interest of the focal species, with 29 (Barramundi) and 20 (NPF prawns) relevant studies found. There was no Australian flow related research found for Golden Snapper. Most of the research across the focal species was found within peer reviewed journal articles (78%), with fewer studies located in reports (21%) and theses (1%) (Fig. 7).

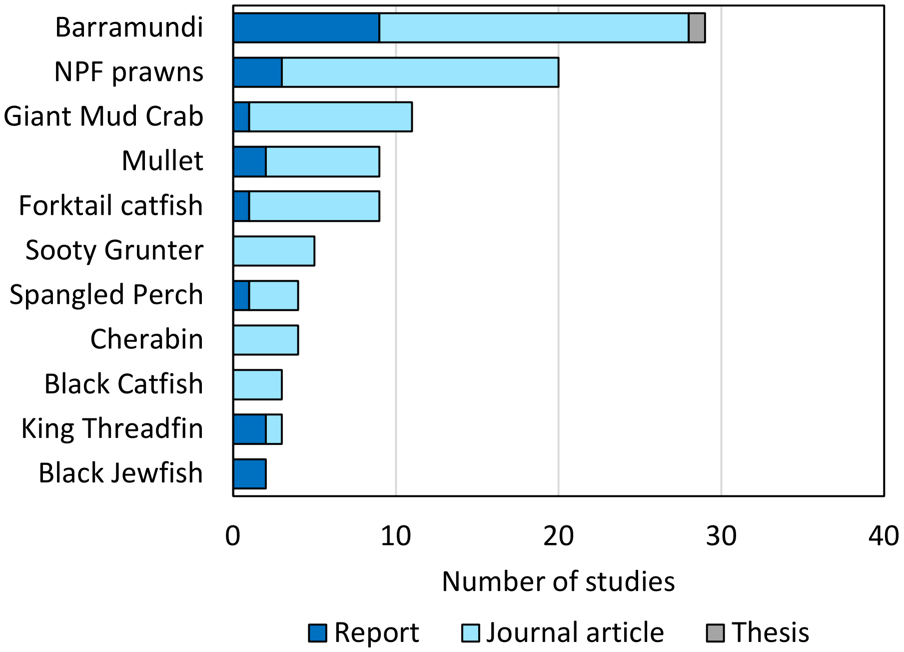


Figure 7. Publication types of relevant flow related Australian research on focal fisheries species

The number of studies found across the categories of flow/impact focus for the focal fisheries species was consistent with what was found in the global systematic literature review of aquatic species, with most of the Australian research on the focal fisheries species focusing on relationships with flow, rather than impacts of water abstraction (Fig. 8). Fisheries catch data was used to study relationships with flow in 57% of the studies on the focal species. Some studies on Barramundi, NPF prawns, Giant Mud crabs, and Sooty Grunter used relationships with flow to predict (model) impacts of water abstraction under various abstraction scenarios. Barramundi, NPF prawns, forktail catfish, and Spangled Perch were the only focal species for which we found studies that measured impacts of water abstraction in northern Australia.

These impacts varied and included barrier impacts to movement for Barramundi (Dostine & Crook, 2016; Morrissy, 2000), entrainment in irrigation pumps for Spangled Perch and forktail catfish (Hutchison *et al.*, 2022), and flow alteration impacts (via salinity changes) for prawns (Kenyon *et al.*, 2004).

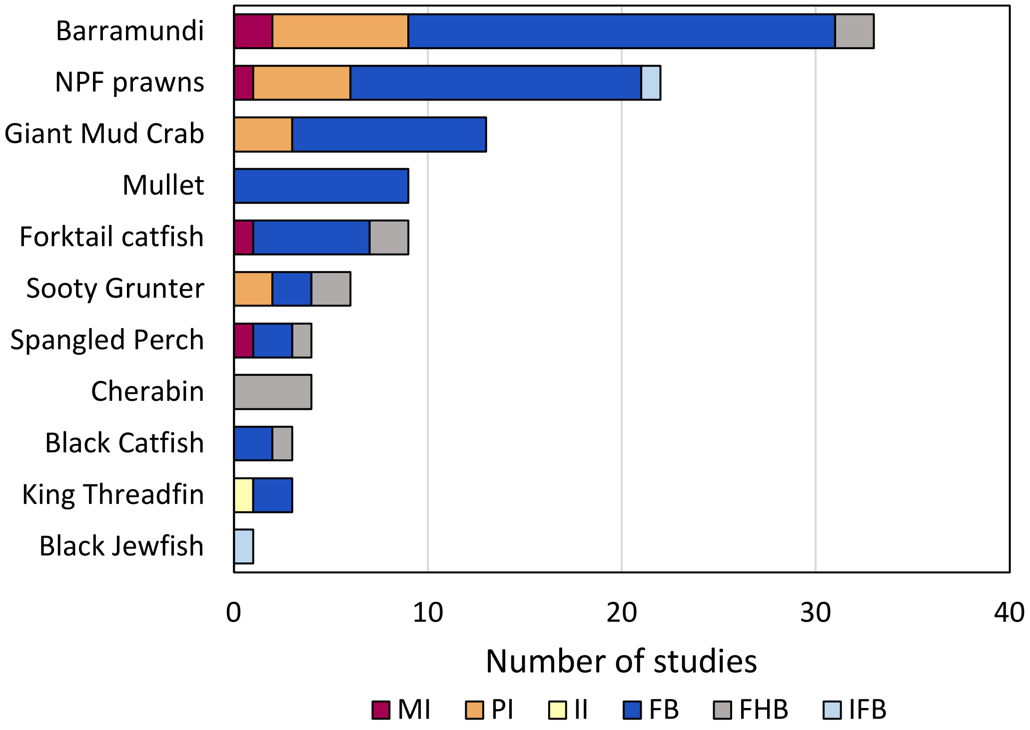


Figure 8. Categories of flow/impact focus for relevant Australian studies on the focal fisheries species. MI = measured impact, PI = predicted (modelled) impact, II = inferred impact (from known biology or observed pattern), FB = direct flow-biota relationships studied, FHB = flow-habitat-biota (indirect flow) relationships studied, IFB = inferred flow-biota relationship from an observation.

Available Australian literature on the focal species, and expert knowledge and opinion was used to identify the focal species most likely to be impacted by various flow, connectivity, habitat, and water quality changes associated with various modes of water abstraction (Table 1). This information can be used to guide decision making around choosing types of water abstraction that will have minimal impact on these species and to develop future research to fill knowledge gaps.

Table 1. Species most likely to be impacted by various possible hydrological/environmental changes caused by water abstraction, the mechanisms behind these likely species responses, the quality of available supporting evidence, and knowledge gaps. These responses were elucidated by expert opinion after reviewing available Australian literature on the flow dependencies and impacts of water abstraction of the focal species. The three types of water abstraction (blue, green, brown text) are modes that may be used in northern Australia and each mode is likely to have common as well as unique environmental and hydrological impacts.

Change variable	Mechanism	Types of water abstraction to cause impact	Focal species likely to be impacted	Ecological impact and quality of evidence	Critical knowledge gaps
Flow	Elevated dry season flows due to dam releases: change in timing of spawning behaviour and reduced survival of larvae and juveniles due to sub-optimal water quality	In-channel dams	*Coastal species, Cherabin, Black Catfish, Spangled Perch*	*One study indicating reduced salinity in dry season may reduce juvenile prawn abundance in estuary. Evidence for importance of sufficiently high salinity for larval crabs and prawn survival and recruitment. Saline water likely required for larval survival of Cherabin. Few studies directly linking flow to spawning migrations of freshwater species.*	Impacts of artificial flows in the dry season on spawning movements and success of all focal species. Effects of lowered salinity in the estuary in the dry season on focal species behaviour.
	Elevated dry season flows due to dam releases: maintenance of preferred freshwater habitat, good water quality in refuge pools, and longitudinal connectivity	In-channel dams	*Euryhaline and freshwater species*	*There is evidence showing freshwater habitat preferences for Sooty Grunter, Spangled Perch, and Barramundi that suggests that these species may benefit from maintained preferred habitat and longitudinal connectivity through the dry season.*	Impacts of altered species abundance and distribution (e.g. Spangled Perch, Sooty Grunter, Barramundi) on fish assemblage composition and food webs.
	Altered frequency, duration, and volume of high flow events: change in spawning and migration cues and nutrient delivery to estuary	In-channel dams, wet season water abstraction	*All focal species*	*There is evidence linking catch and recruitment success of Barramundi, King Threadfin, and White Banana Prawns to flow. Better recruitment during high flow years is critical to maintaining stocks and results from increased nutrient delivery from catchments to estuaries in high flow years, fuelling higher food web productivity than low flow years. Evidence to suggest changes to recessional flows could impact Cherabin recruitment. Correlations between movement and flow events indicate possible changes to movement behaviour, including offshore migrations of prawns, estuary-freshwater migrations of euryhaline species, and spawning and feeding movements of freshwater species.*	Importance of wet season flows to estuary for mullet, Black Jewfish, and Golden Snapper early life history stages. Mechanisms for movement during flow events for mullet and forktail catfish species. Impacts of altered duration of spawning seasons on focal species productivity.
	Reduced inter-annular	In-channel	*Euryhaline*	*There is evidence supporting the significant contribution*	Impacts of reduced interannual

	hydrological variation: reduced diversity of life histories within species and species within communities	dams, wet season water abstraction	*and freshwater species*	*(via faster growth rates) of Barramundi that access freshwater to the coastal fishery. There is little research on life history diversity for other focal species. Strong body of evidence supporting changes to community structure for Australian fish species in response to changing hydrological connectivity/environment through favourable conditions for some species. Reduced distribution (e.g. restricted to below dams) of migrating species due to reduced connectivity commonly observed, with likely additional loss of species that require seasonally flow dependent habitats for spawning/reproduction (e.g. Sooty Grunter).*	variability long-term (e.g. decades) on focal species population life history diversity and fishery productivity.
	Reduced dry season baseflow can increase saline intrusion from estuaries to freshwater reaches and floodplains	In-channel dams, dry season direct pumping or groundwater extraction	*Coastal species, Barramundi, forktail catfish, Spangled Perch, Cherabin*	*There are many studies demonstrating that the distribution of coastal species that frequent estuaries is driven by salinity gradients, suggesting encroachment further upstream if salinity increased. Saline intrusion into wetlands is likely to negatively impact productivity through reduced availability of freshwater habitat and reduced diversity of aquatic flora and fauna but there is a lack of research of these impacts on the focal species.*	Changes to food webs in wetlands with saline intrusion and changes to river food webs if reliance on river food webs were to increase.
	Reduced dry season baseflow can reduce in-channel refugia waterhole size, quality, and persistence, which is critical to the survival of aquatic species through the dry season	In-channel dams, dry season direct pumping or groundwater extraction	*Euryhaline and freshwater species*	*There are many fish abundance studies showing that these euryhaline and freshwater species use in-channel refugia waterholes to survive the dry season in intermittently flowing rivers.*	Impacts of reduced refugia waterhole size, quality, and persistence on fish and invertebrate populations.
Connectivity	Reduced longitudinal connectivity due to water storage and extraction. Fragmentation can result in isolated populations and changes in species distributions.	In-channel dams, wet season water abstraction, dry season direct pumping or groundwater extraction	*Euryhaline and freshwater species*	*While not all Barramundi spend time in freshwater, there is evidence of enhanced growth for those that do. It is highly likely that Cherabin need saltwater for larval development, but more evidence is needed. There is strong evidence that mullet and forktail catfish species move large distances upstream to feed, suggesting possible growth and condition impacts, as well as changes to energy transfer along the river. Freshwater species that migrate to spawn (Black Catfish, Spangled Perch, Sooty Grunter) may experience reduced spawning success, but*	Salinity requirements of Cherabin, mullet, and forktail catfish for completing life history stages. Impacts of reduced longitudinal connectivity on the spawning behaviour and success of freshwater fish species.

