Northern Australia Environmental Resources Hub

National Environmental Science Programme

Contribution of three rivers to floodplain and coastal productivity in the Gulf of Carpentaria

Final report (component 1)

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Cover photographs

Front cover: Flinders River estuary (photo: Stephen Faggotter).
Back cover: Gilbert River estuary (photo: Stephen Faggotter).

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Acronyms

CSIRO .... Commonwealth Scientific and Industrial Research Organisation

FGARA.......... Flinders and Gilbert Agricultural Resource Assessment

NAER Hub .... Northern Australia Environmental Resources Hub

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

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

NPF................ Northern Prawn Fishery

QDAF .... Queensland Department of Agriculture and Fisheries

QDES .... Queensland Department of Environment and Science

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Executive summary

Component 1: Effect of flow on fisheries species in Flinders, Gilbert and Mitchell Rivers

The Queensland State Government has identified three river systems, Mitchell, Gilbert and Flinders Rivers in the Gulf of Carpentaria region where water development for irrigated agriculture is already occurring or likely to occur. Information on the water needs of estuarine ecosystems and their associated fisheries is needed to ensure that water development is done in a sustainable way, and economic and social tradeoffs between agriculture, fisheries and the environment are well understood.

Component 1 of the NESP project therefore examined the links between freshwater flow and estuarine/coastal productivity as a mechanism for understanding how changes in flow may impact on estuaries and adjacent coastal environments. A range of approaches were used, including examining the effect of flow on end-of-river nutrient loads and coastal/estuarine primary productivity. The premise is that this productivity is the fundamental underpinning of the resource needs of aquatic species and other environmental assets. Additionally, links between freshwater flow through estuaries, and the cue for fisheries species, i.e. banana prawns, to migrate offshore were determined. Fisheries information was also integrated into a modelling framework to make predictions about how changes in river flow will likely impact on fisheries.

The study involved a series of field trips to the three rivers, capturing both wet and dry seasons. Modelling, remote sensing and GIS approaches were also used to complement these field studies.

Key findings from the research were:

- There were many similarities in the characteristics of the Mitchell, Gilbert and Flinders River estuaries, climatic drivers and water quality. However, the Mitchell River has more consistent flow year-to-year, and a more extended period of flow each year compared with the other two rivers. Conversely, on the other end of the spectrum, the Flinders has the most extreme conditions, with lowest rainfall, highest evaporation and highest year-to-year variability in flow.
- In the wet season, when salinities in the estuaries decreased due to freshwater flows, total nitrogen and phosphorus concentrations only increased in short term spikes, and for much of the wet season do not increase above dry season values. The large volumes of water discharged from the estuaries in the medium to large wet seasons in our study resulted in substantial loads of nutrients into the nearshore area, directly and indirectly driving coastal productivity. There were no consistent differences in the nutrient loads between the estuaries with the scale of the freshwater flow from year-to-year being the major driver.
- There was no consistent difference in water column or benthic algal biomass, or benthic primary productivity rates between the estuaries. Rates and biomasses were comparable with other tropical estuaries. However, in contrast to other tropical estuaries, respiration rates and the organic carbon content of sediments was low suggesting limited organic carbon availability from sources other than primary production on the mudflats. By

inference, mangrove detritus is not a major contributor to mudflat productivity. There is little evidence for major organic carbon inputs from freshwater flows in the wet season.

- We tested experimentally whether the input of nutrients to the mudflats was important for stimulating primary production on the mudflats. Primary productivity rates increased in all three estuaries in response to nutrient inputs in both the dry and wet season. The inference is the estuaries are chronically nutrient limited, and therefore, wet season inputs of nutrients are critical to maintain primary productivity. This has flow-on effects to food availability for animals within the system.
- Juvenile banana prawns (*Penaeus merguiensis*) use Gulf estuaries each year for some months as feeding and refuge areas. This study found that the densities and the total number of juvenile banana prawns in each estuary varied substantially between years, with no statistical differences between estuaries, with the exception of the Gilbert River estuary in November 2017. This suggests that all three estuaries are important to the fishery, with the relative importance varying from year to year.
- The study confirmed previous studies in other Gulf rivers showing that during the wet season most banana prawn juveniles leave the estuaries. Prawns continued to be captured in lower densities in the nearshore area, highlighting that not all prawns are migrating to the offshore fisheries.
- A spatio-temporal Bayesian model was used to quantify the relationship between low, medium and high-level flows, and banana prawn catch in the offshore fishery. This model incorporated novel climatic measures. The effect of loss of flow, due to water extraction or diversion, on the prawn catch was examined. Three water development scenarios were tested. One of the most important findings of this study was the predicted proportional decline in banana prawn catch with decreasing flow-levels due to water extraction. Catch was most impacted by water extraction during low flows, with all three rivers predicted to impact catch. The impact of water extraction was greatest for a scenario with dam construction on the Mitchell River, where during low river years predicted a 53% reduction in catch. Overall, our results imply that maintenance of low-level flows is a crucial requirement for sustained fishery yields.

This study has a number of new and important findings with implications for water planning.

- Firstly, given the importance of nutrient inputs to fuelling primary productivity, maintenance of flow in low and medium flow years is critical if estuarine productivity is to be maintained. Additionally, first flush flows at the start of the wet season are critical to ensure there is sufficient food for fisheries and other species. The first flush is also important to reducing salinity, which is typically hypersaline and highly stressful for the plants and animals living in the estuaries. The Flinders River estuary is likely to be the system most vulnerable to loss of first flush, due to the longer period of no flow each year compared with the Gilbert and Mitchell Rivers.
- In low to medium flow years, reduction of flow from water extraction will keep salinities high, and as a result, prawns will be less likely to emigrate from estuaries into the offshore fisheries. As prawns are a shortlived species and because prawns in estuaries are predated at a rapid rate, prawns that do not move out of estuaries are unlikely to contribute to the next generation. Therefore, fisheries catch will be affected in both the short and long term. The scale of impact in the short term has been quantified via a model of flow and fisheries catch, with significant effects on catch.

- Water extraction in a year following multiple years of little or no flow will have major impacts. The scenario is not unusual, particularly for the Flinders which has the highest interannual variability in flow, and can have multiple consecutive years of no flow. Therefore, species will be highly vulnerable to additional years of no or little flow. It is not clear what impact climate change, and resulting changes of weather patterns will have as there is too much uncertainty in current models for this area of Australia.

1. Introduction

1.1 Background

Sustainable water development in northern Australia requires information on the current ecosystem service benefits of water resources to the environment, and local communities and businesses. This need has been identified by various tiers of Government, natural resource management groups and industry groups. The white paper on developing northern Australia (Commonwealth of Australia, 2015) identified the need for studies on the effect of freshwater flows in supporting natural environments. This information is needed to inform decisions about sustainable water allocations, improving certainty for investors and governments. Three rivers in the Gulf of Carpentaria in northern Australia have been earmarked for water development. They are the Flinders, Gilbert and Mitchell Rivers.

A resource assessment study of the Flinders and Gilbert rivers in the southern Gulf of Carpentaria, commissioned by the Commonwealth Government, identified the need for further information on flow thresholds for river/coastal floodplume connectivity and associated ecosystem effects (Waltham et al, 2013). This includes species of high economic and ecological value associated with the river systems, including wetlands of national significance, important recreational and commercial fisheries, and threatened species. There is concern that these ecological assets may be impacted by intensive land and water resource development.

The Queensland (Qld) Government has also identified the need to understand the dependencies of estuarine and nearshore marine productivity on freshwater flow in the Gulf of Carpentaria (DSITIA, 2014). Additionally, a desktop study of the Flinders and Gilbert Rivers and associated fisheries undertaken by CSIRO (Griffith et al, 2014) identified prawns and barramundi as a high risk from water development. They flagged a knowledge gap on the extent of effects of flow alterations in coastal productivity and species that rely on this. A follow-on CSIRO desktop study of the Mitchell River also identified prawns and barramundi as two species at high risk from changes in flow regimes (Pollino et al, 2018). Additionally, the northern prawn fishery (NPF) identified the need to understand the effect of freshwater flow and flow alterations on fisheries catch and larger ecosystem effects on coastal areas.

At the regional level, an environmental research plan for natural resource management in northern Australia identified the need to determine the water extraction effects on biodiversity, and to determine best practice for minimising impacts on marine and coastal systems (Crowley et al, 2014a). The Northern Gulf Regional Management Group have also identified the need for tools to improve the knowledge base on minimum flow requirements for iconic species, including migratory species, and the need to determine the economic values of ecosystem services (Crowley et al, 2014b).

Future water planning by the Queensland State Government needs information on which rivers are the dominant contributors to ecological and economic assets in the Gulf of Carpentaria (Qld Government regional rankings). There are proposed or potential applications for water development in three rivers in the Gulf of Carpentaria, i.e. Flinders, Gilbert and Mitchell. Therefore, research determining which rivers are most vulnerable to water resource development is needed. This will have implications for setting policy on water allocations.

The current risk assessment framework used by the Qld Department of Environment and Science (QDES) inputs time-step information on the effect of flow alterations in rivers on the response of key flow indicators. Measures of ecological assets can provide indicators within this framework (McGregor et al, 2017). One of the challenges is our low level of understanding of many of these assets. However, long-term research conducted by CSIRO and the Qld Department of Agriculture and Fisheries (QDAF) on two of the species influenced by flow, banana prawns and barramundi, has provided a detailed understanding of their life histories. These species therefore provide ideal flow indicator species for the effect of flow and flow alterations on the aquatic environment.

This study will provide information that will feed into QDES's framework and enable decision makers to identify which river catchments make the biggest contributions to aquatic production, wetland and coastal ecosystems and biodiversity within the Gulf of Carpentaria. It will also improve our ability to predict the consequences of water resource development on these important flow-dependent assets in priority catchments. The proposed research will use a combination of novel and well-established methods, and a multidisciplinary approach to determine the importance of flow for floodplains, estuaries and the coastal zone as habitats and food sources.

In Component 1, the focus was on the effect of flow on end-of-river nutrient loads and coastal primary productivity. This productivity is the fundamental underpinning of the resource needs of aquatic species and other environmental assets. Additionally, links between freshwater flow through estuaries and the cue for animals to migrate offshore will be determined. This will involve using a flow indicator species, the banana prawn, for which the lifecycle is well understood. The main focus will be on rivers earmarked for future development, i.e. Flinders, Gilbert and Mitchell Rivers.

1.2 Objectives

The objectives for Component 1 of NESP Project 1.4 *Links between Gulf rivers and coastal productivity* are outlined below:

1. Determine the hydrological regimes at end-of-river for each river and estimate the annual nutrient loads discharged during the wet season. This provides an estimate of the importance of wet season flow to coastal productivity.
2. Following on from the studies in Objective 1, determine the effect of freshwater flow on coastal primary productivity will be quantified to assess the importance in supporting higher trophic levels, including the flow indicator species and migratory shorebirds in this study.
3. In order to determine which rivers have the major contribution to coastal productivity, a flow indicator species with a well understood life cycle (banana prawns) will be studied. The areal extent of available habitat for juvenile banana prawns (mangroves, intertidal mudflats) and the density of animals will be determined in the Flinders, Gilbert, Mitchell and other major rivers.
4. Novel tracing methods will be tested to trace the origin of the juvenile stage of the flow indicator species, banana prawns caught offshore, trialling trace element and isotopic methods using samples of prawns, sediment and water from estuaries, nearshore and offshore.

5. Develop a prawn population model and examine different scenarios of flow, including climate change related, on prawn fisheries catch.
6. Hold planning, synthesis and integration meetings with other flow-related projects in the NESP NAER Hub

1.3 Characterisation of study sites

The Flinders River starts in the Great Dividing Range, extends westward into gulf savanna country towards Julia Creek then heads north to drain through a delta into the Gulf of Carpentaria (Figure 1). The Gilbert River rises below Conical Hill in the Einasleigh Uplands, draining the eastern slopes of the Gregory Range and the western slopes of the Newcastle Range, north of Hughenden. A third of the catchment is a vast estuarine delta largely consisting of tidal flats and mangrove swamps. The Mitchell River rises on the Atherton Tableland about 50 km northwest of Cairns, and flows about 750 km across Cape York Peninsula from Mareeba to the Gulf of Carpentaria. The Mitchell River has Queensland's largest annual discharge. It has 34 tributaries and is also a vast estuarine delta flowing into the Gulf. All the catchments are dominated by pastoral activities, and more recently an increasing number of agricultural irrigation schemes.

The Mitchell, Gilbert and Flinders Rivers are located in the Australian wet-dry tropics. They are all classified as Class 10 rivers, i.e. unpredictable summer flow which is highly intermittent (Kennard et al, 2010). The catchment areas are 71 670, 46 406 and 109 000 km^2, for Mitchell, Gilbert and Flinders Rivers respectively. The mean annual rainfall is typically highest in the Mitchell River catchment, with headstreams in the wet tropics, followed by the Gilbert then the Flinders (Figure 2). Evaporation showed similar patterns. The Gilbert and Flinders River estuaries are characterised as having simple meandering river channels with some small tidal creeks, fringed with a relatively narrow line of mangroves, behind which are extensive saltflats which are only inundated during the wet season or at the highest astronomical tides. The Mitchell River estuary has many of the same characteristics but is a deltaic fan with multiple estuary mouths.

Modelled end-of-system flows are available for the three rivers from 1984 to 2011 (CSIRO data, Figure 3). Annual flow was typically highest in the Mitchell River estuary compared with the other two rivers. Flinders River estuary had the greatest interannual variability while Mitchell River estuary had the least. The Flinders River estuary also had multiple years of little or no flow, unlike the two other river systems.

Figure 1. Location of the three study rivers in north Queensland.

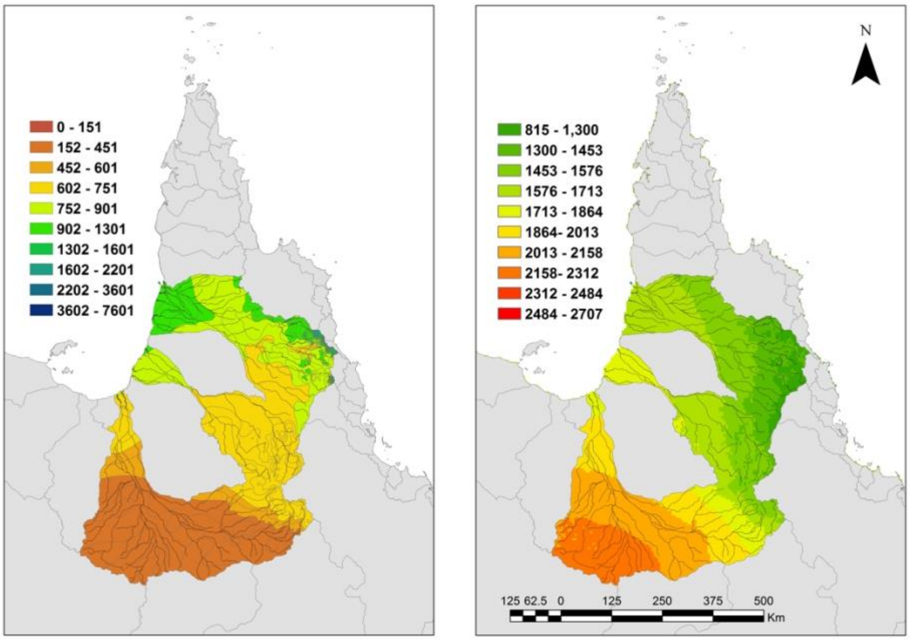

Figure 2. (a) Mean annual rainfall (mm) and (b) evaporation (mm) in the three study catchments, Mitchell, Gilbert and Flinders Rivers (generated by J. Coates-Marnane, Bureau of Meterology data).

