Addressing knowledge gaps for studies of the effect of water resource development on the future of the NPF: juvenile banana prawn abundance in estuarine habitats in the Mitchell, Gilbert and Flinders Rivers

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2016/047	Addressing knowledge gaps for studies of the effect of water resource development on the future of the Northern Prawn Fishery

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OBJECTIVES:

1. Synthesise historical data available on surveys of the fishery and recruitment of prawns.
2. Contribute to the sampling design for field trips to the southern Gulf of Carpentaria to estimate juvenile prawn densities across estuarine nursery habitats.
3. Undertake field sampling across estuaries in the southern Gulf of Carpentaria to estimate juvenile prawn densities and explore linkages to primary production in rivers with different characteristics and catchment features compared to the Norman River, expanding knowledge to other GOC rivers.
4. Contribute to data analysis from field sampling effort (Objective 2) and provide advice on sample sorting and analysis.

NON TECHNICAL SUMMARY:

OUTCOMES ACHIEVED TO DATE

Accounting for past and current estuarine and offshore banana prawn survey outcomes, contributed to the sampling design for prawns, meiofauna and productivity in the Mitchell, Gilbert and Flinders Rivers during field trips from 2016 to 2019. Meiofauna and productivity sampling was undertaken by Dr. Michael Venarsky and Professor Michele Burford, colleagues (and a co-investigator) from Griffith University as part of NESP 1.4 (Links between Gulf Rivers and Coastal Productivity).

For the first time in 40 years, provided estimates of juvenile banana prawn abundance in the Mitchell, Gilbert and Flinders Rivers, rivers previously studied in the 1970s by Staples and Vance (1979). For the first time, measured the spatial distribution of juvenile banana prawns in tributary habitats and main channel habitats in each of the three rivers. Historically, their estuarine tributary habitats have never been sampled as the importance of ‘upper creek’ habitats was not realised (Vance *et al*. 1990). Related aspects of the population biology of juvenile banana prawns to the environmental conditions in each of the estuaries. Explored how impacts of seasonality and dimension of low flows due to water resource extraction affect the banana prawn population, emigration and commercial catch.

Provided estimates of juvenile banana prawn abundance in the Mitchell, Gilbert and Flinders River estuaries over two years (2016 and 2017) in the late dry season (November) that can be linked to estimates of intertidal and shallow-subtidal habitat extent, together with simultaneous productivity and meiofaunal abundance within the same habitats (see Burford *et al*. 2020). Provided estimates of juvenile banana prawn abundance in the Flinders River estuary during the wet season (February) and after the wet season (May) of 2018 that can be linked to habitat, productivity and meiofauna. Provided estimates of abundance at a sub-set of sites in the Mitchell, Gilbert and Flinders River estuaries after the wet season in March 2019. The summation of the FRDC and NESP funded activities will provide measures of the relative contribution of the three estuaries to the offshore commercial banana prawn catch (see Burford *et al.* 2020).

Identified a difference in the behavior and habitat use of juvenile banana prawns in the Mitchell, Gilbert and Flinders River estuaries during a ‘dry’ late-dry season when river estuaries remain marine-equivalent or hypersaline; and during a ‘wet’ late-dry season when early river flows created a brackish estuary. Euryhaline estuarine habitats condition a more dynamic system where juvenile banana prawns utilize the full extent of estuarine habitats. A higher relative abundance of prawns in the lower-estuary main river habitats in 2017 was due to juvenile prawns cued to move downstream by the low-level river flows and brackish conditions.

Demonstrated that in the Gilbert River in November 2017, a higher prawn abundance in main river habitats was matched by salinity-cued emigration of a cohort of juvenile prawns from the river to nearshore habitats (~5-7 mm CL). The restricted size range (3 mm CL) and small size of the juvenile prawns was freshwater-cued early-season emigration that would contribute to good catches of large-sized commercial prawns early in the fishing season. Prawns emigrating in November remain un-fished offshore over four months until April. Early emigrants supplement the bulk of the population that emigrate in response to monsoon floods occurring ~three months later during the wet season.

Identified low-level flows that, if harvested or impounded by water resource infrastructure, would have a disproportionate negative effect on downstream flow volume and would reduce the annual contribution of juvenile banana prawns to the seasonal offshore fishery. Maintaining these flows was crucial as ecosystem process cues that support banana prawn growth, survival and emigration, and subsequent fishery catch. Early recruitment complements later wet season floodflow-cued mass emigration and offshore recruitment.

Historical research from the Northern Prawn Fishery (NPF) has shown that a reduction in monsoon-driven river flows will impact estuarine habitats and ecosystem processes and will reduce fishery catch and the economic performance of the NPF (Vance *et al*, 1998, 2003; Kenyon *et al.* 2018; Broadley *et al*. in press). More broadly, inshore fisheries including those for important table species such as barramundi and mud crabs, as well as iconic and endangered species will also be negatively impacted (Balston 2009; Meynecke *et al*. 2012; Pollino *et al.* 2018a,b).

The catchments of the Mitchell, Gilbert and Flinders Rivers contain 10,000s of hectares of agrarian soils capable of supporting agriculture (Petheram *et al.* 2013a,b, 2018c). The Commonwealth of Australia has demonstrated significant support for the placement of infrastructure and land management to encourage irrigated agriculture and economic expansion in these catchments. However, these sparsely populated, hot, seasonally-dry catchments are not subject to temporally sustainable rainfall patterns that would support dryland agriculture. Irrigated agriculture is feasible in these catchments and in-stream or off-channel dams have the capacity to provide water resources with an ~85% guarantee in any year (Petheram *et al*. 2013a,b, 2018c). The Mitchell, Gilbert and Flinders catchments receive 996, 775 and 492 mm of rainfall annually, but 90% of the rainfall occurs during January to March; the annual monsoon season (Bayliss *et al*. 2014). Utilisation of this rainfall necessitates Water Resource Development (WRD) in the form of in-stream dams or pumped extraction and off-stream storage to capture and hold monsoon rains for use over the dry 9 months of the year. Both instream and offstream storage of monsoon-driven river flows causes modification of downstream flows and the reduction of ecosystem services to riverine and estuarine habitats. Water extraction will reduce river flows and has the capacity to impact groundwater, overland flows and both wet-season and dry-season inputs to rivers and estuaries.

Outcomes of the Northern Australian Water Resource Assessment (Petheram *et al.* 2018a,b,c; Pollino *et al*. 2018a,b) show that the diversion of water due to WRD has a lesser 'percentage of flow' impact when water is extracted from high-level river flows and major floods. In contrast, WRD has the capacity to disproportionately modify the seasonality of flow and the magnitude of low flows. WRD can remove or impound most low-level flows including early flows that in Australia's wet/dry tropics occur in October to December each year. These early flows have significant positive effects on riverine and estuarine environments that often are stressed after about nine months of no dry-season rainfall. The regulation of water extraction via trigger levels and a guarantee of an end-of-system annual flow volume can allow the downstream passage of critical seasonal low flows including the early flows (Broadley *et al*. in press). Informed management can maintain both the connectivity and rejuvenation of river pool habitats, and conditioning estuaries to optimal brackish conditions for many fishery species after dry-season months of hypersalinity (Pollino *et al.* 2018b).

Prime estuarine juvenile banana prawn mangrove/mudbank habitats within the Mitchell, Gilbert and Flinders Rivers in the late-dry season of 2016 (November) supported abundances of juvenile prawns that ranged from 1.34±0.48 to 1.85±1.11 prawns m^{-2}, not significantly different between the three estuaries. These results match estuarine productivity experiments which showed that the water column and benthic productivity measured in each estuary also did not differ in 2016 (Burford *et al*. 2020). In 2017, the abundance of juvenile prawns in the Gilbert river was significantly higher (4.52±2.03 prawns m^{-2}) than abundances in the other two rivers which were <1 prawn m^{-2}. Despite the difference in prawn abundance, the water column and benthic productivity measured in each estuary in 2017 remained equivalent between estuaries. Each of the three river estuaries has extensive mangrove forest/fringe and intertidal mudbank habitats to support the abundant levels of juvenile banana prawns that recruit annually to their tributary habitats. Historically, the estuarine tributary habitats had never been sampled as the importance of the mangrove/mudbank matrix in the 'upper creek' tributary habitats of GoC tropical rivers was not realised (Vance *et al*. 1990). The estuaries have the capacity to contribute high numbers of banana prawn recruits to the annual first-season banana prawn fishery in the GoC. Historical data show that prawn abundance is highly variable between locations within an estuary and between years in the same estuary (Staples 1980a; Vance *et al*. 1998), so the variability in prawn abundance over 2016 and 2017 was expected.

In 2017, within the brackish Gilbert River estuary, juvenile prawns moved downstream from their benthic recruitment habitats in the creek/mangrove matrix in the upper reaches of estuarine tributaries to extensive mudbank/mangrove habitats in the lower reaches of river estuarine, and where density-dependent predation likely is lower. In November 2017, 5.95±2.92 prawns m^{-2} (80%) of juvenile prawns were found in the estuarine upper-tributaries while ~20% (1.44±0.38 prawns m^{-2}) occupied main river habitats. In contrast, in the Gilbert River in November 2016, 96% of juvenile banana prawns (2.34±1.41 prawns m^{-2}) were found in the upper-tributaries while only 4% of juvenile prawns (0.15±0.06 prawns m^{-2}) were found in the main river habitats downstream.

In 2017, low-level river flows and brackish estuarine conditions cued juvenile prawns to move downstream to be found at higher relative abundances in the lower-estuary main river habitats. In the Gilbert River, the higher prawn abundance in the main river habitats was matched by salinity-cued emigration of a cohort of juvenile prawns from the river to nearshore habitats (~5-8 mm CL, but mostly 5-7 mm CL). The restricted size range (3 mm CL) and small size of the juvenile prawns suggested freshwater-cued early-season emigration of juvenile prawns that would be subject to lower predation rates offshore (Lucas *et al.* 1979; Gwyther, 1982), to survive and grow and contribute to good catches of large-sized commercial prawns early in the fishing season. They provide a cohort of large prawns that are available to the fishery at season-start.

Water management harvest regimes are capable of minimising the catch reduction in coastal fisheries through water extraction or impoundment from high-volume floodflows only; flows that are supported by monsoonal flow regimes during the wet season. High floodflows offer the potential to remove a relatively small proportion of the flood hydrograph, while the majority of the flood passes downstream. Maintaining the integrity of most of a flood has a low impact on downstream ecosystem services to estuaries and coasts. Fisheries advocates should engage in the 'water resource planning process' via stakeholder input within the legislative framework, with the aim of impact minimisation on seasonal and annual flow patterns using quantitative targets and triggers, below which water extraction should cease. Their overall aim is to promote water management, water harvest regimes, and infrastructure design and construction that, as much as practicable, mimics historical patterns of natural seasonal flow.

Contingent on the development of irrigated agriculture within Australia's northern catchments, Water Resource Plans (WRPs) will be renewed or developed for each of the river catchments. The enactment of the WRPs and subordinate Resource Operation Plans (ROPs) will provide key windows-of-opportunity for water resource managers to both provide water for successful irrigation and to take account of the concerns of other stakeholders who depend on the catchments. The Northern Prawn Fishery management (NPF Industry) and the managers of other finfish and crustacean fisheries are key stakeholders who depend on unregulated river flows from these catchments to maintain ecosystem services downstream. The development of the revised WRPs offers the opportunity to engage with the legislative process; to deploy most-recent knowledge of ecosystem processes that support and sustain fisheries production via best-practice water management protocols. Fishery managers should engage with WRP development to promote downstream impact minimisation through the management of water impoundment or extraction to minimise the reduction or modification of historical seasonal and monsoonal flows. Maintaining streamflows will maintain the ecosystem services that they sustain in the lower river and estuary.

KEYWORDS: juvenile banana prawn abundance, pre-wet season river flows, estuarine habitat, Northern Prawn Fishery, tropical rivers.

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Acknowledgments

Access to the remote estuaries of the Mitchell, Gilbert and Flinders Rivers was provided by mothership and associated dinghies which were in large part funded by Professor Michele Burford from Griffith University as part of NESP 1.4 (Links between Gulf Rivers and Coastal Productivity). The Master and crew of the vessel MV Eclipse provided the mothership platform. This project is jointly funded through Griffith University and the Australian Government's National Environmental Science Programme (NESP).

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Executive Summary

The objectives of this project were to use historical data and derived knowledge from banana prawn research in the Gulf of Carpentaria (GoC) to identify knowledge gaps and examine estuarine juvenile banana prawn abundance in a subset of Gulf estuaries where water development is planned. The field trips and associated sampling were undertaken jointly with the Northern Australian Environmental Resources' (NAER) NESP Project 1.4 'Links between Gulf Rivers and Coastal Productivity' (NESP colleagues assisted with the prawn sampling). NESP 1.4 was jointly funded through Griffith University and the Australian Government (via NESP). A major objective was to undertake field sampling of the estuaries of a representative subset of GoC rivers to obtain estimates of abundance of juvenile banana prawns within the estuarine habitats at the same time as NESP 1.4 undertook benthic and water column productivity measurements, and macrobenthos sampling. In addition, an objective was to be able to compare the estimates of prawn abundance and habitat productivity between the rivers. Using NESP data on habitat availability, prawn numbers in each estuary were estimated. Our studies show that interannual variability in juvenile prawn densities drives variability, rather than river to river productivity differences.

The distribution and abundance of juvenile banana prawns within each of the Mitchell, Gilbert and Flinders river estuaries was sampled for the first time since the 1970s. In addition, tributary habitats (creek and creeklets among the estuarine mangrove forests) were sampled for the first time. These tributary habitats had not been sampled by Staples (1979); the team only sampled shallow bank habitats along the main river channel. The importance of tributary habitats was recognised in the 1990s during banana prawn research in the Embley and Mission River estuaries (see Vance *et al*. 1990). Together with measurement of the salinity regimes of each estuary, prawn distribution and abundance provide enhanced understanding of the effect of change in freshwater flows on estuarine banana prawn behaviour. Trawl samples were taken during November 2016 and 2017 (the late-dry season), during the critical September to February recruitment window for juvenile banana prawn settlement, survival and growth in tropical Australian estuaries. After the wet season of 2019, a subset of the suite of sample sites was trawled in each of the three rivers. In addition, within the Flinders River only, sampling was undertaken during the wet season in February and after the wet season in May 2018.

The field sampling was undertaken in the remote estuaries using a mothership for accommodation and logistical support. An array of dinghies provided access to river and creek sites. Each river was accessed for two days in 2016 and three days in 2017 and two days in 2019; and both trawl samples and surface nets to catch emigrating prawns were deployed. Temperature, salinity and secchi disc environmental parameters were measured.

<u>Prawn abundance</u>
In November 2016, estuarine juvenile banana prawn habitats within the Mitchell, Gilbert and Flinders Rivers supported abundances of juvenile prawns that ranged from 1.34±0.48 to 1.85±1.11 prawns m^{-2}, not significantly different densities between the three estuaries. These results match the concurrent estuarine productivity experiments which showed that the water column and benthic productivity measured in each estuary also was not consistently different in 2016. In 2017, the abundance of juvenile prawns in the Gilbert River was higher (4.52±2.03 prawns m^{-2}), though not significantly different than abundances in the other two rivers which were <1 prawn m^{-2}. Despite a different trend in average prawn abundance, the water column and benthic productivity measured in each estuary in 2017 remained equivalent between estuaries. Juvenile banana prawn abundance in Australia's tropical rivers is highly variable temporally between the same sites over different years and spatially between sites in proximity (Staples 1980a, Staples and Vance 1985, Vance *et al*. 1998). These trends were characteristic of the prawn abundances found in the Mitchell, Gilbert and Flinders Rivers.

The collaborating NESP project 1.4's ecological productivity experiments suggested that none of the estuaries exhibit high levels of productivity or levels that differ strongly between estuaries in a manner that would support high abundances of juvenile prawns in one estuary or the other. In addition, the productivity experiments demonstrate nutrient paucity within estuaries and suggested that monsoon-cued critical inputs of nutrients via riverine/estuarine connectivity and unregulated floodflows are needed to sustain downstream ecosystem services.

The NESP 1.4 made estimates of the aerial and linear extents of mangrove habitats in the three estuaries and found that the Mitchell River estuary supported the largest areas of mangroves, followed by the Gilbert River estuary and the Flinders River estuary. Scaling up prawn abundance by the area of mangrove habitat, overall population estimates in each of the estuaries ranged from 76.2 (±27.3) million juvenile prawns in the Mitchell River to 13.4 (±8.0) million in the Gilbert River in November 2016. In November 2017, the estimates ranged from 32.7 (±14.7) million juvenile prawn in the Gilbert River to 5.8 (±2.3) million juvenile prawns in the Flinders River in 2017. Using linear extent of the intertidal 'mangrove mudbank' is less speculative, with estimates of 1.9 (±0.7) million juvenile prawns in the Mitchell River to 0.6 (±0.4) million in the Gilbert River in 2016; and 1.5 (±0.7) million juvenile prawns in the Gilbert River to 0.3 (±0.1) million in the Flinders River in 2017.

Prawn distribution within an estuary

In 2017, within the brackish Gilbert River estuary, juvenile prawns moved downstream from their benthic recruitment habitats in the creek/mangrove matrix in the upper reaches of estuarine tributaries to extensive mudbank/mangrove habitats in the lower reaches of river estuarine, and where density-dependent predation likely was lower. In November 2017, 5.95±2.92 prawns m^{-2} (80%) of juvenile prawns were found in the estuarine upper-tributaries while ~20% (1.44±0.38 prawns m^{-2}) occupied main river habitats. In contrast, in the Gilbert River in November 2016, 96% of juvenile banana prawns (2.34±1.41 prawns m^{-2}) were found in the upper-tributaries while only 4% of juvenile prawns (0.15±0.06 prawns m^{-2}) were found in the main river habitats downstream.

In 2017, low-level river flows and brackish estuarine conditions cued juvenile prawns to move downstream to be found at higher relative abundances in the lower-estuary main river habitats. In the Gilbert River, the higher prawn abundance in the main river habitats was matched by salinity-cued emigration of a cohort of juvenile prawns from the river to nearshore habitats (~5-8 mm CL, but mostly 5-7 mm CL). The restricted size range (3 mm CL) and small size of the juvenile prawns suggested freshwater-cued early-season emigration of juvenile prawns that would be subject to lower predation rates offshore (Lucas *et al*. 1979; Gwyther, 1982), to survive and grow and contribute to good catches of large-sized commercial prawns early in the fishing season. Significant emigration from the Flinders River was found as well. The size range of the emigrants was larger than those from the Gilbert River. Given the near-marine salinity of the Flinders estuary and the large size of the emigrants, ontogenetic emigration rather than freshwater-cued emigration was more probable from the Flinders River.

Banana prawn samples of both benthic juveniles and emigrants have been taken using the same gear as was used during the TRaCK project which sampled the Norman and Flinders River in the south-east Gulf of Carpentaria in the 2000s. The same gear was used historically in the Norman River in the 1970s and the Embley River in the 1980s and 1990s. The Gilbert River is the river most like the Norman and Flinders Rivers. It has a large meandering main river channel with shelving mangrove-lined mudbanks on the inner reach of each meander. These fringing mangroves and banks are prime juvenile banana prawn habitats. In addition, several mud-substrate creeks and many small tributaries branch off the main river channel. These are critical first-settlement habitats for immigrating banana prawn postlarvae moving upstream on flood tides. The Mitchell River is the least similar of the three rivers. Its lower estuary has sandy substrates and exposed sandbanks and supported lower densities of juvenile banana prawns. However, muddy tributaries branch off the main river channel and the other delta-channels that form three openings to the Gulf of Carpentaria. These tributaries support high abundances of juvenile banana prawns and contribute to offshore prawn stocks.

Bio-geochemical tracers – estuary to offshore

In November 2016 and 2017, and February and May 2018, in addition to the prawn abundance samples, juvenile banana prawns from each of the three GoC river estuaries were analysed for bio-geochemical trace element signatures. Sediment samples were collected from each of the prawn sample sites and analysed using the same technique. As well, juvenile banana prawns (and sediment samples) were collected from otter trawls undertaken close inshore adjacent to the river estuaries and analysed for bio-geochemical trace element signatures of recent emigrants. During January 2017 and 2018, sediment and banana prawn samples were collected from deeper sites offshore from each of the Mitchell, Gilbert and Flinders river estuaries in the eastern and south-eastern Gulf of Carpentaria and the trace element signatures of offshore prawns and sediment were analysed.