				there are few studies on the spawning movements of these species. Even small barriers such as road crossings can block fish from reaching refugia waterholes to survive through the dry season.	
	Reduced lateral connectivity and extent and duration of floodplain inundation. Opportunity for movement onto the floodplain to feed will likely be reduced.	In-channel dams, wet season water abstraction	*Euryhaline and freshwater species*	*There is evidence that Barramundi, forktail catfish, Spangled Perch, and Cherabin move into floodplain wetlands to feed, with many remaining in wetlands for multiple years. Access to these productive habitats facilitates the transfer of energy from productive floodplains to the river channel and estuary. Reduced lateral connectivity increases reliance of migrating fish and crustacean species on less productive river channel food webs.*	Impacts of reduced connectivity to wetlands and floodplain inundation duration on population size and growth of focal species.
Habitat	Change in channel habitat from lotic to lentic upstream of dam wall, resulting in a change in species composition and available basal food sources	In-channel dams	*Freshwater species*	*Evidence shows preference of flowing habitat for Spangled Perch, Sooty Grunter, and Barramundi. Several studies from across the globe show changes in fish species composition and food webs in dam reservoirs compared to river channels with no dams.*	Impacts of habitat changes to composition of fish species and food web dynamics in northern Australia.
	Altered depth and diversity of floodplain wetlands, resulting in changes to habitat availability, quality, and complexity, and basal food source availability	Wet season water abstraction	Barramundi, forktail catfish, Spangled Perch, Cherabin	*A number of studies show that most of the aquatic primary production of northern Australian wet-dry river systems occurs in floodplain wetlands and their depth and diversity supports food webs. There is evidence that fish and Cherabin move onto the floodplain to access these wetlands, likely to feed and fuel enhanced growth and reproduction.*	Changes in depth and diversity of floodplain wetlands due to various water abstraction methods. Growth and condition advantages for fish and invertebrates that access floodplain wetlands.
	Entrapment in storage reservoirs and irrigation channels, or entrainment in pumps, causing mortality or preventing organisms from moving back to preferred natural areas	In-channel dams, wet season water abstraction, dry season direct pumping or groundwater extraction	Barramundi, forktail catfish, Spangled Perch, Cherabin	*There are few studies on the direct impacts of water infrastructure on tropical Australian fish species, but current research suggests some species (e.g. Spangled Perch) may be particularly susceptible to becoming caught in pumps, channels, and reservoirs. Some studies have shown mitigation methods such as fishways, pump screens, and altering pump locations can reduce these impacts.*	Impacts of water resource infrastructure on freshwater and euryhaline species of northern Australia, including effective mitigative measures.

Water quality	Change in water quality due to land use associated with water abstraction (including the introduction of nutrients, pesticides, and other contaminants), affecting the availability and quality of food sources, and causing stress, disease, or impaired condition	In-channel dams, wet season water abstraction, dry season direct pumping or groundwater extraction	*Euryhaline and freshwater species*	*Early wet season flows can lead to poor water quality that causes fish kills. While research on water quality impacts caused by water abstraction in northern Australia is limited, studies across the globe show stress responses of fish to poor water quality and contamination. Since impacts are usually greater closer to the site of introduction or impact, effects will likely be greater on freshwater species and euryhaline species visiting freshwater reaches than coastal species as inputs are likely to be more diluted in estuaries.*	Multiple stressor impacts on focal fish species in northern Australian river systems.

3.3 Flow and climate relationships with fisheries species and predicted impacts of water abstraction

This review found a substantial body of research conducted in northern Australian that examined the underpinning drivers of abundance, recruitment, spawning, and movement for many of these fisheries species. Flow and rainfall have been identified as important drivers of interannual variation in catch and/or recruitment of Giant Mud Crabs (e.g. Blamey *et al.*, 2023; Meynecke *et al.*, 2012), NPF prawns (e.g. Plagányi *et al.*, 2021; Robins *et al.*, 2005), Barramundi (e.g. Halliday *et al.*, 2010; Staunton-Smith *et al.*, 2004), and King Threadfin (Halliday *et al.*, 2012, 2008). For example, Duggan *et al*. (2019) found that a 2,500,000 ML threshold of peak monthly flow volume was required from the Norman River Estuary to produce high prawn catches in the associated fishery. Climate cycles, such as the Southern Oscillation Index, Australian Monsoon Index, and Madden-Julien Oscillation, are likely to influence interannual flow variability (Higgins *et al.*, 2022) and have been identified as important predictors of catch for Giant Mud Crabs (Blamey *et al.*, 2023; Meynecke & Lee, 2011; Meynecke *et al.*, 2012; Plagányi *et al.*, 2022), NPF prawns (Meynecke & Lee, 2011; Plagányi *et al.*, 2022), and Mullet (Meynecke *et al.*, 2006), and drivers of Barramundi catch (e.g. Meynecke & Lee, 2011; Plagányi *et al.*, 2022), recruitment (e.g. Crook *et al.*, 2022; Morrongiello *et al.*, 2020), and growth (Leahy & Robins, 2021; Morrongiello *et al.*, 2020).

Specific flow requirements have been reported for preferred habitat maintenance and movement of some species. For example, the area of preferred Sooty Grunter habitat is highest at 8 $\mathrm{m}^3\ \mathrm{s}^{-1}$ discharge (Crook *et al.*, 2021a), and a drop in water temperatures and conductivity (< $-10\ \mathrm{m}^S\ \mathrm{cm}^{-1}\ \mathrm{d}^{-1}$) following heavy rainfall triggers Giant Mud Crab spawning migrations in northern New South Wales estuaries (Hewitt *et al.*, 2022). Flow requirements have also been noted for some species to be able to use fishways or migrate over weirs or past natural barrier such as bars. For example, Forktail Catfish (*Neoarius graeffei*) required >32 000 ML d^{-1} to move past a fishway in the Fitzroy River, Queensland (Stuart *et al.*, 2007), the mullet *Trachystoma petardi* and *Mugil cephalus* required flows of >250 $\mathrm{m}^3\ \mathrm{s}^{-1}$ to migrate past a weir in the Logan River, Queensland (Harding *et al.*, 2019), and flow >40 $\mathrm{m}^3\ \mathrm{s}^{-1}$ was required for fish to move past a bar in the Roper River, NT (Dostine & Crook, 2016).

Understanding the impacts of water abstraction during different flow phases (e.g. dry season/low flows, first wet season flows, wet season flood flows, and recessional flows), as well as how these impacts may vary between high and low flow years, is important in the wet-dry tropics of northern Australia due to the highly variable flow regime (Douglas *et al.*, 2019). Several predicted impact studies in both freshwater and coastal environments of northern Australia have found varied predicted impacts depending on which river the water is extracted from (e.g. Plagányi *et al.*, 2023), the timing of extraction (e.g. Chan *et al.*, 2012; Crook *et al.*, 2022), the strength of flow year (e.g. Broadley *et al.*, 2020; Crook *et al.*, 2021a, 2022), whether the river is perennial or intermittent (Blamey *et al.*, 2023), and the mode/threshold of water abstraction used (e.g. take from dams or pumping with various thresholds; Leahy & Robins, 2021; Plagányi *et al.*, 2023). For example, Crook *et al.* (2022) studied environmental drivers of Barramundi recruitment in four estuaries in the NT and found that water abstraction resulted in strong declines in recruitment but the effect varied with timing of extraction and strength of flow for the year (e.g. low, moderate, or high flow year). Specifically, dry season abstraction had a negative impact on predicted recruitment across all years, but the effect was strongest in the high flow year (Crook *et al.*, 2022). Wet season abstraction also had a negative impact on recruitment across all years, however the effect was strongest in the low and moderate flow years (Crook *et al.*, 2022). They concluded that limiting abstraction to the receding arm of the hydrograph during the wet season reduced the predicted decline in recruitment (Crook *et al.*, 2022).

The flow related research reviewed is synthesised below for each species and includes further examples of predicted impacts of water abstraction for these species.

3.4 Results: focal species life history, current flow ecology knowledge, and likely impacts of water abstraction

Coastal species

Fishery penaeid prawns

The Northern Territory coastline constitutes part of the Australian Northern Prawn Fishery (NPF). The NPF extends from the northern coast of Cape York in Queensland west to Cape Londonderry in Western Australia, with much of the fishing activity concentrated around the NT coastline. There are six short-lived prawn species that constitute most of the catch in the NPF, including Banana Prawns (White Banana Prawn *Penaeus merguiensis* and Redleg Banana Prawn *Penaeus indicus*), Tiger Prawns (Brown Tiger Prawn *Penaeus esculentus* and Grooved Tiger Prawn *Penaeus semisulcatus*), and Endeavour Prawns (Blue Endeavour Prawn *Metapenaeus endeavouri* and Red Endeavour Prawn *Metapenaeus ensis*). Banana Prawns comprise the majority of the catch (>60 % of the catch in 2020 and 2021), ahead of Tiger Prawns (20-30 % of the catch in 2020 and 2021) and Endeavour Prawns (<10 % of the catch in 2020 and 2021) (https://www.afma.gov.au/fisheries/northern-prawn-fishery). The spatial distribution of these species is related to depth and sediment type (Somers, 1994). There are two separate fishing seasons in the NPF, with mostly Banana Prawns caught in April to June when adult prawns congregate offshore to breed after migrating from the estuary (Staples & Vance, 1986), and mostly Tiger Prawns caught in August to November during peak Tiger Prawn spawning (Condie *et al.*, 1999).