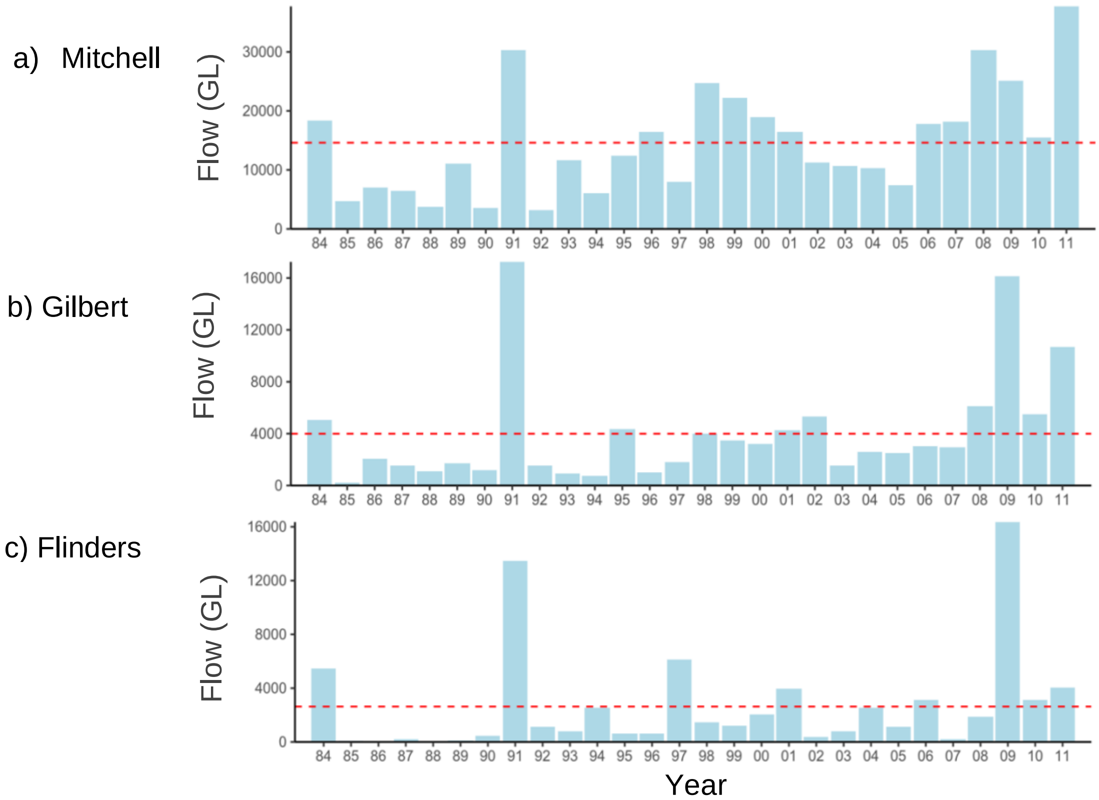

Figure 3. Annual flow (GL) from 1984 to 2011 based on modelled end-of-system flow (generated by A. Broadley, CSIRO data). Red dashed line represents mean annual flow across the years.

2. Methodology

2.1 Objective 1 – End of system nutrient loads

Determine the hydrological regimes at end-of-river for each river and estimate the annual nutrient loads discharged during the wet season. This provides an estimate of the importance of wet season flow to coastal productivity.

Three sources of data were used to determine the annual volumes of water discharged from each estuary during the study period. CSIRO generated end-of-system modelled flow, based on models developed in the FGARA (Bayliss et al, 2014), and NAWRA reports (Petheram et al, 2018). Note that only the NAWRA data is available for the end-of-system flow for the Mitchell River. The difference between the FGARA and NAWRA (called the AWRA-L model) model outputs is that the NAWRA model builds on the FGARA model with some bias correction applied to more closely match gauge data.

Additionally, gauging station data was used to generate hydrographs for the three river systems (DNRM). Data from the gauging station lowest in the catchments were used, i.e. Dunbar (139 km from Mitchell River mouth), Burke Development Rd (102 km from Gilbert River mouth) and Walkers Bend (103 km from Flinders River mouth) (water-monitoring.information.qld.gov.au) (Figure 4). It should be acknowledged that all these gauging stations are 100-140 km upstream from the river mouths. Hydrographs for the three data sources, i.e. gauging station and modelled, are compared in Appendix 1.

Total nitrogen and total phosphorus data were collected during field trips in consecutive wet seasons and used to calculate loads for each wet season (Table 1). Most trips were done from a boat (Eclipse D, RV CSIRO One) while others in the wet season were done by lowering bottles from a helicopter. Only surface nutrient data was available, and methods for sampling and processing are outlined under Objective 2. More sampling trips were conducted in the Flinders River estuary than the other two estuaries as it was more accessible by boat in the wet season.

In order to calculate total nutrient loads, in tonnes, exported from each estuary in each wet season, the nutrient concentrations measured as outlined above, were multiplied by the volume of flow for each wet season, based on the gauging station as well as the end-of-system flow data.

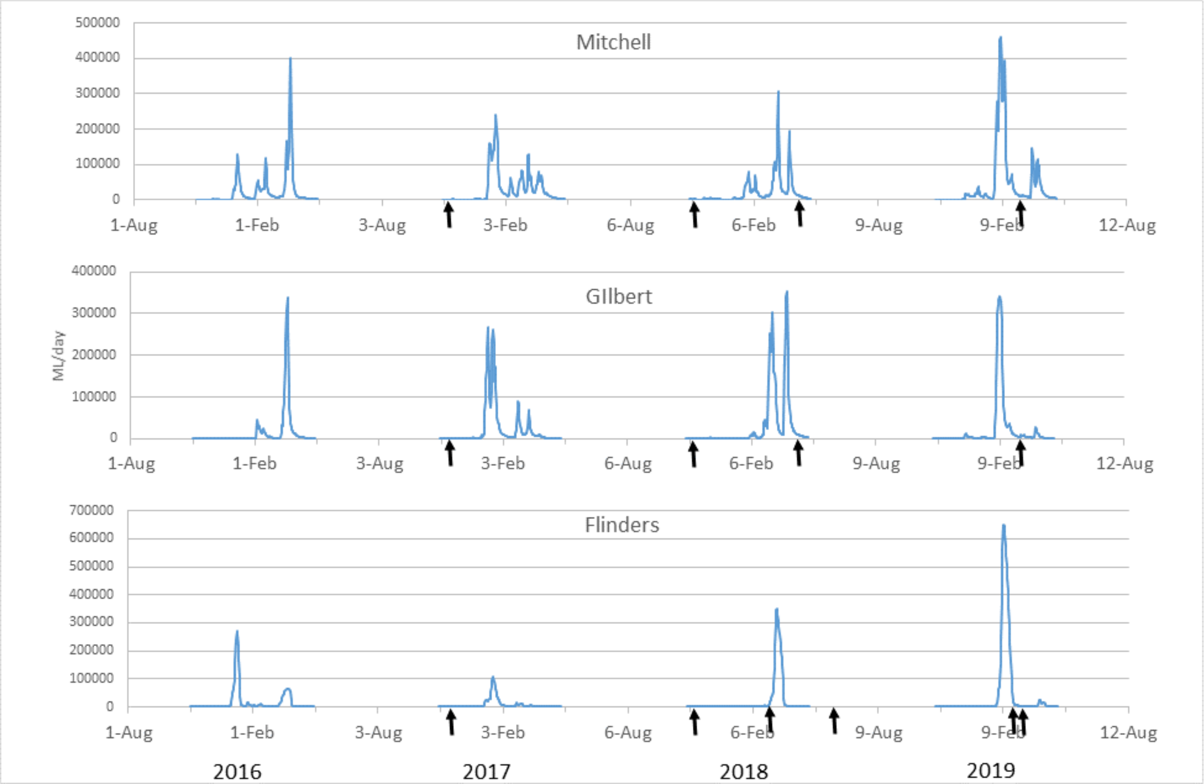

Figure 4. Hydrograph (ML day-1) in three rivers over the period of the study, based on DNRM gauging station data at Dunbar (139.4 km from Mitchell River mouth), Burke Development Rd (102.5 km from Gilbert River mouth) and Walkers Bend (103 km from Flinders River mouth). Arrows show sampling times.

Table 1. Number of cease-to-flow days each year of the study based on the downstream gauging station in each river.

Year	Mitchell (days)	Gilbert (days)	Flinders (days)
2016	0	93	162
2017	0	38	190
2018	0	77	224
2019	14	118	205

2.2 Objective 2 – Estuarine primary productivity

Following on from the studies in Objective 1, determine the effect of freshwater flow on coastal primary productivity will be quantified to assess the importance in supporting higher trophic levels, including the flow indicator species and migratory shorebirds in this study.

In order to determine the links between freshwater flow and primary productivity in estuaries and the nearshore area, a series of field trips were conducted to compare productivity and the drivers in the dry season (base conditions) and wet season. At the commencement of the study, the intention was to focus on fisheries and migratory shorebird species. However, subsequently, Project 3.6 (*Links between Gulf rivers and food for migratory shorebirds*) commenced with a focus on shorebirds and their food supply. Therefore, details of sampling for this component will be addressed in the report for Project 3.6.

Seven field trips were conducted to the estuaries of the three rivers on the catamaran, MV Eclipse D or monohull, RV CSIRO One (Table 2, Figure 5). The first two trips were conducted in the dry season (November 2016 and 2017, December 2019), and one in the wet season (March 2019). Additional trips were conducted in the Flinders River in May 2018 and early March 2019 (water column sampling only). In the case of the MV Eclipse D, small boats were deployed from a mother boat for sampling in the estuary. Some helicopter sampling was also conducted at the height of the wet season (April 2018 for Gilbert and Mitchell, and February 2019 for Flinders), but only surface water samples could be collected.

Table 2. Summary of sampling trips to the Mitchell, Gilbert and Flinders River estuaries and parameters measured.

Date	Vessel	Estuary	Coastal	Water column chlorophyll	Nutrients	Sediment chlorophyll	Sediment primary productivity	Physicochemical measures
7–13 Nov 2016 (dry season)	MV Eclipse D	Mitchell, Gilbert, Flinders		Yes	Yes	Yes	Yes	Yes
7–15 Nov 2017 (dry season)	MV Eclipse D	Mitchell, Gilbert, Flinders		Yes	Yes	Yes	Yes	Yes
28 Feb 2018 (wet season)	RV CSIRO One	Flinders	Floodplume	Yes	Yes	No	No	Yes
13 Apr 2018 (wet season)	Helicopter	Mitchell, Gilbert	Floodplume	Yes	Yes	No	No	Yes
23 May 2018 (transition season)	RV CSIRO One	Flinders	Post-floodplume	Yes	Yes	Yes	Yes	Yes
23 Feb 2019 (wet season)	Helicopter	Flinders	Floodplume	Yes	Yes	No	No	Yes
8 Mar 2019 (wet season)	MV Eclipse D	Mitchell, Gilbert, Flinders	Floodplume	Yes	Yes	Yes	Yes	Yes

2.2.1 Physicochemical and water column sampling

There were three routine sampling sites within each estuary on representative intertidal mudflats (WQ1-3; see Appendix 2). These sites were sampled in November 2016 and 2017, May 2018 and March 2019. Measurements of physico-chemical parameters were done in the overlying water of the intertidal mudflats typically on the lowering tide. A calibrated logger (Hydrolab) was used to measure temperature, salinity, pH, dissolved oxygen (DO), and turbidity. Photosynthetically active radiation (PAR) profiles were also done through the water column using a 4 pi sensor and Licor logger. All readings were done during the morning.

Water samples were also taken from the surface for nutrients and chlorophyll *a* samples. For nutrients, triplicates of surface water were also collected in separate buckets, then subsampled for total nitrogen and phosphorus. Subsamples were also filtered through 0.45 µm membrane filters for ammonium, nitrate, and phosphate analyses. A subset of filtrate was also used to measure total dissolved nitrogen and phosphorus. All nutrient samples were frozen until analysed. For chlorophyll *a* concentrations, known volumes of water was filtered onto GF/F glass fibre filters, then the filters were kept on ice until frozen at -80°C in the laboratory.

Sampling was also conducted during the wet season by helicopter (Table 2, Figure 5). It was not possible to sample at the same three sites in the estuary, however, an estuarine sample was taken mid-river as well as a transect of sampling along the floodplume in the nearshore environment. Replicated samples were processed for nutrient and chlorophyll using the methods outlined above.

In order to confirm the contribution of freshwater flow to nutrient concentrations in the estuaries in the wet season, sampling was done every 2 h, over a 24 h cycle in March 2019 on the Eclipse D moored in each estuary. Samples were taken with a bucket for surface water, and using a van Dorn for bottom samples (1 m from the bottom). Processing followed protocols outlined above. Physico-chemical parameters were also measured with a datalogger (Hydrolab) at the same time.

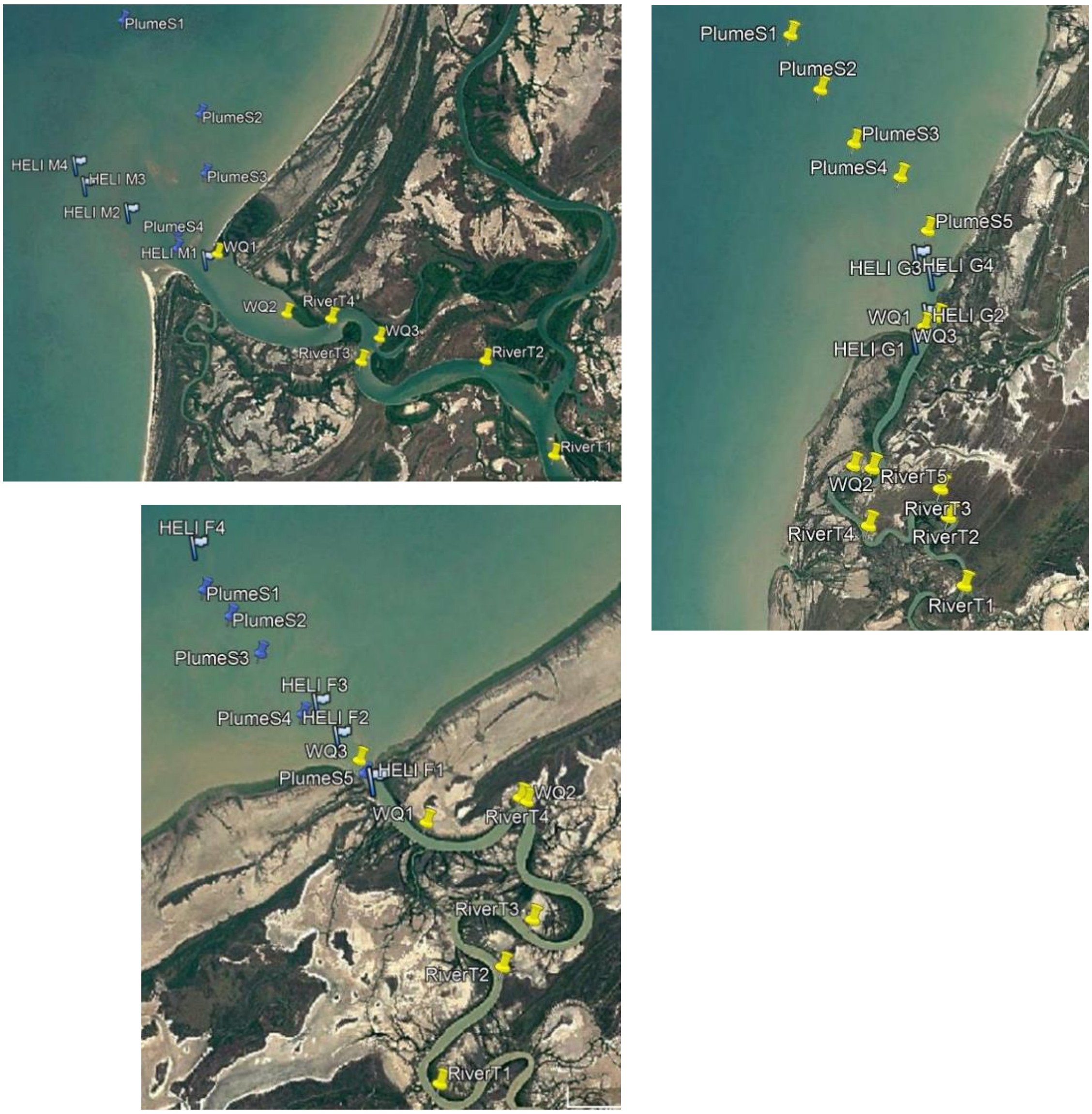

Figure 5. Google Earth maps showing water quality sampling sites in each estuary and associated floodplume sampling. Top left: Mitchell; top right: Gilbert; bottom left: Flinders. Heli = helicopter transect sampling, Plume = floodplume transect sampling from boat, WQ = routine water quality sampling sites associated with sediment sampling sites, River T = estuary transect sites.

Nutrients were analysed using standard colorimetric approaches (APHA 2012). Filters for chlorophyll *a* analyses were sonicated in 90% acetone to extract the pigments, then the extract was filtered to remove glass fibres. Absorbances of extracts were measured at 750, 665, 664, 647 and 630 nm on a spectrophotometer (Jeffrey and Welshmeyer, 1997). Hydrochloric acid treatment was used to adjust chlorophyll *a* values for phaeopigments.