Over each year and set of samples, trace element analyses have shown that the offshore marine sediment and offshore prawns show a similar signature among and between locations. The mixed offshore signature differed from the estuarine signatures and no link to juvenile prawns from a particular estuary to those caught offshore of that estuary had been identified. Each of the estuaries has a different signature identified using the bio-geochemical tracers. However, the strongest signal identified as part of these analyses was between the 'upper' and 'lower' estuary, a trend found in each estuary. These analyses and their interpretation will be reported as part of NESP 1.4.

Implications

Historical research from the NPF has shown that recently-settled postlarval banana prawns use estuarine tributary mangrove/mudbank habitats as their preferred transition habitat to their benthic juvenile phase. Juveniles forage and grow in the tributaries before moving downstream and emigrating. Juvenile banana prawns in the Mitchell, Gilbert and Flinders rivers follow the same ecological cycle. In addition, historical research has shown that a reduction in monsoon-driven river flows due to the diversion of water resources to support irrigated agriculture will reduce fishery catch and the economic performance of the NPF (Vance *et al*, 1998, 2003; Kenyon *et al*. 2018). Water resource development in GoC catchments and current riverflow-dependent fisheries such as the NPF are likely to successfully co-exist in Australia's wet-dry tropics if water is harvested from monsoon-season high-flows only. During the annual wet season, high flow volumes dominate the catchment and during strong wet seasons, the highest flows may dominate the capacity of in-stream or off-steam dams. Significant volumes of water can be harvested from high-level floodflows as a small proportion of the total flow volume resulting in minimal impact on the downstream ecosystem services provided by the floodfow. The quantum of water reaching the estuary would be of similar magnitude to an unregulated river.

In contrast to the harvest of water from high flows, the seasonality, magnitude and duration of low flows must be maintained. The harvest of low-floodflows diverts a large proportion of the total flow volume with major impacts on downstream ecosystem services. Both the magnitude and duration of low flows are reduced with a disproportionate impact on offshore banana prawn catch (Broadley *et al.* in press). Both seasonal low flows and low-level floods in years of poor wet season rainfall require protection. WRPs and ROPs should incorporate trigger levels of flow below which environmental flows must be maintained. Trigger levels should be based on quantitatively modelled flows estimated from ecosystem-based research and that withstand scrutiny by water managers and water users. NPF management need to engage with the WRD process via stakeholder consultation processes to promote a legislature that specifies water management protocols and infrastructure design that maintain ecosystem services downstream to minimise impacts on fishery production.

Background

The Northern Prawn Fishery (NPF) has operated across the tropical Australian coast for 50 years with recent catch value of $115 million in 2013-14 and $118 million with a net return of $30.3 million in 2016-17 (Savage and Hobsbawn 2015 and http://agriculture.gov.au/abares). Initially in the late 1960s and 1970s, the target species was the common banana prawn, *Penaeus merguiensis*, with fishing grounds in the eastern and south eastern Gulf of Carpentaria. In subsequent decades, new fishing resources in the form of tiger prawns (*Penaeus semisulcatus* and *Penaeus esculentus*) and red-legged banana prawns (*Penaeus indicus*) were found in the western Gulf of Carpentaria, and Joseph Bonaparte Gulf, respectively. As well, prawn resources were found across the Northern Territory's Top End. Since the 1960s, the sustainability of the NPF has relied, in large part, on the pristine nature of Australia's tropical coasts to support the estuarine juvenile phase of their life cycle (Kenyon *et al.* 2018). Historically, this reliance has been fulfilled. Apart from scattered mining ventures and the City of Darwin, Australian tropical coasts are remote with minimal anthropogenic impact. As well, the catchments of northward-flowing rivers that empty into Joseph Bonaparte Gulf, the Timor Sea and the Gulf of Carpentaria mostly are sparsely inhabited, supporting rangeland grazing and little industrial, mining or agricultural infrastructure. Apart from small weirs to provide water to remote communities, the majority of these rivers have little water resource infrastructure and their water resources are not developed (Petheram *et al.* 2008, 2012). However, the pristine nature of rivers and coastal habitats across the tropical north is at future risk due to Government and commercial initiatives which are encouraging the placement of infrastructure and economic investment in these remote tropical catchments (see the White Paper on Developing Northern Australia (Commonwealth of Australia 2015) and https://seafarms.com.au/about-project-sea-dragon/).

Water Resource Development across tropical northern Australia has the potential to impact fisheries in general and the NPF in particular, due to modification of the quanta and seasonality of flows. The juvenile phase of banana prawns recruits to estuaries from September to April annually. To support the offshore fishery, the critical recruitment period is from September to January, allowing juveniles to grow and emigrate from estuaries, attain adult size and to move to the fishing grounds by April when the fishing season opens. The critical role of flood flows as an emigration cue, and the positive correlation between flow and catch was documented 35 years ago and has been reinforced since (Vance *et al.* 1985, Bayliss *et al.* 2014, Buckworth *et al.* 2014, Duggan *et al.* 2019). However, not only are peak flows important to banana prawns, low floodflows during October to December condition brackish estuaries during the critical juvenile banana prawn recruitment time-window and may lead to enhanced juvenile prawn growth and survival (Kenyon *et al.* 2018). In addition, banana prawns move downstream in brackish estuaries, utilising the full extent of the estuarine habitats as a source of food and refuge (Staples 1980a, Vance *et al.* 1990, 1996, 1998, 2002). At decadal scales, flows are critical to maintaining sediment loads deposited in the estuary and nearshore zone that sustain the integrity of intertidal and supra-littoral estuarine habitats such as mangrove forests and saltflats (Asbridge *et al*. 2016). Dynamic tropical estuaries not only support commercial species, but also iconic and threatened species such as shorebirds, sawfish and freshwater sharks and rays.

Not only are flood flows critical to banana prawn fishery production, the extent of juvenile estuarine habitat is a major determinant of banana prawn distribution and fishery production (Staples *et al*. 1985, Manson *et al*. 2005). In the 1970s, mangrove-lined estuaries were shown to be critical habitats for juvenile prawns (Staples 1980a,b). Building on that knowledge, research in the 1980s and 1990s demonstrated that the 'mangrove-mudbank-creek' matrix within a habitat complex of mangrove forest and meandering tributaries within each estuary is critical habitat for first-settlement of banana prawns from the pelagic to benthic phase (Vance *et al*. 1990, 1998, Kenyon *et al*. 2004, Vance and Rothlisberg in press). After settlement, small and large juvenile prawns inhabit the mangrove forest where they forage and find refuge among the physical structure provided by the roots and trunks, only leaving when forced from the forest by the ebb tide (Vance *et al.* 2002). They inhabit mangrove forests both within upper-reach tributary habitats and adjacent to broad lower-reaches of the main river channels. Juvenile banana prawns move 100s of metres into the forest using the tidal currents to enter and exit (Vance *et al.* 1996, 2002). They are most abundant near the forest edge (particularly the smallest juveniles) where intertidal mud substrates support a productive epibenthic algal community and abundant meiofauna (Burford *et al*. 2012, 2016, Duggan *et al*. 2014). The cumulative length of mangrove-lined creek, extent of intertidal mudbank and aerial extent of mangrove forest within each estuary are major determinants of the carrying capacity of banana prawns within each estuary (Loneragan *et al*. 2005) and at the regional scale (Manson *et al*. 2005).

Prior to the wet season, Australia's tropical estuaries can be hypersaline, a condition that inhibits prawn growth and increases mortality (Staples and Heales 1999), but also inhibits the movement of banana prawns from their initial settlement habitats in the upper reaches of tributaries downstream to lower reaches and the main river habitats (Kenyon *et al.* 2018). Low-level freshwater flows during October to December are critical to condition brackish estuaries that create a dynamic estuary supporting high abundances of fast-growing juvenile banana prawns over the full extent of longstream mangrove/mudbank habitats. Moreover, other key fisheries species such as barramundi, mudcrabs, threadfin and mullet populations are enhanced in the brackish estuarine ecotone facilitated by low flows, as well as by emigration cues provided by high floodflows (Grant and Spain 1975; Ruscoe *et al.* 2004; Robins *et al.* 2005; Balston 2009; Whitfield *et al.* 2012; Welch *et al*. 2014; Alberts-Hubatsch *et al.* 2016).

Irrigated agriculture requires the impoundment or pumped extraction of seasonal river flows; the water reserve to be stored and used across the growing season. In the monsoon tropics, 90% of rainfall and peak flood flows occur during January to March each year (Bayliss *et al.* 2014). The three-month time window offers a short opportunity for water extraction. In addition, flood flows are erratic, high floods can be followed by 4-6 years of very low wet season flows. Consequently, for irrigated agriculture to succeed, it is critical to capture monsoon floodflows during January to March and deploy that water over subsequent months and years to support irrigated crops during the cropping seasons. In conjunction with wet-season flows, late-dry season flows can occur (~October to December), but they are more erratic than monsoon floodflows, only occurring in some years. When they do occur, they are of great benefit to estuarine fishery species as explained in previous paragraphs. The harvest and storage of these October-December flows for irrigation is more consequential for fisheries production than the harvest of monsoon-season high-level floods. The extraction of water from flows during September to December can remove 40-60% of the total volume of the flow (Pollino *et al.* 2018a,b). Particularly if pumping begins at low river-flow rates, the proportion of the flood hydrograph that is extracted can be high (Pollino *et al*. 2018a,b). Thus, the positive effects of freshwater river flows on fish and crustacean habitats within a dry-season hypersaline estuary are much reduced if October to December flows are extraction or impounded. The harvest of monsoon high-level flood flows is less consequential for fisheries production. A smaller proportion of the total flow volume is taken; and the relatively high flood-volume that remains and reaches the estuary can have the same impact as an unimpeded tropical flow, improving the condition of the estuary or acting as an emigration cue.

The multi-themed Flinders Gilbert Agricultural Resource Assessment (FGARA) and Northern Australia Water Resource Assessment (NAWRA) projects assessed the water and landscape resources of several major tropical rivers across northern Australia including the Mitchell, Gilbert and Flinders Rivers. FGARA and NAWRA provided a broad range of information and key outputs that described the trade-offs between WRD for irrigated agriculture versus the economic impact on current industries (Petheram *et al.* 2013 a,b, 2018 a,b,c; Stokes *et al.* 2017). They compared selected examples of water resource infrastructure that provide the required volumes of water, against the depletion of ecosystem services that are sustained by the unregulated river flows within catchments adjacent to the NPF. Hydrologic models were developed to determine current and future river flow regimes under unregulated and modified flow scenarios due to new water infrastructure and water resource use. Flow estimates were modelled with current catch-series from fisheries to estimate the impact of reduced water availability due to WRD on fishery catch. In conjunction, qualitative assessments of the impact of reduced flows on crucial aspects of the life histories of key fishery and iconic species were described.

Across northern Australia, many large un-regulated rivers deliver a significant annual discharge of water to the Gulf of Carpentaria, the Timor Sea and the Joseph Bonaparte Gulf (Petheram *et al.* 2008) and regions within their catchments have considerable extents of productive soils (Petheram *et al.* 2013 a,b, 2018 a,b,c). The provision of reliable year-round water demonstrates the viability of irrigated agriculture in Australia's tropics, but the achievement of favourable long-term economic returns from agriculture in these remote regions will require rigorous consideration and planning (Stokes *et al.* 2017).

We worked with the Griffith University team undertaking NESP 1.4 (Links between Gulf Rivers and Coastal Productivity) to scope and plan productivity, macrobenthos and juvenile banana prawn sampling in the Mitchell, Gilbert and Flinders River estuaries during 2016 to 2019. NESP 1.4 operates under the auspice of NAER and Griffith University. We contributed to designing field sampling programs for these process studies and taxa in a manner that quantifies abundance in the estuaries, and related observed abundances to historical work from other Gulf of Carpentaria estuaries.

Objectives

The objectives of the project were:

- Synthesise historical data available on surveys of the fishery and recruitment of prawns.
- Contribute to the sampling design for field trips to the southern Gulf of Carpentaria to estimate juvenile prawn densities across estuarine nursery habitats.
- Undertake field sampling across estuaries in the southern Gulf of Carpentaria to estimate juvenile prawn densities and explore linkages to primary production in rivers with different characteristics and catchment features compared to the Norman River, expanding knowledge to other GOC rivers.
- Contribute to data analysis from field sampling effort (Objective 2) and provide advice on sample sorting and analysis.

Methodology

Sample design for field sampling and historical comparison

We interacted with NESP collaborators both personally and via two workshops (NESP/ Knowledge Gaps project conceptualisation 2016, NESP/ Knowledge Gaps project discussions 2017, Workshops- February and August 2018) to incorporate historical data from GoC estuarine and offshore survey work, the current state of knowledge on prawn fishery productivity and best advice from the current suite of GoC sampling (e.g. NPF Monitoring) to best design NESP-funded productivity and meiofauna sampling, as well as juvenile prawn sampling for this project. In addition, as part of FRDC 2016-015, two workshops were held with an expanded array of participants, including NESP collaborators, where highly relevant discussions were undertaken (24th May 2017 and 1st August 2017). The outcome of these discussions was the sampling design and continuing review to undertake two mothership-based field surveys to the Mitchell, Gilbert and Flinders River estuaries during the late-dry season (pre-wet) in November; during the annual critical banana prawn recruitment window to estuaries. The suite of rivers sampled was increased from the originally planned two rivers to three with the addition of the Gilbert River. Post-wet season sampling was maintained via a reduced suite of river sampling; the Flinders River only in February and May 2018 using a CSIRO small vessel. Our considerations took account that only 2–5% of annual flows occur during the 'late-dry season' (October to December), while 85–90% of annual flows occur during January to March, and ~7% are late-wet season flows (April and May). One to four percent of flows occur during the dry season (Petheram *et al*. 2008; Bayliss *et al*. 2014).

In the south east GoC's Norman River in the 1970s, the ecology of the banana prawn population was described; immigration, population structure, growth and emigration (Staples 1980 a,b). Staples (1980a) trawled for juvenile banana prawns at 8 sites from the mouth of the River upstream to the upper extent of the mangrove-lined estuary (85 km upstream, using a workboat). Prior to freshwater flows in the river, Staples found juvenile banana prawns (≥3 mm CL) along the full extent of the estuary. Between November to January their average abundance across all eight locations ranged between ~1±~1 to 3±~1 prawns m^{-2} , with an single peak of about 15 prawns m^{-2} in early December 1976 (Staples 1980a, Staples and Vance 1987). With the onset of the wet season, juvenile prawns were confined to the lower estuary during January and February, returning to the upper estuary in March/April as salinity increased. Staples (1980a) did not trawl for juvenile banana prawns in tributaries and creeks off the main river channel. In the nearby Flinders River, Staples and Vance (1987) found prawns were abundant (1±~1 to 4±~1 prawns m^{-2}) in the main river channel during the same monthly time window in the same decade. In addition, Staples (1979) sampled the river channels of the Mitchell and Gilbert rivers from a float plane in the 1970s and found juvenile banana prawns were abundant in each river. Staples caught 100 prawns min^{-1} in the Mitchell River and 50 prawns min^{-1} in the Gilbert River. Although not directly comparable with the catches described in Staples (1980) and Staples and Vance (1987), the catch rates were higher than simultaneous samples taken in the Norman and Flinders Rivers.

In the 1980s, Vance *et al*. (1990) sampled the juvenile banana prawn community in the Embley River in the north east Gulf of Carpentaria. Dr. Staples was also part of this team. They transferred the strategy of sampling progresively upstream within the main river channel to 10 sites from near the mouth of the estuary (3 km upstream) to 48 km upstream. Juvenile banana prawns were abundant in the lower mangrove-lined 28 km or the river (to Site 5) (2±~1 to 4±~1 prawns m $^{-2}$ during November to January), though they were sparse to absent further upstream where river-bank mangrove habitats declined. During this time, the researchers realised that the early postlarval settlement phase of the banana prawn life cycle may not be adequately sampled if trawls were restricted to the main river channel (Vance *et al*. 1990). Changing strategy, the research team included tributary beam trawl sites as a focus of their sampling and a six year series demonstrated the abundance of postlarval and small juvenile prawns in tributary habitats in both the Mission River (5±~3 to 15±~5 prawns m $^{-2}$ during November to January) and Embley Rivers (Vance et al. 1998). Three years of data from tributary habitats and main river habitats in the Embley River showed four times the abundance of juvenile prawn in the upper tributary habitats (9±~3 prawns m $^{-2}$) than the mud-bank habitats along the main river (1.5±~0.5 prawns m $^{-2}$) (Vance *et al*. 1990). Moreover, the length frequency data form the catches showed that while postlarvae (1-2 mm CL) were abundant in both the main river and tributary habitats, small juvenile banana prawns (3-4 mm CL) comprised only 14% of the catch in the main river, compared to 43-59% of the catch at tributary sites. These data suggested that postlarvae were moving up-river to the tributary habitats where they recruited to the mud-mangrove matrix in the upper creek, grew during their earliest benthic phase, and then migrated downstream to river habitats as larger juveniles. The full suite of juvenile banana prawn life stages and ecology was identified: postlarval settlement, key habitats, juvenile growth and ontogenetic movement from the tributary habitats to main river habitats prior to emigration (Vance *et al.* 1990, 2002)

Subsequent studies attempting to sample juvenile banana prawns in tropical estuaries have trawled both tributary and main river habitats to adequately sample all size classes and behavioural phases (emigration, settlement, recruitment, and estuarine growth and survival) of the inshore phase in the life history of juvenile banana prawns (Vance *et al*. 1998, 2002; Kenyon *et al*. 2004; Burford *et al*. 2010). The TRaCK project in the Norman River estuary in 2008-10 found greater abundances of small juvenile prawn in the upper reaches of the Walker Creek (and its tributaries) and Russel Creek (0.41±0.32 prawns m $^{-2}$; 0.83±1.32 prawns m $^{-2}$, respectively) than main river channel sites (0.2±0.22 prawns m $^{-2}$). The main river sites were the same locations that were sampled by Staples (1980a) in the 1970s. Staples (1980a) did not sample tributary habitats in the 1970s. Vance *et al*. (1990) opined that small juvenile banana prawns would have been abundant in Norman River tributaries, had the research team of the 1970s trawled these habitats.

During this project (FRDC 2017/047), we sampled both tributary creek and main river habitats in each of the Mitchell, Gilbert and Flinders Rivers to adequately sample the recruitment of small juvenile banana prawn to their critical settlement habitats in each estuary. Juvenile prawn trawls in each river were made across similar micro-habitats in each estuary as sampled in the Embley River estuary (GoC) by Vance *et al*. (1998), including in small creeks or gutters that branched off the tributaries. At low tide, we trawled exposed mud-bank habitats in small tributaries and main river habitats to ensure that the distribution of recently-settled, small juvenile, and larger juvenile banana prawns was recorded in each estuary. Trawls were conducted at low tide as juvenile banana prawns accumulate in remnant waters that have receded from mangrove forest and fringe habitats where they reside at high tide; both in small tributaries and in the main river channel. We also sampled emigrants leaving the estuary.

As mentioned, CSIRO sampled the Mitchell, Gilbert and Flinders Rivers in the 1970s using a seaplane to access the rivers. Consequently, the current sampling and historical seaplane sampling are not equivalent. The current sampling sites in small tributaries (often 4-6 m wide) of the three rivers represent waterbodies that could not be accessed by seaplane (Figure 1); though some of the main river sites may be similar. During the 1970s, GPS was not available and the exact locations of each sample sites from this era are vague as described in the literature.

Table 1. Juvenile prawn abundance (≥3 mm CL) from a range of GoC rivers (historical projects) in the main river channel habitats and tributary habitats of the Mitchell, Gilbert and Flinders River estuaries, and other rivers, in the Gulf of Carpentaria. The data were from Staples (1980a), Staples and Vance (1987), Kenyon *et al*. 2004, Vance *et al*. (1990, 1998, 2002), Burford *et al*. (2010). Some means and standard errors listed here are approximations from figures in the literature.