Banana Prawns are a short-lived species (1 - 1.5 years) and spawn offshore. A small proportion of the postlarvae are advected into estuaries where they feed and grow into juveniles prior to the wet season each year when they emigrate to the offshore fishery (Vance & Rothlisberg, 2020). Estuaries provide food and ideal growth and refugial conditions for postlarval and juvenile Banana Prawns, with optimum salinity for growth and survival determined to be ~25 ppt (Kumlu, 1998; Staples & Heales, 1991). Research on prawns of the NPF has focused on their biology and ecology, with environmental drivers of variability in *P. merguiensis* catch rates and recruitment also extensively examined (Broadley *et al.*, 2020; Plagányi *et al.*, 2023; de Souza & Gondro, 2013; Toscas *et al.*, 2009; Turschwell *et al.*, 2022). Correlated links between Banana Prawn catches/migration and rainfall (Plagányi *et al.*, 2021; Toscas *et al.*, 2009; Vance *et al.*, 1985), or river flow (Turschwell *et al.*, 2022) have been made. Catches of *P. merguiensis* are likely to be most severely impacted by water abstraction during low flow years (Broadley *et al.*, 2020) and cumulative impacts of developments across multiple catchments are likely to occur in the NPF (Plagányi *et al.*, 2023). While predicted impacts on prawn catches have been thoroughly studied for the Gulf of Carpentaria, other flow related impacts on Banana Prawns are also documented. Osmotic stress due to salinity reduction during high flow events is experienced by prawns (Vance & Rothlisberg, 2020) and their prey, i.e. macrobenthos and meiofauna, resulting in reduced food supply (Duggan *et al.*, 2014; Lowe *et al.*, 2022). Recent research also shows the critical nature of freshwater flow for providing nutrients over longer time frames to fuel productivity in these nutrient depauperate estuaries (Burford & Faggotter, 2021). Changes to the natural flow regime that cause higher than normal freshwater flows to the estuary in the dry season will reduce salinity and therefore affect Banana Prawn survival and recruitment into estuaries (Duggan *et al.*, 2019). Evidence for this has been observed in the Ord River, with juvenile Banana Prawns absent from reaches with lowered salinity in the dry season caused by dam releases, compared to nearby unregulated estuaries (Kenyon *et al.*, 2004).

Tiger and Endeavour Prawns inhabit coastal waters with sand or mud substrate (Somers, 1994). Juvenile Tiger Prawns and *M. endeavouri* are mainly associated with seagrass beds (Haywood *et al.*, 1995; Loneragan *et al.*, 1994), while juvenile *M. ensis* occur across seagrass beds, mangroves, mud flats, and open channels. Adult tiger and Endeavour Prawns are mostly found offshore in deeper waters where they spawn (Loneragan *et al.*, 1994). Migration patterns and spawning periods in northern Australia differ between *P. esculentus, P. semisulcatus, M. endeavouri,* and *M. ensis* (Buckworth, 1992; Condie *et al.*, 1999; Crocos *et al.*, 2001; Watson & Turnbull, 1993). Research on tiger and Endeavour Prawns in northern Australia has focused on their biology and ecology, with few studies on the environmental drivers of variability in catch, recruitment, or migration (Bishop *et al.*, 2016; Meynecke & Lee, 2011). Rainfall drives movement of *P. semisulcatus* to offshore spawning grounds in the western Gulf of Carpentaria (Bishop *et al.*, 2016). The influence of rainfall on catches of tiger and Endeavour Prawns varies between regions on a large spatial scale (Meynecke & Lee, 2011). In subtropical Moreton Bay, which has a less predictable and seasonally variable natural flow regime than the wet-dry tropics, temperature (but not rainfall) was found to influence the recruitment of *P. esculentus,* and overseas Ben-Hasan *et al.* (2018) found no correlation between *P. semisulcatus* recruitment in the Arabian Gulf and river flow. Links between catch or recruitment in the NPF and flow have not been well studied for tiger or Endeavour Prawns, but similar rainfall driven emigration to the fishery as *P. merguiensis* suggests these drivers need to be further explored to determine possible impacts of flow alteration on tiger or Endeavour Prawns (Bishop *et al.*, 2016). Because juvenile tiger and Endeavour Prawns do not penetrate as far upstream in estuaries as Banana Prawns, the severity of recruitment and catch impacts relating to altered salinity in estuaries may be less severe for tiger and Endeavour Prawns than predicted for Banana Prawns (Bayliss *et al.*, 2014). Even so, their close proximity to the coast and reliance on benthic fauna for food (Wassenberg & Hill, 1987) flag them as species potentially susceptible to flow alteration through more indirect changes, such changes to habitat and food quality and availability. Seagrass community characteristics in northern Australia have been linked with the survival or offshore emigration of postlarval Tiger Prawns (Loneragan *et al.*, 1998, 1994) and the distribution of Tiger Prawns offshore in the Gulf of Carpentaria is related to the inshore distribution of seagrass (Staples *et al.*, 1985), suggesting that Tiger Prawns may be sensitive to any changes to seagrass communities that occur as a result of water resource development.

Giant Mud Crab

The Giant Mud Crab *Scylla serrata* is a large swimming crab that inhabits nearshore and estuarine mangrove habitats throughout temperate, tropical, and subtropical regions of Australia and the Indo-West Pacific (Alberts-Hubatsch *et al.*, 2016). Adult Giant Mud Crabs migrate downstream from estuarine to offshore coastal environments during rainfall events to spawn (Alberts-Hubatsch *et al.*, 2016; Hewitt *et al.*, 2022). Following spawning they may return to the estuary that they migrated from or move to a new location (Hewitt *et al.*, 2022). Larvae disperse by drifting in the zooplankton and undergo development through five stages before settling to the benthos of an estuary when they reach a megalopa stage (Baylon, 2010). Survival and successful transition through the five larval stages is highly dependent on the temperature and salinity of the surrounding water, with tolerance to lower salinity increasing as development progresses (Baylon, 2010; Hill, 1974).

Juvenile Giant Mud Crabs are found in shallow intertidal muddy environments such as at the mouth of estuaries, in nearshore seagrass beds or macrophytes, and around mangroves (Calogeras, 2007). While there is no clear seasonal influx of juvenile Giant Mud Crabs to these habitats, there tends to be few detections during the wet season and the highest number of detection of juvenile Giant Mud Crabs in these habitats following the wet season (Calogeras, 2007). This is likely due to the salinity tolerance of juvenile *S. serrata*, which do not tolerate low salinity as well as other *Scylla* species. In tropical regions such as the NT coast, freshwater runoff and the post-wet season increase in salinity may cue recruitment to estuarine and nearshore habitats (Chandrasekaran & Natarajan, 1994). Adult Giant Mud Crabs are generally found in the subtidal zone of mangrove estuaries where they feed on mainly crustaceans and molluscs (Hill, 1976). Ontogenetic shifts in habitat use are likely to be a mechanism to avoid predation (Alberts-Hubatsch *et al.*, 2014).

Studies on the flow dependency of Giant Mud Crabs show correlations between catches and rainfall or river flow in northern Australia (Blamey *et al.*, 2023; Meynecke *et al.*, 2011, 2012, 2006; Robins *et al.*, 2020), eastern QLD (Loneragan & Bunn, 1999; Robins *et al.*, 2005), and NSW (Saintilan & Wen, 2012). Blamey *et al.* (2023) linked both adult catchability and juvenile recruitment to flow and the SOI in the Flinders and Gilbert River regions in the Gulf of Carpentaria. Changes to Giant Mud Crab catches under water resource development have been modelled in the Gulf of Carpentaria to find large variations in the severity of predicted impacts between perennial and intermittent rivers, with more severe impacts predicted for intermittent rivers (Blamey *et al.*, 2023; Plagányi *et al.*, 2023, 2022). Blamey *et al.* (2023) also predicted a large reduction in crab catches in the coastal region adjacent to the Gilbert River under reduced flow for wet years, suggesting that wet years contribute greatly to crab biomass in some regions. Antecedent conditions are therefore important and changes to the frequency and strength of large wet years as a result of wet season water abstraction will likely cause large reductions in Giant Mud Crab abundance in estuaries of regulated rivers and adjacent coastal areas.

Flow releases from dams in the dry season are also likely to significantly impact Giant Mud Crabs. Tagging of adult Giant Mud Crabs in two NSW estuaries has demonstrated that the downstream spawning migration is cued by lower salinity in the estuary following rainfall (Hewitt *et al.*, 2022). Spawning migration cues may therefore be impacted by flow releases in the dry season. The impacts of an altered flow regime on the more salinity sensitive earlier life stages remain largely unknown. Given that Giant Mud Crab megalopa and juveniles are less tolerant to lower salinity than sub-adult and adult Giant Mud Crabs (Baylon, 2010) and recruitment increases after wet season flows subside (Chandrasekaran & Natarajan, 1994), a less variable flow regime and low salinity in the estuary in the dry season resulting from flow releases may severely impact the recruitment and survival of early life stage Giant Mud Crabs. Salinity and nutrient supply changes in the estuary are also likely to influence the availability of Giant Mud Crab prey species.

King Threadfin

King Threadfin *Polydactylus macrochir* (also known as threadfin salmon, king salmon, blind salmon, and gold threadfin) inhabit shallow sand or mud substrates in turbid coastal waters, estuaries, and mangrove creeks across northern Australia and Papua New Guinea (GBRMPA, 2011). They are a long-lived, and large-bodied protandrous hermaphroditic fish species targeted by commercial, recreational, and Indigenous fishers (GBRMPA, 2011). While they are a fast-growing species, they do not change sex until around 6-8 years old (~75-100 cm fork length), making them vulnerable to fishing and other pressures (Welch *et al.*, 2010). Several studies have revealed that King Threadfin across northern Australia are segregated into several spatially distinct stocks with very limited movement or mixing between them (Moore & Simpfendorfer, 2014; Moore *et al.*, 2012; Newman *et al.*, 2010). This spatial stock structure makes King Threadfin vulnerable to localised stressors and there is evidence of profound demographic impacts in the Gulf of Carpentaria stocks due to overexploitation (Moore *et al.*, 2017).

King Threadfin spawning occurs from October to March in the NT (Kailola *et al.*, 1993), coinciding with the movement of adults out of estuaries to the coast as salinity lowers with wet season flows and recruitment of juveniles to the estuary as the salinity rises following the wet season (Williams, 2002). While peak catches occur during February and March, relationships between flow and spawning, catch, or recruitment success have not been quantified for this region and it is unclear how catchability and fisher behaviour influences catch rates (Halliday *et al.*, 2012). Halliday *et al.* (2008) collected King Threadfin otoliths from fishery catches to study the drivers of recruitment success in the Fitzroy River region (QLD) and found that year class strength was correlated with freshwater flow and coastal rainfall in spring and summer. They speculated that higher recruitment success with higher flows may be supported by increased productivity in the estuary, a larger area of habitat that is presumed to be favoured by juvenile King Threadfin (lower salinity than coastal waters), or increased turbidity which may reduce predation rates (Halliday *et al.*, 2008; Hecht & Van der Lingen, 1992; Robins *et al.*, 2006). Aside from this work by Halliday *et al.* (2008) in eastern QLD, there is little existing research on the flow requirements of King Threadfin and it is therefore not clear how this species would respond to flow alteration. Given their movement downstream with flow events, recruitment to the estuary, and relationship between year class strength and flow (Halliday *et al.*, 2008), King Threadfin may be impacted by a change in the magnitude of wet season flows to the estuary as reduced wet season flows are likely to alter nutrient delivery to the estuary and conditions in the estuary such as turbidity and available area of preferred salinity (Halliday *et al.*, 2012). King Threadfin are also likely to be affected by a change in the timing of flows to the estuary, with reduced seasonal variability in flow likely to impact spawning and recruitment success because of the species presumed reliance on salinity changes to cue adult spawning movements out of the estuary and juvenile recruitment movements to the estuary, as well as survival of juveniles and larvae in the estuary which is likely to be negatively impacted if dry season flows cause very low salinities in the estuary.