2.2.2 Sediment parameters

At the same times and sites (see sampling sites in Appendix 2) as for routine water quality sampling (WQ1-3), sediment samples on the intertidal mudflats were also taken for chlorophyll *a,* primary productivity, and total nitrogen, phosphorus, organic carbon and grain size analyses. Early in the day at low tide or close to low tide, three replicate sediment samples were collected. In the case of chlorophyll *a* and nutrient analyses, cores (2 cm deep) were collected using a core tube (2.4 cm dia.) and kept on ice until frozen. In the laboratory, samples were kept at a temperature of -80°C until analysed.

In addition to the sampling of the mudflats, in the second year, samples were also taken on the intertidal sandflats at the mouth of each estuary. Cores were taken for chlorophyll *a* concentrations, using the same sampling protocol as for the mudflats (Appendix 2). The same analysis method was used as for the water column chlorophyll *a* concentrations (Jeffrey and Welshmeyer, 1997), but a known weight of sediment was used as a proportion of the total core. For sediment nutrient analyses, the kjedahl method was used, and for organic carbon, the combustion method (APHA 2012).

For primary productivity measurements on the sediment, cores (4.5 cm dia.) were collected at the same sites as the chlorophyll *a* samples using perspex tubes and bungs. These cores, with overlying water, were then used for incubations to measure oxygen fluxes (see Figure 5). Primary productivity cores were equilibrated open to the air for a few hours prior to the experiment. Cores were completely filled with water so no air remained, and capped so they were completely sealed. Presens® fiber-optic oxygen sensor (FIBOX) and oxygen-sensitive optode patches glued to the inside wall of each core (Presens). were used to measure oxygen concentrations in each core over time (Figure 6, Duggan et al, 2014). Two of the cores were used for dark incubations, and five for light incubations. On the last two trips (March and December 2019), five replicate dark incubations were done, rather than two. Sealed cores were placed in a rank in a bin with flowing seawater to maintain temperature in situ, and kept in full sunlight. Dark incubations were covered with dark plastic to remove the light source. Extra cores with surface water and no sediment were used to determine the contribution of water to oxygen fluxes. The oxygen levels in the overlying water were read periodically in each core over a few hours in the morning until sufficient readings were obtained, i.e. 5-7 readings, to determine a linear change in dissolved oxygen levels. Oxygen production (and consumption in the dark controls) was calculated based on the rate of change of oxygen concentrations, standardised to the area of sediment, and expressed per unit time. Water column primary productivity was accounted for using cores containing only water.

In addition to the incubations outlined above, samples were also taken on the field trips to determine the effect of nutrient additions to the overlying water on oxygen fluxes. This was designed to be a simulation of nutrient delivery from wet season flow. At each site, one dark and four light replicate cores with and without nitrogen and phosphorus addition were used. Ammonium chloride solution, to give a final concentration of 1.8 mg N L^{-1}, was added to overlying water of each core. Sodium dihydrogen phosphate solution, to give a final concentration of 0.25 µmol P L^{-1}, was also added. Open cores with overlying water were kept in tubs with flowing seawater in the full sun for two days. After this, all cores were filled with estuarine water, capped and incubated. Primary productivity measurements were done using the same protocol outlined above for sediment core samples.

On one field trip in November 2017, in the Flinders River estuary, sediment cores were incubated in freshwater for two days, to determine the effect of freshwater on primary productivity, and then the primary productivity was measured using the protocol above.

Figure 6. Incubation and measuring equipment used for measuring primary productivity in mudflat samples. Photos: Michele Burford, Stephen Faggotter.

Statistical comparisons between rivers and sampling occasions for benthic and water column data were done using R software. ANOVA, followed by a post hoc Tukey's HSD pairwise test, was used in the case of parametric data. In the case of non-parametric data, a Kruskal test with post hoc Nemenyi-Test test was done. Treatments in the nutrient addition experiment were compared using a Welsh's test.

For the correlations between water quality parameters, a Spearman test was conducted. Data was tested for normality.

2.3 Objective 3 – Banana prawn densities

In order to determine which rivers have the major contribution to coastal productivity, a flow indicator species with a well understood life cycle (banana prawns) will be studied. The areal extent of available habitat for juvenile banana prawns (mangroves, intertidal mudflats) and the density of animals will be determined in the Flinders, Gilbert, Mitchell and other major rivers.

In order to determine the contribution of each estuary to banana prawns (*Penaeus merguiensis*) available to be caught in the fishery, we undertook four field surveys to catch postlarval and juvenile banana prawns in the Mitchell, Gilbert and Flinders River estuaries. The mother ship was the catamaran, Eclipse D with a small boat used to sample in the estuary and associated tidal creeks. Sampling was conducted in the dry season, November/December of 2016 and 2017, and wet season, i.e. March 2019 (wet season). Typically, 2-3 days were spent in each estuary. Additional sampling was done in February and May 2018, but only in the Flinders River estuary. The monohull boat, RV CSIRO One was used.

During each survey, we deployed a 1 x 0.5 m beam trawl (2 mm mesh body with a 1 mm mesh codend) trawled at recorded distances to sample postlarval and juvenile banana prawns on intertidal mudflats throughout the estuary (see sampling sites in Appendix 2, Figures A2-4 to A2-6). In addition, on a subset of the surveys, we trawled in the nearshore zone adjacent to the river mouth with an otter trawl (28 mm mesh size) for recently emigrated larger juvenile prawns. We sampled a suite of sites in both the main river channel and in estuarine tributaries, as well as sites in the nearshore zone in a water depth of about 2–6 m (Table 3). All trawls were GPS recorded for position and trawl distance. All samples were bagged and frozen until analysed.

Table 3. Number of trawls taken in the Mitchell, Gilbert and Flinders Rivers and the Fishery by the Northern Prawn Fishery (NPF). Nearshore trawls used otter trawls, all others used beam trawls.

	2016	2017	2017 nearshore	2018	2018 nearshore	2019	2019 nearshore
Mitchell River	21	25	nil	nil	–	4	5
Gilbert River	18	22	nil		–	8	5
Flinders River	15	20	5	3 in February 18 in May	7 in February 5 in May	10	7
NPF Monitoring Project	–	5	–	4	–	–	–

All prawn samples were processed in a laboratory at Griffith University. Each sample was defrosted and washed using a 1 mm sieve. Prawns were identified to species level, counted, carapace length, and sexed (for animals >10 mm carapace length (CL)). Once counted, the catch per unit area was calculated using Excel software, by dividing each trawl total catch by the distance trawled.

Mangrove areal extent in each estuary was mapped using Esri World Imagery and ArcMap 10.6 software with a semi-automated approach. The spatial resolution was 0.5m, captured from the WorldView2 satellite, and horizontal accuracy was 10.2 m. Imagery were downloaded over the estuaries of Mitchell, Gilbert and Flinders-Bynoe at the maximum resolution of 1 m pixels. split into Red, Green and Blue bands. Mangrove patches were separated from water using pixel value thresholds of the Red Band. The landward side of mangrove patches was mostly digitised by hand at a map scale of around 1:3000. The capture date was 16/05/2016.

Quantification of the areal extent of mudflats across the three estuaries was calculated using low-tide satellite imagery in Google Earth. The Polygon tool was used to outline the mudflats, and then an area in square metres was calculated. The Path tool was used in very small mangrove lined creeks where the extent and width of mudflats could not be easily defined. This tool gave a length measurement only so an arbitrary width measurement of 2m was given in all cases for the three estuaries to calculate square metres.

2.4 Objective 4 – Tracer methods to determine prawn movement

Novel tracing methods will be tested to trace the origin of the juvenile stage of the flow indicator species, banana prawns caught offshore, trialling trace element and isotopic methods using samples of prawns, sediment and water from estuaries, nearshore and offshore.

Prawn samples (from analyses outlined in Objective 3) were also used to measure trace element signatures in each estuary and compare within-estuary and nearshore signatures. In addition, frozen banana prawn samples were received from the Australian Fisheries Management Authority-funded Northern Prawn Fishery Monitoring Project (January 2017 & February 2018). These were caught in the fishery waters of the southern Gulf of Carpentaria for the purpose of comparing trace element signals between the fishery in the Gulf and the three rivers in this project.

After counting and measuring the carapace length, prawns were peeled and the digestive tract was removed from the tail. Prawns were then freeze dried (Viritis 2KBTXL-75) for four days. At least 1g of dried sample was required for geochemical analyses. For some samples, multiple prawns had to be combined to make up 1g. Once dried, samples were submitted to QDES for geochemical analyses i.e. major and trace elements (Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) for 10 major element concentrations (Na, Mg, Al, Si, P, K, Ca, Ti, Mn and Fe) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) for 31 trace element concentrations (S, Sc, V, Cr, Co, Ni, Cu, Zn, As, Rb, Sr, Y, Zr, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Pb, Th and U). Prawn samples were also submitted for stable isotope analyses (^{13}C-carbon and ^{15}N-nitrogen) at the Griffith University Stable Isotope Laboratory.

Trace element and stable isotope data was analysed using linear discriminant analysis to determine if there were differences in the signatures of estuaries, and habitats, i.e. estuary, nearshore and fishery. R software was used.

2.5 Objective 5 – Modelling prawn fisheries and flow

Develop a prawn population model and examine different scenarios of flow, including climate change related, on prawn fisheries catch.

See accepted paper (Appendix 3).

Andrew Broadley, Ben Stewart-Koster, Christopher J. Brown, Rob A. Kenyon, Michele A. Burford. Predicted impacts of reduced river flows on the catch of a commercial marine fishery. *Ecosphere*.

3. Results and discussion

3.1 Objective 1 – End of system nutrient loads

Wet season total nitrogen and phosphorus loads were calculated for each end-of-river system based on wet season nutrient sampling from either a boat or helicopter, combined with using either upstream gauging station data or modelled end-of-system flow data (Bayliss et al, 2014; Petheram et al, 2018). The CSIRO FGARA modelled flow data has also been included for completeness, although it is acknowledged that the NAWRA model is an enhancement of the FGARA model (see section 2.1). There were differences between the models vs. gauging station with the NAWRA model have significantly higher volumes than the gauging station data (Table 4). This is expected as the lower Mitchell River, below the gauging station has a major floodplain likely to contribute substantially to end of system flows as water flows off these areas. In the case of the Gilbert River, values from the NAWRA model were a little higher than the gauging station, whereas for the Flinders River, values were somewhat lower. The nutrient data was limited temporally across each wet season. Acknowledging these caveats, the tonnes of total nitrogen and phosphorus discharged from each river in the wet season have been calculated.

Total nutrient loads varied considerably between rivers and years (Table 4). However, no one river was consistently higher in terms of nutrient loads, although the unprecedented flood in the Flinders, when sampling was conducted on the peak of the flood (February 2019) had the highest overall. However, by March 2019, calculated wet season loads, at least for total phosphorus, were much lower.

A comparison was made with calculated end-of-system flows for an adjacent Gulf river, the Norman River (Burford et al, 2012). In this previous study, nutrient data was available fortnightly, and the gauging station was only 80 km from the river mouth. The wet season in 2009 resulted in a calculated total of 4300 t N and 800 t P exported from the estuary, while in 2010, 2500 t N and 400 t P were exported. These values are similar to values for our rivers, with the exception of the higher total nitogen loads in 2009 in the Norman River estuary.

Another study in the adjacent river, the Norman River, also showed that supratidal mudflats, which are extensive across the southern Gulf, also provided a significant source of nutrients during large flood years (Burford et al, 2016).

*Table 4. Total wet season loads of total nitrogen (TN) and total phosphorus (TP, tonnes) each wet season in the three rivers based on wet season nutrient sampling and both gauging station data (DNRM) and end-of-system (EOS) modelled flow (NAWRA and FGARA). Water years are from July to June to capture entire wet season flows which are typically from December–April. *Loads were calculated using both nutrient concentrations in February and March 2019 data.*

Estuary	Water year	Gauge station annual flow (GL)	Annual modelled EOS flow (GL) NAWRA	Annual modelled EOS flow (GL) FGARA	Wet season TN (mg L^{-1})	Wet season TP (mg L^{-1})	TN loads (t) using gauge data	TN loads (t) using NAWRA model	TP loads (t) using gauge data	TP loads (t) using NAWRA model
Mitchell	2015–16	4,638	11,572	n/a	nd	nd	-	-	-	-
	2016–17	5,307	11,499	n/a	nd	nd	-	-	-	-
	2017–18	4,015	9,306	n/a	0.29	0.01	1144	2652	45	105
	2018–19	8,057	n/a	n/a	0.35	0.12	2833	-	967	-
Gilbert	2015–16	2,165	3,169	7,717	nd	nd	-	-	-	-
	2016–17	4,640	3,469	7,740	nd	nd	-	-	-	-
	2017–18	5,653	5,664	7,807	0.36	0.02	2035	2039	92	92
	2018–19	3,949	n/a	3,997	0.26	0.02	1017	-	87	-
Flinders	2015–16	2,989	2,926	1,814	nd	nd	-	-	-	-
	2016–17	1,335	634	1,545	0.6	0.22	797	378	294	139
	2017–18	3,768	3,542	2,537	0.46	0.05	1739	1635	182	171
	2018–19	7,564	n/a	13,278	0.48 (Feb)	0.38 (Feb)	3605	-	2849	-
					0.47 (Mar)	0.12 (Mar)	3583*	-	870*	-

3.2 Objective 2 – Estuarine primary productivity

3.2.1 Water quality

In the dry season, the estuaries were hypersaline, with the exception of the Mitchell River estuary in year 2 (November 2017) (Table 5). Flinders River typically had the highest salinity water, and Mitchell River the lowest. In the wet season, salinities in the rivers were statistically lower than the dry season, but the scale of reduction was related to the timing of sampling, i.e. sampling was not always on the peak of the flow (Table 5, Figure 7, Figure 8). In the transition period between the wet and dry seasons in May 2018 (data only available for Flinders River estuary), the salinity was close to seawater (29.55).

There were many similarities between the three estuary systems in terms of temperature, dissolved oxygen concentrations, pH and turbidity, based on sampling at three sites within each estuary (Table 5). The Flinders River estuary typically had higher turbidity values which were also highly variable between the sites and sampling occasions; therefore it was not statistically higher. There were also no consistent statistical differences between the wet and dry seasons for these parameters within each estuary (statistical outputs not shown). The combination of tidal and wind mixing in these systems makes turbidity highly variable.

Temperature varied considerably depending on the time of year, despite the tropical climate. For example, in May 2018, the water temperature was 18.23°C in the Flinders, compared with summer temperatures of 29–33°C.

*Table 5. Physico-chemical data from sampling at Sites WQ1-3 in each estuary. Sampling was conducted in the mornings. *The exception was helicopter sampling on April 2018 and Feb 2019 where a transect was done. Only helicopter data from within the estuary is shown in the table. Statistical analyses were only done on Sites 1–3, not the helicopter transects. The analyses include F values, statistical significance, a, b and c to show statistical differences, and *, ** and *** to show significant level.*

Date	Estuary	Temperature (°C)	Salinity	pH	DO (mg L^{-1})	Turbidity (NTU)
		NS	(F 10.72, $P < 0.05$)	NS	NS	NS
Nov-16 (dry)	Flinders	33.12 (0.21)	**40.39 (0.13)[b]**	8.02 (0.08)	6.45 (2.02)	349.4 (271.3)
	Gilbert	33.38 (0.90)	**40.23 (0.24)[b]**	7.96 (0.05)	6.05 (0.54)	95.7 (24.8)
	Mitchell	31.65 (0.84)	37.15 (1.65)[a*]	7.83 (0.15)	6.23 (1.54)	36.1 (12.2)
		(F 9.78, $P < 0.05$)	(F 55.62, $P < 0.001$)	NS	NS	
Nov-17 (dry)	Flinders	29.05 (0.15)[b]	**39.21 (0.05)[b]**	8.18 (0.02)	5.52 (0.02)	No data
	Gilbert	29.96 (0.58)[a,b]	**37.29 (0.49)[b]**	7.97 (0.13)	4.66 (0.91)	No data
	Mitchell	**30.97 (0.70)[a*]**	31.12 (1.64)[a***]	8.02 (0.06)	6.06 (0.75)	No data
Feb-18 (wet)	Flinders	31.74 (0.46)	5.29 (0.98)	7.91 (0.14)	5.30 (0.39)	231.0 (71.0)
April-18* (wet)	Gilbert	31.9	2.3	8.4	7.7	39.5
	Mitchell	29.8	8.8	8.6	7.10	13.5
May-18 (transition)	Flinders	18.23 (0.80)	29.55 (1.42)	9.35 (0.08)	7.96 (0.26)	261.4 (245.0)
Feb-19* (wet)	Flinders	30.5	0.1	7.4	7.7	110
		NS	(F 34.72, $P < 0.001$)	(F 55.42, $P < 0.001$)	NS	NS
Mar-19 (wet)	Flinders	29.74 (0.72)	**12.17 (0.76)[a**]**	**8.79 (0.06)[b]**	7.63 (0.31)	291.0 (213.2)
	Gilbert	31.13 (0.56)	4.53 (1.28)[b]	**8.72 (0.04)[b]**	7.20 (0.46)	40.2 (30.3)
	Mitchell	30.71 (1.16)	5.93 (1.44)[b]	8.34 (0.07)[a***]	7.03 (0.59)	42.6 (35.3)

Salinities were also measured in a transect out from the estuaries in the wet and dry seasons. In the wet season, salinities typically remained at seawater or close to seawater salinities in the nearshore environment, despite the scale of the wet season (Figure 7, Figure 8). The exception was in February 2019 in the Flinders system, which had an unprecedented volume of flow, with salinities in the floodplume close to zero (Figure 7).