Year	River	Prawn density (m^{-2}±SE)	Prawn density (m^{-2} ± SE)	Source of data
		River Habitat	Tributary Habitat	
1970s	Norman River	1 ± ~1 to 3 ± ~1	Not sampled	Staples, 1980a
1970s	Mitchell River	100 prawns min^{-1}	Not sampled	Vance and Staples, 1987
1970s	Gilbert River	50 prawns min^{-1}	Not sampled	Vance and Staples, 1987
1970s	Flinders River	1 ± ~1 to 4 ± ~1	Not sampled	Vance and Staples, 1987
1980s	Embley River	2 ± ~1 to 4 ± ~1	Not sampled	Vance *et al*. 1998
1990s	Mission River	5 ± ~3 to 15 ± ~5	Probably 15 ± ~5	Vance *et al*. 1998
1990s	Embley River	1.5 ± 0.5	9.0 ± 3.0	Vance *et al*. 1990
1990s	Embley River	0.03 ± 0.01 to 0.06 ± 0.04	0.05 ± 0.01 to 0.13 ± 0.04	Vance *et al*. 2002
2000s	Forsyth Creek	1.0 ± 1.0	8.3 ± 1.1	Kenyon *et al*. 2004
2000s	Lyne River	0.1 ± 0.02	0.60 ± ~0.40	Kenyon *et al*. 2004
2000s	Berkeley River	2.5 ± ~1	8.0 ± ~2	Kenyon *et al*. 2004
2010	Norman River	0.2 ± 0.22	0.41 ± 0.32; 0.83 ± 1.31	Burford *et al*. 2010

In addition, the discussions with NESP colleagues contributed to the sampling design for estuarine meiofauna and productivity sampling in the Mitchell, Gilbert and Flinders Rivers during the field surveys (2016 to 2018). The meiofauna and productivity sampling was undertaken by Dr. Michael Venarsky and Professor Michele Burford, colleagues (and a project co-investigator) from Griffith University as part of NESP 1.4 (Links between Gulf Rivers and Coastal Productivity).

Figure 1. CSIRO vessel in a tributary creeklet of the Flinders River exits the creek after trawling for juvenile banana prawns.

Prawn samples

We undertook four mothership-based field surveys to the Mitchell, Gilbert and Flinders River estuaries; three during November/December of 2016, 2017 and 2019, and one during March 2019. The surveys were conducted during the late-dry season and were 9, 12 and 9 days respectively. In addition, during February and May 2018, we undertook two Karumba-based field surveys to the Flinders River estuary; two-days and five-days duration conducted during the wet season and post-wet season, respectively. During each juvenile banana prawn survey, we deployed a 1x0.5 m beam trawl (2 mm mesh body with a 1 mm mesh codend) to sample postlarval and juvenile banana prawns on benthic substrates; and during the ship-based surveys, a surface deployed 1x0.5 m stationary net (2 mm mesh) was deployed to catch prawns moving long-stream on tidal currents (targeting emigrants on the ebb tie). In addition, during a subset of the surveys, we trawled in the nearshore zone adjacent to the river mouth with an otter trawl (28 mm mesh) for recently emigrated larger juvenile prawns.

During November 2016, we were stationed in each of the three rivers for two days, aiming to sample a suite of sites in both the main river channel and in estuarine tributaries. During November 2017, we were stationed in each of the three rivers for three days, aiming to sample a suite of sites in both the main river channel and in estuarine tributaries, as well as sites in the nearshore zone adjacent to river mouths (in about 2-6 m water depth) (Table 2). Some estuarine tributary sites were selected in 'creeklets' and 'gutters' where, at low tide, remnant waters often supported high abundances of small banana prawns that had moved from surrounding mangrove forest/fringe habitats as the tide ebbed (Vance *et al*. 1998; Vance *et al*. 2002; Kenyon *et al*. 2004). These habitats are prime settlement habitats for postlarval prawns recruiting to a benthic existence (Vance *et al*. 1998), and then the early benthic phase. Sampling small, remnant creeks provides good estimates of first recruitment of postlarval prawns. The main river sites, as well as sites on the broader down-river portions of tributaries, were targeted as habitats that would support large juvenile prawns as they grew and moved downstream as an ontogenetic response, or a flow-cued response in years of freshwater riverflow.

Table 2 Number of trawls taken in the Mitchell, Gilbert and Flinders Rivers and the trawls taken in small waterbody habitats (creeklets and gutters), and trawls with the otter trawl, during 2016, 2017 and 2018.

River habitat	2016	Creeklets/ gutters	2017	Creeklets/ Gutters	2017 offshore	2018	Creeklets/ gutters	2018 offshore
Mitchell River	21	20	25	23	Nil	-	-	-
Gilbert River	18	14	22	15	nil	-	-	-
Flinders River	15	8	20	12	5	3 and 18	2 and 10	7 and 5
-	-	-	-	-	-	-	-	-
Large-vessel deep-water trawls	-	-	5	-	-	4		

During February 2018, we were based in Karumba on the Norman River and travelled daily for two days to the Flinders River by 6.5 m vessel were the beam trawl and otter trawl were deployed. We made three beam trawls in the Flinders River at a subset of the sites previously trawled (two in tributary creeks and one in the main river), and seven (7) otter trawls in the nearshore zone. We had limited time in the estuary in February as colleagues undertaking the NESP project required vessel-time to measure water quality parameters and to take water samples. The three estuary sites were few, but the river was in flood and near-zero salinity. The creek/river sites were to check that few prawns were resident in the freshwater estuary in February. The sites in the nearshore zone were comprehensive, they were trawled to detect recent emigrants from the Flinders River; emigrants cued by freshwater flows to leave the river.

During May 2018, we were based in Karumba on the Norman River and travelled daily for five days to the Flinders River by 6.5 m vessel were the beam trawl and otter trawl were deployed. As in February, colleagues undertaking the NESP project took a full suite of water quality samples and estuarine productivity experiments. A full suite of beam trawl samples was taken also; 18 trawls in creek and main-river habitats. In addition, seven (7) trawls were taken in the nearshore zone using the otter trawl.

During March 2019, we beam-trawled a subset of estuary and nearshore zone sites at each of the Mitchell (4 estuarine sites, 5 nearshore sites), Gilbert (8 estuarine sites, 5 nearshore sites) and Flinders Rivers (10 estuarine sites, 7 nearshore sites). The rivers were sampled after significant floods during the 2019 wet season; >450,000 ML d^{-1} for each of the Mitchell, Gilbert and Flinders Rivers. In the Gilbert River, five beam trawls were made on beach habitats south of the river mouth; and in the case of the Flinders River, three samples were taken in small gutters on the inundated saltflats surrounding the estuary.

In addition, in December 2019 we trawled a subset of the previously-trawled sites with the addition of five new sites in the north arm of the Mitchell River estuary to estimate the extent of banana prawn habitat in the delta of the river. Previously, due to time constraints our sampling was mostly in the Central Arm of the river. The South Arm is a protected fisheries habitat, so no trawls were undertaken in this portion of the delta This survey was outside the remit of FRDC 2016-047, so the majority of these frozen samples have not been sorted. However, the banana prawns from 8 samples have been counted and measured, including the five sites in the North Arm of the Mitchell River.

Environmental data

We measured salinity, temperature and secchi depth (light penetration) at each site where a trawl was undertaken. Water depth was measured, together with estimates of cloud cover, and tide phase was recorded.

Geo-spatial data

The latitude and longitude of both the start position and the finish position of each trawl was recorded. These data were loaded in a Graphic Information System (GIS) where the distance of each trawl was calculated, and the trawl positions were located on electronic maps of the estuarine systems.

Statistical analysis

The prawn abundance data per trawl were analysed using a two-level ANOVA in EXCEL. Both river system and water body type (river, creek, gutter) were the two facets of the ANOVA.

Bio-geochemical analyses of prawn and sediments

A part of the NESP research suite, bio-geochemical samples of juvenile prawns and sediments were taken to link the 'estuary of residence' for juvenile prawns to prawns caught offshore of each estuary. The hypotheses were that the trace element geochemical signature of prawn flesh within an estuary would match the trace element signature in the estuarine sediments on which they lived; and that emigrant prawns from these estuaries would retain the trace element signature as they moved offshore and be able to be identified as having originated from a particular estuary.

To achieve this aim, large juvenile prawns were collected from a range of sites within each of the Mitchell, Gilbert and Flinders estuaries, from near the estuary mouth to the most upstream site. In addition, prawns were collected offshore from each of the rivers using the large-vessel capacity of the AFMA-funded NPF Monitoring Project (Rob Kenyon, PI). Emigrant adult prawns were collected during January 2017 and February 2018 from shallow locations (~6-8 m deep) adjacent to each of the river estuaries. Some trawls were made as part of NPF Monitoring standard trawls (offshore from the Flinders River), while some (offshore from the Mitchell and Gilbert Rivers) were undertaken with the goodwill of management and vessel crew of A Raptis and Sons while NPF Monitoring vessels were transiting from Karumba to Albatross Bay (Weipa region) in the Gulf of Carpentaria.

Results

1. Environmental parameters determining estuary condition

Environmental parameters

During 2016, all trawls were conducted during daylight; during the last third of the ebb phase, and during the first portion of the flood tide. During 2016, the estuary of each of the rivers was marine-equivalent in tidally mixed locations near the mouth, through to hypersaline in the upper reaches of tributaries (35 to ~38) (Table 3). The water temperature was relatively constant throughout the study area and ranged from 30 to 35. The Mitchell River was a relatively clear river with secchi disc readings ranging from 0.3 to 0.5. The Gilbert River was more turbid with secchi disc readings from 0.1 to 0.4. The Flinders River was the most turbid of the three rivers, secchi disc ranged from 0.1 to 0.2.

During 2017, trawls were conducted during daylight around the low tide, similar tide conditions to 2016. In 2017, the temperature ranged from 27 to 36 throughout the study area, a similar range to 2016 though in a few creeks cooler temperatures occurred (Table 3). In 2017, secchi disc readings demonstrated a broader range than in 2016 (0.0 to 1.2), and the clearest water was found in the Mitchell River. The environmental parameter that differed between 2016 and 2017 was salinity. During October/November 2017, early-season rainfall occurred in the headwaters of the Mitchell and Gilbert Rivers in eastern Cape York and low-level freshwater flows occurred. Salinity in the estuaries ranged from 1.5 to 32.6 (mostly 20-30) in the Mitchell River and from 24.7 to 36.5 in the Gilbert River; brackish conditions in the tributary channels of both rivers and the main river channel of the Mitchell River. No rainfall occurred in the Gulf Savannah where the Flinders River rises, and the estuary remained marine-equivalent to hypersaline (~34-38).

Table 3 Environmental parameters conditioning the estuaries of the Mitchell, Gilbert and Flinders Rivers. Turbidity estimates were made with a secchi disc. Freshwater riverflows in the late dry season prior to the estuary surveys; and subsequent peak floodflows during the wet season are provided. Temperature - ºC; Salinity - ppt; Flow – ML d^{-1} 12 days prior to the survey; Turbidity – m.

Parameter	Mitchell River	Gilbert River	Flinders River
Temperature -2016	30-35	30-35	30-35
Temperature – 2017	27-36	27-36	27-36
Temperature – 2018	na	Na	February 31-34, May 20-24
Salinity – 2016	35-38	35-38	35-38
Salinity – 2017	1.5 – 32.6	24.7 – 36.5	34-38
Salinity – 2018	na	Na	February 4.3-4.7, May 12 -28
Flow – November 2016	48	0	0
Flow – November 2017	1595	283 (peak of 1000)	0
Subsequent high floods	160,000; 108,000	270,000; 350,000	104,000; 348,000
Turbidity – 2016	0.3-0.5	0.1-0.4	0.1-0.2
Turbidity – 2017	0.2-1.2	0.1-0.2	0.0- 0.1
Turbidity – 2018	na	Na	February 0.05-0.1, May 0.05 – 0.4

2. Banana prawn abundance in GoC estuaries that contribute to catch production in the Northern Prawn Fishery

Banana prawn abundance

Trawls samples taken in November 2016 demonstrated that the abundance of juvenile banana prawns (≥3 mm CL) was not significantly different between the three rivers (range 1.39 to 1.85 prawns m^{-2}) (Table 4). The size range of juvenile prawns in each estuary was similar at 3-12 mm CL for the majority of the juveniles. In the Flinders River, in addition to the common size range of juveniles, a few larger juveniles were caught (14-17 mm CL).

Only 6 postlarvae (1-2 mm CL) were found in the Mitchell River, while over two thousand postlarvae were caught in one trawl in the main river channel in the Gilbert River in 2016. These postlarvae were mostly 1 mm CL animals and likely were ephemeral in the main river, travelling upstream to their preferred settlement habitat. Four other trawls in the Gilbert River caught 30-60 postlarvae. Four to 42 postlarvae were caught in only four of the Flinders River trawls.

Trawl samples taken in November 2017 showed that the Gilbert River estuary (4.52 ± 2.03 prawns m^{-2}) supported a greater density of juvenile banana prawns than each of the other two estuaries, in which prawn abundances were similar (<1 prawn m^{-2}) (Table 4). However, a two-way ANOVA showed that the difference between years was not significant and neither were the differences between rivers in any year. In 2017, the size range of the majority of juvenile prawns in each estuary was similar at 3-10 mm CL. In each river, a few prawns 11-20 mm CL were caught. The size range of prawns in each of the tree estuaries was generally smaller in 2017 than 2016, with relatively fewer 11-12 mm CL prawns found.

During November 2017, postlarval prawns were encountered in both the Mitchell and Gilbert Rivers mostly in small creeks, while only a few were encountered in the Flinders River (7 in total). In the Mitchell River, a total of 642 postlarvae were encountered among most trawls, mostly in creeks and gutters and 448 of the postlarvae were caught in one creek trawl. In the Gilbert River, 448 postlarvae were encountered among a majority of trawls, mostly in creeks and gutters.

During February 2018, three beam trawls were made at a subset of sites in the Flinders River during monsoon freshwater flows. A total of 29 prawns were caught, and four were postlarvae. The average density of juvenile prawns ≥3 mm CL was <0.1 prawns m^{-2} (Table 4), and their size range of all prawns was 1 to 11 mm CL with a mode at 5 mm CL.

During May 2018, all the survey sites in the Flinders River were sampled during the tail-end of a large monsoon-driven floodflow. A total of 132 prawns were caught, and 29 were postlarvae. The average density of juvenile prawns was <0.05 prawns m^{-2} (Table 4), and their size range was 1 to 25 mm CL with a mode at 8 mm CL. The total catch of prawns was much lower in May 2018 than in either November 2016 (965) or November 2017 (975).

A sub-set of the sites in each of the three rivers were sampled in March 2019, during freshwater flows associated with the tail-ends of moderate monsoon-driven floodflows in each river. In the Mitchell River, the average density of juvenile prawns was 0.20 ± 0.12 m^{-2} (4 beam trawls, Table 4), and their size range was 3 to 11 mm CL with a mode at 6 mm CL. A total of 102 juvenile prawns were caught, while the presence of 2627 postlarvae demonstrated recent 'opportunistic' recruitment to the estuary after the flood. In addition, two large juveniles were caught 5 otter trawls in the nearshore zone.

In the Gilbert River, an average of prawns was 0.22 ± 0.20 m^{-2} were caught in eight beam trawls. The banana prawns (49 juveniles) were mostly caught at one site within the estuary and only four postlarvae were encountered in all trawls. No large juveniles were caught in the five otter trawls made in the nearshore zone.

The density of juvenile prawns in the Flinders River was the same as the other two rivers; 0.21 ± 0.08 prawns m^{-2} among 10 beam trawls. In the Flinders River, some trawls were made in small water-filled gutters among the saltflats away from the main river. As found in the Mitchell River, postlarval prawns (numbering 1206) were abundant, but only 183 juveniles were caught in total. As found in previous years after a floodflow in the Flinders River, 84 large juveniles were caught in the nearshore zone adjacent to the river mouth.

During December 2019, a fourth survey campaign was mounted to the three rivers. This survey was outside the scope of the original project (FRDC 2016-047). However, the juvenile prawns from the eight samples that have been sorted mostly come from new sites selected in the North Arm of the Mitchell River estuary 'delta' to investigate the abundance of juvenile prawns over a larger spatial extent in the multi-channel estuary. The density of juvenile prawns in the north arm prior to the 2019/20 wet season was 0.71 ± 0.28 prawns m^{-2}, a typical density of juvenile prawns prior to any floodflow-cued emigration in these estuaries. Two sites supported abundant juvenile prawns - 1.23 prawns m^{-2} and 2.36 prawns m^{-2} . The second site quoted here was a site trawled in 2016 and 2017 where it supported 1.80 prawns m^{-2} and 1.44 prawns m^{-2}, respectively.

Table 4. Juvenile prawn abundance (≥3 mm CL) in the Mitchell, Gilbert and Flinders River estuaries (and close-in nearshore shore) in the Gulf of Carpentaria.

Year	*River*	*Prawn density (estuary)* m^{-2} ± SE	*N*	*Nearshore trawls*
2016	***Mitchell River***	1.39 ± 0.47	21	Na
2016	***Gilbert River***	1.85 ± 1.11	18	Na
2016	***Flinders River***	1.71 ± 1.18	15	Na
2017	***Mitchell River***	0.51 ± 0.16	22	Two prawns from 1 x 400 m trawl
2017	***Gilbert River***	4.52 ± 2.03	22	12 prawns from 2 x 400 m trawls
2017	***Flinders River***	0.62 ± 0.21	18	82 prawns from 8 x 600 m trawls
2018	***Flinders River – February***	0.08 ± 0.05	3	122 prawns from 7 x 600 m trawls
2018	***Flinders River – May***	0.03 ± 0.01	18	Two prawns only from 5 x 600 m trawls
2019	***Mitchell River – March***	0.20 ± 0.12	4	2 prawns from 5 x 400 m trawls
2019	***Gilbert River – March***	0.22 ± 0.20	8	0 prawns from 5 x 400 m trawls
2019	***Flinders River – March***	0.21 ± 0.08	10	84 prawns from 7 x 400 m trawls
2019	***Mitchell River – December***	0.71 ± 0.28	8	Na

The size range of banana prawns resident in the Mitchell River in November 2017 was 1 mm CL to 15 mm CL with a mode for juvenile prawns at 5 mm CL and clear evidence of recent postlarval recruitment (Figure 2). No prawns were caught emigrating from the Mitchell River.

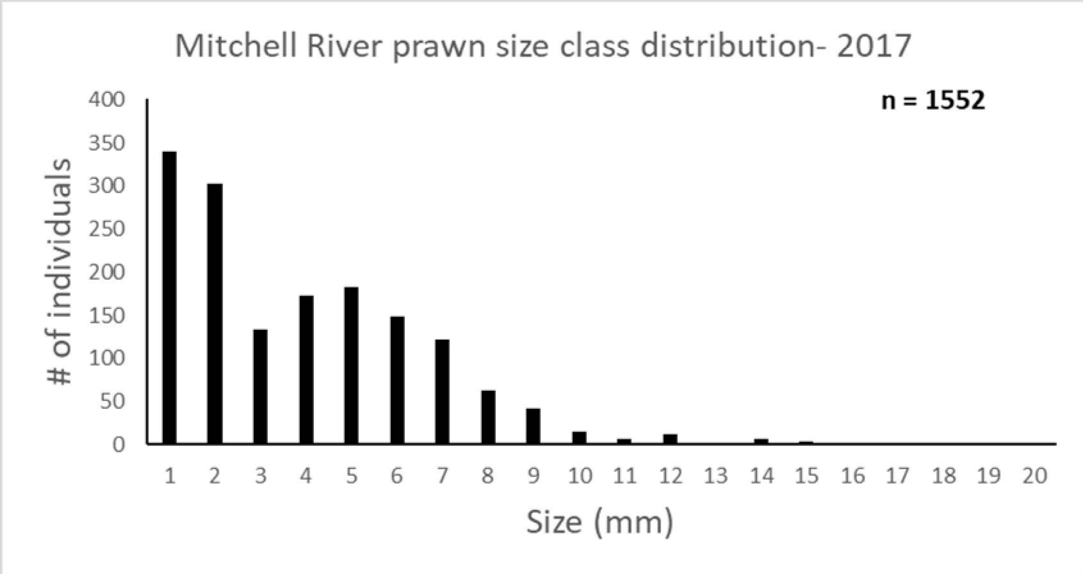


Figure 2 Length frequency of juvenile banana prawns (black columns) in the Mitchell River in 2017.

The size range of banana prawns resident in the Gilbert River in 2017 was 1 mm CL to 15 mm CL with a mode for juvenile prawns at 5-6 mm CL and with few recent postlarval recruits (Figure 3). The size range of juvenile prawns in the Flinders River in 2017 was 2 mm CL to 15 mm CL with a mode for juvenile prawns at 7 mm CL and with negligible postlarval recruitment (Figure 4).

The size range of banana prawns resident in the Mitchell River in March 2019 was 1 mm CL to 11 mm CL with a mode for juvenile prawns at 6 mm CL and clear evidence of recent postlarval recruitment. In December 2019 it was 1 mm CL to 14 mm CL with a mode for juvenile prawns at 4 mm CL and clear evidence of recent postlarval recruitment.