Golden Snapper

Golden Snapper *Lutjanus johnii*, also known as John's snapper or fingermark, are a long-lived (up to 30 years) and large bodied (up to 100 cm) coastal fish species occurring across northern Australia and in other tropical waters including southeast Asia (Allen, 1985; Cappo *et al.*, 2013). Juvenile Golden Snapper live in mangrove estuaries for several years before moving to inshore coral and rocky reefs (Kiso & Mahyam, 2003; Tanaka *et al.*, 2011). Mangrove estuaries are an important habitat for the early life stages of Golden Snapper, with juveniles recruiting to estuaries and feeding on crustaceans such as penaeid prawns, amphipods, shrimp and crabs, as well as small fish (Kiso & Mahyam, 2003; Ogawa, 2003; Tanaka *et al.*, 2011).

Our literature search did not find any research conducted on the dependency of Golden Snapper on natural river flows. However, the early life history habitat preference of Golden Snapper for mangrove estuaries suggests they may be somewhat impacted by flow alteration. Welch *et al.* (2014) inferred that Golden Snapper in northwestern Australia would be moderately impacted by changes to rainfall, river flow, and nutrient delivery to the estuary from freshwater habitats. Given that freshwater delivery to the estuary and resulting salinity changes is a key driver of estuarine invertebrate composition (Lowe *et al.*, 2022; Venarsky *et al.*, 2022), changes to rainfall and river flow are likely to alter the types of food available to juvenile Golden Snapper. Reduced nutrient delivery as a result of river fragmentation or reduced floodplain inundation would likely reduce the amount of food available to Golden Snapper through a reduction in invertebrate prey biomass as a result of reduced primary productivity (Burford *et al.*, 2011). As well as vulnerability of juveniles to changes in food availability, Golden Snapper are late maturing and therefore slow to replenish populations, and are locally overfished in the Darwin region (Saunders *et al.*, 2020), suggesting they may have a low capacity to adapt to change (Welch *et al.*, 2014).

Another Lutjanid popular with fishers, the Mangrove Jack *Lutjanus argentimaculatus,* is known to similarly spawn offshore and recruit to estuaries and lowland rivers for juvenile life history stages (Russell & McDougall, 2008) and is therefore likely to share similar impacts of water abstraction to Golden Snapper (Griffiths *et al.*, 2014). Growth of juvenile Mangrove Jack is positively correlated with wet season rainfall (Ong *et al.*, 2015). Changes to the magnitude of wet season flows could therefore impact growth, while magnitude and seasonality of flow may impact cues for recruitment to estuaries from offshore. Russell and McDougall (2005) studied Mangrove Jack in offshore, estuarine, and freshwater environments and found most juvenile Mangrove Jack (<300 mm length of caudal fork) inhabited the lower reaches of freshwater streams in eastern Queensland rivers. Penetrating further upstream than Golden Snapper means that Mangrove Jack also rely on longitudinal connectivity between fresh and marine waters to complete their unidirectional movement to offshore waters to spawn. Ensuring that this connectivity remains intact is therefore essential for mitigating impacts of water abstraction.

Black Jewfish

Black Jewfish *Protonibea diacanthus* (also known as blackspotted croaker) are a fast growing, large-bodied, schooling fish species that inhabit estuarine, coastal, and offshore waters around the coast of northern Australia, as well as other tropical regions of the Indo-West Pacific Ocean (Mok *et al.*, 2009). The Black Jewfish population across northern Australia appears to be made up of several spatially distinct stocks with little to no mixing between stocks (Rolls *et al.*, 2012; Saunders *et al.*, 2016; Semmens *et al.*, 2010; Taillebois *et al.*, 2017). The large, dense aggregations they form during spawning are targeted by recreational, commercial, and Indigenous fishers with huge success (Coleman, 2004; Semmens *et al.*, 2010). This aggregating behaviour, as well as low connectivity between stocks and late maturation (females becoming mature at 790 mm TL; Phelan & Errity, 2008), makes Black Jewfish highly vulnerable to local overexploitation and local environmental impacts (Taillebois *et al.*, 2017).

Black Jewfish spawn during the late dry to wet season (August to January; Phelan & Errity, 2008), and females are in peak spawning condition from September to November (Randall *et al.*, 2023). Anecdotal evidence from a single river system in the Cape York region suggested that aggregation forming at spawning sites may be cued by freshwater discharge in the wet season (Phelan, 2002), though a more recent study in the NT found aggregations to be more dependent on tide than river flow (Randall *et al.*, 2023). Juveniles are thought to use estuarine mangroves and creeks as nursery habitats until they reach around 420 mm TL (~1 year old), where they move out to the fishery in coastal waters but remain immature until they are ~2-3 years old (Phelan, 2002). They consume fish, crabs, prawns, and gastropods (Phelan & Errity, 2008), with a higher reliance on invertebrates (mostly prawns) as juveniles before switching to a mostly fish diet as adults (Rao, 1963). Dependence on freshwater derived nutrients is likely to be low for adult Black Jewfish, with a mostly marine diet observed for adult Black Jewfish collected from river mouth locations in the NT (Randall *et al.*, 2023). Randall *et al.* (2023) also found a spatially variable but generally negative association between Black Jewfish body condition and flow (Randall *et al.*, 2023). Adult Black Jewfish do not appear to respond to hydrological variability the same way as many of the other focal species and are therefore less likely to be impacted by water abstraction (Randall *et al.*, 2023). However, more research is needed to investigate the impacts of altered timing, duration, and magnitude of wet season flows to the estuary on Black Jewfish spawning and recruitment. There is a lack of information available on the early life biology and salinity tolerance of larval and juvenile Black Jewfish in northern Australia. However, given that they are a mostly marine species, larval and juvenile Black Jewfish may be impacted by a less variable flow regime that lowers salinity in the estuary in the dry season.

Euryhaline species

Mullet

Mullet are tolerant to a range of salinity conditions, from freshwater to hypersaline (0 - >100 ppt), and are widespread across temperate and tropical coastal waters around the world (Krispyn *et al.*, 2021). There are several mullet species with a schooling, migratory life history that spawn in marine or estuarine waters, with many individuals migrating between marine, estuarine, and freshwater zones (Crook *et al.*, 2017; Fowler *et al.*, 2016; Saboret *et al.*, 2021). The sea mullet *Mugil cephalus* (also known as grey, flathead, or striped mullet) is a widespread migratory species that is common in fisheries catches (Whitfield *et al.*, 2012). Access to saltwater is important for gonad development, spawning, and growth of juveniles, and access to freshwater is not obligatory for *M. cephalus* but mullet often move into freshwater to feed on abundant low trophic level food sources (Loi *et al.*, 2022; Masson & Marais, 1975; Shireman, 1975). However, the construction of dams has limited the migration of mullet between rivers and estuaries, constraining them to estuaries and lower freshwater reaches in regulated rivers (Gehrke *et al.*, 1999).

There are several commercial mullet fisheries around the Australian coastline and catch data from these fisheries has been used in studies determining environmental drivers of catch (Loneragan & Bunn, 1999; Scheltinga *et al.*, 2006). These studies have mostly occurred on the QLD and NSW east coast with varied results indicating the influence of rainfall and season on coastal mullet catches may vary with latitude. While several studies identified correlations between mullet catches and rainfall or river flow (e.g. Gillson *et al.*, 2009; Saintilan & Wen, 2012), Meynecke *et al.* (2011) found correlations between SST and mullet catch in southeast Queensland, but not rainfall or river flow. Mullet use flows to migrate downstream from freshwater reaches into estuaries/coastal areas (Harding *et al.*, 2019). Movement of mullet along the Australian east coast for spawning is particularly seasonal and therefore likely to be closely linked to SST (Ditty & Shaw, 1996). Movement also varies with fish size and individual fish do not migrate to spawn every year (Fowler *et al.*, 2016; Kesteven, 1953; Saboret *et al.*, 2021). Therefore, differences in movement behaviour may contribute to varied results of studies that correlate mullet catches with rainfall or river flow.

In the wet-dry tropics of northern Australia, it is expected that correlations with river flows would be more pronounced due to the highly predictable seasonality in rainfall compared with temperate and subtropical regions of eastern Australia. Meynecke *et al.* (2006) found the Southern Oscillation Index to be positively correlated with catches of total mullet (several mullet species including *Mugil cephalus*) in the Gulf of Carpentaria, accounting for 41% - 49% of the variation in mullet catch. Mullet in the NT are therefore likely to be impacted by water abstraction in multiple ways. Firstly, a change in the magnitude and duration of wet season flows to the estuary, or change in seasonality of flows, is likely alter mullet movement patterns and impact coastal mullet catches. Secondly, increased fragmentation due to in-channel barriers or reduced longitudinal connectivity are likely to affect mullet distribution in freshwater reaches of rivers, with restricted distribution to lower freshwater and estuarine reaches likely for highly regulated rivers (Gehrke *et al.*, 1999). The impacts of reduced access to freshwater habitats for feeding on mullet growth and condition are largely unknown.

Barramundi

Barramundi *Lates calcarifer* are an iconic, large-bodied, predatory fish species found throughout freshwater, estuarine, and coastal environments in northern Australia (Jerry, 2013). They are commonly harvested commercially, culturally, and recreationally and are farmed for consumption across northern Australia (Chong-Montenegro *et al.*, 2022; FRDC, 2021; Jackson *et al.*, 2011). This fisheries interest is matched by substantial research attention, as they are perhaps the most well studied fishery species of northern Australia, with many studies examining various aspects of their biology and ecology, including environmental drivers of their distribution, abundance, movement patterns, growth, recruitment, and catchability.

Understanding the life history of Barramundi has contributed to the successful sustainable management of wild fisheries and productive aquaculture in northern Australia (FRDC, 2021; Jerry, 2013). Most Barramundi are born as males and undergo a sex change as adults (Roberts *et al.*, 2021). A consistent aspect of Barramundi life history in northern Australia is their spawning in the saline waters of estuaries and nearshore coastal environments between September and March (Davis, 1985). Following birth in saline waters, the behaviour of Barramundi varies greatly between individuals (Crook *et al.*, 2022; Pender & Griffin, 1996). Some individuals remain in estuarine/nearshore coastal environments their entire lives, while others migrate to freshwater environments where they can remain for several years before returning to the estuary to spawn, with some changing sex after returning and others changing sex in freshwater (Crook *et al.*, 2022; McCulloch *et al.*, 2005). While access to freshwater is not crucial for completing their life cycle, it appears to have several advantages for Barramundi survival, including protection from predators as juveniles, and access to abundant high quality food sources that supports faster growth than Barramundi that spend their entire life in estuarine waters (Roberts *et al.*, 2019; Sawynok & Platten, 2008).