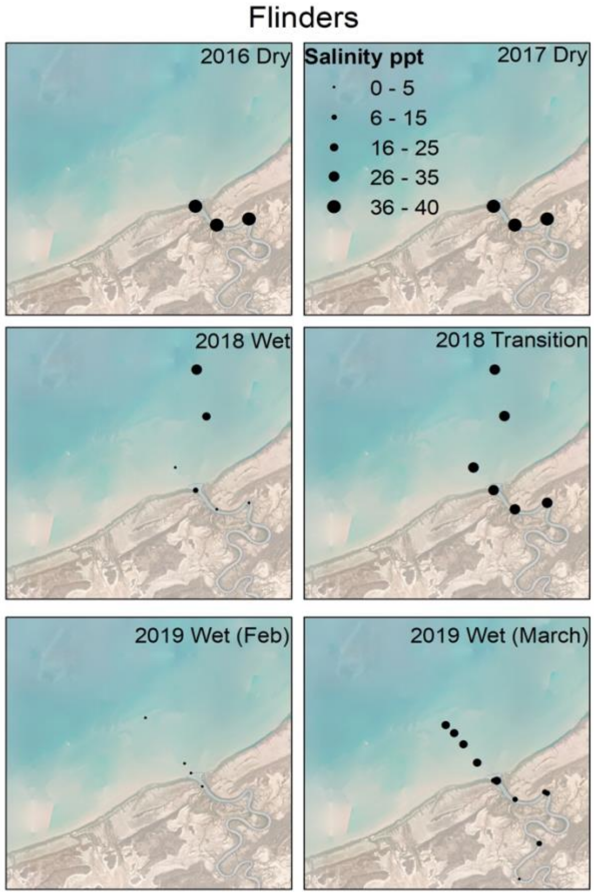

Figure 7. Salinity transects in Flinders River estuary and nearshore area.

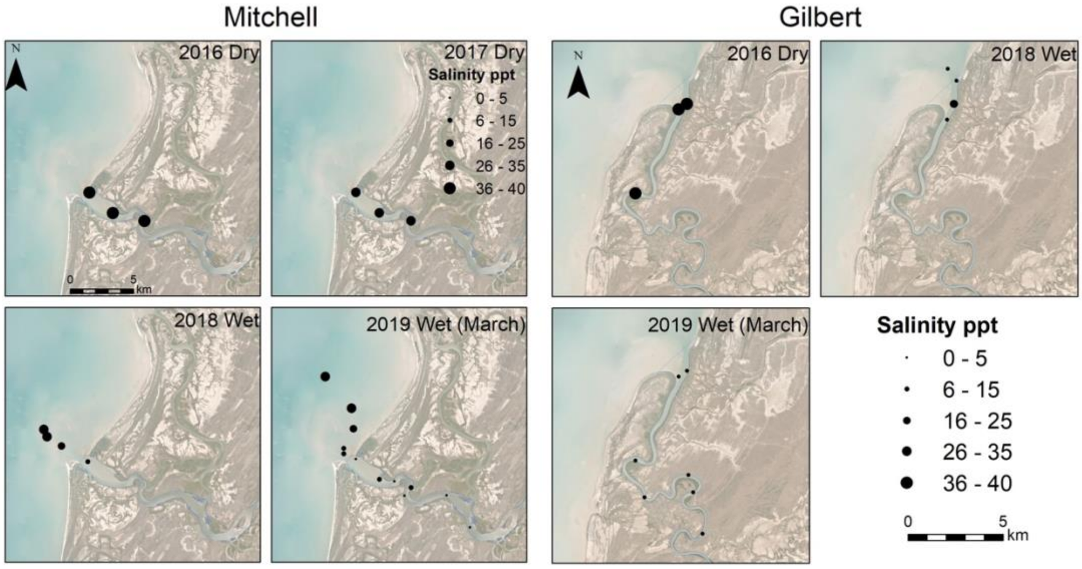

Figure 8. Salinity in the Mitchell and Gilbert River estuaries and nearshore zone.

Figure 9. Photos of Flinders River estuary and nearshore area showing scale of unprecedented flood in Febuary 2019. Photos: Michele Burford.

Total nitrogen and phosphorus concentrations were statistically higher in the Flinders River estuary than the other two estuaries in the dry season (Table 6). On one sampling trip in the dry season (November 2016), nitrate/nitrite was also higher, while in November 2017, ammonium concentrations were higher in the Flinders River estuary than the other two estuaries. Concentrations of total nitrogen, total phosphorus, ammonium and nitrate/nitrite were also statistically higher in the Mitchell River estuary in the wet season compared with the dry seasons. In contrast, for the Flinders and Gilbert River estuaries, there was no statistical increase in total nitrogen and phosphorus, or dissolved nutrients, in the wet season compared with the dry season. This is consistent with a study in the adjacent Norman River estuary which found that nutrient concentrations did not increase over the wet season, based on fortnightly sampling (Burford et al. 2012).

Although freshwater flow typically did not have higher nutrient levels, there was one sampling trip done at the height of the flood (February 2019, unprecedented flood scale, Figure 9) in the Flinders River estuary when total phosphorus, phosphate and nitrate concentrations were much higher than at other times (Table 6). However, this data could not be compared statistically with the other sampling occasions, as there were differences in the location of the sampling sites. A previous study in the Flinders catchment has shown relatively high concentrations in phosphorus in the soils (Faggotter et al, 2013), with channel and gully erosion of subsurface soils being the predominant source of sediment transported to estuaries (Caitcheon et al, 2012).

Transect sampling was undertaken out to the nearshore area from the three rivers in the wet season, both by boat (March 2019) and helicopter (March 2018 – Mitchell and Gilbert, February 2019 – Flinders) In March 2019, total nitrogen and total phosphorus were higher in the estuary compared to the nearshore environment in the Mitchell and Gilbert (Figure 10). In February 2019, total phosphorus was high in the Flinders nearshore (Figure 11).

*Table 6. Statistical comparison of nutrient and chlorophyll a concentrations from sites WQ1-3 in each estuary for each sampling occasion. *The exception was helicopter sampling on April 2018 and Feb 2019 where a transect was done, and hence it was not included in the statistical analyses. Statistical analyses included F values, statistical significance, a, b and c to show statistical differences between rivers on each sampling occasion, and *, ** and *** to show significant level.*

Date	River	Total nitrogen (mg L^{-1})	Total phosphorus (mg L^{-1})	Ammonium (mg L^{-1})	Nitrate/nitrite (mg L^{-1})	Phosphate (mg L^{-1})	Chlorophyll *a* (µg L^{-1})
Nov-16 (dry)		(*F* 19.99, *P*<0.01)	(*F* 19.37, *P*<0.01)	NS	(*F* 13.25, *P*<0.01)	NS	NS
	Flinders	**0.457 (0.085)**^{a**}	**0.033 (0.010)**^{a**}	0.022 (0.018)	**0.043 (0.013)**^{a*}	0.017 (0.002)	4.5 (1.9)
	Gilbert	0.237 (0.038)^{b}	0.008 (0.000)^{b}	0.019 (0.012)	0.014 (0.011)^{b}	0.012 (0.001)	3.7 (0.8)
	Mitchell	0.193 (0.020)^{b}	0.006 (0.001)^{b}	0.013 (0.007)	0.003 (0.002)^{b}	0.009 (0.006)	3.9 (1.2)
Nov-17 (dry)		(*F* 21.65, *P*<0.001)	(*F* 7.90, *P*<0.05)	(*F* 7.94, *P*<0.05)			
	Flinders	**0.897 (0.173)**^{a*}	**0.052 (0.008)**^{a*}	**0.057 (0.028)**^{b}	0.030 (0.006)	0.016 (0.001)	**9.7 (1.9)**^{a*}
	Gilbert	0.482 (0.129)^{b}	0.031 (0.024)^{a,b}	**0.049 (0.003)**^{b}	0.026 (0.016)	0.024 (0.019)	4.5 (2.8)^{b}
	Mitchell	0.227 (0.031)^{b}	0.005 (0.000)^{b}	0.006 (0.006)^{a*}	0.009 (0.001)	<0.002 (0.000)	5.1 (1.0)^{a,b}
Feb-18 (wet)	Flinders	0.462 (0.010)	0.048 (0.013)	0.069 (0.004)	0.033 (0.001)	0.020 (0.001)	3.7 (1.2)
April-18* (wet)	Gilbert	0.357 (0.050)	0.017 (0.005)	0.013 (0.013)	0.007 (0.003)	0.004 (0.005)	8.8 (0.2)
	Mitchell	0.287 (0.042)	0.008 (0.006)	0.013 (0.014)	0.004 (0.004)	0.002 (0.003)	2.7 (0.3)
May-18 (transition)	Flinders	0.322 (0.113)	0.018 (0.015)	0.004 (0.005)	0.021 (0.021)	0.007 (0.007)	4.2 (1.7)
Feb-19* (wet)	Flinders	0.477 (0.051)	0.377 (0.022)	0.022 (0.009)	0.102 (0.009)	0.063 (0.004)	2.8 (1.7)
Mar-19 (wet)		(*F* 15.23, *P*<0.01)	(*F* 4.08, *P*<0.08)	NS	(*F* 10.89, *P*<0.05)	(*F* 49.81, *P*<0.001)	(*F* 51.67, *P*<0.001)
	Flinders	0.285 (0.044)^{b}	0.115 (0.072)	0.018 (0.010)	**0.021 (0.005)**^{a*}	0.005 (0.002)^{b}	**18.4 (3.0)**^{a***}
	Gilbert	0.222 (0.058)^{b}	0.022 (0.008)	0.027 (0.009)	0.011 (0.004)^{b}	**0.012 (0.002)**^{a*}	3.5 (0.3)^{b}
	Mitchell	**0.515 (0.093)**^{a*}	0.120 (0.038)	0.042 (0.010)	0.010 (0.001)^{b}	0.001 (0.000)^{c}	4.3 (1.8)^{b}

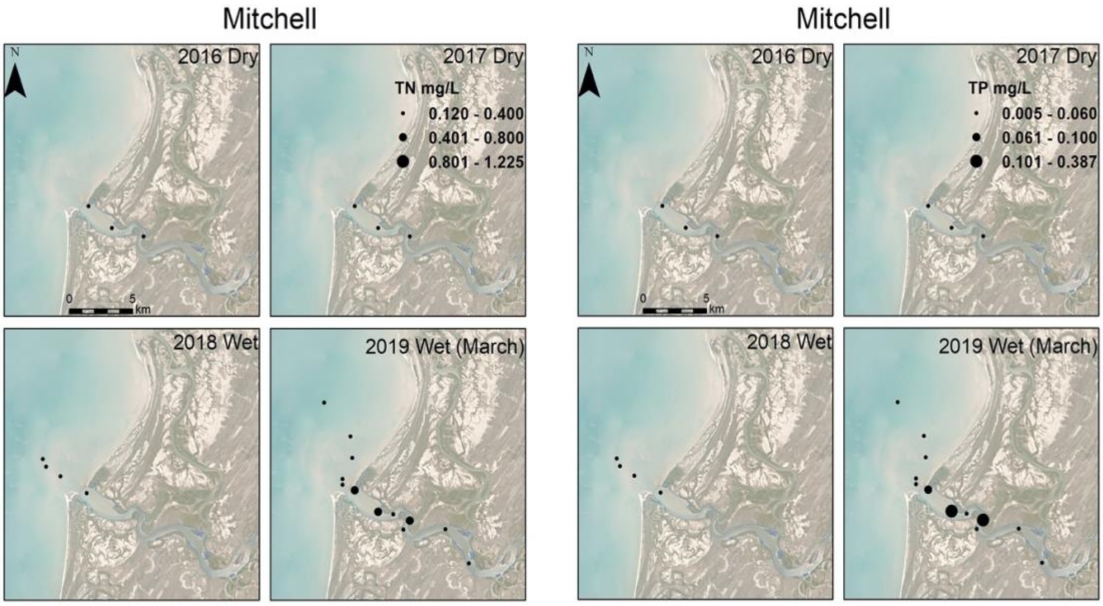

Figure 10. Total nitrogen and phosphorus floodplume sampling in two wet seasons and comparison with estuarine concentrations in the Mitchell River estuary.

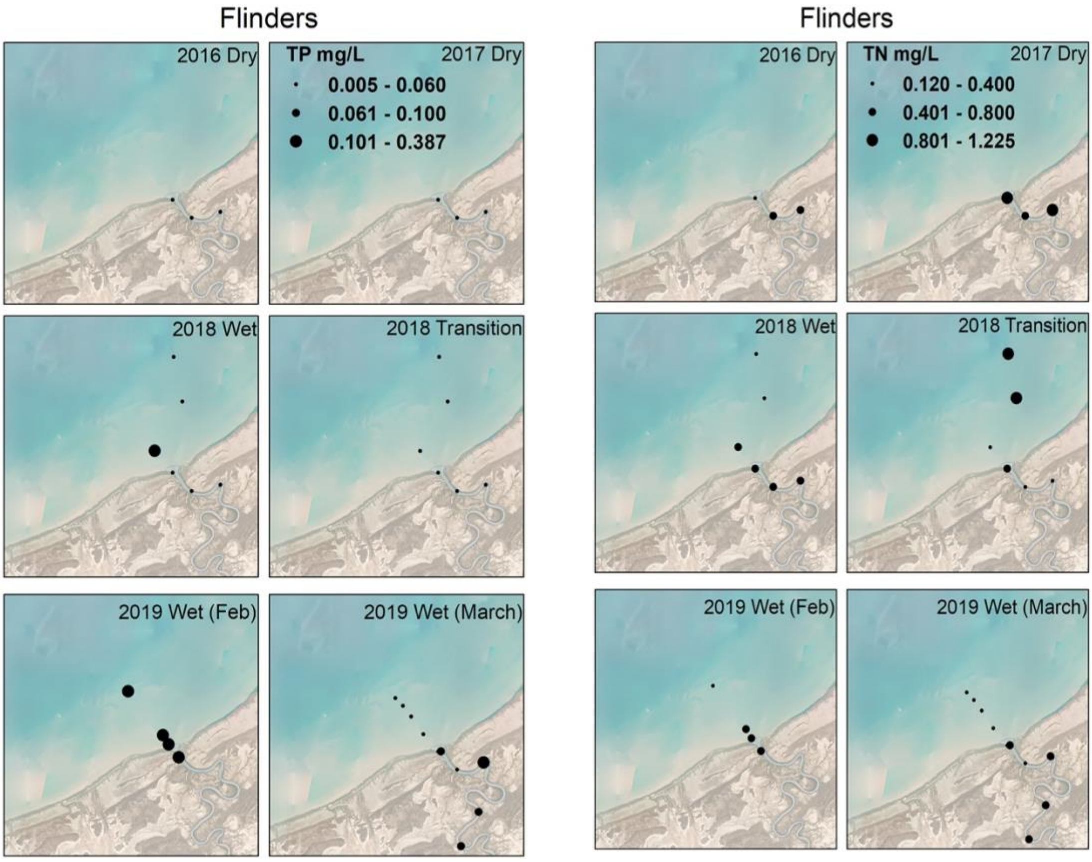

Figure 11. Map of total phosphorus and nitrogen concentrations in the Flinders estuary and nearshore.