The size range of banana prawns resident in the Gilbert River in March 2019 was 1 mm CL to 20 mm CL with a mode for juvenile prawns at 6-7 mm CL and with only four recent postlarval recruits. The size range of banana prawns in the Flinders River in March 2019 was 1 mm CL to 23 mm CL with a mode for juvenile prawns at 3 mm CL and high levels of postlarval recruitment.

Prawn emigration

In 2016, no emigrant prawns were caught in any of the surface set nets in either of the rivers. Nets set on the ebb tide over two consecutive days caught no prawns. Nets set on the flood tide to check for longstream movement on the tides also caught no prawns.

In 2017, the surface nets set on the ebb tide in the Mitchell River caught no prawns. However, nets set in the Gilbert and Flinders Rivers caught about 100 prawns in each river over several deployments. In the Gilbert River, 106 prawns were caught during a ~three-hour period of ebb tide. During a subsequent three-hour period, no prawns were caught. The size range of the emigrants was 5-8 mm CL (Figure 3), a narrow size range of juvenile prawns cued to emigrate by freshwater flows entering the estuary (brackish conditions ~25 in the tributary habitats).

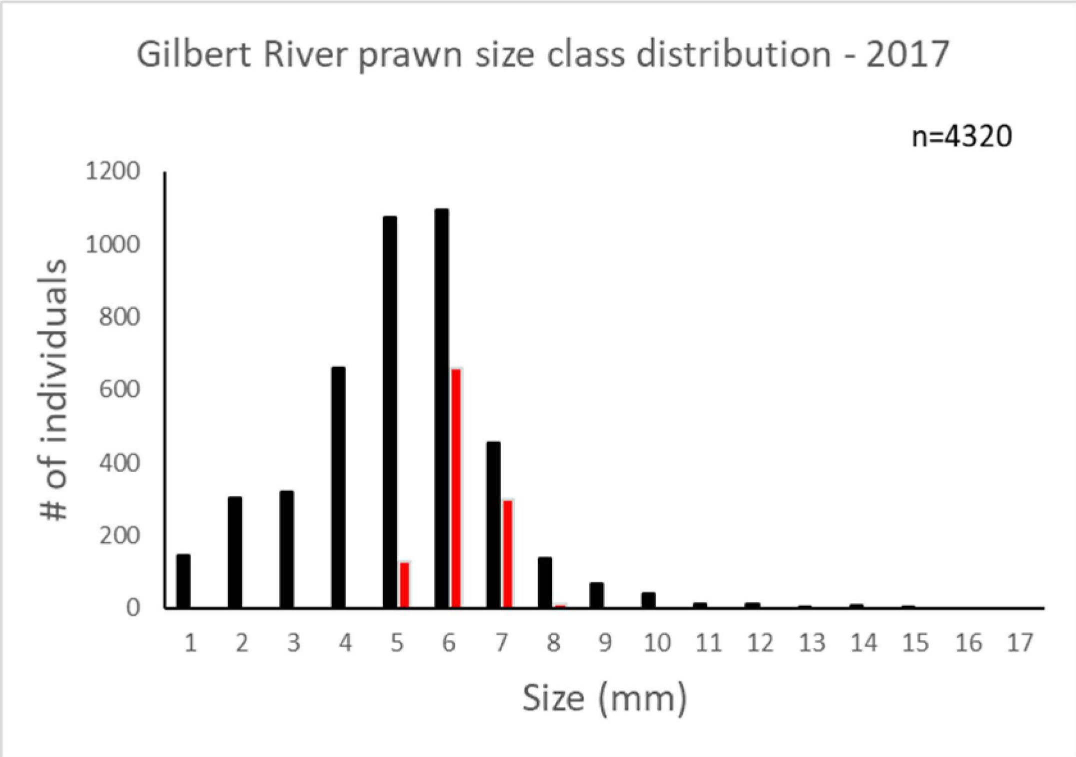


Figure 3 Length frequency of juvenile banana prawns (black columns) in the Gilbert River estuary and emigrant banana prawns from the estuary (red columns) in 2017.

In 2017, the nets set in the Flinders River caught 156, 57 and 65 emigrants in three sets, two on subsequent ebb tides and the last net deployed in a later stage of that second tide. The size range of the emigrants was 5-17 mm CL (Figure 4), a broad size range likely representing ontogenetic emigration from the estuary which was marine equivalent. The mode carapace length of emigrants was 8-9 mm CL, 2 mm CL larger than emigrants from the Gilbert River. Unlike the size range of Gilbert River prawns, large juveniles from 10-15 mm CL also emigrated.

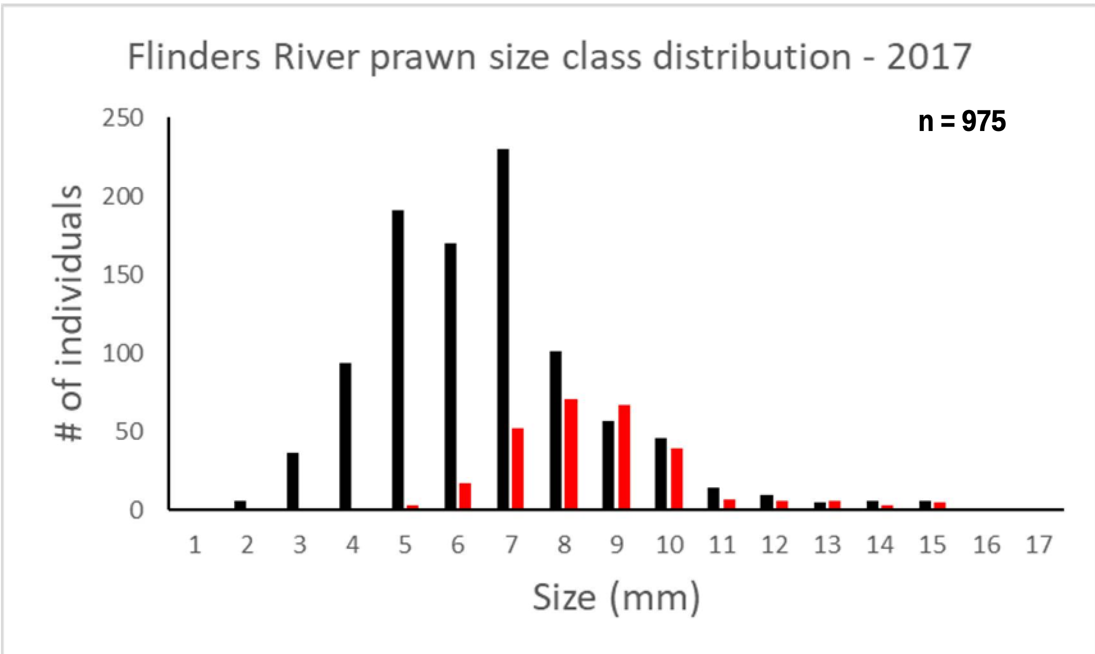


Figure 4 Length frequency of juvenile banana prawns (black columns) in the Flinders River estuary and emigrant banana prawns from the estuary (red columns) in 2017.

Prawn distribution within the nearshore environment adjacent to the Flinders River estuary

In November 2017, 82 banana prawns were caught among 5 otter trawls made in depths of 4-6 m offshore from the Flinders River estuary (<0.1 prawn m^{-2}). These prawns were emigrants that have left the estuary and will move further offshore. The recent emigrants were relatively large (yellow bars in Figure 5) with a mode at 25 mm CL. They were emigrating due to an ontogenetic response, large prawns (21-27 mm CL) were the most abundant emigrants.

In February 2018, 122 banana prawns were caught among 7 otter trawls made in depths of 4-6 m offshore from the Flinders River estuary (<0.1 prawn m^{-2}, (Table 3). Again, these prawns were recent emigrants from the estuary and will move further offshore. The February emigrants were smaller (15-23 mm CL) than those found during November with a mode at 20 mm CL. They were emigrating due to a salinity-cued response, so smaller juvenile prawns (15-23 mm CL) were characteristic of this cohort.

In May 2018, 2 banana prawns were caught among 5 otter trawls made in depths of 4-6 m offshore from the Flinders River estuary. These emigrant prawns were much less abundant after the floodwater emigration cues in March/April 2018 had caused most of the estuarine banana prawn population to emigrate offshore prior to the May survey. They were large juvenile prawns (25 and 26 mm CL) and were characteristic of the few prawns remaining in the Flinders River at the end of the wet season in May.

In March 2019, 84 banana prawns were caught among 7 otter trawls made in depths of 4-6 m offshore from the Flinders River estuary. These emigrant prawns were abundant after the floodwater emigration cues in February 2019 had caused most of the estuarine banana prawn population to emigrate offshore. They spanned a broad size range (13 and 27 mm CL) and were characteristic of the abundant prawns leaving the Flinders River during the wet season.

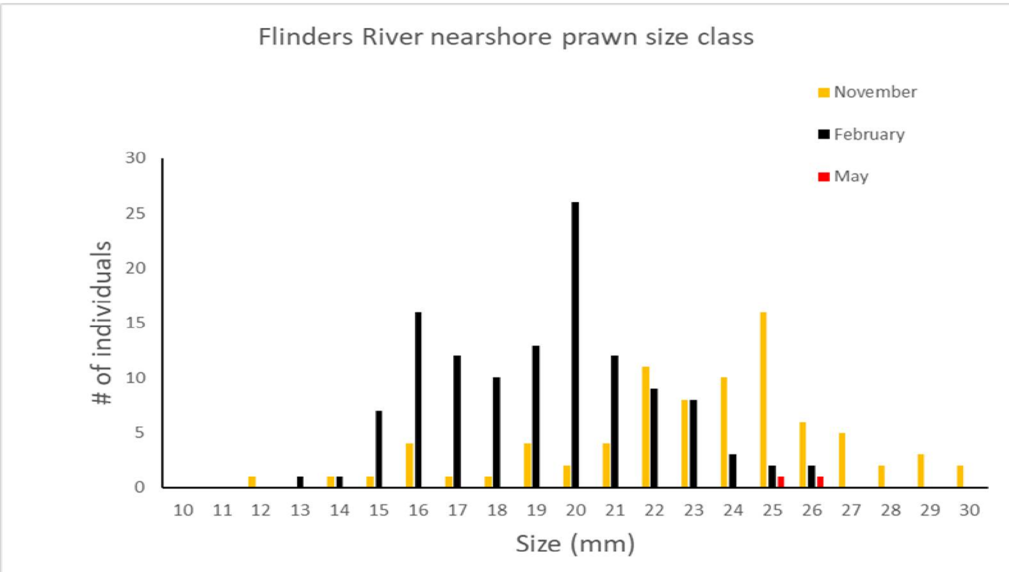


Figure 5 Length frequency of recently emigrated banana prawns in November 2017 (yellow columns), February 2018 (black columns) and May 2018 (red columns) adjacent to the Flinders River estuary.

Prawn distribution within marine-equivalent and brackish estuaries

In each river estuary, the abundance of juvenile prawns was higher in tributaries than it was in the main river. Large and small tributaries of both the Michell and Gilbert Rivers supported the highest abundances of juvenile prawns (Table 5, Figure 7, Figure 8). Within the Flinders River, large tributaries were absent from the estuary, however, the highest abundances of juvenile prawns were found in the small side-creeks off the main river channel (Table 5, Figure 9).

In 2016, the differential in prawn abundance between the estuarine tributaries and the main river channel was about 15 times. That is, during November in each of the Mitchell, Gilbert and Flinders Rivers, the densities of prawns in the tributaries within the estuary was about 15 times higher than in the main river habitats (Table 5). Each of the estuaries were marine-equivalent or hypersaline during November 2016.

If only the smallest of the tributaries were considered, this relative difference increased in the Gilbert and Flinders Rivers. A typical small ‘creeklet’ tributary of the Flinders River is shown in Figure 1.

Table 5. Relative abundance of juvenile banana prawns (≥3 mm CL, mean ± SE) in tributary and main river habitats during the late-dry season in 2016 and 2017. During 2016, no rainfall occurred in the river catchments during the late-dry season and all estuaries were marine-equivalent. During 2017, about 200-300 mm of rainfall occurred in the catchments of the Mitchell and Gilbert Rivers and the estuaries were brackish, while the estuary of the Flinders River remained marine equivalent.

Year	*Estuarine habitat type*	*Mitchell*	*Gilbert*	*Flinders*
2016	Tributary habitats	1.43 ± 0.50	2.34 ± 1.41	3.03 ± 2.16
	Lower river habitats	0.0 ± 0.0	0.15 ± 0.06	0.19 ± 0.04
2017	Tributary habitats	0.55 ± 0.17	5.95 ± 2.92	1.07 ± 0.35
	Lower river habitats	0.30 ± 0.28	1.44 ± 0.38	0.18 ± 0.07
2016	Upper-most tributary habitats	1.03 ± 0.47	3.45 ± 1.97	5.78 ± 4.09
	Lower tributary habitats	1.52 ± 0.68	0.36 ± 0.08	0.29 ± 0.16
	Lower river habitats	0.0 ± 0.0	0.15 ± 0.06	0.19 ± 0.04
2017	Upper-most tributary habitats	0.79 ± 0.38	11.76 ± 5.67	0.86 ± 0.27
	Lower tributary habitats	0.38 ± 0.14	0.87 ± 0.15	1.33 ± 0.77
	Lower river habitats	0.30 ± 0.28	1.44 ± 0.38	0.18 ± 0.07

In 2017, the differential in prawn abundance between the estuarine tributaries and the main river channel was about 4-5 times. That is, during November in each of the Mitchell, Gilbert and Flinders Rivers, the densities of prawns in the tributaries within the estuary was about 4 times higher than in the main river habitats (Table 5). The Mitchell and Gilbert River estuaries were brackish (riverflows of 1595 and 283 ML d^{-1}, respectively, prior to the survey) while the Flinders River estuary was marine-equivalent during November 2017 (no riverflow prior to the survey). If only the smallest of the tributaries were considered, the difference in abundance between 2017 and 2016 increased to about 8 times in the Gilbert River. A typical main-river habitat of the Flinders River is shown in Figure 6.

Figure 6. CSIRO vessel in the main river channel of the Flinders River after trawling for juvenile banana prawns.

Within the Mitchell River estuary, the spatial distribution of juvenile prawns among the creeks and main channel of the estuary remained very similar between 2016 and 2017 (Figure 7). A higher density of prawns was found in the main river in 2017, though the number of samples taken there also increased to improve the sampling of main river habitats, suggesting more prawn likely would be caught. Only two sites were samples in the main channel due to the sand substrates and banks encountered.

Particularly for the Gilbert River, juvenile banana prawn distribution demonstrated the diverse patterns of prawn abundance between the marine-equivalent conditions in 2016 and the brackish conditions in 2017 (Figure 8). A higher density of prawns was found in the main river habitats of the Gilbert River in 2017. Four main river sites were sampled in 2016 and a good estimate of prawn abundance obtained. The sites sampled were increased to seven in 2017, but the greater abundance in the river in 2017 was clear. In 2017, the downstream migration of juvenile prawns from high densities in tributary habitats to the brackish lower river estuary was evident. In 2016, within the marine-equivalent estuary, high numbers of juvenile prawns at the main river sites were not found.

In the Flinders River, the abundance and distribution of juvenile banana prawns were the same between 2016 and 2017 (Figure 9). Three new sites were added in 2017, one in an upstream main river habitat, and two in a mid-estuary side ‘creeklet’. These sites were added to improve the longstream survey coverage, and because the creek had been sampled in 2011 as part of the TRaCK project. In 2011, the river was in high flood during the wet season; the saltflats surrounding the creek were inundated by about 0.5 m of water and the banana prawn population mostly had emigrated. Therefore, beam trawl data from the creek habitats describing the prawn community under pre-wet season conditions when the estuary was marine equivalent was valuable. Prawn abundance at the nearshore sites (4-6 m deep) adjacent to the river month are also displayed in Figure 9.

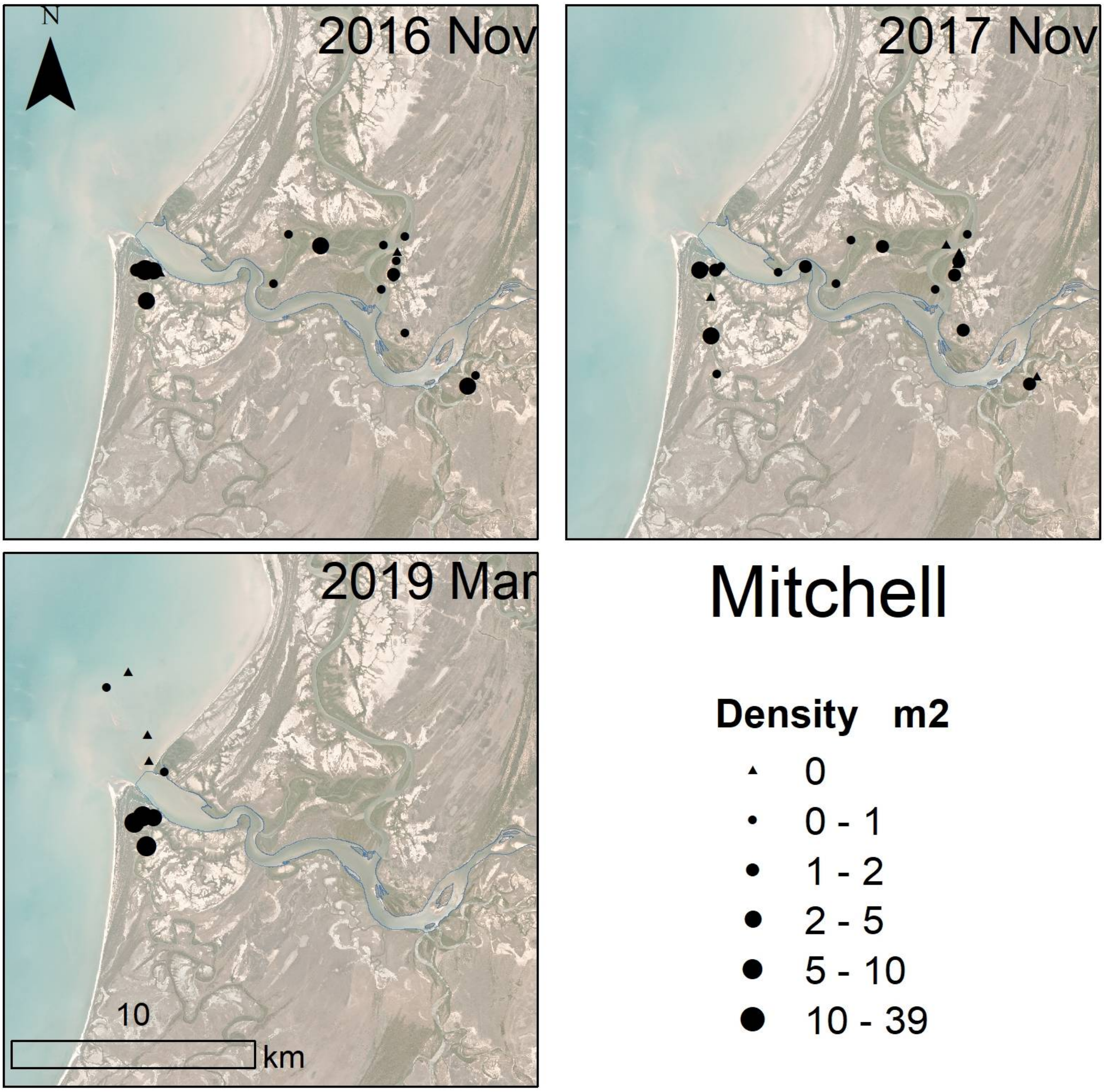


Figure 7 Spatial representation of prawn distribution in the Mitchell River estuary in 2016 (marine-equivalent) and 2017 (brackish conditions) showing juvenile prawns in the main river channel in 2017 relative to 2016.