The distribution of Barramundi across freshwater reaches is dependent on hydrological connectivity (O'Mara *et al*., unpublished data) and hydrological aspects of habitat (Keller *et al.*, 2019; Turschwell *et al.*, 2019), with widespread movements between freshwater habitats observed in unregulated rivers (Walther *et al.*, 2011). Barramundi use flow events to move between freshwater reaches and between freshwater habitats and the estuary (Crook *et al.*, 2016, 2020). River flow is also a primary driver of catch (e.g. Balston, 2009; Marine, 2021; Meynecke & Lee, 2011; Robins *et al.*, 2005) and growth (Leahy & Robins, 2021; Robins *et al.*, 2006) of Barramundi in estuarine fisheries across northern Australia, and high flow years are critical for successful recruitment that sustains Barramundi populations (Crook *et al.*, 2022; Halliday *et al.*, 2010; Staunton-Smith *et al.*, 2004). Crook *et al.* (2022) used relationships between Barramundi recruitment in the NT fishery and hydrodynamic predictors to model potential impacts of water abstraction on Barramundi populations and predicted both wet and dry season water abstraction to have significant negative impacts on Barramundi recruitment, with impacts of dry season abstraction most pronounced in high flow years and wet season abstraction impacts most pronounced in low and moderate flow years. Water abstraction at the end of the wet season on the falling limb of the hydrograph had the lowest impact on Barramundi recruitment of all modelled scenarios (Crook *et al.*, 2022). Water abstraction modelling by Chan *et al.* (2012) also predicted the seasonal timing of water abstraction to be an important factor influencing the abundance and distribution of sub-adult Barramundi in freshwater reaches of the Daly River, NT. In contrast to predictive models of water abstraction scenarios, climate change predictive models indicate that Barramundi fisheries are likely to remain stable or experience enhanced CPUE following changes in temperature and rainfall due to climate change (Jerry *et al.*, 2013).

Models have been used to predict impacts of water abstraction on Barramundi recruitment, freshwater distribution, and abundance in the NT (Chan *et al.*, 2012; Crook *et al.*, 2022) and Barramundi catch and biomass in the Gulf of Carpentaria (Plagányi *et al.*, 2023) and eastern Queensland (Tanimoto *et al.*, 2012). However, there are also other aspects of Barramundi ecology that are likely to be impacted by water abstraction, including movement patterns and growth. Barramundi are known to make substantial movements onto the floodplain to feed during the wet season (Crook *et al.*, 2020), with some remaining in floodplain wetland refuges during the dry season (Heupel *et al.*, 2011; Jardine *et al.*, 2012; O'Mara *et al.*, 2021a). The extent and duration of floodplain inundation is important for lateral connectivity between the floodplain and river channels and wet season water abstraction is likely to reduce lateral connectivity and therefore reduce movement opportunity. This would reduce access to highly productive floodplain food sources and increase reliance on river channel food sources, as well as increasing the risk of Barramundi moving onto the floodplain to become trapped in wetlands for consecutive low or moderate flow years. Barramundi trapped in floodplain wetlands are denied the opportunity to move to the estuary to spawn and therefore do not contribute to the fishery in those years.

Access to productive freshwater habitats enhances Barramundi growth (Halliday & Robins, 2001; Roberts *et al.*, 2019; Robins *et al.*, 2021), which also causes early sex change (Roberts *et al.*, 2021). These fast-growing fish can make a high contribution to population fecundity (Roberts *et al.*, 2021), but this relies on them migrating back to the estuary to spawn. Given that movements onto the floodplain and movements to the estuary from freshwater are stimulated by high flow wet season events (Crook *et al.*, 2016, 2020), maintaining both the magnitude and timing of wet season flows, as well as maintaining a seasonally variable flow regime, is likely to be important for ensuring that Barramundi both have access to highly productive food sources and can contribute this benefit to the population by moving back to estuaries to spawn (Milton & Chenery, 2005).

Forktail catfish

There are several species of large-bodied fork-tailed catfish in the *Neoarius* genus with similar appearance and behaviour that are found in tropical and subtropical regions of Australia (up to ~60 cm for *Neoarius leptaspis* and *Neoarius graeffei*, up to 140 cm for *Neoarius midgleyi, FishBase*). *Neoarius* species are widespread, common, and abundant in freshwater, estuarine, and inshore coastal areas in northern Australia. They are known to be generalist feeders that can adapt their feeding strategies to match available food (O'Mara, 2019; Pusey *et al.*, 2020). The dependence on access to marine and freshwater is likely to differ between *Neoarius* species, with evidence of time spent in saline waters in juvenile *N. leptaspis* otoliths suggesting essential diadromy, and absence of saline signatures in many *N. graeffei* otoliths suggesting they may be euryhaline but not diadromous (Oughton, 2014). The spawning of *N. leptaspis* and *N. graeffei* was found to be highly seasonal in the Daly River (NT), with both species spawning estimated to occur in the mid to late wet season (Tyler *et al.*, 2021). *Neoarius graeffei* are among the most common of the forktail catfishes in Australia and while they do not need to migrate to the coast to reproduce, they undertake significant lateral and longitudinal movements, likely to forage (O'Mara *et al.*, 2021a; Oughton, 2014). The dependence of forktail catfish abundance (Keller *et al.*, 2019; Stuart & Berghuis, 2002; Stuart *et al.*, 2007), movement (Crook *et al.*, 2020), and foraging behaviour (Beesley *et al.*, 2021; Jardine *et al.*, 2012; O'Mara *et al.*, 2021a; Pusey *et al.*, 2020) on various aspects of the flow regime has been examined in several studies across northern Australia and eastern Queensland. These studies have shown that forktail catfish use various aspects of the flow regime to move to preferred habitat or to forage. The first wet season flow appears to be important for triggering a movement response from forktail catfish, including longitudinal movements (Stuart *et al.*, 2007) and lateral movements onto the floodplain to feed, with larger movements occurring when floodplain inundation area is greater (Crook *et al.*, 2020). As the wet season comes to an end and overbank flows subside, some individuals retreat to in-channel dry season refuges with recessional flows (Crook *et al.*, 2020), while others use off-channel wetlands as dry season refuges (Jardine *et al.*, 2012; O'Mara *et al.*, 2021a). The magnitude and duration of wet season flows are likely to influence the area of habitat available to forktail catfish and the quality/quantity of available food, with catfish in the Fitzroy River (WA) found to have better energy reserves in years of moderate to high flow than low flow, and in larger compared to smaller pools (Beesley *et al.*, 2021).

The abovementioned research across northern Australia demonstrates that these catfish use several aspects of the natural flow regime to support their growth and survival and respond to changes in the environment. Therefore, while there are few studies on the impacts of water abstraction on forktail catfish, there are likely to be multiple impacts and *Neoarius* catfishes may be good indicator species for quantifying impacts (Beesley *et al.*, 2021; O'Mara, 2019). Damming of river channels is likely to impact forktail catfish through barrier effects and alteration of downstream flows, however, the nature of these impacts is likely to be affected by the design and operation of the dams. Given that they have been shown to use fishways, effective fishway design may mediate the barrier effects imposed by water resource infrastructure (Stuart & Berghuis, 2002; Stuart *et al.*, 2007). Other infrastructure impacts are likely to occur depending on the type of water infrastructure used. Entrainment of *Neoarius graeffei* in irrigation pumps has been observed in the Fitzroy River (QLD), though the severity of these impacts may be mitigated by the location and depth of the pump within the channel, as well as the flow phase chosen to extract water from (Hutchison *et al.*, 2022). Alteration of downstream flows are likely to change the area of preferred in-channel habitat, connectivity that facilitates longitudinal movement, and quality of dry season refuges utilised by forktail catfish (Beesley *et al.*, 2021; Keller *et al.*, 2019; O'Mara *et al.*, 2021a). A less variable flow regime resulting from dry season flow releases may maintain longitudinal connectivity for longer periods and facilitate more movements between the estuary and freshwater reaches. This may also present forktail catfish with more opportunity to move around and find food to sustain biomass through the dry season. However, if the released flow does not provide the preferred habitat for forktail catfish (moderate to deep habitats (100–200 cm) with moderate to high flow velocity (30–90 cm s-1): Keller *et al.*, 2019), their distribution and abundance may be impacted.

The extensive use of floodplain inundation for movement and foraging (Crook *et al.*, 2020; O'Mara *et al.*, 2021a) indicates that forktail catfish are likely to be impacted by wet season water abstraction that will alter the timing, duration, and extent of floodplain inundation. These impacts would be caused by changes to lateral connectivity, amount and quality of food produced on the floodplain that can be accessed by catfish, and size and quality of wetland refugia. Water take during the wet season would reduce the opportunity for forktail catfish to move around the floodplain between wetlands and the river channel and increase their reliance on in-channel food sources, which may lead to reduced growth and condition.

Forktail catfish reproduction is characterised by mouth brooding and low fecundity, and they are likely to be equilibrium strategists and therefore vulnerable to change (Beesley, 2006; Sternberg & Kennard, 2014; Winemiller & Rose, 1992). Wet season spawning (Tyler *et al.*, 2021) indicates that these catfish species are likely to be dependent on the natural seasonality of the flow regime, however impacts from reduced magnitude of wet season flows on spawning and survival of larvae and juveniles is unknown, warranting further research. Changes to estuary salinity may impact *Neoarius leptaspis* recruitment, while *Neoarius graeffei* have been shown to be able to sustain populations in reservoirs and may therefore have more adaptable reproductive traits than other *Neoarius* species (Somaweera *et al.*, 2011).

Cherabin

Cherabin, also referred to as giant freshwater shrimp or river prawns, are a large, caridean shrimp species from the *Macrobrachium* genus (*Macrobrachium spinipes,* formerly referred to as *Macrobrachium rosenbergii*) found in tropical rivers of northern Australia (Short, 2004). Caridean shrimp are migratory, amphidromous shrimp with spawning generally occurring in freshwater following the downstream migration of reproductive adults (Bauer, 2013). Eggs and larvae drift to the estuary where the larvae develop through moult stages in estuarine waters before migrating back to freshwater reaches as juveniles (Bauer, 2013). Estuarine larval development is thought to be important for Cherabin in northern Australia. Novak *et al*. (2016) determined successful larval development to be dependent on access to saltwater within seven days of hatching. Evidence for an estuarine nursery and recruitment of juveniles to freshwater has been observed in northern Australia (Beesley *et al.*, 2023; Novak *et al.*, 2015). Novak *et al*. (2017a) studied juvenile Cherabin migration in the Daly River (NT) and found that mass upstream migration of juveniles from the estuary to freshwater occurred only during the falling limb of wet season flows (recessional flows) and within a six-week period. Juvenile Cherabin have also been observed migrating upstream over a weir in the Fitzroy River (WA) in the late wet season (L. Beesley Pers Comms). However, the downstream migration of adults may not be necessary for Cherabin, with high abundances of reproductive females found throughout the Daly River, including in upstream reaches (Novak *et al.*, 2015).