Dissolved inorganic nitrogen (ammonium, nitrate/nitrite) was a relatively small proportion of the total nitrogen in the three rivers, while dissolved organic nitrogen overall comprised 64 ± 17%.

Chlorophyll *a* concentrations in the water column at the WQ1-3 sampling sites were typically comparable between estuaries and sampling occasions (Table 6). The exception was the Flinders River estuary in both November 2017 and March 2019, when concentrations were statistically higher.

Transect sampling for chlorophyll *a* concentrations was undertaken out to the nearshore area from the three rivers in the wet season, both by boat (March 2019) and helicopter (March 2018 – Mitchell and Gilbert, February 2019 – Flinders). Chlorophyll *a* concentrations were highly variable in the transects and concentrations often comparable with the estuaries (Figure 12).

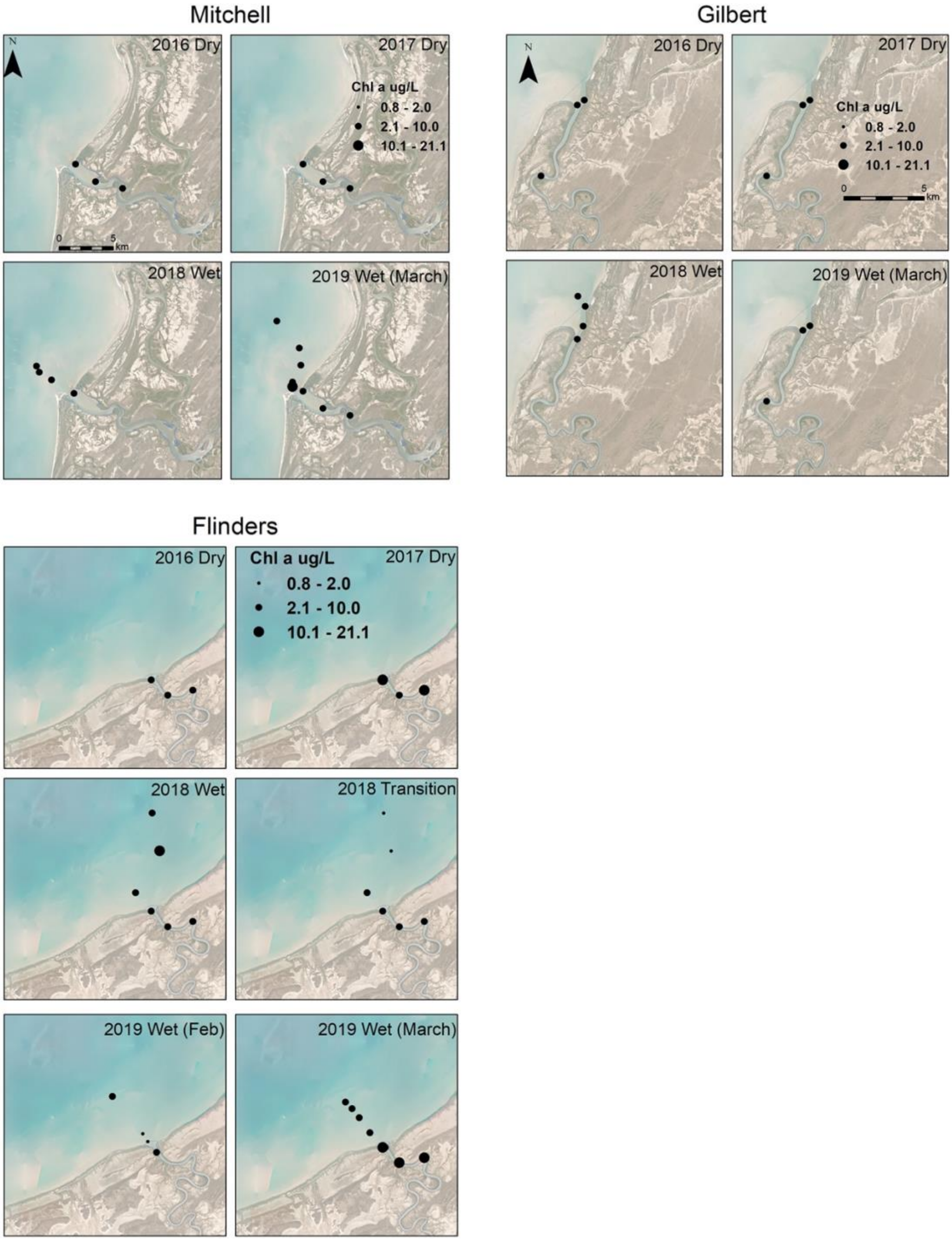

Figure 12. Transect of water column chlorophyll a concentrations in the Mitchell, Gilbert and Flinders River estuaries on each sampling occasion.

Dissolved nutrients typically decreased in a transect out from the estuaries (Appendix 4). The exception was elevated total phosphorus, nitrate and phosphate concentrations in the Flinders River nearshore area in the March 2019 wet season.

Correlations between nutrients were examined and most parameters were not highly correlated. However, total nitrogen and phosphorus were highly correlated with each other, but the slope and strength of the correlation varied between the Mitchell River estuary and the other two estuaries (Figure 13a). Total phosphorus was highly correlated with phosphate, and total nitrogen with both ammonium and nitrate. Slopes of the correlations between total phosphorus and dissolved inorganic nitrogen (ammonium, nitrate/nitrite) also varied between the Mitchell River estuary and the other two estuaries.

In order to understand the interaction between tidal and freshwater flow influences on the nitrogen and phosphorus concentrations in the estuaries, sampling was done every 2 h over 24 h in March 2019. Most parameters were not highly correlated despite the wide range of salinities throughout the tidal cycle. The exception was the Flinders River estuary where total nitrogen, ammonium and nitrate were highly negatively correlated with salinity (Figure 14). This suggests that the source of nutrients was the lower salinity water flowing downstream from the Flinders catchment. Therefore, this points to an important source of nutrients from the catchment contributing to nutrients in the estuary.

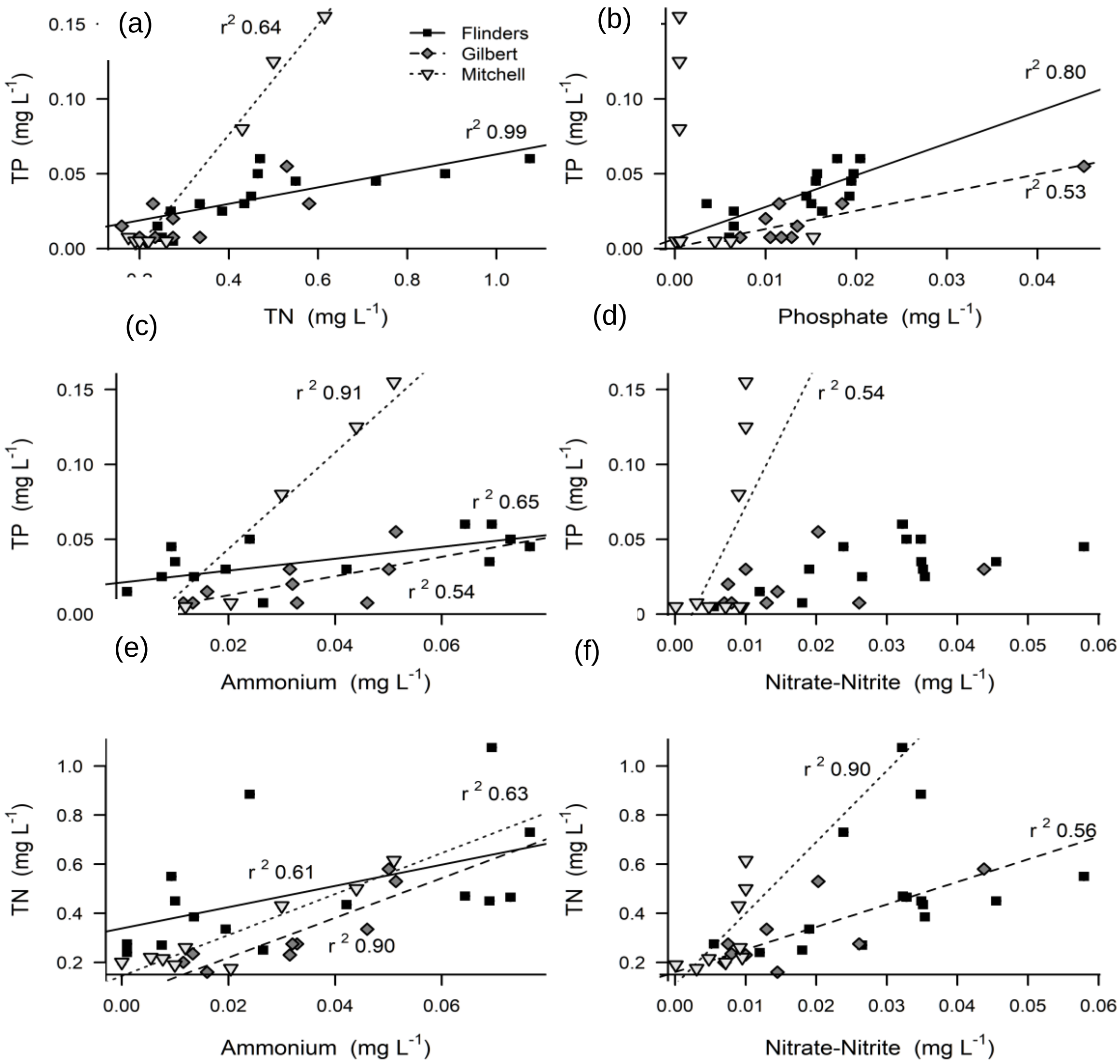

Figure 13. Correlations between water quality parameters for all sampling occasions in the three estuaries. R2 values are only provided for significantly correlated parameters, i.e. P < 0.05.

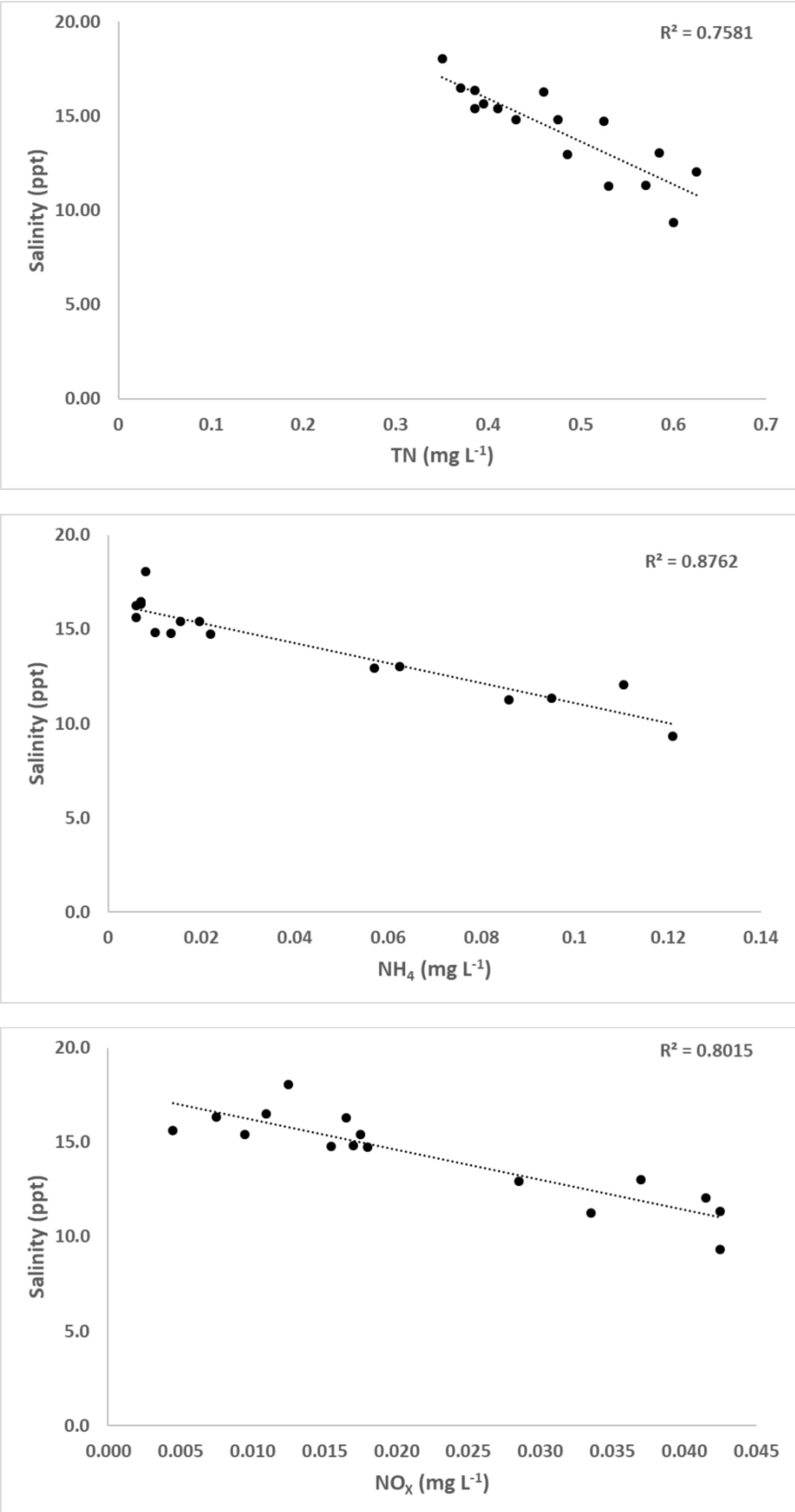

Figure 14. Correlation between salinity and nutrient parameters in Flinders River estuary during 24 h sampling across the tidal cycle in March 2019 trip.

The mean nutrient concentrations in the wet season in the Gulf estuaries were compared with other studies of estuaries in the wet-dry tropics of northern Australia (Table 7). Typically, mean nutrients and chlorophyll *a* concentrations were comparable between studies. The exception was higher phosphate concentrations in the Flinders River estuary compared with other studies.

Table 7. Comparison of water quality in estuaries of Australian wet-dry tropical estuaries during wet season sampling. For this study, only data from routine estuarine sampling sites is included. nd = no data.

	Normanby River estuary, Cape York	Norman River estuary, Gulf of Carpentaria	Ord river estuary, WA	Mitchell River estuary	Gilbert River estuary	Flinders River estuary
Reference	Howley et al, (2018)	Burford et al, (2012)	Burford et al, (2011)	This study	This study	This study
Parameter	Three wet seasons	Two wet seasons	One wet season	One wet season	One wet season	Two wet seasons
TN (mg L^{-1})	0.524 (0.119)	0.520 (0.190)	nd	0.267 (0.031)	0.214 (0.007)	0.351 (0.109)
TP (mg L^{-1})	0.177 (0.130)	0.086 (0.053)	nd	0.015 (0.007)	0.007 (0.002)	0.175 (0.158)
Ammonium (mg L^{-1})	0.034 (0.018)	0.020 (0.022)	0.025	0.020 (0.018)	0.009 (0.007)	0.015 (0.09)
Nitrate (mg L^{-1})	0.045 (0.103)	0.043 (0.040)	0.210	0.014 (0.008)	0.008 (0.003)	0.035 (0.043)
Phosphate (mg L^{-1})	0.010 (0.013)	0.005 (0.004)	0.022	0.001 (0.001)	0.001 (0.001)	0.035 (0.027)
Chlorophyll *a* (µg L^{-1})	nd	4.1	1.5	5.8 (3.0)	1.6 (0.6)	4.2 (2.4)

3.2.2 Benthic algal biomass, production/respiration and sediment nutrients

At the intertidal mudflat sites, overall there were no statistical differences in benthic chlorophyll *a* concentrations between the estuaries. Values were also statistically comparable between the dry seasons in 2016 and 2017, with no differences between the estuaries. Concentrations were typically lower in the transition period in 2018 (Flinders data only) and wet season in 2019 compared with the dry season (Figure 15 and Figure 16). The sandflats (Figure 15) at the mouth of the estuaries were also sampled and concentations were higher on the sandflats than the mudflats in the Mitchell and Flinders but the reverse was true in the Gilbert (Table 8). Overall, the Gilbert and Mitchell River mudflat and sandflats were statistically different (Table 9).