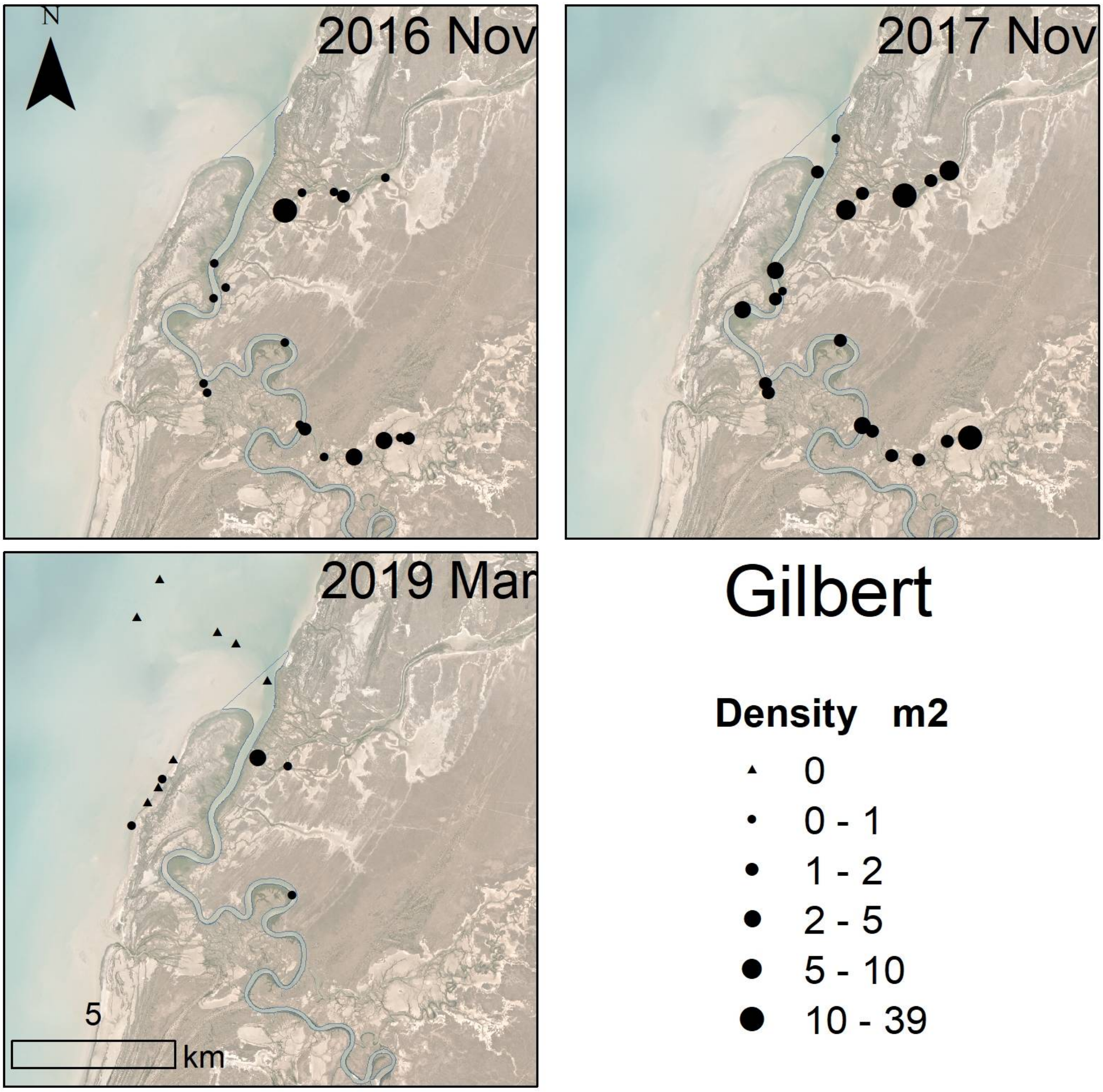


Figure 8 Spatial representation of prawn distribution in the Gilbert River estuary in 2016 (marine-equivalent) and 2017 (brackish conditions) demonstrating the downstream shift in prawn abundance in 2017 relative to 2016.

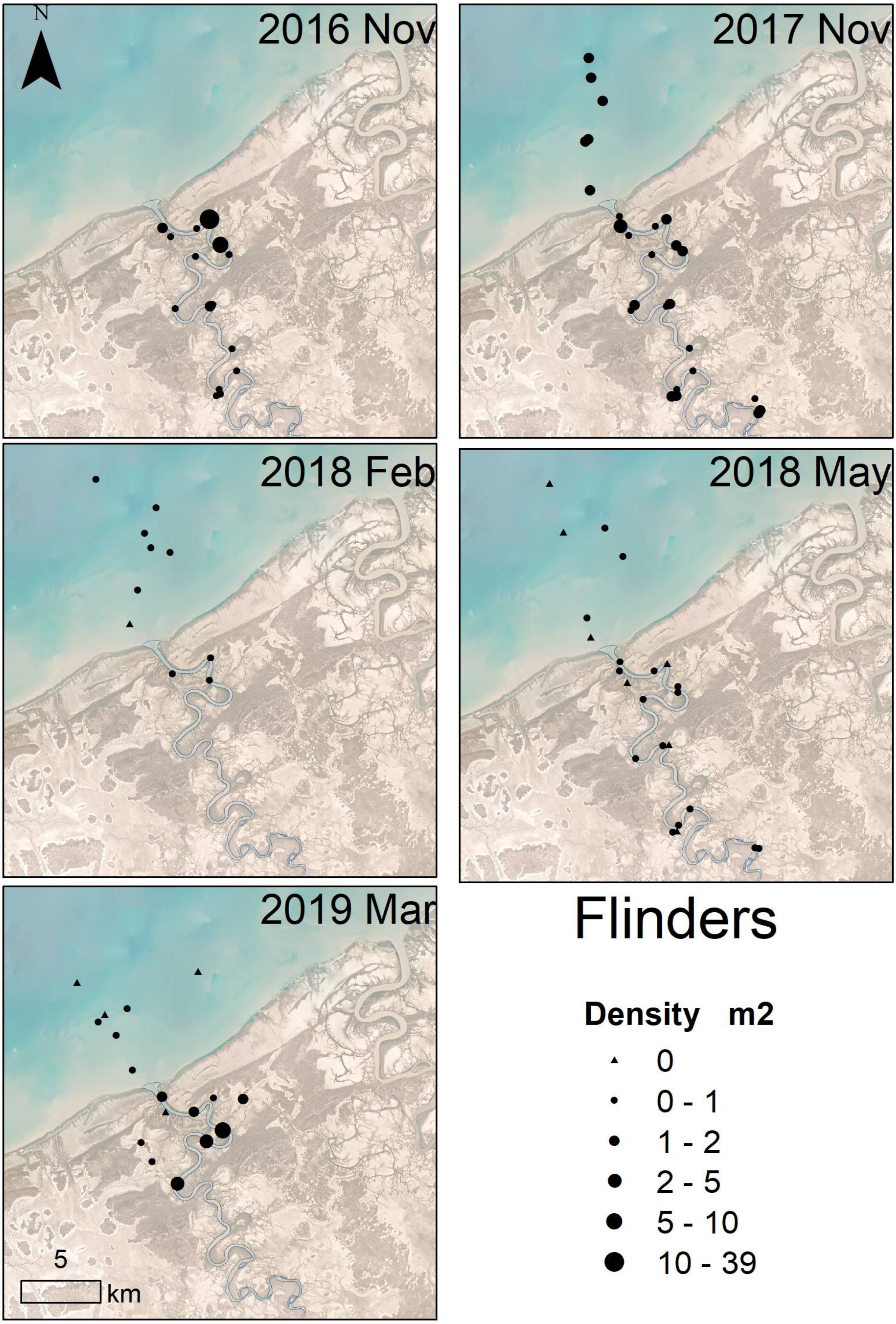


Figure 9 Spatial representation of prawn distribution in the Flinders River estuary in 2016 (marine-equivalent) and 2017 (marine-equivalent) demonstrating a similar prawn distribution in 2017 relative to 2016. Three sites were sampled further upstream in 2017.

3. Bio-geochemical links between juvenile prawns, adult prawns and the sediments that they occupy

An added objective to this project, in conjunction with NESP 1.4 “Links between Gulf Rivers and Coastal Productivity”, was to collect prawns and sediment to conduct bio-geochemical analyses. We sampled prawns, sediment and water in the estuaries, the adjacent nearshore zone just offshore from the estuary, and shallow strata of the adjacent banana prawn fishing grounds. Our aim was to investigate links and possible recruitment pathways between juvenile prawns within the estuary, recent-emigrants in shallow depths (~3-6 m) just nearshore, and sub-adult banana prawn within the fishery (depths of ~8-10 m). With the generous cooperation of the fishing company A Raptis and Sons, we leveraged vessel access from the AFMA funded project (AFMA 2015/0810) “An integrated monitoring program for the Northern Prawn Fishery, 2015-18” to sample sub-adult banana prawns offshore from the Mitchell, Gilbert and Flinders River estuaries during January/February 2017 and 2018. The prawns in the samples would be recruits from the estuarine populations in the latter months of 2016 and 2017, respectively. The aim was to compare similarity of the geo-chemical signatures of the adult prawns acquired offshore to those estuarine and inshore juvenile prawns analysed for geo-chemical signatures that were collected within or just offshore the river estuaries as part of this project survey work.

Bio-geochemical similarity

From the November 2016 and 2017, and May 2018 beam and otter trawl samples, larger juvenile banana prawns encountered in each of the three GOC rivers were analysed for bio-geochemical trace element signatures. Sediment samples were collected from each of the prawn sample sites and analysed using the same technique. Water samples were collected form the rivers during the November 2016 and 2017, and February and May 2018 surveys.

During January 2017, large-vessel-capacity was deployed during trawls taken as part of the NPF Monitoring Surveys (AFMA 2015/0810) to sample offshore from the Flinders River. During February 2018, large-vessel-capacity was deployed to trawl extra locations while travelling from region to region as part of the NPF Monitoring Surveys. Sediment and banana prawn samples were collected from sites in the eastern Gulf of Carpentaria, offshore from the Mitchell and Gilbert Rivers. In November 2016 and 2017, and February and May 2018, otter trawls were undertaken close inshore adjacent to the river estuaries to sample recent emigrants. In collaboration with Professor Michele Burford (Griffith University, NESP project “Links between Gulf Rivers and Coastal Productivity”), the trace element signatures of offshore prawns and sediment were analysed.

Over each year and set of samples, trace element analyses have shown that the offshore prawns and offshore marine sediment show a similar signature among and between locations. The mixed offshore signature differs from the estuarine signatures and no facility to be able to link juvenile prawns from a particular estuary to those caught offshore of that estuary has been identified.

Each of the estuaries has a different signature and it may be possible to allocate unknown juvenile banana prawns to an estuary using the bio-geochemical tracers. However, the strongest signal identified as part of these analyses is between the ‘upper’ and ‘lower’ estuary (Figure 10, M. Burford, pers. comm.). These analyses and their interpretation are ongoing as part of NESP 1.4 and not reported fully here.

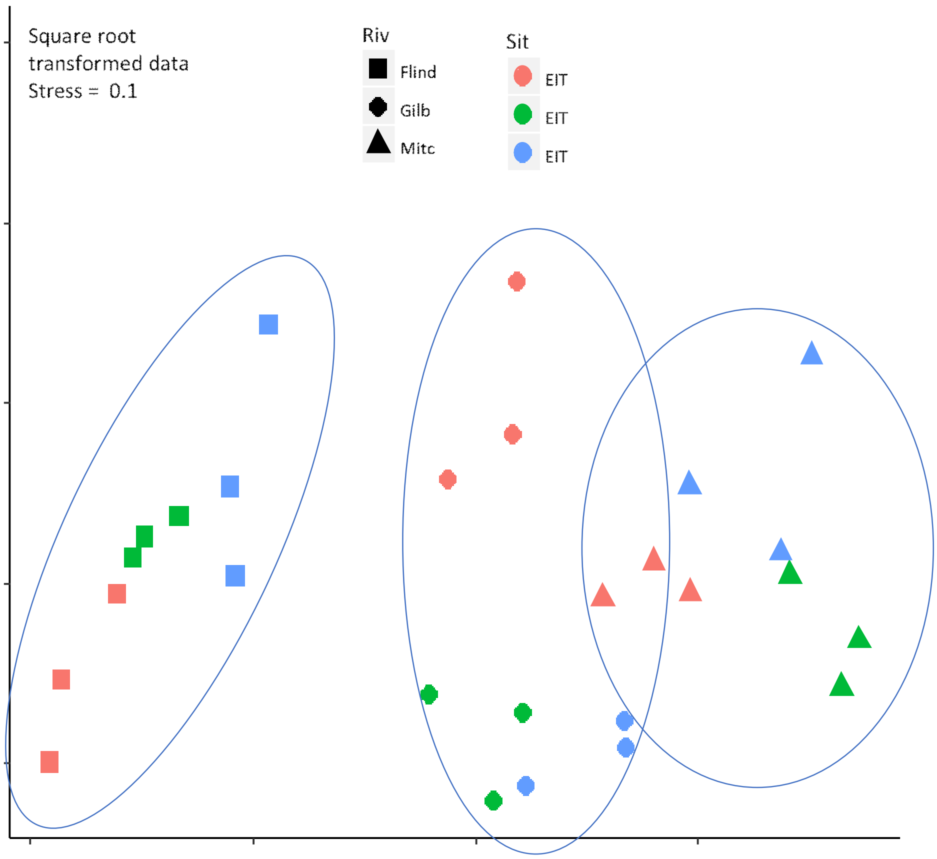


Figure 10 Results of bio-geochemical analyses of banana prawn samples from the Mitchell, Gilbert and Flinders Rivers during 2017/2018. Estuarine signatures differ and a 'long-stream' signal is evident.

4. Estuarine productivity drivers that support Northern Prawn Fishery productivity

The productivity values of each of the Mitchell, Gilbert and Flinders Rivers as estimated using measurement of water column and epibenthic primary production were not significantly different. Both in 2016 and 2017, epibenthic productivity between the rivers was equivalent. Epibenthic productivity was measured incubating sediment cores from the substrates of a typical intertidal bank (Figure 11).

The analyses of the data collected during the NESP research is ongoing, and the NESP project has been extended beyond the time frame of this FRDC project, so analyses and interpretation of NESP results will not be complete and able to be referred to in full as part of this project report. A more substantive exploration of the links between estuarine productivity and juvenile banana prawn abundance can be found in Burford et al. (2020).

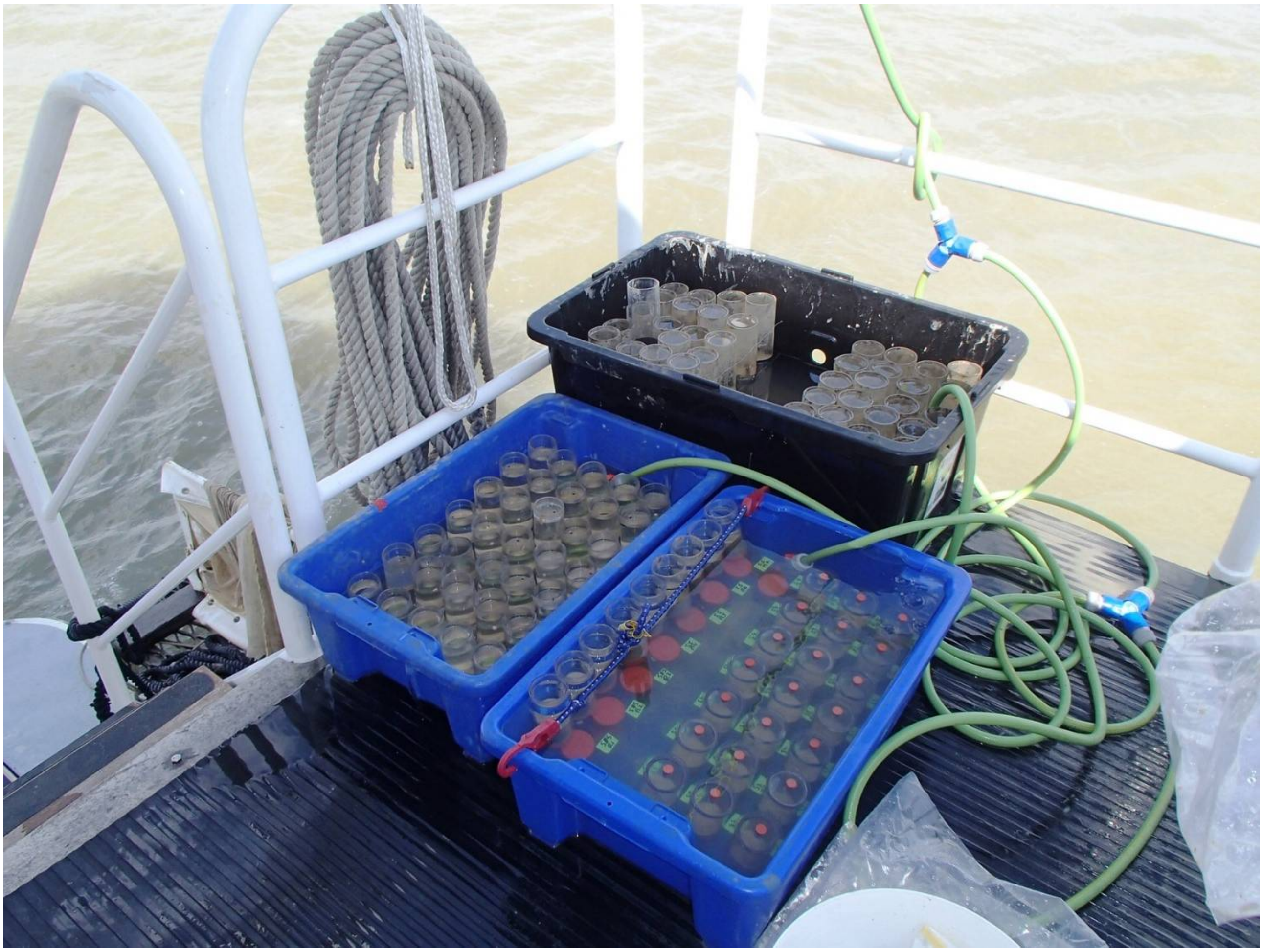


Figure 11 Primary production experiment incubating sediment cores taken from an estuarine mudbank in either of the Mitchell, Gilbert or Flinders Rivers in November 2016 or 2017.

Benthic algal biomass, measured as chlorophyll *a* concentration, was compared between the two sampling occasions in the late dry season, 2016 and 2017, and between the intertidal mudflats within the estuaries, and the sandflats at the mouth of the estuaries. There were clear differences between the two sampling occasions (Figure 12). The effect of previous flow regimes on this finding are still being explored. Additionally, chlorophyll *a* concentrations were higher on the sandflats than the mudflats in two of the three estuaries (only measured in the second year).

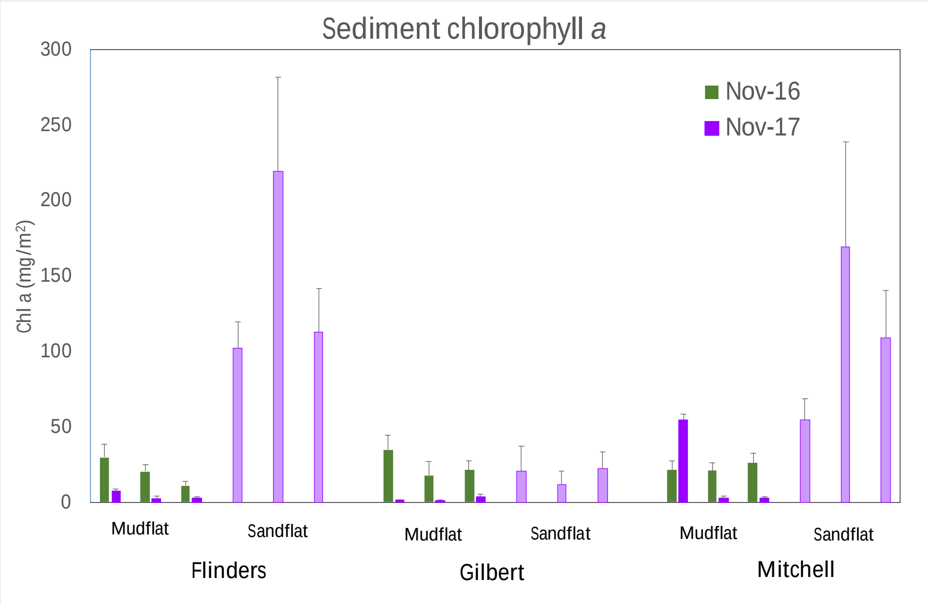
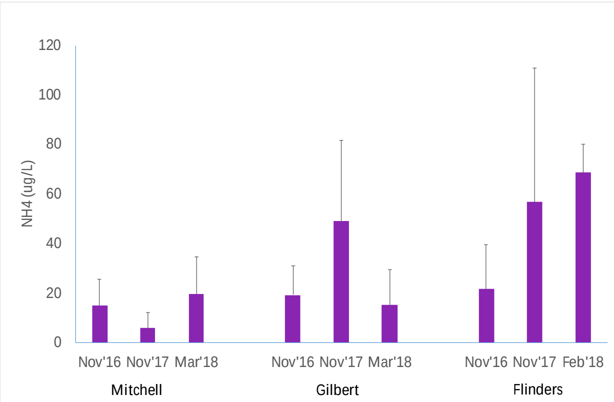
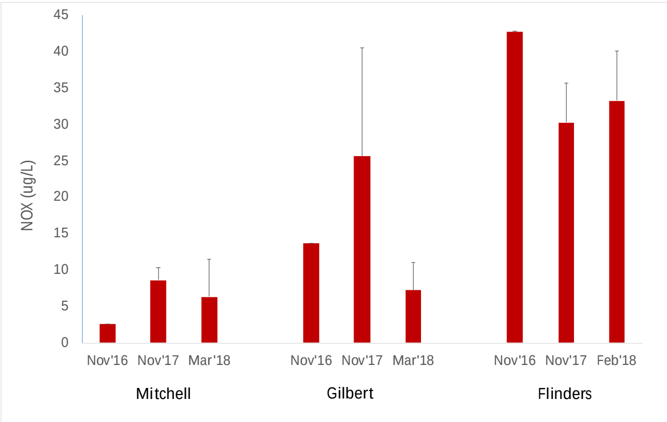


Figure 12 Chlorophyll *a* production in sediment cores taken from an estuarine mudbank and adjacent sandflat in the Mitchell, Gilbert or Flinders Rivers in November 2016 or 2017.