Flow rate and seasonal variability in flow is likely to be important for various Cherabin life history stages. Reproduction is restricted to the wet season months and unobstructed within-bank flows are critically important for transporting eggs and larvae to lower river reaches (Novak *et al.*, 2016). High flow years are also likely to yield better recruitment years than low flow years, because they promote recruitment and provide more aquatic habitat across the riverine landscape (Beesley *et al.*, 2023). Flow-mediated connectivity between river channel, wetland, and estuarine habitats facilitates population connectivity and dispersal, with widespread use of these habitats by *Macrobrachium* species observed (Beesley *et al.*, 2023; Carini *et al.*, 2006). Flows and groundwater inputs to surface water environments that maintain dry season refugia are also likely to be important for Cherabin (Beesley *et al.*, 2023; Novak *et al.*, 2017b), as they have been found to be for *Macrobrachium australiense* (Carini *et al.*, 2006).

While there are no studies on the impacts of water abstraction on Cherabin in northern Australia specifically, the clear dependence of Cherabin on wet season flow and lateral and longitudinal connectivity for various aspects of their life history (Beesley *et al.*, 2023; Novak *et al.*, 2016, 2017a, 2015), as well as research on water abstraction impacts on similar species in other countries (e.g. Covich *et al.*, 2003; Silva *et al.*, 2020), suggest that impacts on Cherabin could be numerous. Due to their migratory nature, impacts on Cherabin distribution and abundance due to changes in connectivity (such as from flow alteration, barriers, or climate change) are likely (Chappell *et al.*, 2019). Conversely, a reduction in the seasonality of the flow regime (such as flow releases in the dry season), may maintain connectivity for longer periods but may influence the spawning and recruitment behaviour of Cherabin, which are closely linked to wet season flows and recessional flows (Novak *et al.*, 2016, 2017a).

In tropical streams of the Caribbean, dams have decimated upstream populations of amphidromous migratory freshwater shrimp and fish, changing the structure of food webs upstream of dams (Greathouse *et al.*, 2006; Holmquist *et al.*, 1998). Increased frequency or duration of periods of low flow may be detrimental to the abundance of shrimp from the *Macrobrachium* genus (Covich *et al.*, 2006). However, there is unlikely to be local extinction because *Macrobrachium* species show high levels of ecological and morphological plasticity in response to changing environmental conditions (Silva *et al.*, 2020). For example, amphidromous species (such as *Macrobrachium amazonicum*) may be able to complete their life cycle in freshwater, including reservoirs (Moraes-Valenti & Valenti, 2010; Silva *et al.*, 2017). Beesley *et al.* (2023) found juvenile Cherabin in freshwater reaches with presumably no access to the estuary, suggesting that this larval development adaptability to freshwater seen in *M. amazonicum* in Brazil may also occur in Cherabin in Australia. Whilst the possibility exists for

Cherabin to complete their lifecycle in freshwater, this is still likely to come at a cost to recruitment success, including reduced fecundity (Silva *et al.*, 2020). Lower fecundity has been observed in *M. amazonicum* in dammed rivers than in unregulated rivers or estuaries (Meireles *et al.*, 2013; Silva *et al.*, 2010, 2017). In Brazil, in-channel dams alter the distribution and behaviour of breeding female *M. amazonicum* (Miranda *et al.*, 2020; Rodrigues *et al.*, 2020). This may also occur in Australia where reduced connectivity arises from water resource development. Water resource infrastructure is also likely to have both barrier and entrainment mortality effects on Cherabin, as observed with other amphidromous shrimp species (Benstead *et al.*, 1999), and Cherabin are likely to benefit from mitigative design measures.

Freshwater species

Sooty Grunter

The Sooty Grunter (*Hephaestus fuliginosus*) is a medium sized freshwater fish found in rivers across northern Australia (Pusey *et al.*, 2004). Sooty Grunter are a potamodromous fish, using wet season flows to move to shallow, lateral, slack water habitats adjacent to riffle habitats, where they spawn in aggregations (Bishop *et al.*, 1995; King *et al.*, 2021; Pusey *et al.*, 2004). The first wet season flows may serve as cues for Sooty Grunter movement (Crook *et al.*, 2021b) and spawning (Tyler *et al.*, 2021), highlighting the importance of preserving the timing of flow events throughout each year and not permitting water take from the first wet season flows. Following spawning, adults return to deeper parts of the river channel (often with woody debris) where they can be relatively resident throughout the dry season (Chan *et al.*, 2012; Keller *et al.*, 2019; King *et al.*, 2021), with few individuals moving to forage (O'Mara *et al.*, 2021a). Sooty Grunter are mostly reliant on in-stream food resources and may therefore be vulnerable to changes to food availability due to flow reduction (King *et al.*, 2021).

Juvenile Sooty Grunter show a strong habitat preference to shallow, fast-flowing riffle habitats (Chan *et al.*, 2012; Crook *et al.*, 2021a; Keller *et al.*, 2019; Stewart-Koster *et al.*, 2011) and higher wet season flows may enhance recruitment success through increased food availability for larvae and juveniles (Pusey *et al.*, 2004). Changes to flow due to water abstraction or climate change are likely to severely impact Sooty Grunter because this species is highly reliant on depth and velocity at various life stages (Stewart-Koster *et al.*, 2011). A reduction in seasonality of flow may impact the timing of spawning migrations, but may maintain shallow, fast-flowing habitats used for spawning and by juveniles for longer periods. The potential impacts of reduced flow as a result of water abstraction have been modelled by Chan *et al.* (2012) and Crook *et al.* (2021a) for Sooty Grunter in the Daly River catchment (NT) using two different techniques, with both concluding a high likelihood of severe impacts on juvenile Sooty Grunter under reduced flow scenarios. These impacts are likely to occur because of a reduction in the magnitude of within-bank flows, as well as a reduction in the duration of connection of intermittent reaches, which will reduce the availability of spawning habitat and suitable juvenile Sooty Grunter habitat (Chan *et al.*, 2012; Pusey *et al.*, 2004). Crook *et al.* (2021a) tracked habitat use by juvenile Sooty Grunter in the Katherine River (NT) using radio telemetry and used hydrodynamic modelling under several discharge scenarios in the study reach to show that the area of preferred habitat was highest at a flow rate of 8 $m^3 s^{-1}$, with large declines in habitat area likely under low flows (61% decline in habitat area at 0.5 $m^3 s^{-1}$ compared to the discharge of 2.8 $m^3 s^{-1}$ at the time of radio-tracking). This study provides information on flow rate that is useful for managers to use in models that determine water take limits with the lowest impact on Sooty Grunter habitat, however the transferability between river systems needs to be researched.

Spangled Perch

The Spangled Perch *Leiopotherapon unicolor* is a small to medium sized common freshwater fish species inhabiting freshwater environments throughout tropical and subtropical Australia (Pusey *et al.*, 2004). Spangled Perch undertake large migrations throughout freshwater reaches during high flows to disperse and spawn (Ellis *et al.*, 2015; Kerezsy *et al.*, 2013), with periods of higher flow potentially supporting better recruitment (Wilson, 2018). They have a well-defined annual spawning cycle (November to February) that is thought to be triggered by wet season flows and resulting rising water levels (Tyler *et al.*, 2021), with evidence of spawning migrations observed in the Ross River, Townsville, during wet season flows (Beumer, 1979; Lintermans, 2007; Llewellyn, 1973). Wet season flows also allow random dispersal throughout the river system and are therefore likely to be important for population connectivity and for finding suitable dry season refuges (Beumer, 1979). Overbank flows are utilised by Spangled Perch moving extensively over inundated floodplains and between floodplain wetlands and the river channel (e.g. Balcombe *et al.*, 2007; Jardine *et al.*, 2012; Kerezsy *et al.*, 2011; O'Mara *et al.*, 2021a). In-channel flows may also be important for maintaining preferred Spangled Perch habitat, as depth was found to be an important predictor of Spangled Perch distribution throughout the Daly River (Keller *et al.*, 2019). Spangled Perch residing in river channels feed on in-channel resources in the dry season (King *et al.*, 2021) and make use of lateral connectivity in the wet season (O'Mara *et al.*, 2021a).

The lack of detailed research on the influence of flows on Spangled Perch ecology makes it difficult to predict the impact of an altered flow regime on this species. However, available research suggests that Spangled Perch distribution, movement, and spawning is likely to be linked with flow, and may be impacted by flow alteration. Direct impacts of water resource infrastructure (entrainment in irrigation pumps) on Spangled Perch have also been observed, and this species will likely benefit from mitigative strategies such as irrigation screens and fishways (Hutchison *et al.*, 2022; O'Brien & Marsden, 2010).

Black Catfish

The black/eeltail catfish (*Neosilurus ater*) is one of the larger species of catfish inhabiting the tropical freshwaters of northern Australia, southern Papua New Guinea, and Irian Jaya (Pusey *et al.*, 2004). While little is known about the flow or habitat requirements of various life stages, it is thought that adult Black Catfish prefer deeper river reaches with undercut banks and woody debris (Allen, 1982; Pusey *et al.*, 2004; Rayner *et al.*, 2008). Juvenile Black Catfish tend to use the cover of smaller microhabitat features such as leaf litter or aquatic macrophytes (Pusey *et al.*, 2004). In low gradient rivers (such as the Mitchell), Black Catfish are found throughout freshwater reaches, while in steeper gradient rivers (such as in the wet tropics of Queensland), Black Catfish are more common in lowland reaches (Pusey *et al.*, 2004). The Black Catfish is a potamodromous species, undertaking significant upstream spawning migrations in the wet season, triggered by rising water levels during seasonal flow events in November to March in northern Australia (Orr & Milward, 1984). Mating occurs in pairs in upstream tributaries, and eggs are laid in gravel substrate to prevent them from drifting downstream (Orr & Milward, 1984). Studies of Black Catfish larvae and juveniles in the Daly River (NT) provide evidence that the spawning of this species is highly seasonal (Tyler *et al.*, 2021) and recruitment is stronger in wetter years (King *et al.*, 2021).

Given that the spawning cycle of the Black Catfish is the most well-known flow dependency of this species (King *et al.*, 2019; Orr & Milward, 1984; Tyler *et al.*, 2021), changes to spawning and recruitment success may be the most obvious potential impacts of water abstraction, though other impacts are largely unknown. A reduction of seasonality of the flow regime and a reduction in the magnitude of wet season within-bank flows are likely to alter the timing of migrations and spawning events, and the availability of suitable spawning habitat, potentially reducing spawning and recruitment success. Barriers such as weirs and dams may also impede upstream movement in regulated reaches. Given that Black Catfish are also mostly reliant on in-stream food resources, they may be vulnerable to changes to food availability due to flow reduction (King *et al.*, 2021).