Chlorophyll *a* concentrations on the intertidal mudflats in November 2016 and 2017 were comparable with comparable mudflats in tropical Darwin Harbour, i.e. 28.0 to 53.2 mg m^{-2} (Burford et al, 2008). However, concentrations in the wet season were lower than in Darwin Harbour. Concentrations were also comparable with the Norman River mudflats (river nearby to Flinders River) with comparable mean concentrations of 32.5 mg m^{-2} in the late dry (Duggan et al, 2014).

Figure 15. Photos showing examples of intertidal mudflats (left) and sandflats (right) at the mouth an estuary. Photos: Stephen Faggotter.

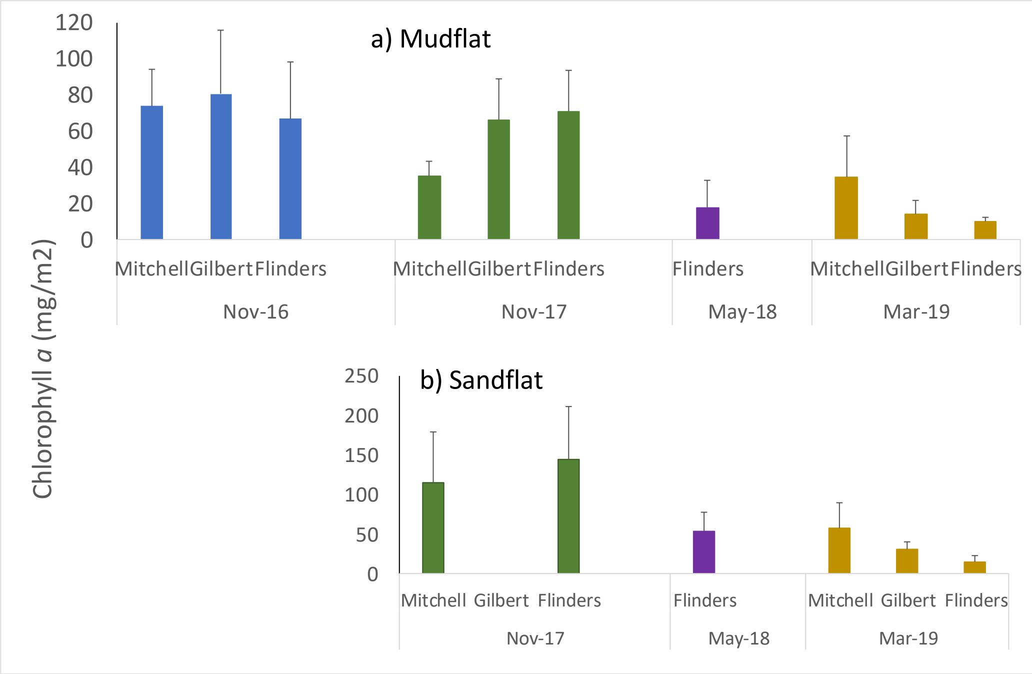

Figure 16. Sediment chlorophyll a concentrations (mg m^{-2}) in (a) mudflat and (b) sandflat habitats in the three estuaries on each sampling occasion. nd = no data. a, b and c denote differences between rivers in each sampling occasion, and bold notations mean differences between sampling occasions for each river.

Benthic primary productivity rates, measured as oxygen fluxes, were comparable between the Gilbert and Flinders estuaries, and higher than the Mitchell estuary (Table 9). There was little difference between the wet and dry seasons (Figure 17). Primary productivity rates in the Norman River estuary were also comparable with the first sampling occasion (dry 2016) of our study, i.e. 160 mg O_2 m^{-2} h^{-1} (Duggan et al, 2014).

Respiration rates on the mudflats were higher in the Flinders compared with the Gilbert and Mitchell systems (Table 9). Rates were typically only a tenth of primary productivity rates in our study (Figure 18). In contrast, on Darwin Harbour mudflats, respiration rates (-102.2 mg O_2 m^{-2} h^{-1}) were higher with primary productivity rates (42.8 mg O_2 m^{-2} h^{-1}) and ten times higher than respiration rates measured in the Mitchell, Gilbert and Flinders River estuaries in our study (Burford et al, 2008).

Sediment nutrients were also measured in each estuary in November 2017, and in the Flinders River estuary in May 2018 (Table 10). There was considerable variability within estuaries. The organic carbon: nitrogen ratios were low in all three estuaries pre-wet season compared with wet season. Grain size distribution in sediments was also measured at these times and data is presented in Appendix 5. Grain size distribution was consistent between the estuaries, and mudflat sites had much smaller grain size particles than sandflat sites.

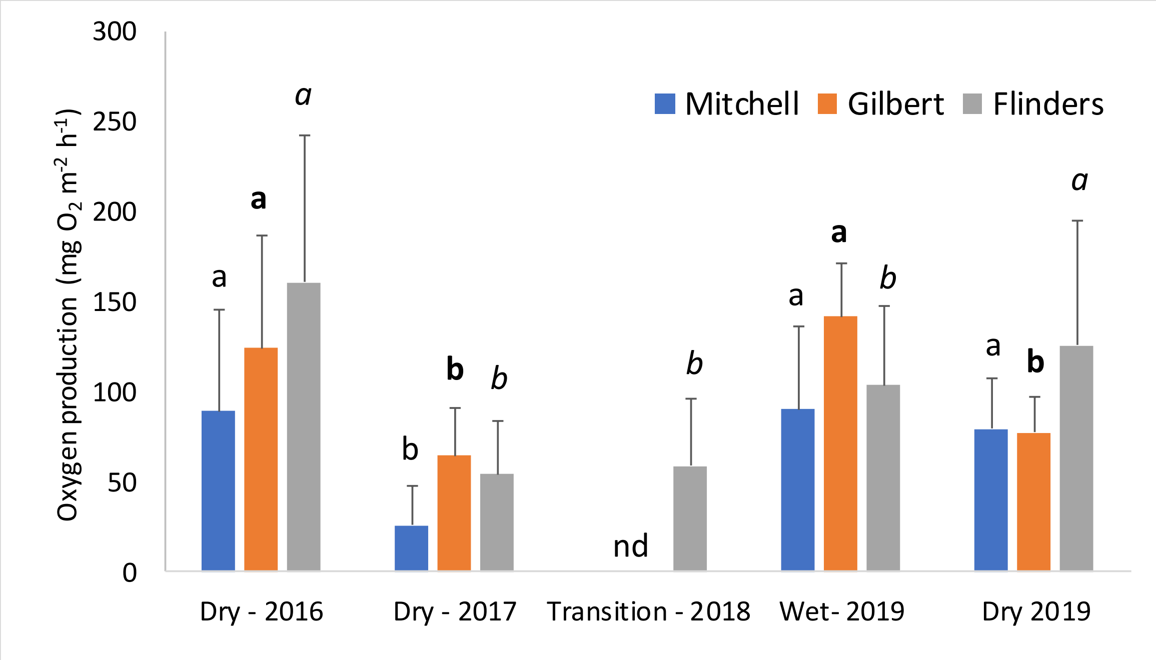

Figure 17. Primary productivity (measured as oxygen production, mg O_2 m^{-2} h^{-1}) on mudflats in the three estuaries. a, b and c denote differences between rivers in each sampling occasion, and bold notations mean differences between sampling occasions for each river.

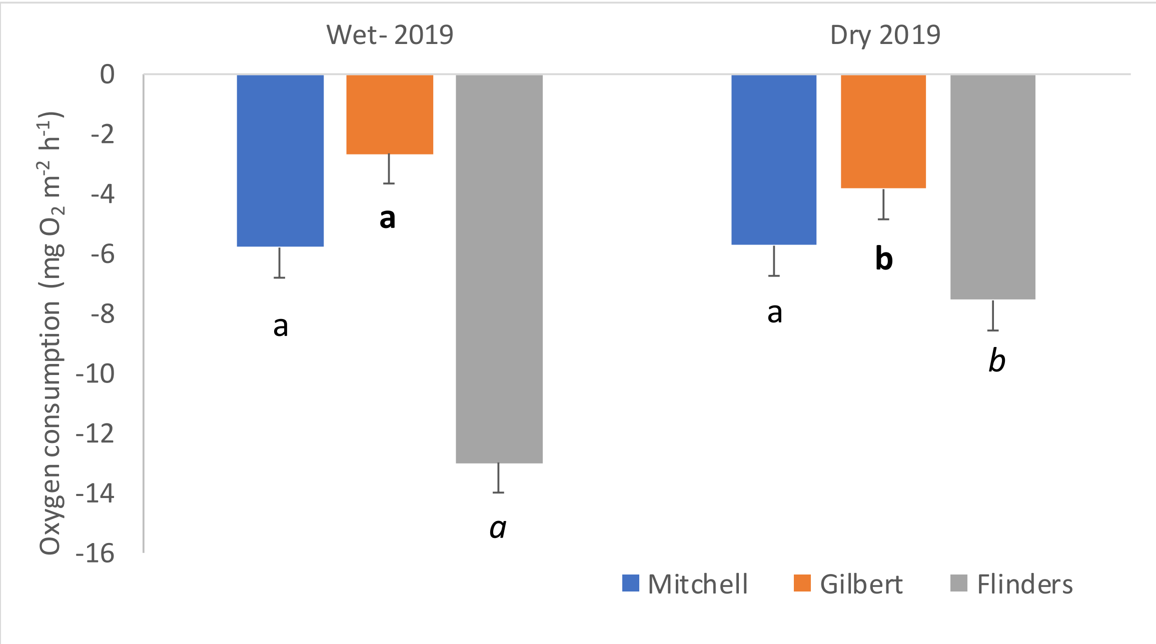

Figure 18. Respiration (measured as oxygen consumption, mg O_2 m^{-2} h^{-1}) on mudflats in the three estuaries. a, b and c denote differences between rivers in each sampling occasion, and bold notations mean differences between sampling occasions for each river.

Table 8. Comparison of chlorophyll a concentrations (mg m^{-2}) on the mudflats and sandflats in the estuary/nearshore environments of the three rivers. Bold numbers show statistical differences between mud and sand.

Estuary	Habitat	Benthic chl *a* (mg m^{-2})
Flinders (*Welch t* -3.30, *df* = 49.1, *P* < 0.01)	Mud	43.22 (35.13)
	Sand	**85.08 (69.30)****
Gilbert (*Welch t* 4.24, *df* = 32.9, *P* < 0.001)	Mud	**65.80 (40.17)*****
	Sand	30.74 (9.29)
Mitchell ns	Mud	76.88 (79.72)
	Sand	**95.90 (60.82)**

Table 9. Statistical comparisons of algal production and respiration across all mudflat and sandflat sites in the three estuaries.

Estuary	Benthic chl a (mg m^{-2})	Primary productivity (mg O_2 m^{-2} h^{-1})	Respiration (mg O_2 m^{-2} h^{-1})
	ns	(*F* 4.84, *P* < 0.01)	(*F* 8.48, *P* < 0.01)
Flinders	61.8 (56.7)	*93.12 (69.19)* [a]**	*-10.21 (6.40)* [a]**
Gilbert	60.0 (39.0)	94.62 (50.19) [a]	-5.93 (5.83) [b]
Mitchell	84.7 (72.5)	65.48 (48.76) [b]	-6.02 (5.36) [b]

Table 10. Mean (SD) sediment nutrient and organic carbon concentrations (%) at the three sediment sampling sites in each estuary.

Date	Estuary	TN %	TP %	TOC %	Mol C:N	Mol N:P
Nov-17 (dry)	Mitchell	0.059 (0.042)	0.014 (0.006)	0.468 (0.349)	9.3	9.6
	Gilbert	0.080 (0.016)	0.021 (0.001)	0.604 (0.117)	8.8	8.5
	Flinders	0.061 (0.016)	0.023 (0.001)	0.518 (0.098)	9.9	5.9
May-18 (wet)	Flinders	0.059 (0.017)	0.028 (0.003)	0.868 (0.119)	17.3	4.7
	Flinders (nearshore)	0.082 (0.011)	0.028 (0.001)	1.132 (0.149)	16.2	6.4

3.2.3 Effect of nutrient additions on benthic productivity

In order to determine the potential for nutrient additions to stimulate primary productivity on the mudflats in the three estuaries, trials were conducted on multiple trips. An example of the findings is shown in Figure 19 for the Flinders River estuary, comparing with and without nutrient addition at the three sampling sites on the mudflats.

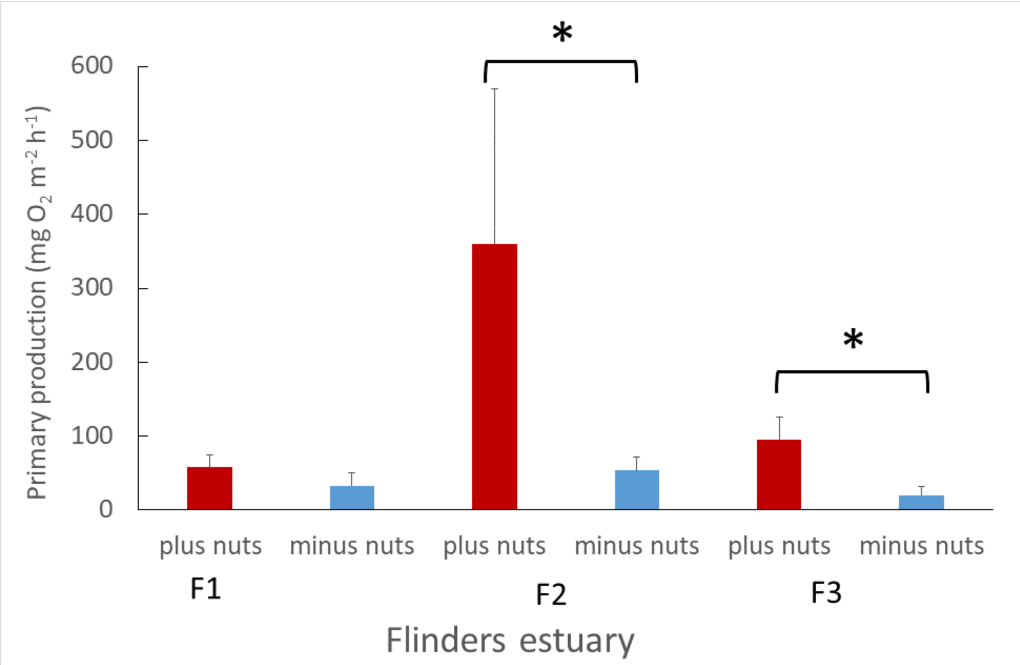

Figure 19. Example of nutrient addition experiment for the mudflat sampling sites in the Flinders River estuary in the transition season, May 2018.

Overall, the study found that the addition of nutrients resulted in statistically higher rates of primary productivity in all three rivers, compared with no addition (Table 11). However, there were differences in responses between individual sites in each estuary, i.e. addition of nutrients did not always stimulate primary production (Figure 20). Interestingly, nutrients stimulated production in both the wet and dry seasons.

A study was also conducted in the Flinders River estuary in November 2017 to test the effect of the addition of freshwater to primary productivity in the cores. Rates were statistically higher in the samples with hypersaline water compared with those which had this replaced with freshwater and incubated for two days prior to measuring primary productivity. This was consistent with a previous study on the mudflats of the Norman River estuary which also showed that a reduction of salinity reduced primary productivity during the wet season (Duggan et al, 2014).

Table 11. Comparison of the effect of nutrients on primary productivity rates (mg O_2 m^{-2} h^{-1}) on the mudflats of the three estuaries across all sampling trips. Bold numbers show statistical differences between treatments within each estuary.