Nutrient concentrations were also measured in the water column in the three rivers for both years and a comparison was made with a wet season (March 2018). There was no evidence that ammonium, nitrate and phosphate concentrations were higher in the wet season compared with the dry season (Figure 13). This is consistent with a previous study in the Norman River which showed similar nutrient concentrations in the wet and dry seasons. Highest nitrate levels were in the Flinders River, and lowest nitrate and phosphate levels were in the Mitchell River, but further analysis is needed to substantiate this.





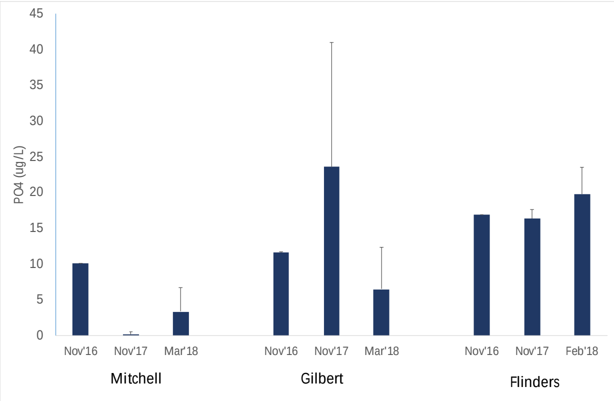


Figure 13 Ammonium, nitrate and phosphate concentrations in the Mitchell, Gilbert and Flinders rivers in two dry season sampling trips and one wet season trip (2018) in November 2016/2017, and March 2018.

Discussion

Not since the 1970s have the banana prawn populations of the estuaries of the Mitchell, Gilbert and Flinders rivers been surveyed. This study provides the first descriptions of their estuarine prawn communities in about 40 years. Each of the estuaries of these rivers support high abundances of juvenile banana prawns that contribute strongly to the annual first-season banana prawn catch of the Northern Prawn Fishery. Moreover, this project is the first to sample the tributary habitats (creeks and creeklets), as well as main river channel habitats in the three estuaries. Juvenile banana prawns were found to inhabit mangrove communities that are prolific in the lower to mid-reaches of each estuary. The collaborating NESP Project 'Links between gulf rivers and coastal productivity' used remotely sensed images and GIS software to calculate both the aerial and linear extents of the mangrove habitats in each river. The 'three-channel delta' of the Mitchell River supports the greatest aerial extent of mangroves (5685 ha), while the Gilbert (723 ha) and the Flinders (939 ha) rivers support both mangrove forests and mangrove fringes along the linear extent of the river banks (Burford *et al.* 2020). The area of intertidal mudbank at the mangrove/mudbank interface are less disparate at 1418 ha, 342 ha and 539 ha for each river, respectively.

In 2016, mean densities between the three rivers were not significantly different (~1.3 to 1.9 prawns m^{-2}), while in 2017 the density in the Gilbert River (~4.5 prawns m^{-2}) was roughly 2–4 times higher than all 2016 densities and 2017 densities in the Mitchell and Flinders rivers (~0.6 prawns m^{-2}). Extrapolating these juvenile prawn densities for the area of mangroves in each estuary, large juvenile prawn population estimates are derived for each estuary: from 76 million juvenile prawns in the Mitchell River, to 13 million in the Gilbert River and 16 million in the Flinders River, in 2016. However, in 2017, the population estimates change due to the different prawn densities estimated in each estuary that year: 30 million juvenile prawns in the Mitchell River, 33 million in the Gilbert River and 6 million in the Flinders River. The estimates are speculative: they are only a snapshot over two days from a ~4-month seasonal recruitment window. In addition, prawn densities are estimated when the juvenile banana prawns are concentrated in remnant water bodies during the low tide, not when they are foraging among the mangrove forests at high tide.

Scaling the abundance of juvenile banana prawns in each estuary using the area of intertidal mudbank provides different estimates: 1.95 million juvenile prawns in the Mitchell River, to 0.64 million in the Gilbert River and 0.92 million in the Flinders River in 2016; and 0.75 million, 1.56 million and 0.33 million in each of the rivers, respectively in 2017 (Burford *et al.* 2020). A conservative approach used the estimates of Vance *et al.* (2002), who suggested that juvenile prawns are found in mangrove forests at about a 50th to a 100th of the density they occupy when they are trawled from mudbank habitats at low tide. Even so, these revised estimates range from ~800,000 to 60,000 juvenile prawns in an estuary on any particular day; and a river may support 130,000 prawns d^{-1} in one year and 320,000 prawns d^{-1} the next.

Importantly, these prawn abundance and habitat extent estimates highlight the possible variation in an estuary's contribution to the fishing sector as a dependent extractive industry. Critical aspects of juvenile banana prawn abundance that are characteristic of Australia's tropical rivers are - high temporal variation between the same sites over different years, high variation between the same sites over a month, and spatial variation between sites in close proximity (Staples and Vance 1985, Vance *et al.* 1990, 1998). These trends were characteristic of the prawn abundances found in the Mitchell, Gilbert and Flinders rivers over 'snap-shot' beam trawl sampling during this study. In addition, variable nutrient concentrations but consistent primary productivity values for each estuary support productive food webs in each estuaries' mangrove habitats. Each of these estuaries has the capacity to provide ecosystem services to millions of juvenile prawns annually over the October to February inshore recruitment window characteristic of banana prawn life history. The dynamic prawn abundances among these estuaries highlight the need to maintain each estuary as productive habitat: in any year, one river or the other may be critical to support the NPF. One of the key ecosystem services provided to the banana prawn population is an emigration cue to move to offshore habitats; and patchy spatial rainfall patterns observed in GoC catchments mean that a strong cue may be delivered by floodflows in one river but not others. In addition, the productivity experiments demonstrate nutrient paucity within estuaries and the monsoon-cued critical inputs of nutrients via riverine/estuarine connectivity and unregulated floodflows to sustain downstream ecosystem services

The sampling regime for juvenile banana prawns involved mothership-assisted visits to the estuaries of the three rivers once each year in November for two years taking a full suite of samples (2016 and 2017), and two more years taking a subset of samples (March and December 2019) (Figure 14). Consequently, assessing temporal trends for aspects of the prawn population was not possible. Spatial assessment was possible, and a range of sample sites were selected: both in the main river channel and in tributary channels; waterbodies of different characteristics. Sites ranged from the mouth of the estuary to about 20–30 nautical miles upstream; a distance whereby a range of sites could be realistically sampled from a small vessel over two days. The Flinders River was sampled subsequent to November (in February and May 2018), yet the time-gaps of two to three months between visits made the assessment of temporal trends probabilistic.

Figure 14 The mothership vessel MV Eclipse and one of the workboats used to sample the estuaries of the Mitchell, Gilbert or Flinders rivers over the period November 2016 to December 2019.

Distinct and contrasting environmental characteristics were encountered during the late dry seasons of 2016 and 2017. In November 2016, the Mitchell, Gilbert and Flinders rivers were marine salinity to hypersaline and no freshwater flows were evident in each of the rivers. In the 12 days prior to the survey, no riverflow was documented in either the Gilbert or Flinders rivers, and only an average of 48 ML d^{-1} was recorded in the Mitchell River. In contrast, during October/November 2017 rainfall had occurred on the Great Dividing Range in the headwaters of the Mitchell and Gilbert rivers, the rivers were flowing, and tributary habitats in their estuaries were brackish in condition (1.5–32.6 and 24.7–36.5, respectively). In the 12 days prior to the survey, an average flow of 1595 ML d^{-1} occurred in the Mitchell River, while an average flow of 283 ML d^{-1} (peaking at 1000 ML d^{-1}) occurred in the Gilbert River. In 2017, no significant rainfall occurred in the Flinders River catchment (no flow recorded), so it remained marine equivalent. The salinity contrast between the two years offered an opportunity to contrast the spatial distribution of juvenile banana prawns within the estuaries in a year of no-flow (hypersaline) and a year of late-dry season low-flows (brackish). In each of the subsequent wet seasons, peak flows of 240,000, 270,000, 106,000 ML d^{-1} in 2017, and 108,000, 350,000, 348,000 ML d^{-1} in 2018 were recorded in the Mitchell, Gilbert and Flinders rivers, respectively. The magnitude of these floodflows dwarfs the early-season flows recorded in October/November.

The seasonal sampling of the rivers and particularly the Flinders River (pre-wet, wet season and post-wet) and the trawl samples from the three estuaries in March 2019 allowed a spatial assessment of the distribution of juvenile banana prawns over the annual seasonal cycle of dry, wet and post-wet catchment flows and estuarine conditions. In all cases, the abundances of juvenile banana prawns in the Mitchell, Gilbert and Flinders river estuaries during the wet season and afterwards were lower than prior to the onset of the monsoon (i.e. 0.03±0.01 to 0.22±0.20 prawns m^{-2}). During late February 2018, floodflows of ~5,000 ML d^{-1}

cued juvenile banana prawns to emigrate from the Flinders River and the flows increased to ~350,000 ML d^{-1} in March, prior to the May survey. In May, a few prawns were found throughout the estuary. In February 2019 prior to the survey, floodflows of 460,000, 340,000 and 650,000 ML d^{-1} (respectively) cued juvenile prawns to emigrate from each of the Mitchell, Gilbert and Flinders rivers, reducing juvenile banana prawn densities in their estuaries (~0.2 prawns m^{-2}, Table 4); a post-monsoon trend typical of banana prawns throughout their range (Vance and Rothlisberg, in press).

In 2016, prior to the wet season, the great majority of juvenile banana prawns remained in the tributaries of each of the rivers; the key settlement habitats within the mud-mangrove-creek matrix of the upper reaches of estuarine tributaries. In these habitats during that year, the juveniles likely were subject to slower growth and higher natural mortality under hypersaline conditions (Staples and Heales 1991), and high predation at high densities relative to elsewhere in the river (Haywood and Staples 1993). Consequently, fewer juveniles would be available to emigrate when the wet season eventuated and high-level floodflows occurred.

In 2017, while most juvenile prawns remained in the tributaries, many had moved to lower reaches of the estuary in response to the low-level freshwater flows, and were found at greater densities than in 2016. While the density of prawns in upper-tributary reaches was always highest, the differential between the density of prawns in upper tributary habitats and main river habitats was much lower in 2017 than in 2016. In 2016, the density of prawns in the upper tributaries was 20 times that of river habitats. In contrast in 2017, the differential was 4–5 times between these two habitat types, due to the downstream movement of juvenile prawns due to the brackish conditions associated with low-level flows. Typical 'main river' mudbank/mangrove habitat is shown in Figure 15; juvenile banana prawns would move into the mangrove fringe with the flood tide. Lower mortality and predation at lower densities ensured that when the wet season eventuated, more juveniles would be available to emigrate.

Historical data show that prawn emigration is strongly driven by river flow and flow can be significantly different between rivers in the same wet season. However, not just the levels of the highest floodflows are important; the timing of floodflows, particularly early flows, can be equally as important. Usually, early season flows (October to December), and in some years wet season flows, are low. Consequently, any withdrawal of water from rivers during periods of low flow, due to water impoundment or extraction for agriculture, could have disproportionately high impacts on the estuarine distribution of juvenile banana prawns and their emigration; and hence peak productivity of the NPF.

While the impact of flow on the emigration of banana prawns previously has been described, this project has measured the spatial distribution of juvenile banana prawns in tributary habitats and main channel habitats in each river. Historically, estuarine tributary habitats in these rivers have never been sampled as the importance of the mangrove/mudbank matrix in the 'upper creek' tributary habitats of GoC tropical rivers was not realised (Vance *et al*. 1990). Moreover, the project has related aspects of the population biology of juvenile banana prawns to the likely environmental conditions is each estuarine habitat. In doing so, the project has explored how impacts on the seasonality and dimension of low flows due to water resource extraction might affect the banana prawn population, particularly emigration and eventual commercial catch.

Past research shows that, under brackish conditions and at lower densities than in upstream habitats, juvenile banana prawns would grow faster, and suffer lower natural mortality and mortality due to predation (Staples and Heales 1991, Haywood and Staples 1993; Wang and Haywood 1999). The estuarine juvenile banana prawn population would be enhanced in main river habitats. In addition, in the Gilbert River many prawns emigrated in November at a 5–7 mm CL size range. They emigrated due to the drop in estuarine salinity, rather than an ontogenetic response. At the onset of the wet season, an abundant population of larger juvenile banana prawns would inhabit the estuary and eventually emigrate.

These processes are represented in the life history diagram of banana prawns (Figure 16). The lower portion of the figure represents estuarine habitats and provides a conceptual framework to best understand the growth and survival of postlarval banana prawns through to large juveniles, and emigration cues that may cause prawn cohorts to move offshore (from Kenyon *et al*. 2018). Emigration could occur either as an ontogenetic response, at low rates for larger juveniles cued by low flows, or in the case of a strong wet season, emigration *en masse* in response to high floodflows (Dall 1981; Staples 1980b).

Importantly, banana prawns emigrating early in October to December likely have a significant effect on the stock available to be fished. In the NPF, fishing begins on April 1st annually. Both the size of the individual prawns caught, and the overall tonnage of catch is important to fishery revenue (Somers 1985). The dollar value of a kilogram of prawns is dependent on their size, with the larger prawns being more valuable (Somers 1985). While the maximum level of river flow during the wet season is the major determinant of tonnage caught during a fishing season, the size of individual prawns caught at fishing season opening, and hence the value of the catch, is strongly dependent on the time of emigration from the estuary (Somers 1985). From one year to the next, the size of prawns caught is dependent on the onset of the wet season and the timing of the flood event. A large flood event in January cues a cohort of juveniles to move offshore where mortality is lower. They have a two-to-three-month time window to grow before fishing begins in April. In contrast, a large flood event in March cues a cohort of juvenile prawns to emigrate, with barely a month before they are fished. The March cohort would be smaller and less valuable on the market. NPF fishers discuss the 'quality' (size) of the first catches of prawns each banana prawn season.

Moreover, if late-dry season low-level flows (such as those encountered in November 2017) occur, then a cohort or several cohorts of juvenile prawns emigrate relatively early and remain offshore for four to five months before being fished. The emigration event would be small relative to those associated with wet season floods (Duggan *et al.* 2019). However, early emigration followed up by significant emigration associated with large wet season flows contribute to a high-value seasonal catch. Banana prawns emigrating from October to December survive and grow large for ~five months prior to being fished. Large banana prawns aggregate in schools and are readily detected by echo-sounder and are fished in peak condition (Somers 1985). In addition, the emigration of prawns from the estuary would reduce the density of large juvenile banana prawns in estuarine habitats. Early emigration of a portion of the population would allow new recruits to better survive and grow in upper estuarine reaches until they emigrate.

Historical modelling of spring (September to November) and summer (December to February) rainfall has shown significant positive effects of 'early-rainfall' on prawn catch in some rivers (Vance *et al*. 2003). Wet season (summer) rainfall shows the strongest positive relationship between flow and commercial prawn catch (Vance *et al*. 2003). The consideration of early season flows and the cumulative effect of successive years of low flows is critical to fully understanding the impacts of flows on catch.

Anecdotal comments from vessel skippers and fleet managers after the 2018 banana prawn season commented on the good 'quality' of prawns caught offshore from the Mitchell and Gilbert Rivers at the beginning of the season (i.e. the prawns caught in the first days of the season were large) (R. Kenyon, pers. comm.). The banana prawns caught in 2018 in this region likely were from the juvenile cohorts that recruited to the estuary from October 2017 to ~March 2018. The large prawns caught first-off may have been the November emigrants which thrived offshore for five months. In addition, during the 2018 wet season, large floods in the Mitchell and Gilbert Rivers would have cued mass banana prawn emigration from the rivers, moving deeper and being fished as the season progressed. The floods were associated with 400–600 mm of rainfall in the river catchments from December 2017 to February 2018. The Principal Investigator of this project heard an anecdotal report of an NPF vessel that fished the region offshore from these rivers throughout the entire 2018 season (which is unusual). The vessel caught good quantities of large banana prawns early on, with catches dropping away for a week or two, only to re-establish as large catches for a few days. This catch/decline cycle continued into May 2018. Supposedly, the vessel remained in the vicinity for the 2018 fishing season and their aggregate season catch was high.

In tropical Australia, river flow is crucial to the ecosystem services that support the life cycles of a suite of estuarine and marine species that sustain commercial, recreational and indigenous fisheries. The importance of freshwater flow on coastal and estuarine fisheries catch has been well established (Robins *et al*. 2005; Balston 2009; Buckworth *et al.* 2014; Duggan et al. 2019). Estuarine production supports an abundant population of juvenile banana prawns (Burford *et al*. 2010; Duggan et al. 2014, 2019), supplemented by episodic recruitment and reduced by constant predation. Seasonal floods (low estuarine salinity), together with a reduction in the abundance of estuarine meiofauna food resources, cue the emigration of banana prawns (Duggan *et al.* 2014, 2019). Ecosystem services in these habitats are sustained by the pulsed monsoonal flows within these wet-dry tropical river systems (Burford *et al.* 2012). Additionally, large loads of nutrients are exported on high floodflows to shallow coastal waters, fuelling substantial nearshore primary production with flow-on effects for fisheries, including banana prawns (Burford *et al.* 2016). Interannual and seasonal cycles of high- and low-flows sustain both the integrity of species' lifecycles and of their habitats; and these communities have co-evolved with these cycles for millennia (Arthington *et al*. 2018). Modification of the timing, magnitude or duration of the annual, unpredictable wet-season floods will have flow-on effects for the distribution and abundance of many species along tropical coasts.

CSIRO's recent assessments of the water resources of Gulf of Carpentaria rivers have provided quantitative estimates of water volumes available for harvest to support irrigation. The Flinders and Gilbert Agricultural Resource Assessment (FGARA) identified offstream water storage (350 GL potential, delivering 175 GL pa) as optimum in the Flinders River catchment (Petheram *et al*. 2013a). In-stream dams were capable of delivering a combined 80 GL of irrigation water. The total water storage capacity could support 10,000–20,000 ha of irrigation in 70–80% of years. The FGARA assessment also identified two sites in the Gilbert River catchment for in-steam dams of approximately 500 GL and 220 GL delivering ~320 and 170 GL of water at 85% reliability (Petheram *et al.* 2013b). The water could support 20,000–30,000 ha of irrigation in 85% of years. The subsequent Northern Australia Water Resource Assessment (NAWRA) identified four optimal sites in the Mitchell River catchment for in-steam dams, two large dams with a capacity of 2316 GL (Pinnacles Dam) and 1288 GL (Rookwood Dam). In total, the four dams deliver ~2800 GL of water at 85% reliability (Petheram *et al.* 2018c). The water could support 140,000 ha of irrigation in 85% of years.