Other species

Sawfish

There are four sawfish species that live in the waters of northern Australia: the Dwarf (*Pristis clavata*), Green (*Pristis zijsron*), Narrow (*Anoxypristis cuspidata*), and Freshwater Sawfish (*Pristis pristis*). All four species are threatened, with *P. pristis* and *P. zijsron*, listed as critically endangered under the EPBC Act 1999. More is known on the biology of the Freshwater Sawfish compared to the other sawfish species. However, both the Freshwater and Dwarf Sawfish are known to use rivers as nurseries (Morgan *et al.*, 2021; Thorburn *et al.*, 2007). Flood flows (overbank flows) promote recruitment of the Freshwater Sawfish, presumably because these flows assist pups to move into freshwater via the floodplain where they face lower predation pressure than the main channel or the estuary (Lear *et al.*, 2019). The magnitude of overbank and within-bank flows during the wet season also affects the body condition of Freshwater Sawfish at the start of the dry season which in turn influences their body condition late during the dry season when they are most stressed (Lear *et al.*, 2021). Thus, wet season flows are likely linked to juvenile survival (Lear *et al.*, 2021). Flows within the channel are important for dispersal of Freshwater Sawfish along the river (Phillips *et al.*, 2009), with in-channel barriers and periods of 'no flow' that fragment the river limiting movement (Phillips *et al.*, 2009; Thorburn *et al.*, 2007). Flow also influences the movement of the Dwarf Sawfish via its influence on salinity (Morgan *et al.*, 2021). This species moves upstream during low flow/high salinity periods and downstream during high flows/low salinity (Morgan *et al.*, 2021). Low flows are important for the foraging of juvenile Freshwater Sawfish, a species that prefers to forage at night-time in shallow sandbar (run/riffle) habitats (Whitty *et al.*, 2017). Low flows can change the resting behaviour of Freshwater Sawfish if pools thermally stratify, with individuals resting in deep cool waters during the day to reduce metabolic demands (Gleiss *et al.*, 2017).

Water resource development is likely to impact sawfish in several ways. In-channel barriers, such as weirs and dams, will limit the upstream dispersal of juvenile Freshwater Sawfish, reducing their distribution (Morgan *et al.*, 2005). In-channel barriers may also increase the mortality of juveniles trapped below barriers in intermittent systems by increasing their exposure to predation from crocodiles, sharks, and fishing mortality (Morgan *et al.*, 2005). Water abstraction that reduces the magnitude of wet season flows may reduce the survival of sawfish during the dry season in intermittent systems by reducing system-wide food production, increasing competition for resources, and reducing suitable habitat – all of which will negatively impact body condition (Lear *et al.*, 2019). Groundwater abstraction that reduces the size and persistence of permanent main-channel pools where sawfish reside during the dry season is likely to cause similar negative impacts. Lastly, development that impacts the duration of extreme high flow events may reduce recruitment (Lear *et al.*, 2019); however, development would need to be extremely widespread, or involve very large dams for this threat to emerge as typically very large flood events are relatively unchanged by development.

4. Cumulative impacts of small developments compared to singular larger scale developments

While the impact of a large dam will be marked, the cumulative impact of numerous smaller developments can cause more damage to river flow and the fisheries they support. For instance, recent research in the Murray-Darling Basin (MDB) has shown that numerous small farm dams scattered across a catchment cause a greater reduction in flow than a single large dam (Morden *et al.*, 2022). Small farm dams also greatly increase the spatial footprint of water resource development even though their total water storage capacity may be small. For instance, in the MDB small farm dams account for only 7% of total water storage capacity across the system but increase the length of waterways impacted by flow by 380% (Morden *et al.*, 2022). Altering flow in the small streams of a catchment (i.e., headwaters) is particularly detrimental to the resilience of river systems in general, as these locations often act as refuges at the catchment scale because they are protected from the downstream impacts of land use change. Additionally, small developments may have less stringent environmental impact assessments, monitoring requirements and water licensing rules, due to the perceived lower impact of individual developments on the environment (Morden *et al.*, 2022). There is an urgent need to recognise the cumulative impacts of both small and large water storages, and to legislate or develop policy to protect against cumulative impacts of developments of all sizes (Brown *et al.*, 2022).

5. Multiple stressors

Altered flow is not the only threat NT fisheries will face over the coming decades as the region develops. Agriculture will increase nutrient and chemical inputs (herbicides, pesticides) into waterways (Ganf & Rea, 2007), which will reduce water quality and cause lethal and sublethal effects on fish, particularly early life stages (Moreira *et al.*, 2010; Yang *et al.*, 2021). Water quality-related fish kills in Australian rivers typically arise because nutrient-fueled blooms of blue-green algae (cyanobacteria) create overnight oxygen deficits as the algae respires or when the bloom dies (Baldwin, 2021). Peak delivery of nutrients and chemicals into waterways is likely to occur during the first rains of the wet season as surface runoff mobilises nutrients, organic carbon, and chemicals that have built up in the soil during the dry season (Brodie & Mitchell, 2005; Mitchell *et al.*, 1997). Elevated nutrients and chemicals will increase the frequency and severity of fish kills in the NT that already occur naturally (Townsend, 1994), particularly if initial rains are not followed up by diluting flushing flows. Nutrients and chemicals will also stress fish during the dry season as low flows increase contact between aquatic biota and chemicals sorbed to sediments (Scoggins *et al.*, 2007; Suren *et al.*, 2003). Fish in river reaches that stop flowing during the dry season are arguably most at risk from nutrient-driven oxygen crashes (Vertessy *et al.*, 2019); however, fish in perennial rivers may also be stressed by elevated nutrients if they cause an overgrowth of channel clogging algae (e.g., *Spirogyra*) and macrophytes, leading to oxygen declines at night. Nutrient and chemical issues also cause problems for fish in estuaries if river eutrophication causes coastal algal blooms and anoxic dead zones (Diaz & Rosenberg, 2008). The contamination of groundwater via agricultural land use can also have long lasting effects, leading to reductions in biodiversity that remain despite rehabilitation of the riparian zone (Harding *et al.*, 1998).

Land use change, i.e. the removal of vegetation and replacement by crops, will cause in-channel changes that may impact fisheries. Infiltration will decline and runoff will increase (Tooth & Nanson, 2000) leading to flashier and more erosive flows that scour banks and widen or incise the channel. These changes also lead to the simplification of in-channel habitat (Vietz *et al.*, 2014), negatively affecting fish that have strong habitat associations, such as Barramundi. Slow-flowing depositional zones in rivers are likely to become clogged with silt as more topsoil is entrained in runoff and riverbeds and banks are eroded (Hancock, 2002; Wilcock *et al.*, 1996). Sediment buildup toward the river mouth can restrict the movement of diadromous species (e.g. juvenile Cherabin) into the river and impact their ability to complete their life cycle. Increased suspended sediment in the water column also causes problems because it can negatively impact the growth and health of some fish species (Kemp *et al.*, 2011). Sediment problems are likely to be complicated by the presence of dams. In the Ord River (WA), reductions in flood flows due to dams has increased sedimentation in the freshwater reaches of the river (Cluett, 2005) and has allowed the tide to move sediment into the estuary, shallowing and narrowing the channel (Wolanski *et al.*, 2001). Sedimentation has also reduced the length of saline water in the lower reaches of the Ord River (Wolanski *et al.*, 2001) which may negatively impact prawn recruitment. Clearing of riparian vegetation is especially problematic, as this vegetation exerts a disproportionate influence on the healthy ecological functioning of rivers, particularly through reduced erosion and increased filtration (Beesley *et al.*, 2017; Pusey & Arthington, 2003).

Along with land use change, the presence of alien species also significantly impacts healthy ecosystems through predation, competition, and habitat degradation (Marshall & Negus, 2019). There are many non-native freshwater fish in the NT, including Guppies (*Poecilia reticulata*), Platys (*Xiphophorus maculatus*), Swordtails (*Xiphophorus hellerii*), and Siamese Fighting Fish (*Betta splendens*). Most of these species have come from the aquarium or aquaculture trade and are problematic because they compete with native fish for resources, prey on native fish, and carry disease and parasites (DAWR). Tilapia (*Oreochromis mossambicus* and *Pelmatolapia mariae*) are another ornamental pest fish that have successfully invaded many river systems in eastern Queensland and have recently been found in the western draining Mitchell River catchment (O’Mara *et al.*, 2021b). Tilapia pose a significant risk to native fish biodiversity in the NT because they are a large bodied species that can prey on the eggs, larvae, and juveniles of native species, can reproduce rapidly in tropical waters, display aggressive behaviour towards native fish when nesting, and degrade the environment through oxygen consumption and bioturbation when nesting and feeding (Deines *et al.*, 2016; Greiner & Gregg, 2008; O'Mara *et al.*, 2023). Keeping tilapia out of the NT is therefore important for maintaining biodiversity.

There are several other pests additional to fish that impact habitat quality and biodiversity in the NT, including alien aquatic plants and terrestrial animals that access water for drinking. For example, aquatic grasses *Urochloa mutica* and *Hymenachne amplexicaulis* displace native floodplain vegetation and reduce abundance of culturally significant fish (Adams *et al.*, 2018), and the floating exotic herb *Eichhornia crassipes*, can clog waterholes and compete with native plants (Pettit *et al.*, 2012). Pigs cause damage to waterhole vegetation (Pettit *et al.*, 2012; Waltham *et al.*, 2013) which can increase thermal and asphyxia exposure risk to freshwater fish in wetlands (Waltham & Schaffer, 2018). The impacts of alien species on native biodiversity may be exacerbated by climate change because native species under stress of climate change impacts are likely to be less competitive against their invasive counterparts whose invasive characteristics are likely to make them better adapted to climate change.

The impacts of climate change on fisheries species of the NT are uncertain due to climate model uncertainty for northern Australia, with climate models similarly predicting both a wetter and drier future (Li *et al.*, 2009; Petheram & Yang, 2013). Flood flows associated with a wetter climate increase bank erosion and pool sedimentation (Miloshis & Valentine, 2011; Wasson *et al.*, 2010), which alters fish habitat. Decreased river flows associated with a drier climate will exacerbate the stress to riverine systems and fisheries associated with water abstraction (McJannet *et al.*, 2014; Tanimoto *et al.*, 2012). A hotter climate will also cause stress to fish, and research in waterholes of the Flinders and Gilbert Rivers showed that summer temperatures at the bottom of waterholes already exceeded the optimal temperature for growth of some tropical fish (Wallace *et al.*, 2015). A hotter, drier climate in northern Australia will also render riparian vegetation more vulnerable to fire (Tabacchi *et al.*, 1998), which will impact fisheries species through impacts on water and habitat quality. Some impacts of climate change are already being observed in northern Australia, with sea level rise due to melting of the polar ice caps causing saltwater intrusion, which is impacting coastal wetlands and streams and their fish, particularly in the Kakadu region (Humphrey *et al.*, 2016; Saintilan *et al.*, 2019). It is important to recognise that the stressors discussed in this section are likely to arise in concert with water abstraction and manifest in impacts that are greater than the sum of their parts.

6. Risk mitigation

Numerous methods exist to assess environmental water requirements. These methods use varying levels of knowledge about the ecohydrology of a river system and its floodplain wetlands/delta (Poff *et al.*, 2017). Ideally, detailed environmental flow assessments should be undertaken for all existing and future water-resource development scenarios so that the flow requirements of important assets (valued aquatic biota, valued habitats, ecosystem services) can be evaluated, and the risks of hydrological change to these assets can be mitigated. Environmental flow assessments are an important step for decision-makers as they make tradeoffs among competing users of water (e.g., environment, agriculture, hydropower, urban supply, and industry) explicit (Arthington, 2012).