Estuary	Treatment	Primary productivity (mg O_2 m^{-2} h^{-1})
Flinders (*Welch t* -3.22, *df* = 46, *P* < 0.01)	minus nutrients	49.6 (24.2)
	plus nutrients	**110.5 (123.0)*** **
Gilbert (*Welch t* -4.70, *df* = 45, *P* < 0.001)	minus nutrients	59.1 (16.7)
	plus nutrients	**88.8 (30.2)*****
Mitchell (*Welch t* -2.70, *df* = 30, *P* < 0.05)	minus nutrients	61.1 (29.0)
	plus nutrients	**94.5 (47.6)***

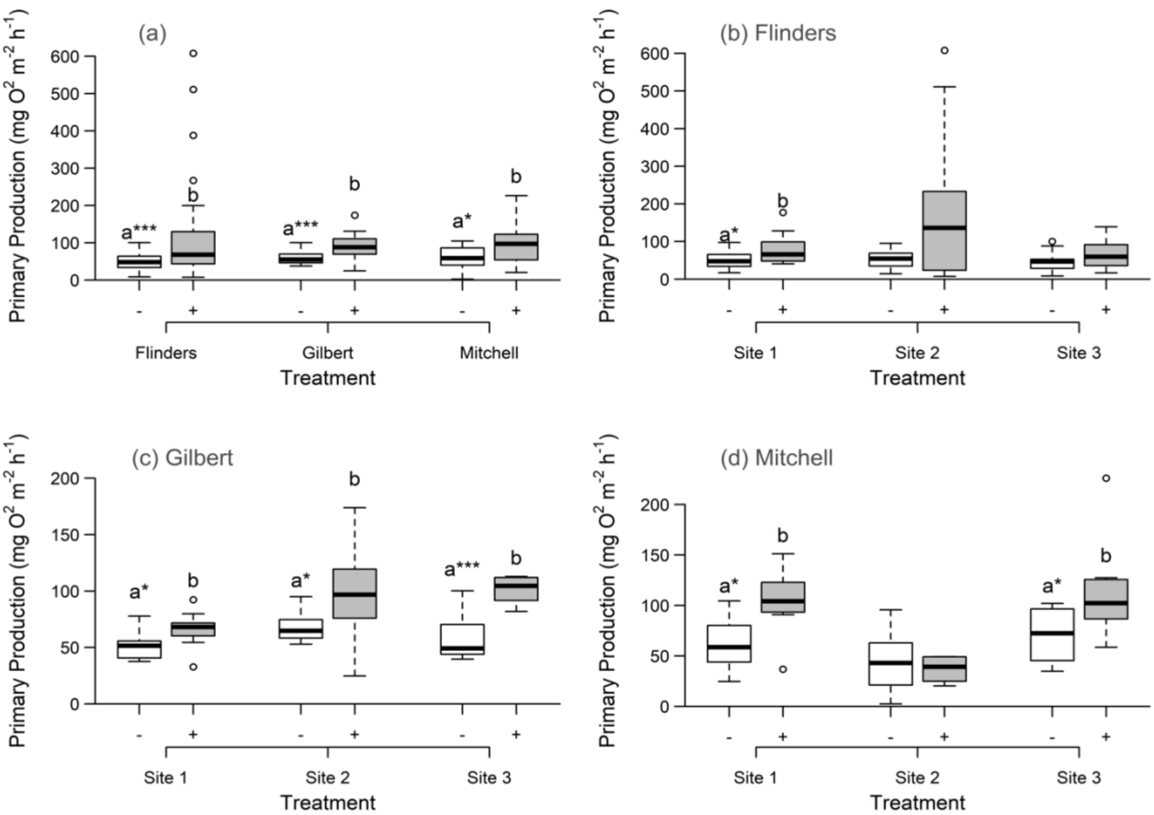

Figure 20. Comparison of the effect of nutrient additions on primary productivity (mg O_2 m^{-2} h^{-1}) at the three sites in the three estuaries, and for the three estuaries with all data combined across multiple trips. - = no nutrient addition, + = nutrient addition. a and b denote statistical differences between treatments.

3.3 Objective 3 – Banana prawn densities

In order to determine which of the three rivers have the major contribution to coastal productivity, a flow indicator species with a well understood life cycle (banana prawns) will be studied. The areal extent of available habitat for juvenile banana prawns (mangroves, intertidal mudflats) and the density of animals will be determined in the Flinders, Gilbert, Mitchell and other major rivers.

3.3.1 Prawn abundances across estuaries

Previous research has shown that the banana prawn postlarvae are recruited into estuaries from offshore spawning twice a year in the Gulf of Carpentaria (Vance and Rothlisberg, in press). This recruitment is via tidal movement of animals into estuaries. The two cohorts are in October/November and February/March. The prevailing theory is that the October/November cohort primarily contributes to the fishery, and much of the February/March cohort is predated within the estuary. The October/November cohort feed and grow in Gulf estuaries for some months until the wet season when the salinity decreases substantially. Previous research has shown that the low salinity depletes the food supply and physiologically stresses the prawns that then move out of the estuaries into the nearshore zone, and ultimately out into deeper waters where they are caught in the fishery (Duggan et al, 2014, Vance and Rothlisberg, in press).

In the current study the aim was to sample prawns in each of the three estuaries to determine the abundance of animals in the late dry season when densities were most likely to be high. Typically, there are two main groups of animals: postlarvae (< 3 mm carapace length (CL)) which have densities that are highly variable in time and space. Previous research has shown that many of these animals are predated and do not reach a juvenile phase (Wang and Haywood, 1999). The second group is comprised of juvenile prawns (> 3 mm CL).

Two trips were conducted to assess prawn densities in the estuaries: November 2016 and November 2017. On the first trip, there was no difference in the abundance of juvenile banana prawns (≥3 mm CL) between the three rivers (range of densities1.34 to 1.85 prawns m^{-2}, Table 12). The size range of juvenile prawns in each estuary was similar (3-12 mm CL for the majority of the juveniles, see Appendix 6). In contrast, in November 2017, the Gilbert River estuary supported a greater density of juvenile banana prawns (4.52 ± 2.03 juvenile prawns m^{-2}) than the other two estuaries (<1 prawn m^{-2}) (Table 12).

Postlarval prawns, i.e. < 3 mm CL, were also quantified with densities being highly variable between estuaries and sampling occasions (Table 13). This variability is expected given previous research in Gulf estuaries (Wang and Haywood 1999).

Densities of prawns were comparable with a study of the Flinders and adjacent Norman Rivers in 1978 (Staples and Vance 1987). A study in the Norman River with fortnightly sampling over the late dry season for two years had somewhat lower densities, i.e. 0.07 – 0.83 animals m^{-2} (Burford et al, 2010). In the November sampling, banana prawns were also sampled in the nearshore zone in the dry season. As expected, the abundance of animals was much lower, i.e. ~0.02 individuals m^{-2}.

Sampling was also conducted in the wet season, i.e. Flinders River estuary in February 2019, and all three estuaries in March 2019. During the wet season in February 2018, the average density of juvenile prawns in the Flinders River estuary was <0.1 prawns m^{-2} (Table 12), with a size range of 1 to 11 mm CL. In the nearshore zone, the prawn density was ~0.03 individuals m^{-2}, much lower than densities found in the river estuary. This is consistent with previous studies showing that lower salinity correlates with prawn emigration due to salinity stress (Staples and Vance 1987). Additional sampling in the transition period between the wet and dry seasons in the Flinders River estuary (May 2018) also found a low average density of juvenile prawns, i.e. <0.05 prawns m^{-2} (Table 12).

Table 12. Juvenile prawn abundance (≥3 mm CL) in the Mitchell, Gilbert and Flinders River estuaries (and closeby nearshore zones) in the Gulf of Carpentaria. n = number of trawls.

Year	Estuary	Juvenile prawn density (m^{-2} ± SE)	n	Nearshore trawls (m^{-2} ± SE)	**n**
November 2016	Mitchell River	1.34 ± 0.48	21	-	-
	Gilbert River	1.85 ± 1.11	18	-	-
	Flinders River	1.71 ± 1.18	15	-	-
November 2017	Mitchell River	0.51± 0.16	22	-	-
	Gilbert River	4.52 ± 2.03	22	-	-
	Flinders River	0.62 ± 0.21	20	83 prawns (0.02 ± 0.01)	8
2018	Flinders River – February	0.08 ± 0.05	3	122 prawns (0.03 ± 0.01)	7
	Flinders River – May	0.04 ± 0.01	18	2 prawns (~0.001)	5
March 2019	Mitchell River	0.20 ± 0.12	4	2 prawns (~0.001)	5
	Gilbert River	0.22 ± 0.20	8	0 prawns	5
	Flinders River	0.21 ± 0.08	10	84 prawns (0.03 ± 0.02)	7

Table 13. Postlarval prawn abundance (< 3 mm CL) in the Mitchell, Gilbert and Flinders River estuaries in the Gulf of Carpentaria. n = number of trawls.

Year	Estuary	Postlarval prawn density (m^{-2} ± SE)	n
November 2016	Mitchell River	0.06 ± 0.58	21
	Gilbert River	0.80 ± 0.61	18
	Flinders River	0.05 ± 0.03	15
November 2017	Mitchell River	0.35 ± 0.18	22
	Gilbert River	2.13 ± 1.59	22
	Flinders River	0.62 ± 0.21	20
2018	Flinders River – February	0.04 ± 0.00	3
	Flinders River – May	0.01 ± 0.01	18
March 2019	Mitchell River	5.75 ± 1.62	4
	Gilbert River	0.02 ± 0.02	8
	Flinders River	1.29 ± 0.62	10

During the wet season sampling in March 2019, the abundances of juvenile banana prawns in each of the estuaries of the Mitchell, Gilbert and Flinders Rivers were relatively low (<0.25 prawns m^{-2}) and not significantly different to each other. Nearshore densities were ~0.001 m^{-2} in the Mitchell, no prawns caught in the Gilbert and ~0.03 m^{-2} in the Flinders area.

3.3.2 Spatial distribution of prawns within estuaries

Overall, in each river estuary, the abundance of juvenile prawns was higher in tributaries than it was in the main river in November 2016 and 2017. Large and small tributaries of both the Michell and Gilbert Rivers supported the highest abundances of juvenile prawns (Figure 21, Figure 22). Within the Flinders River, large tributaries are absent from the estuary, however, the highest abundances of juvenile prawns were found in the small side-creeks off the main river channel (Figure 23).

During November 2016, 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. During November 2017, in each of the Mitchell, Gilbert and Flinders Rivers, the densities of prawns in the tributaries within the estuary was about four times higher than in the main river habitats.

After the wet season, during May 2018 in the Flinders River the abundances of juvenile banana prawns in the tributaries (0.03 ± 0.01 prawns m^{-2}) and main river channel (0.04 ± 0.01 prawns m^{-2}) were similar, supporting the contention that downstream movement from the tributaries to the river would be cued by the floodwater event that occurred during March 2018.

There were less sites sampled in the wet season with a focus on the lower estuary and nearshore environments, given that it was already well known that the drop in salinity in the wet season will move prawns out of the smaller creeks into the lower estuary and nearshore environment (Vance and Rothlisberg, in press). There were localised areas of higher densities in the lower estuaries (e.g. Figure 21), but the overall density of animals was lower than the late dry season sampling (Figure 21, Figure 22, Figure 23).

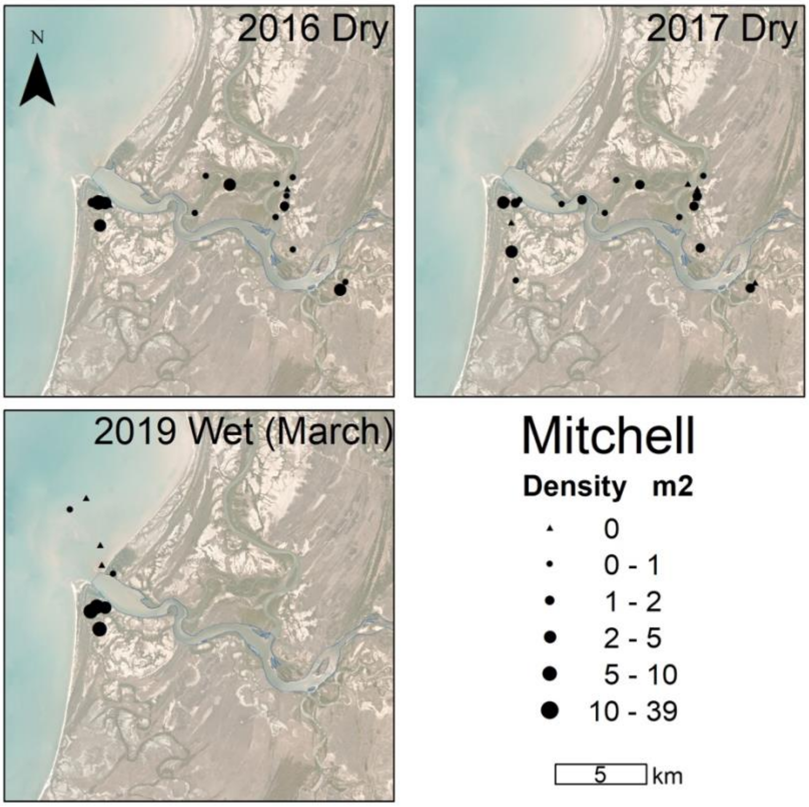

Figure 21. Spatial representation of prawn distribution in the Mitchell River estuary in November 2016 (marine equivalent), November 2017 (brackish conditions) and March 2019 (post floodwater).

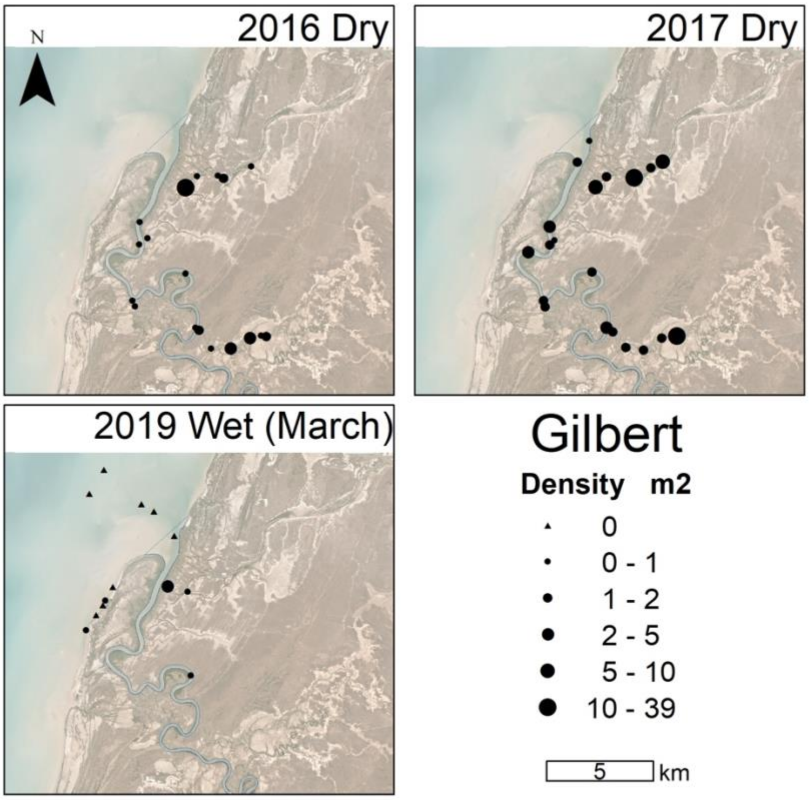

Figure 22. Spatial representation of prawn distribution in the Gilbert River estuary in November 2016 (marine equivalent), November 2017 (brackish conditions) and March 2019 (post floodwater).

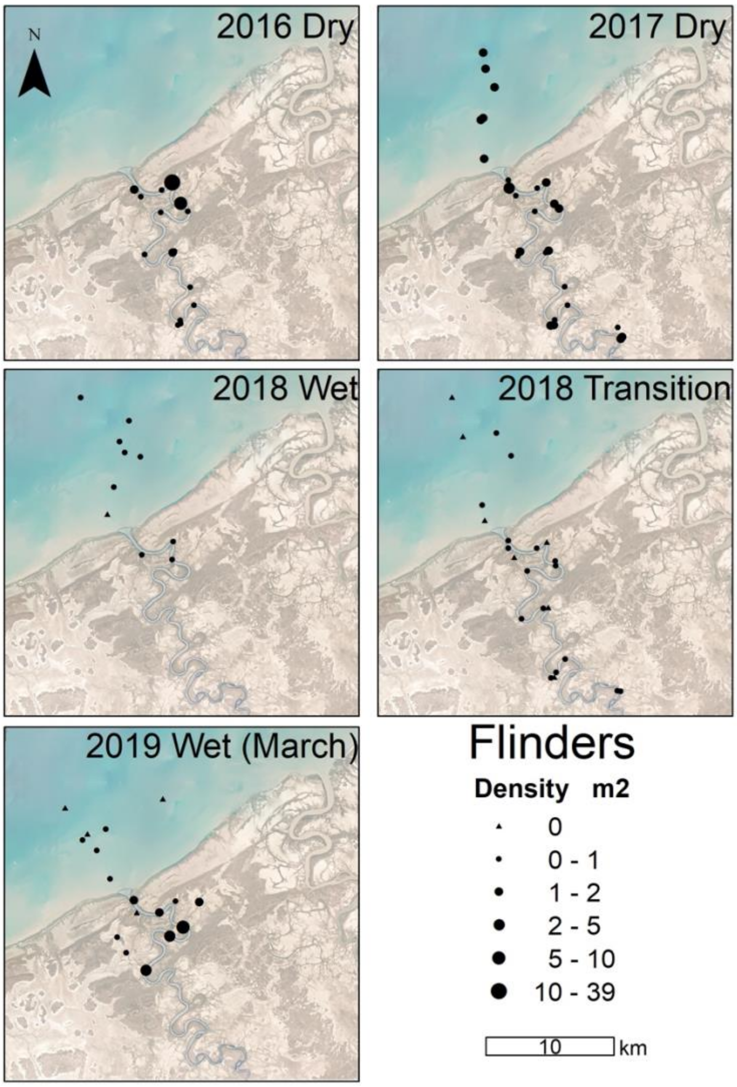

Figure 23. Spatial representation of prawn distribution in the Flinders River estuary in November 2016 (marine equivalent), November 2017 (brackish conditions), February and May 2018 and March 2019 (post floodwater).