Proponents of irrigated agriculture sourcing water from catchments in the wet-dry tropics promote their water requirements as the minimal use of natural flows, e.g. 20% of end-of-system flows. Stanbroke Pastoral is a proponent for irrigated agriculture in the Flinders River catchment. In their Initial Advice Statement, Stanbroke Pastoral suggested that the reduction of river flow would be at most 28% of median flow (Anon. 2015). In support of their proposition, they quote the FGARA analyses of the likely reduction in barramundi and prawn catch in response to 212 and 532 GL of water extraction from the combined flows of the Flinders and Gilbert Rivers. The estimated reduction in fishery catch was 3–13% for prawns and 4–19% for barramundi, scenario dependent (Bayliss *et al*. 2014). A prominent high extraction scenario estimated a 2–8% likely catch reduction for prawns and a 3–12% likely catch reduction for barramundi.

However, stating water requirements as a percentage of annual flow does not account for the extraction of high percentages of the volumes of low-level flows, or the negation of the seasonal cycle of flows. Extraction or impoundment of the early-season October to December flows may remove 100% of the flow volume, particularly if large dams were constructed with no engineered facility for environmental flows, or if barriers were placed in rivers to enable pumped extraction. Furthermore, series of years with low-level wet season flows are common: low flows in each of the Mitchell, Gilbert and Flinders rivers in the same year occurred 22% of the time over the last 110 years (Broadley *et al.* in press). Importantly, extraction of water from low-level flows has a disproportionate impact on offshore fishery catch; up to a 53% reduction in catch for a scenario of dam construction on the Mitchell River as scoped by the NAWRA (Broadley *et al*. in press). A 53% reduction to an already-predicted low catch would be devastating for the fishing industry. In contrast, a small percent reduction of a high-level flow and predicted catch would be unwelcome, but a high tonnage catch would remain to be fished and lucrative to the fishing industry.

Until the recent FGARA, NAWRA and NESP project work, the reported modelling had used rainfall as a proxy for flow and seasonal flow, or not considered the seasonality of floodflows (Vance *et al*. 1985, 2003; Bayliss *et al.* 2014; Vance and Rothlisberg, in press). The recent projects report significant detrimental effects on banana prawn catch due to the loss of late-dry season low-level flows (Pollino *et al*. 2018a,b) and low-level wet season flows (Broadley *et al.* in press; Burford *et al*. 2020). The loss of low-level flows reduces key riverine inputs to ecosystem services and estuarine processes. Flow-catch modelling to explore ecological interactions and ecosystem level impacts at finer temporal and spatial scales remains critical. The FRDC project (2018-079) "Ecological modelling of the impacts of water developments in the Gulf of Carpentaria with particular reference to impacts on the Northern Prawn Fishery" will address the impact of seasonal flows and flow reduction on fishery catch as part of an ecosystem model (see Plaganyi e*t al.* 2014).

To uphold the water requirements of all stakeholders, Water Resource Plans should legislate trigger levels of flow below which impoundment or extraction cannot occur; both for early-season low-level flows and low-level flows associated with the wet season. Extraction or impoundment should occur from high-level flows only, whereby the bulk of flow volumes continue downstream (Kenyon *et al.* 2018; Pollino *et al*. 2018b). Both extraction from or impoundment of low-level flows and the placement of barriers to create pump-pools, impact natural base flows and early-season low-flows and reduce the estuarine brackish ecotone, with subsequent habitat impairment for key commercial species. As well, in-stream barriers interrupt longstream riverine connectivity for commercial and threatened species such as barramundi, freshwater sawfish and freshwater whiprays (Pollino *et al.* 2018b).

Figure 15 Trawling main river channel mudbank/mangrove habitat in the Flinders River in May 2018. Banana prawns move into the mangrove fringe as the tide rises and are forced from the protective refuge of the mangroves as the tide recedes. They are available to be caught in towed nets near low tide.

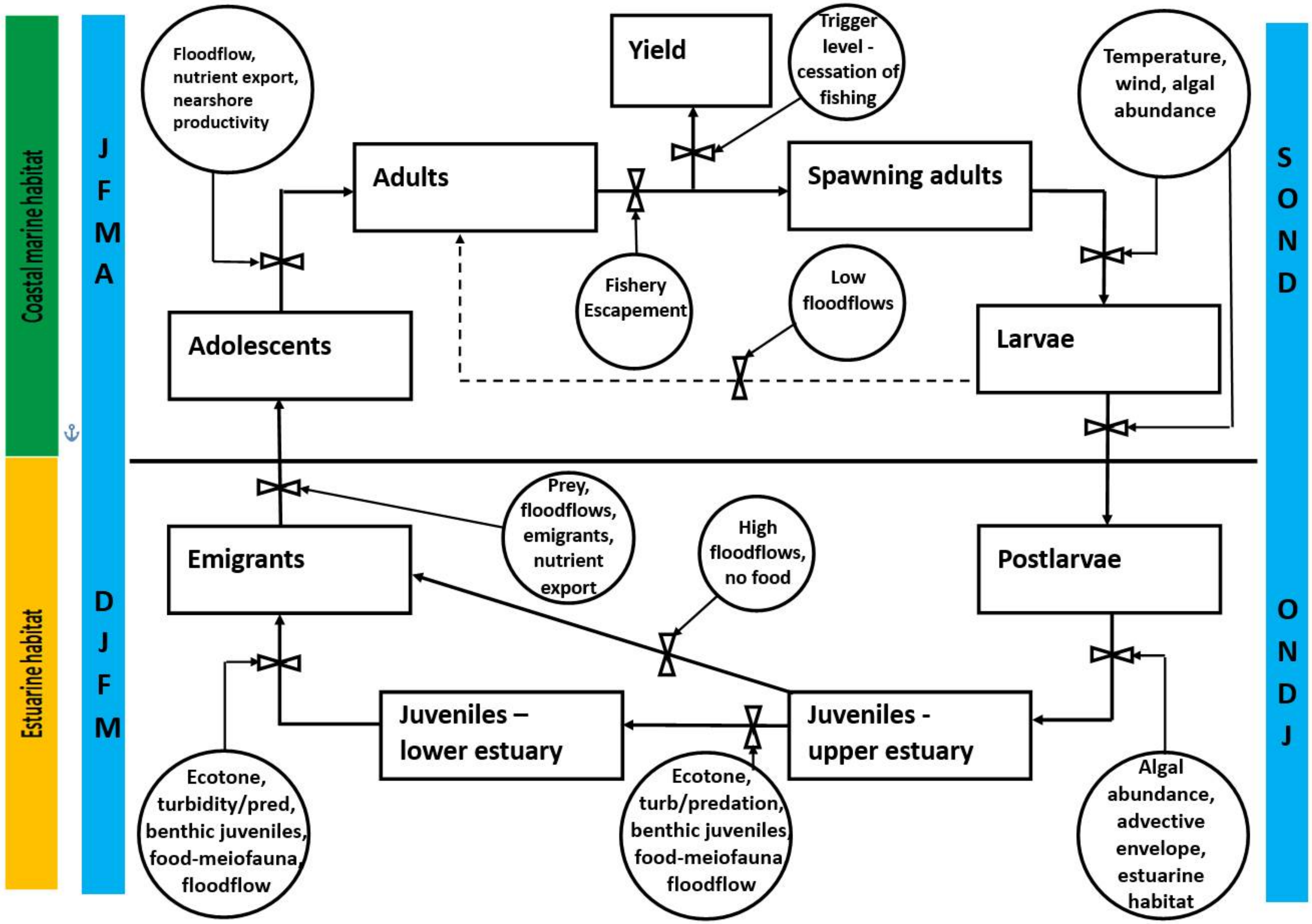


Figure 16 Life history model of banana prawns (*Penaeus merguiensis*) showing abiotic and biotic factors that determine abundance and survivorship of key phases the cycle. (Turbidity/pred and turb/predation refer to turbidity and predation) (drawn with the benefit of concepts from Vance *et al*. (1985)). The letters in the blue columns represent months (the late dry season—September to December (S,O,N,D); the wet season—January to March (J,F,M).

Qualitative descriptions of the Mitchell, Gilbert and Flinders Rivers

The main channel of the Mitchell River was a relatively sandy-substrate habitat with exposed sand banks observed in the lower estuary. The further upstream one travelled, the sandier the estuary became. The upstream estuary was not trawled for prawns due to distances involved to access these reaches within limited time, and the fact that side creeks off the main river channel in the lower estuary were muddy-substrate habitats typical of creeks inhabited by banana prawns. Therefore, the limited time available to us was deployed sampling the side creeks. Large creeks or delta-channels which eventually opened to the GoC, branched off the Mitchell River. Small creeks and 'creeklets' or gutters branched off the larger tributaries. The estuary did not have a 'meandering form' that most south-eastern GoC rivers exhibit. The Mitchell River was not like rivers of the southern GoC, rivers in which considerable juvenile banana prawn survey effort has been deployed over past decades.

During the two years of the study, few resident banana prawns were found in the main river channel. Some locations attempted to be trawled were too shallow to access the river water's edge where banana prawns were likely to be found. Our dinghy ran aground well before we closed on the water's edge and the 30 m of shallow water remaining between the vessel and the water's edge could have supported juvenile banana prawns. We trawled a main-river site in 2016 and caught nothing (200 m trawl) and sought out other sites to make a useful trawl. Experience from the GoC and Joseph Bonaparte Gulf (JBG) showed that banana prawns do not inhabit shallow waters adjacent to the sand banks and other sandy features in rivers (Kenyon *et al*. 2004). Effort was directed to Mitchell River tributaries to estimate prawn abundance there. In 2017, we trawled the main river site again and caught 6 postlarval and juvenile prawns over a 200 m trawl. We trawled a second 100 m main river trawl site and caught 70 prawns. In 2017, the greater abundance of prawns in the main river channel seemed to reflect downstream movement of juvenile prawns in the brackish estuary.

The tributary creeks of the Mitchell River supported abundant postlarval and juvenile prawns. The first creek encountered upstream from the river mouth on the southern bank was trawled in 2016 and prawns were abundant. Just upstream a shelving mudbank supported 2.7 and 9.5 postlarval and juvenile prawns m^{-2} and further upstream 2.7 prawns m^{-2} were caught. In 2017, the same sites supported 0.41 to 7.2 postlarval and juvenile prawns m^{-2}, while upstream 0.5 to 2.5 prawns m^{-2} were found. In 2016, small creeks off the North Arm of the Mitchell River supported 1.8 prawns m^{-2} at high density sites. In 2017, these creeks supported 1.9 postlarval and juvenile prawns m^{-2} at high density sites.

The Gilbert River is a river more typical of the rivers of the south east GoC such as the Norman River and the Flinders River. The estuary exhibited a 'meandering form' like most south-eastern GoC rivers. Muddy-shelving banks were encountered on the inside of each meander; banks that were productive juvenile banana prawn habitat. During 2016, 0.1 to 0.5 prawns m^{-2} were found on these banks; except one site where 11.2 prawns m^{-2} were found. As explained in the Results Section, 10.8 prawns m^{-2} of the catch were 1 mm CL postlarvae, probably immigrating upstream. They would move upstream on the flood tide and a trawl made at this site on the subsequent low tide likely would encounter a prawn abundance similar to the 0.1 to 05 prawns m^{-2} range. In 2017, the abundance of prawns in these main river channel habitats reflected downstream movement of juvenile prawns in the brackish estuary (0.4 to 2.7 prawns m^{-2} were found; and less than 0.1 postlarvae m^{-2} were encountered). Two large creeks branched off the northern bank of the Gilbert River. We sampled both creeks for juvenile prawns. Small 'creeklets' also branched off the main river channel and the large creeks (Figure 17).

Figure 17 Upstream mangrove/mudbank habitat in a typical tributary creek and 'creeklet' in the estuary of the Gilbert River. Trawls were made on both banks and high catch rates were observed. Similar upstream habitats were found in the Mitchell and Flinders rivers.

The tributaries of the Gilbert River supported abundant postlarval and juvenile prawns. The first creek encountered upstream from the river mouth was trawled in 2016 and prawns were caught on shelving mudbanks (0.3 and 0.4 juvenile prawns m^{-2}), while creeklets/gutters supported up to 22.5 prawns m^{-2}. In 2017, the same sites supported 0.6 to 2.2 juvenile prawns m^{-2}, while creeklets/gutters supported 18.8 to 73.4 postlarval and juvenile prawns m^{-2}. In 2016, the second creek off the Gilbert River supported 0.3 to 0.6 prawns m^{-2} on shelving mudbanks and 3.2 to 4.6 prawns m^{-2} in creeklets/gutters. In 2017, these creeks supported 2.2 to 6.1 prawns m^{-2} at high density sites and up to 27.5 prawns m^{-2} in creeklets.

The Flinders River is a south-eastern GoC river with a typical meandering estuary. No large creeks branch off the Flinders River, though creeklets and gutters extend inland often only 20–50 m navigable by small vessel at low tide, neap. Each meander of the Flinders River supports a muddy-shelving bank; banks that provide productive juvenile banana prawn habitats (Figure 16). During 2016, 0.2 to 0.6 prawns m^{-2} were found on these inner-meander banks. During 2017, 0.04 to 0.64 prawns m^{-2} were found on these inner-meander bank habitats. As found in the Mitchell and Gilbert rivers, the creeklets and gutters were the habitats where the greatest densities of juvenile banana prawns were found. They accumulate in these remnant waters as the tide ebbs. During 2016, 5.3 to 17.5 postlarval and juvenile prawns m^{-2} were found in some creeklet habitats, though densities of 0.1 to 0.2 prawns m^{-2} were also found in creeklets. In 2017, 1.7 and 3.6 postlarval and juvenile prawns m^{-2} were found at high density creeklet sites, though densities similar to those at the main river sites were also found.

An important point to note is that prawn densities at specific sites varied strongly over time, i.e. between the two years. That is, a site where prawns were very abundant in 2016 was not necessarily a site where they were abundant in 2017. For example, in the Flinders River a creeklet where 17.5 prawns m^{-2} were found in 2016 supported 0.5 prawns m^{-2} in 2017. In contrast, in the Gilbert River a creeklet where 22.5 prawns m^{-2}

were found in 2016 supported 18.8 prawns m^{-2} in 2017. In the Mitchell River, a creeklet where 3.3 prawns m^{-2} were found in 2016 supported 1.4 prawns m^{-2} in 2017; whereas a creek in the Mitchell River supported 1.8 prawns m^{-2} in 2016 and 1.9 prawns m^{-2} in 2017.

A second example from the Mitchell River shows that 1.0 to 3.2 prawns m^{-2} were found in trawls undertaken on one day during 2016, while the next day trawls at the same sites caught 0.7 to 9.5 prawns m^{-2}. These sites were the first sites trawled as part of this project and the juvenile prawn catch seemed abundant, so they were trawled on the subsequent day to check if the high abundances of juvenile prawns remained at the sites. In 2017, 0.4 to 0.6 prawns m^{-2} were found at the same sites, not so inspiring catches as in 2016. Overall, the trawl results from this project reinforce the known trend for juvenile banana prawn distribution–that abundance is ephemeral both spatially and temporally (Staples 1980, Vance *et al*. 1998). However, historical trends for high juvenile prawn abundance in tributary habitats, lower abundances in river habitats, and salinity-cued estuarine distribution shifts within the estuary and nearshore zone were evident.

Conclusion

This study provides the first descriptions of the estuarine prawn communities of the Mitchell, Gilbert and Flinders rivers undertaken in 40 years. The project is the first to measure and contrast the spatial distribution of juvenile banana prawns in tributary habitats and main channel habitats in each of the three rivers. Historically, when the Mitchell, Gilbert and Flinders rivers were first surveyed, the importance of the mangrove/mudbank matrix in the 'upper creek' tributary habitats of GoC tropical rivers was not realised. Each of the estuaries of the Mitchell, Gilbert and Flinders rivers support high abundances of juvenile banana prawns that contribute strongly to the annual first-season banana prawn catch of the NPF. The project has related aspects of the population biology of juvenile banana prawns to the likely environmental conditions in each category of estuarine habitat. The project has explored how impacts on the seasonality and dimension of low flows due to water resource extraction might affect the banana prawn population, particularly emigration and eventual commercial catch.

Prawn emigration is strongly driven by river flow, and flow can be significantly different between rivers in the same wet season. However, not just the levels of the highest floodflows are important; the seasonal timing of floodflows can be equally as important. Particularly, early season flows (October to December) and when wet-season flows are low. Withdrawal of water from rivers during periods of low flow will have disproportionately high impacts on the ecosystem services that sustain the estuarine population of banana prawns. The modification of flows will impact the distribution of juvenile banana prawns and their emigration; and hence the productivity of the NPF. Water impoundment or extraction for irrigated agriculture in GoC catchments has the capacity to reduce both high flows and low flows, but low flows disproportionally.

By good fortune, the salinity regime of the Mitchell, Gilbert and Flinders rivers differed during 2016 compared to 2017. In 2016, all estuaries were marine equivalent or hypersaline, whereas in 2017 two estuaries were brackish. This contrast was opportunistic for the 'Knowledge Gaps' project with the resulting data suggesting that juvenile banana prawn behaviour in brackish estuaries supplemented by early-season freshwater flows was different to their behaviour in marine equivalent estuaries. In 2017, while the density of prawns in upper-tributary reaches of each of the river estuaries was high, the differential between the density of prawns in upper tributary habitats and main river habitats was much lower in 2017 than in 2016, demonstrating downstream movement of juvenile prawns to main river habitats while estuaries are brackish.

The impoundment or extraction of river flows modifies natural flow regimes with downstream effects for the stability of the estuarine fauna community. Environmental drivers that cue the behaviour of crustaceans and fish are lost. If floodflows are large and estuarine salinity nears zero, emigration occurs *en masse* (Vance *et al*. 1985; Duggan *et al*. 2019). However, when floodflows are small, the emigration cue is weak, and the modification of a low flow has a disproportionately large effect on prawn behaviour. In the case of banana prawns under WRD to support irrigated agriculture, the emigration cue in the form of a sharp decline in salinity in the estuary may be lost. The exact relationship between salinity decline and emigration cue has not been quantified, but the relationship is probably not linear (Duggan *et al*. 2019) and results in a particularly large percent-decline in catch during years of low flow (Broadley *et al*. in press). Maintaining the highest floodflow levels elicits a strong emigration response from the estuarine juvenile population which results in an improved offshore catch of banana prawns during the fishing season.

Less prominent to observation is the banana prawn's response to a lesser decline in salinity to brackish conditions. While emigration of some cohorts of prawns occurs, in a brackish estuary, a large proportion of the juvenile prawn population moves from upper tributary habitats to lower tributary and main river channel habitats. Larger juvenile prawns move downstream to the main river where they are found at lower densities and are exposed to reduced predation. In all likelihood, the estuarine juvenile banana prawn population is greater in a dynamic brackish estuary where the population disperses throughout the estuary, than in a hypersaline estuary where most of the population remains in the upper tributary habitats not distant from where they settled to a benthic existence.

Water extraction or impoundment with no legislated water management protocols incorporated into WRPs will impact low-level floodflows to a greater extent than high floodflows. High pump capacity can extract and divert a large proportion of low-level flows, and remnant downstream flows may be negligible. In the case of in-stream dams, the total volume of a small flow may be impounded. In the Australian wet-dry tropics, low-level river flows in the late-dry season (October to December) are critical flows to restore and reconnect stressed riverine and estuarine habitats following the dry season's extended period of no flow. Early low-level flows are highly vulnerable to reduction due to WRD (Pollino *et al.* 2018a,b). Extraction or impoundment of early-season low-level flows may remove 90–100% of the flow volume, negating estuarine inflows. The interruption of early flows prevents the formation of the brackish ecotone that sustains species' growth and survival downstream. Early-season brackish conditions create emigration cues that allow prawn cohorts to move offshore much earlier than cues associated with the subsequent wet season.

Wet season high-level flows also will be impacted by extraction or impoundment, but the proportional loss of flow from above-median-level flows will likely be small and the majority of high floodflows will continue downstream to support ecosystem services in the river estuary.

Late-dry season (early) low-level flows support key ecological enhancement of estuaries during the critical juvenile banana prawn estuarine recruitment window from September to ~ February annually; particularly September to December. The loss of early season flows will cause significant loss of ecosystem services in estuaries with flow-on impacts to banana prawn population dynamics. To protect the delivery of ecosystem services to GoC estuaries, trigger levels of flow should be legislated and enacted; extraction or impoundment of water at levels below trigger-flows should not be undertaken as these low-level flows need to pass downstream to estuaries unhindered.