Following is a series of general principles for environmental flow management (adapted from Pusey & Kennard, 2009) that should be considered to mitigate risks associated with current and future water resource developments in the Northern Territory:

- Undertake environmental flow assessments for all existing and future water-resource developments using appropriate frameworks and methods. Rigorous and well-designed monitoring for developments and across entire catchments is imperative to understanding actual impacts and monitoring data can be used to test the effectiveness of predictive models that assess the likely impacts of proposed developments. The NT is relatively undeveloped compared to other tropical regions of the world and has a high proportion of rivers remaining free-flowing, presenting a unique opportunity to establish effective and consistent long-term monitoring programs that will serve as important baseline data to identify possible future impacts of water abstraction and climate change.
- Implement environmental flow management practices. For example, water infrastructure (dams and weirs) can be designed and operated to be hydrologically transparent (bounded by infrastructure constraints and reductions in yield for other uses). This means that ecologically important flow events (e.g. floods, flow pulses, baseflows, low flow spells) from upstream can be delivered downstream. This would help to mimic ecologically important components of the flow regime for downstream aquatic ecosystems.
- Dry season flow releases from dams (e.g. for delivery of water for irrigation purposes) that result in artificially elevated low flows that may alter available habitat and disrupt spawning and recruitment cues could be avoided by delivering the water through off-channel pipelines, instead of along the river channel, and off-channel storage at the destination.

- Flow releases from dams that result in unnaturally rapid rises and falls in water levels downstream and within impoundments, should be avoided due to the risk of stranding aquatic organisms, disrupting nesting areas, etc.
- Flood harvesting (capture and use of water flowing across a floodplain) and off-channel storage can mitigate the requirement for in-channel storages. Harvesting of floodwaters should only be considered in circumstances where changes to ecologically important components of the natural flood hydrograph (e.g. rates of rise and fall, peak magnitude) can be minimised, and the location of off-channel storages can be situated in areas that avoid habitat for important terrestrial and aquatic biota (e.g. important floodplain wetlands or hotspots of aquatic primary production).
- A precautionary approach applied to the development of new wet season water abstraction on top of pre-existing groundwater and surface water abstraction to minimize unforeseen environmental risks until better information is available. For example, contingency rules are precautionary approaches proposed to be used where scientific research is unavailable to guide allocation setting (e.g. in the Northern Territory Surface Water Flows – Wet Season Take Policy). Understanding of how these contingency rules may impact fisheries species could be improved by modelling responses under scenarios with these contingency rules applied. The predicted impact studies discussed in this report contain models that may be used as a starting point for predicting impacts with these contingency rules applied. Importantly, the combined effects of groundwater abstraction, plus dry season and wet season surface water use need to be considered, as well as natural climate variability and climate change predictions.
- The cumulative impacts of the same type (e.g. multiple farm dams) and different types (e.g. groundwater and surface water) of water abstraction need to be evaluated and rules set to limit the area of a catchment that can be impacted via these means.
- Groundwater and groundwater assets should be clearly defined before groundwater extraction occurs. Groundwater extraction should then be carefully assessed to ensure protection of groundwater-dependent ecosystems, especially during the dry season. Over extraction of groundwater can also lead to land subsidence on floodplains and alter the pattern of flood inundation.
- The cumulative effects of direct pumping of water from streams and rivers can lead to major reductions in low flows and increases in the frequency and duration of dry spells. Similarly, water extraction from isolated waterholes can reduce the duration of persistence and quality of these important dry season refugial habitats. These impacts could be mitigated by setting minimum thresholds for dry season water extraction by riparian users and adequately policing these regulations. Pump offtakes should be positioned well below the water surface to minimise the possibility of removing high-

quality surface waters from deep, stratified waterholes. These offtakes could also be screened to avoid potential entrainment of fish.

- For high-priority aquatic habitats (e.g. conservation zones, those known to be critical dry season refugia and/or supporting species of conservation significance), individual site-specific management rules should be established to protect their ecological values, including specification of permissible drawdown depths and rates.

7. Knowledge gaps and future research priorities

Our review and synthesis of global and Australian literature found that few studies on the impacts of water abstraction have been conducted in northern Australia on the fisheries species reviewed in this study. This was unsurprising given that there are substantially fewer water resource developments in northern Australia than other tropical countries, such as Brazil. However, given that there are new water resource developments being constructed across northern Australia and more proposals are anticipated, it is imperative that research is conducted on the impacts of these developments to inform mitigative management strategies. For example, new proposals are anticipated to support contentious business cases to rapidly expand cotton agriculture in the NT from approximately 4,500 bales in 2019 to over 400,000 bales by 2029 (Beaumont *et al.*, 2022; Pricewaterhouse Coopers Australia, 2019).

Although indigenous fisheries are a vitally important source of protein in remote communities across the NT (Jackson *et al.*, 2012; Woodward *et al.*, 2012), the potential impacts of increasing water abstraction on their food supply requires additional research attention and recognition by managers and policy makers. Similarly, species that are not harvested including diverse assemblages of small-bodied native freshwater fish (which may be important prey species), and large threatened species including euryhaline sharks and rays (Grant *et al.*, 2019) also require additional research attention for mitigation of biodiversity loss caused by water resource developments.

The majority of relevant studies in this review researched the flow relationships of the focal fisheries species, with a number of studies showing evidence that the abundance of most of the focal species is correlated with various hydrodynamic predictors (e.g. rainfall, discharge, or depth). However, the number of studies, and quality of evidence varied markedly between species. The volume of research was heavily skewed towards Barramundi, NPF prawns (particularly White Banana Prawns), and Giant Mud Crabs. We found no studies on the flow dependency of Golden Snapper, and while recent research found adult Black Jewfish unlikely to be flow dependent (Randall *et al.*, 2023), research on the early life stages is still required. Similarly, there were few studies on the importance of flow for spawning movements and recruitment of the freshwater species, with most of the available studies conducted in other regions (e.g. the wet tropics) and on a small spatial scale.

In the absence of long-term monitoring data, fisheries catch data has proved to be valuable to learning about the flow ecology of these species and is the only long-term data available for most of these fisheries species. Studies featuring correlations between catch and flow or climate variables identified flow, rainfall, and climate to be important drivers of catch. Despite correlative studies forming the bulk of the literature on these species, research on some of the focal species appears to be shifting towards more predictive studies. These studies are advancing our understanding of likely impacts of water abstraction and managers would benefit from a greater breadth of these studies across species. Two examples of these studies include

Barramundi and King Threadfin recruitment and growth relationships to flow and predicted changes under water abstraction scenarios with varying timing and modes of water abstraction(Crook *et al.*, 2022; Halliday *et al.*, 2008). Predicting ecological impacts associated with the timing of water take is important for informing decisions regarding when water take can occur within each year in response to antecedent variability in the hydrograph. A key component of these predictive studies is the quantitative relationship between flow/climate/rainfall and important aspects of life history for these species.

Quantified flow ecology relationships can be used in predictive models to find minimal impact solutions for new developments, inform decisions for proposed developments, or modify existing developments to reduce severity of impacts. Studies that explore the flow dependency of growth, condition, reproductive success, movement, and other important components that contribute to healthy individuals and populations while also providing research users with numerical relationships or threshold values is a priority research need for the protection of these species into the future. Some studies of this nature have already been conducted in northern Australian rivers, providing key information such as the flow threshold (in $m^3 s^{-1}$) required to maintain juvenile sooty grunter habitat (Crook *et al.*, 2021a). Similarly, a study in northern NSW found particular temperatures and conductivity (following heavy rainfall) cued spawning migrations of Giant Mud Crabs (Hewitt *et al.*, 2022). Future research that quantifies the environmental conditions (e.g. flow rate) required to cue migrations for spawning (e.g. for Barramundi movement to the estuary or for Spangled Perch, Sooty Grunter, and Black Catfish to move to suitable spawning habitat) or recruitment (e.g. for juvenile Cherabin to migrate upstream) are examples of research that is critical for improving understanding of flow ecology and informing predictive models.

Another future research priority is increasing understanding of floodplain wet season water abstraction. While the hydrological and ecological impacts of dry season water abstraction are well documented (King *et al.*, 2015), the impacts of wet season water abstraction is a research priority requiring attention. Research focusing on the potential impacts of wet season water abstraction should also consider the cumulative effects of additional ground and surface water abstractions and their effects across both wet and dry seasons and antecedent conditions.

This review identified that few studies on the importance of floodplain inundation and lateral connectivity have been conducted on these species. It is known that several of these species, including Cherabin, Spangled Perch, Barramundi, and forktail catfish species access floodplain wetlands to feed. However, the cost of reduced access to these floodplains and restriction to in-channel habitats to the growth, condition, or reproduction of these species is unknown. Faster growth in individuals accessing floodplain habitats has been observed in other species and is therefore also likely for these fisheries species (Pratt *et al.*, 2023). Additionally, reduced wetland quality through reduced flushing with wet season water abstraction is likely to impact the species that access wetlands, as well as other species that inhabit wetlands. This highlights the need for future studies that examine wetland quality and persistence and predict how they will change with wet season water abstraction and climate change.

8. Conclusions

Our review of literature on the impacts of water abstraction on tropical aquatic species found that Australia ranked among the highest for flow ecology research effort in tropical regions. However, very few studies have been conducted in northern Australia that have actually measured the impacts of water abstraction. While this is unsurprising given Australia has fewer water resource developments than many other tropical regions such as South America, it is imperative to conduct studies that measure the impacts of existing developments, including cumulative impacts, given the expansion of water resource development in northern Australia. Since very few studies have measured impacts of water abstraction on the fisheries species focused on in this review, the best estimate of likely impacts comes from examining predictive studies and research on the flow dependency of these species for critical life history stages. We identified several studies that used flow-ecology relationships to predict impacts to these fisheries species under various water development scenarios, providing valuable information to fisheries and water resource managers. By examining studies on flow-ecology relationships or predicted impacts of water abstraction, we concluded that there are likely to be impacts on these species by the various modes of water extraction currently used or proposed to be used in the NT, including dry season direct pumping/groundwater extraction, in-channel dams, and wet season water abstraction. However, the nature and severity of these impacts are likely to differ between each water abstraction mode, as well as with different timing, magnitude, rates, and thresholds of water take. These impacts are also likely to vary between low, moderate, and high flow years which are influenced by natural climatic cycles, changes to which are uncertain for climate change predictions in the north of Australia. We recommend that the flow dependencies of these species be carefully considered when implementing water policies and research be conducted to fill knowledge gaps for species where little is known about their dependency on the natural flow regime.

9. Project materials developed

There are several materials developed during this project that are available from the FRDC project 2021-114 web page, including this report, a fact sheet, and an excel spreadsheet that lists each flow related reference for northern Australian research reviewed during this study for each focal species. This spreadsheet contains a table with a row for each fishery species within each reference, and information regarding where the study was conducted, the type of study, the environment studied (e.g. river, wetland, estuary), the type of data collected, and the main flow related findings.

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