The interruption of natural un-regulated flows has the capacity to cause loss of revenue to the NPF due to a reduction in the seasonal quantum of catch and smaller size of individual prawns (less valuable). A reduction in the size of prawns caught at the fishery opening would in-part be due to a reduction in early emigration cues, thus limiting the early-season offshore movement of prawn cohorts during October to December and their subsequent growth to adulthood offshore.

In tropical Australian catchments, the water resources required to support irrigated agriculture can be impounded or extracted in ways that minimise impacts on natural flow regimes. Both the timing of water extraction and the proportion extracted from flows are critical to the degree of modification of ecosystem services that sustain fish and fisheries downstream. When October to December flows are extracted or impounded, the negative impact on banana prawn population dynamics is disproportionate. In contrast, extraction or impoundment of high floodflows may reduce the flow-volume by 10–20% only; the majority of the water continues downstream maintaining ecosystem services to the estuary. Estuarine salinity declines, the emigration cue remains high, and monsoon-cued ecosystem processes within the estuary are not impacted.

In northern Australia, the stochastic nature of rainfall and river flow in the wet-dry tropics ensures that the temporal and volumetric reliability of flows is unpredictable (Petheram *et al*. 2008). Water resource development for agricultural production requires the large-scale storage of unpredictable river flows via opportunistic or continuous harvest to increase the reliability of water supply. The development and implementation of water management protocols for tropical rivers, if based on poorly-informed perspectives with no scientific basis, will be made to the detriment of estuarine ecosystem services and coastal fisheries, and other downstream users.

Proponents of irrigated agriculture sourcing water from catchments in the wet-dry tropics promote their water requirements as the minimal use of natural flows (e.g. 20% of end-of-system flows is required to sustain their water needs). However, stating a percentage reduction of annual flow does not account for the possible extraction of high percentages of the volume of low flows, and the disproportionate effect on the seasonal cycle of flows. Extraction or impoundment of the early-season October to December flows may remove 100% of the flow volume, particularly if large dams were constructed with no engineered facility for environmental flows, or if barriers were placed in rivers to enable pumped extraction. Water Resource Plans should legislate trigger levels of flow below which impoundment or extraction cannot occur; both for early-season low-level flows and low-level flows associated with the wet season. Extraction or impoundment should occur from high-level flows only, whereby the bulk of flow volumes continues downstream (summarised in Kenyon *et al.* 2018).

Flow-catch modelling to explore ecological interactions and ecosystem level impacts at finer temporal and spatial scales remains critical. Until recently, the reported modelling had not considered the seasonality of floodflows, or the impact of water extraction from low flows that contribute key riverine inputs to ecosystem services and estuarine processes. However, modelling projects currently underway and just reported as part of the NAWRA project have investigated the seasonal components of flow and flow modification, and indicated significant effects on banana prawn catch due to the loss of low-level flows (Pollino *et al*. 2018a). In addition, modelling that differentiates the impact of water extraction at high, moderate and low levels of flow undertaken as component parts of the NESP program has been completed (Broadley *et al*. in press; Burford *et al*. 2020). The FRDC project (2018-079) "Ecological modelling of the impacts of water developments in the Gulf of Carpentaria with particular reference to impacts on the Northern Prawn Fishery" began in the first half of 2019 and will address the impact of seasonal flows and flow reduction on fishery catch. The results of these projects will provide critical knowledge on the impacts of the reduction of flows, particularly low-level flows, on fishery catch in the NPF.

Implications

In recent years, a broader perspective of the value of rivers and river flow has been adopted within Australia. Increased understanding of the contributors to coastal productivity has encouraged a shift from a ‘resource development’ focus on water allocation for irrigation and other extractive commerce, to a broader perspective including a range of economic, social and ecological considerations that underpin sustainable water development (Jackson *et al*. 2008). This perspective offers all commercial enterprises opportunities to influence WRD policy; enterprises other than agriculturalists that also are dependent on catchment flows.

The Australian Government has sponsored research defining soil and water resources potentially supporting irrigated agriculture and quantification of the economic feasibility for planned expansion of agricultural production in northern Australia (Petheram *et al*. 2013 a,b; 2018 a,b,c). The magnitude of catchment runoff, the suitability of catchment soils, and the potential for instream and offstream storage has been documented (Petheram *et al.* 2018 a,b,c). In conjunction, quantitative studies of economic trade-offs between current uses that may be displaced, and crop production have been made (Stokes *et al.* 2017).

The outcomes from our research (FRDC 2016-047) demonstrate that the maintenance of the seasonal cycle of freshwater flows, in particular low-level floodflows, in Australia’s tropical rivers is crucial to sustain downstream ecological services to estuaries and nearshore. Juvenile banana prawns use the estuaries of the Mitchell, Gilbert and Flinders rivers like they do in other GoC rivers, such as the Embley and Norman rivers. In these two rivers, the importance of freshwater floodflows as precursor emigration cues that result in offshore movement of the prawn population and their availability to be fished (measured as commercial catch) has been documented. The same effect of annual monsoon-driven flows supports coastal productivity and key fishery species in the Mitchell, Gilbert and Flinders rivers. We demonstrated that, as for the Norman and Embley rivers, postlarval banana prawns recruit to the mangrove/mudbank matrix in the upper reaches of tributary habitats where they shelter and grow as juveniles. Without freshwater cues, over 90% of the juveniles remain in the tributary habitats; while both early low-level flows and monsoon floods cause downstream migration and emigration to other habitats, to the benefit of the banana prawn population.

Current catchment users and commercial enterprises dependent on estuarine and coastal ecosystems in the GoC need to engage with the revision of water resource planning for catchments in which WRD for irrigated agriculture is intended to occur. Best scientific knowledge of the interaction between catchment and riverine hydrology and banana prawn ecology needs to be deployed to maintain as much as practical the natural flow regime for each catchment. Water Resource Plans should legislate trigger levels of flow below which impoundment or extraction cannot occur; both for early-season low-level flows and low-level flows associated with the wet season. Trigger levels of flow, below which impacts on river flows cannot be undertaken, need to be legislated. These actions will best maintain the ecosystem services provided by natural flows that have historically remained unhindered and unregulated since the instigation of northern fishing enterprises in the 1960s and 70s.

The legislated enactment of these trigger levels of flow is necessary. At levels of flow below the triggers, the harvest of water should be illegal and subject to prosecution. Definition of likely trigger levels of flow is currently being determined by researchers such as Broadley *et al.* in press and FRDC 2018-079 using Plaganyi *et al.*’s (2014) modelling.

Subject to the outcomes of current studies, the harvest of high flows can be supported by fishing enterprises when the upper quartile of flows only is harvested through a minor percentage of extraction or impoundment. Most of the volume of high-level floodflows continues downstream to the estuary. The exact level of flows that can be harvested should be estimated quantitatively using data from the most recent hydrological studies such as NAWRA and NESP.

Research gaps have been addressed by this project. We demonstrated that juvenile banana prawns use the estuarine habitats in the Mitchell, Gilbert and Flinders rivers in the same way that they use well-studied rivers, such as the Embley River in the north-east GoC and the Norman River in the south-east GoC. We measured the abundance of banana prawn population in each of the estuaries simultaneous with measurements of nutrient levels, primary production and meiofauna abundance that would support juvenile prawns in these habitats. These estimates afforded NESP researchers the opportunity to relate estuarine productivity to prawn production from each estuary.

Recommendations

- Each of the estuaries of the Mitchell, Gilbert and Flinders Rivers support extensive aerial and linear extents of mangrove forest and mangrove fringe habitats that form the habitats of juvenile banana prawns. The inundated forests and their low tide mudbank habitats support abundant juvenile banana prawn populations each year between October to March. Emigrants from these habitats contribute strongly to the offshore catch in the Northern Prawn Fishery's annual harvest. The estuarine habitats in these rivers need to be preserved; both from the perspective of the physical integrity of the habitat extent, but also from the perspective of the ecosystem services provided to the habitats by both low- and high-level floodflows associated with the annual monsoon.

- Water Resource Operational Plans for major catchments will be rewritten, in part, in response to the outcomes and recommendations of the water resource assessments such as the Flinders and Gilbert Agricultural Resource Assessment and Northern Australia Water Resource Assessment.

- NPF Management are encouraged to engage with the process of Water Resource Plan development or modification for GoC river catchments. The future placement of irrigated agriculture and water infrastructure will precipitate the revision of catchment WRPs. Managers are encouraged to use most recent scientific knowledge gained via the NAWRA, NESP and FRDC-sponsored projects to optimise the design and construction of water resource infrastructure. They should ensure that both management protocols and water infrastructure incorporate capacity to deliver environmental flows that optimise estuarine processes and fishery production, given constraints from water extraction.

- Best practice WRPs and ROPs have the capacity to serve current and future catchment and coast users. They should aim to:

    - maintain the potential for river flows and floodflows to benefit historical ecosystem service provision downstream, both for within-catchment and downstream water users and habitat features. This facet can be achieved through water harvest protocols that remove a relatively small proportion of the flood hydrograph, yet supply a large volume of water to new users;
    - avoid the diversion of water from low-level flows; extraction or impoundment of low-level flows has a disproportionate impact on downstream flow levels and hence fishery catch;
    - supply water resources to new industries, including irrigated agriculture, via the requirement to extract/impound and store a small proportion of monsoon season high flows that then can be delivered year-round for human use,

- Use best-available knowledge derived from modelling undertaken as part of FGARA, NAWRA, NESP and FRDC 2018-079) "Ecological modelling of the impacts of water developments in the Gulf of Carpentaria with particular reference to impacts on the Northern Prawn Fishery" to define quantitative targets and triggers that achieve impact minimisation of seasonal and annual flow patterns of GoC rivers and other rivers that flows into the NPF managed zone across the majority of tropical Australia.

- The collaborative NESP Project 1.4 'Links between Gulf Rivers and Coastal Productivity' (NAER) used the spatial analysis techniques to map the estuarine habitats used by juvenile banana prawns in each estuary. Estimates of mangrove area and linear interface with the river and creek channels; and area of intertidal mudbank and their linear extent were made. ESRI World Imagery and satellite imagery from Google Earth (images at low tide) were sourced to undertake the mapping in Arc Map 10.6. The technique could be extended to a regional subset or all estuaries in the GoC to estimate mangrove and mudbank juvenile banana prawn habitat extents. Remotely sensed imaging technology is expanding rapidly and it offers the ability to discriminate habitats for a range of fauna in ways previously un-imagined, including modelling estuarine habitat extent estimated at a very fine scale, ecosystem cues such as river flows and coastal hydrology to fishery distribution and productivity.

Further development

Two major questions arise from the 'Knowledge Gaps' project. The first is whether growth and mortality in upper tributary habitats and the lower reaches of main rivers differ (as laboratory experimental work suggests)? These habitats represent the banana prawn postlarval settlement and early-stage juvenile habitats, and resident habitats for juvenile banana prawns prior to emigration, respectively. The second is to quantify how these facets of prawn population dynamics, as well as juvenile prawn longstream distribution and the quanta of emigration, differ between years of no-flow for the late-dry season and years of low-flows during the late-dry season. These scenarios represent a hypersaline estuary during the recruitment phase, and a brackish estuary during the recruitment phase, respectively.

An innovative research project that would assist our understanding of the questions posed by this project would be to measure growth and mortality of juvenile banana prawns in both tributary habitats and main river habitats in an estuary; in years of both a hypersaline estuary and a brackish estuary. The project would require at least a three-month series of weekly sampling to detect and follow cohorts of prawns that recruit to the estuary to estimate growth and mortality. To conduct a new project in the rivers that we sampled as part of 'Knowledge Gaps' would be expensive due to the requirement of a mothership platform for access and accommodation. Sampling the Flinders River from Karumba using a small vessel based out of Karumba would be much less expensive. However, conducting the work in a river such as the Fitzroy River at Rockhampton, Queensland, would be much less expensive again due to the proximity of the river.

A second initiative would be to engage with hydrologists to examine annual flow data for tropical rivers to develop definitions of 'high', 'moderate' and 'low' flows for specific rivers with the aim of determining trigger levels of flow, below which water harvesting should cease. Flow data such as these, are available from projects such as FGARA and NAWRA. CSIRO hydrologists have custody of historical flow series and flow projections using various hydrological models.

An interruption to the survey schedule.

In December 2018 using the same survey plan as in 2017, an attempt to resurvey the estuaries of the Mitchell, Gilbert and Flinders Rivers was made. Colleagues from the NESP team at Griffith University provided the majority support for the survey. The team departed Weipa Harbour on the mothership MV Eclipse on December 8th with a favourable weather forecast (winds at 10-15 knots at most). However, overnight a low-pressure system formed in the Gulf of Carpentaria and by early AM on the 9th the forecast was the formation of a cyclone in the central Gulf of Carpentaria with an easterly path. Forecast wind speeds in subsequent days were for 48 knots and 64+ knots (Cyclone Owen). Due to safety considerations, the Master of the MV Eclipse made the decision to abandon the survey and return to Weipa; and offer the team a subsequent allocation of time to conduct a survey. On December 14th the cyclone crossed the western Cape York coast between the Mitchell and Gilbert Rivers.

The survey eventually was conducted in March 2019 during the wet season. Due to commitments for AFMA 2017/0819 (NPF Monitoring survey in the GoC), the project's PI (Rob Kenyon) did not participate in the survey of the estuaries. A colleague substituted. In February 2019 a cyclone and subsequent rain depression formed over the Gulf of Carpentaria. The three rivers flooded with high flows which would have provided a strong emigration cue for juvenile banana prawns in the estuaries. At the time of the survey in March, the rivers remained in flood, though the flood was declining. However, flood heights dominated the tidal cycle and exposed lateral mudbanks within river and tributary habitats where successful beam trawls could be made for juvenile prawns were not common. In most cases, the banks remined inundated. In each river, a subset of 2017 trawl sites were trawled, and 19 beam trawls were made (about one third of the planned set of beam trawls in each river).

The otter trawl was deployed in nearshore habitats off the mouth of the river estuaries. These trawls were successful and visual observation showed that both large juvenile banana prawns and non-commercial prawns were caught. Nearshore from each river, 23 sites were trawled (about equivalent to the planned set of otter trawls adjacent to each estuary).

A fourth survey of the three estuaries was conducted in November 2019. Colleagues from the NESP team at Griffith University provided the majority support for the survey. The survey set out from Weipa and concluded in Karumba and sampled the estuaries of the Mitchell, Gilbert and Flinders rivers trawling a >50% subset of the 2017 template. The 2019 surveys extended the data series for this project, yet at the time of writing of this report, most of the frozen samples from the November 2019 survey had not been sorted.

Extension and Adoption

Presentation to the NPRAG in November 2016 (Brisbane) discussing project progress.

Presentation to the NPRAG in May 2017 (Brisbane) verbal discussion of project progress.

Presentation to the NPRAG on December 5th, 2017 (Brisbane) discussing the completion of the project and the project outcomes, and Industry responses and likely opportunities. The RAG took stock of our recommendations and had an immediate response to CSIRO staff on the day.

The presentation prompted the RAG to further consider research on the impact of reduction in flows due to water resource use and to invite A CSIRO O&A team to submit a project proposal to a February RAG with the view to support 'Models of Intermediate Complexity for Ecosystem assessment' (Eva Plaganyi). The project proposes to continue exploring the impacts of the reduction in river flows on NPF banana prawn catch in general, and seasonal aspects of flow on prawn catch, in particular.

The RAG clearly recognised the need to engage with the WRP process and the need to have 'environmental flow' projections and proposals that will sustain the fishery and withstand the scrutiny of water managers and the proponents of water diversion for irrigation.

Table 1. "Knowledge Gaps" extension opportunities with collaborating projects and stakeholders.

#	Date	Presentation	Medium	Audience	Location
01	31/08/16	Knowledge Gaps	liaison	NAWRA	Chillagoe
02	17/11/16	Knowledge Gaps	PowerPoint	NPRAG	Brisbane
03	23/11/16	Knowledge Gaps	PowerPoint	NAWRA	Canberra
04	15/02/17	Knowledge Gaps	Verbal	NORMAC	Brisbane
05	11/05/17	Knowledge Gaps component	PowerPoint	NPRAG	Brisbane
06	5/12/17	Knowledge Gaps component to Northern Water Development (FRDC 2016-015)	PowerPoint, liaison	NPRAG	Brisbane
07	~15/02/18 (and liaison during 2017)	Knowledge Gaps component to NESP 1.4	PowerPoint	NESP, QLD DNR, QLD DES	Brisbane, delivered by Michele Burford
08	21/02/18	Knowledge Gaps component to Northern Water Development (FRDC 2016-015)	PowerPoint, liaison	NORMAC	Brisbane, delivered by Trevor Hutton

09	29/03/18 (and liaison during 2017)	Knowledge Gaps	PowerPoint	NAWRA	Canberra
10	23/05/2018	Knowledge Gaps in conjunction with Northern Water Development (FRDC 2016-015).	PowerPoint	NPRAG (supporting the MICE model project)	Brisbane, delivered by Trevor Hutton
11	03/08/2018	Knowledge Gaps component to NESP 1.4	PowerPoint	NESP, QLD DAF	Brisbane, delivered jointly with Michele Burford
12	16/08/2018	NPF Monitoring and Knowledge Gaps component	PowerPoint	NPF workshop, Assessment team, AFMA and others	Queensland Biosciences Precinct, Brisbane
13	11/10/2018	Conceptual model of banana prawn life history (including Knowledge Gaps component)	PowerPoint	Australian Society for Fish Biology Conference - attendees.	ASFB Conference, Melbourne, 2018
14	11/11/2018	Links between Gulf Rivers and coastal productivity, project update.	Newsletter, October 2018.	Public and sent to key stakeholders including NPF	NESP, Northern Australia Environmental Resources HUB Newsletter
15	30 January 2019	Knowledge Gaps component to NESP 1.4	PowerPoint	NESP, QLD DAF	NESP workshop, Griffith University
16	2019	Importance of early season low flows to banana prawn life history and hence fishery production.	PowerPoint	NPRAG,	NPRAG
17	May 2020	Final Report	Report	NPRAG	PDF document

Project materials developed

The project report, project newsletters and PowerPoint presentations to NPF Management and NESP collaborators.

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Appendices

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FRDC FINAL REPORT CHECKLIST

Project Title:	Addressing knowledge gaps for studies of the effect of water resource development on the future of the Northern Prawn Fishery
Principal Investigators:	Rob Kenyon, Michele Burford, Annie Jarrett
Project Number:	2016 / 047
Description:	The project used past and current estuarine and offshore banana prawn survey outcomes to contribute to the sampling design of prawn, meiofanua and productivity sampling in the Mitchell, Gilbert and Flinders Rivers during field trips from 2016 to 2018. The meiofauna and productivity sampling was undertaken by Dr. Michael Venarsky and Professor Michele Burford, colleagues (and a co-investigator) from Griffith University as part of NESP 1.4 (Links between Gulf Rivers and Coastal Productivity). The project sampled the Penaeid prawn community of the Mitchell, Gilbert and Flinders River estuaries over two years (2016 and 2017) in the late dry season (November); and sampled the Penaeid prawn community of the Flinders River estuary during the wet season (February) and after the wet season (May) of 2018. These three river estuaries are key habitats for the juvenile phase of banana prawns within the Northern Prawn Fishery (NPF) Management Zone; and subject to highly variable rainfall events that result from the seasonal monsoon watering of tropical Australian catchments. In addition, large juvenile banana prawns encountered in each of the three GOC rivers were analysed for bio-geochemical trace element signatures. Sediment samples also were collected and analysed using the same technique. In conjunction, adult banana prawns found offshore from each of the three GOC rivers were analysed for bio-geochemical trace element signatures to link residents form estuarine habitats to individuals caught in the offshore population, identifying their source estuary.

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Please use this checklist to self-assess your report before submitting to FRDC. Checklist should accompany the report.

	Is it included (Y/N)	Comments
Foreword (optional)	N	
Acknowledgments	Y	
Abbreviations	N	
Executive Summary	Y	
- **What the report is about**	Y	
- **Background – why project was undertaken**	Y	
- **Aims/objectives – what you wanted to achieve at the beginning**	Y	
- **Methodology – outline how you did the project**	Y	

- **Results/key findings – this should outline what you found or key results**	Y	
- **Implications for relevant stakeholders**	Y	
- **Recommendations**	Y	
Introduction	Y	
Objectives	Y	
Methodology	Y	
Results	Y	
Discussion	Y	
Conclusion	Y	
Implications	Y	
Recommendations	Y	
Further development	Y	
Extension and Adoption	Y	
Project coverage	N	Not applicable
Glossary	N	
Project materials developed	Y	
Appendices	N	