3.3.3 Areal extent of habitat

Previous studies have shown that banana prawns use both mangrove and mudflat habitat in estuaries in their juvenile phase for feeding, and, in the case of mangroves, as refuge from predators (Vance and Rothlisberg in press). It is therefore useful to have a comparison of the areal extent available for prawns. As the prawn densities were measured on the intertidal mudflats, this area combined with the prawn densities was used to estimate a number of prawns in each estuary. As the Flinders River bifurcates at the lower end, forming the Bynoe River, estimates with and without this River were included. As modifications to the flow into the estuary as a result of upstream water development will impact on both the Flinders and the Bynoe, it is relevant to include both. It should be noted that sampling for prawn densities was only done in the Flinders River for logistical reasons.

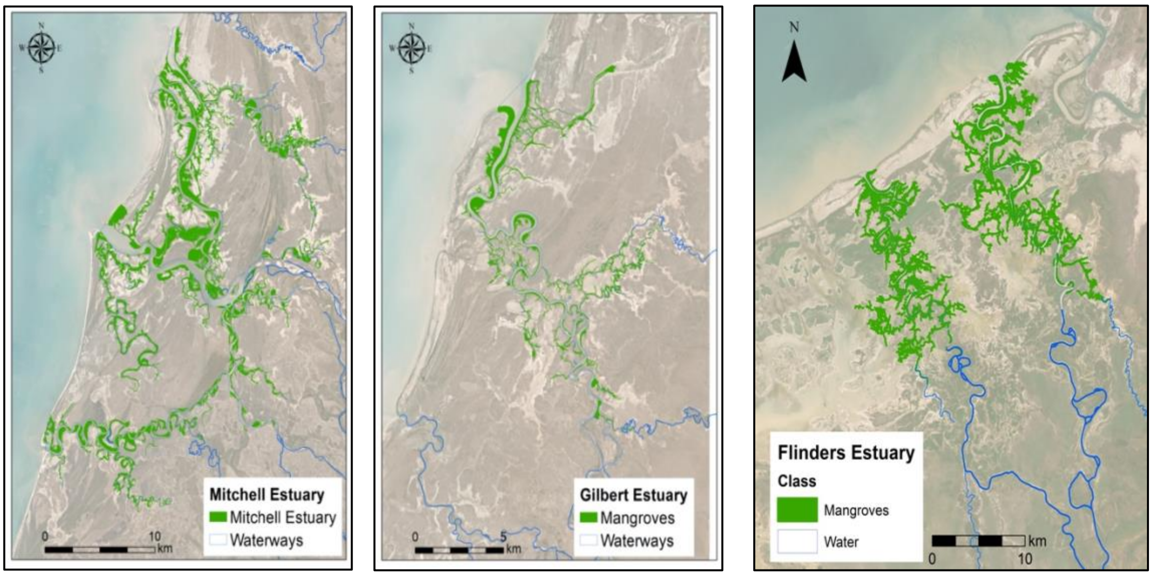

Figure 24. Map showing areal extent of mangroves (green shading) in each of the three estuaries in the study.

The Mitchell River estuary had substantially more mangrove habitat than the other two estuaries (Figure 24, Table 12). Vance et al, (2002) showed that *Rhizophora* was the preferred mangrove species as a habitat for banana prawns. This species is typically closer to the shoreline. Intertidal mudflat area was also higher in the Mitchell River, however the area was also substantial in the Flinders/Bynoe system (Figure 25, Figure 26).

Figure 25. Satellite map showing outline of mudflats to calculate areal extent. Google Maps.

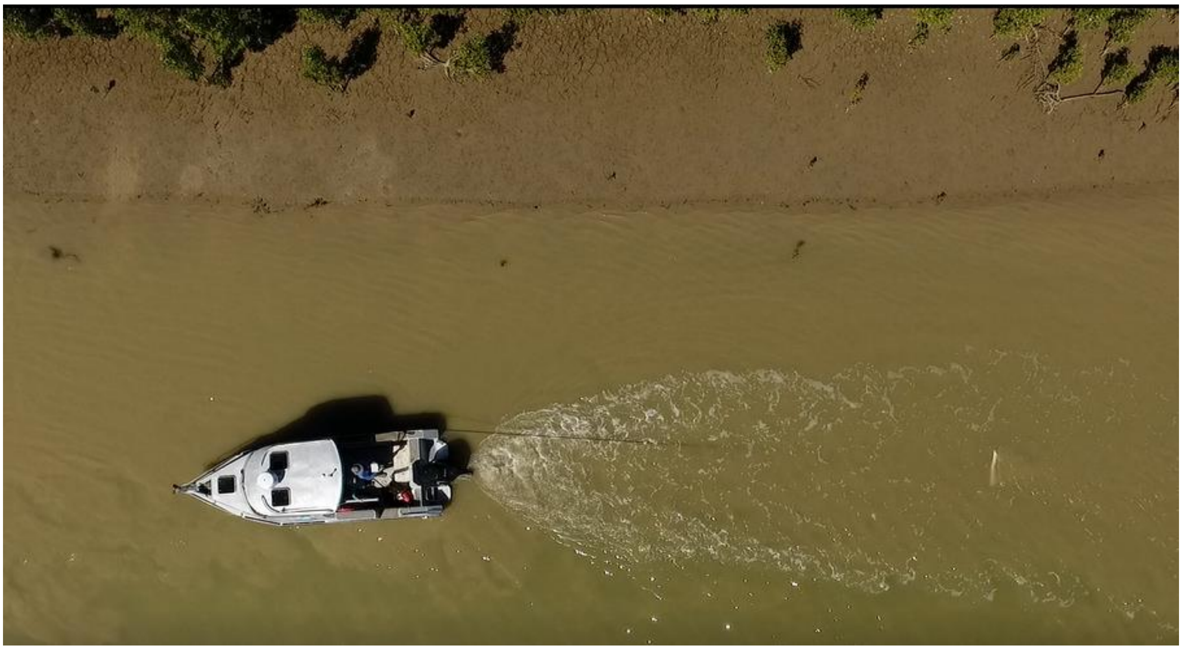

Figure 26. Aerial photo of beam trawling alongside low tide mudflats.

The areal extent of intertidal mudflats calculated for each river was multiplied by the density of prawns in each estuary to estimate the total potential number of prawns in each estuary (Table 14).

In the first year of sampling (November 2016), the total number of prawns in the Mitchell River estuary and Flinders/Bynoe were similar and higher than the Gilbert. Conversely, in the second year, numbers of prawns in the Mitchell and Flinders were lower than the Gilbert River estuary, due to the high density of animals in the Gilbert estuary. Total numbers of animals were substantially lower in the wet season.

The results highlight the high interannual variability in prawn densities in the three estuaries, and also point to the importance of all the estuaries for the fishery, but the relative importance changes from year to year. The interannual differences may be driven by many factors, such as prevailing winds and currents affecting recruitment to the estuaries, differences in predator numbers between years, and spawning effectiveness in nearshore environments.

*Table 14. Total area of mangroves and intertidal mudflats in the three estuaries. Both mangrove and mudflat data were separately combined with prawn abundance to estimate the total potential number of prawns in each estuary. *Although the density of prawns was not measured in the Bynoe for logistical reasons, it is a bifurcation of the Flinders and downstream of the gauging station. Therefore, future water development in the catchment may impact on both Bynoe and Flinders estuaries.*

	Mangrove area (km^2)	Intertidal mudflat (km^2)	Prawn density (m^2)	SE	Total prawn# based on mudflat area	SE
Nov-16 (dry)						
Mitchell	56.85	1.42	1.38	0.48	1,956,150	666,225
Gilbert	7.23	0.34	1.85	1.11	636,823	382,094
Flinders	9.39	0.54	1.71	1.18	921,491	635,883
Flinders/Bynoe*	24.47	1.05	1.71	1.18	1,795,500	1,239,000
Nov-17 (dry)						
Mitchell	56.85	1.42	0.53	0.16	751,275	226,800
Gilbert	7.23	0.34	4.52	2.03	1,555,913	635,883
Flinders	9.39	0.54	0.62	0.21	334,108	129,332
Flinders/Bynoe*	24.47	1.05	0.62	0.21	651,000	252,000
Feb-18 (wet)						
Flinders	9.39	0.54	0.08	0.05	43,111	26,944
Flinders/Bynoe*	24.47	1.05	0.08	0.05	84,000	52,500
May-18 (transition)						
Flinders	9.39	0.54	0.04	0.01	21,555	5,389
Flinders/Bynoe*	24.47	1.05	0.04	0.01	42,000	10,500
Mar-19 (wet)						
Mitchell	56.85	1.42	0.2	0.12	283,500	170,100
Gilbert	7.23	0.34	0.22	0.2	75,730	68,846
Flinders	9.39	0.54	0.21	0.08	113,166	43,111
Flinders/Bynoe*	24.47	1.05	0.21	0.08	220,500	84,000

3.4 Objective 4 – Tracer methods to determine prawn movement

Novel tracing methods will be tested to trace the origin of the juvenile stage of the flow indicator species, banana prawns caught offshore, trialling trace element and isotopic methods using samples of prawns, sediment and water from estuaries, nearshore and offshore.

The use of trace elements and stable isotopes was tested as a method to track prawns from the estuaries into the fisheries, and hence differentiate each estuarine contribution to fisheries catch. The approach has also recently been trialled in Moreton Bay (Munroe et al, 2018, O'Mara 2020). A range of statistical analyses were conducted using the data. There was no benefit in using trace element and stable isotope data together, as the same information was gleaned from trace element data alone.

The initial linear discriminant analysis showed a wide discrepancy between the signatures of the fishery (Gulf of Carpentaria) and the three estuaries (Figure 27). The estuaries also had discrete signatures reflecting the geochemical differences within each catchment.

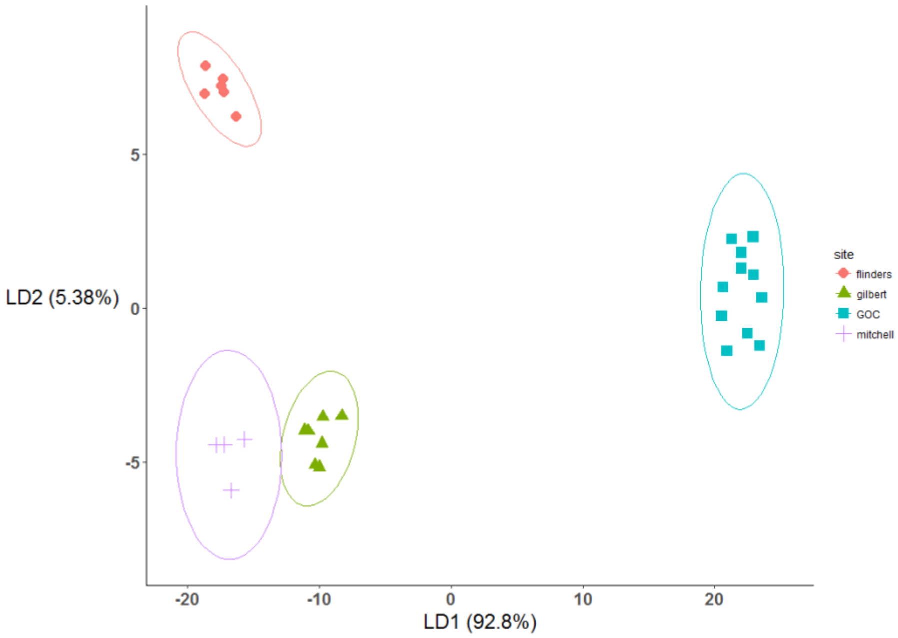

Figure 27. Linear discriminant analysis using trace element data for banana prawns to show differentiation between estuaries, and between estuarine prawns and prawns caught in the offshore fishery.

The lack of a signal link between the offshore fishery and the estuaries means that tracking prawns back to their estuaries of origin was not possible.

A more detailed analysis of the trace elements in prawns was conducted in the Flinders River system, due to the more frequent sampling trips for this river. The size of animals used for analyses is shown in Figure 28. Typically, animals in the nearshore area were larger than those in the estuary, with the exception of May 2018 (transition period after the wet season) when prawns were a similar size in the estuary and nearshore area.

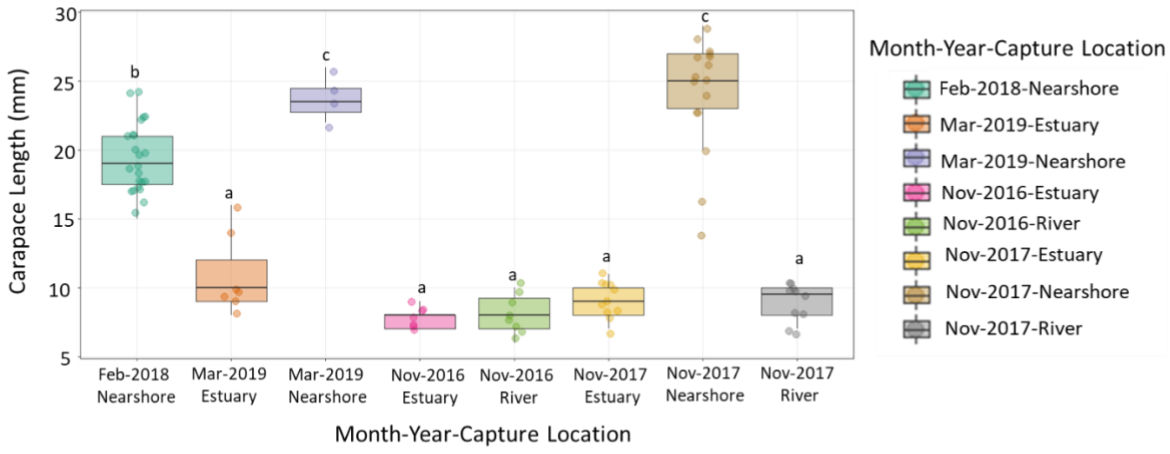

Figure 28. Prawn carapace length (mm) at each unique month-year-capture-locations. Points are raw data, the box defines the first and third quartile of the data, grey bars are the maximum and minimum range of variation, central black bands are the median value for each group. Letters denote significantly different size groups based on the results of a Tukey's HSD post-hoc test following a 1-way ANOVA.

The linear discriminant analysis for the Flinders prawns showed some distinct groupings (Figure 29). The November 2016 lower estuary (> 10 km from mouth, "estuary") and upper estuary (< 10 km from mouth, "river") were grouped and separated from prawn signals for all other sampling occasions. The November 2017 lower and upper estuaries were also grouped, and separated from the November nearshore signal. This is consistent with much larger animals in the nearshore which are likely to be the result of a different cohort.

Conversely, the wet season, March 2019 nearshore and estuary cohorts had similar signals, indicative of a link between the estuary and nearshore as a result of sediment and other material being transported out of the estuary and into the nearshore. It is unlikely that these two habitats had the same cohorts of prawns due to the differences in their size (Figure 28). Finally, the February 2018 prawns in the nearshore, which were sampled just before the major flooding in the wet season, had a similar signal to the November 2017 sampling, as would be expected.

Overall, this study points to the importance of the wet season flow in connecting the estuary and nearshore area via transport of material. This signal is assimilated by the prawns and points to the importance of the floods to stimulate growth of the food supply for prawns in the nearshore area. This is consistent with a study with another penaeid prawn species in Moreton Bay (O'Mara 2019).

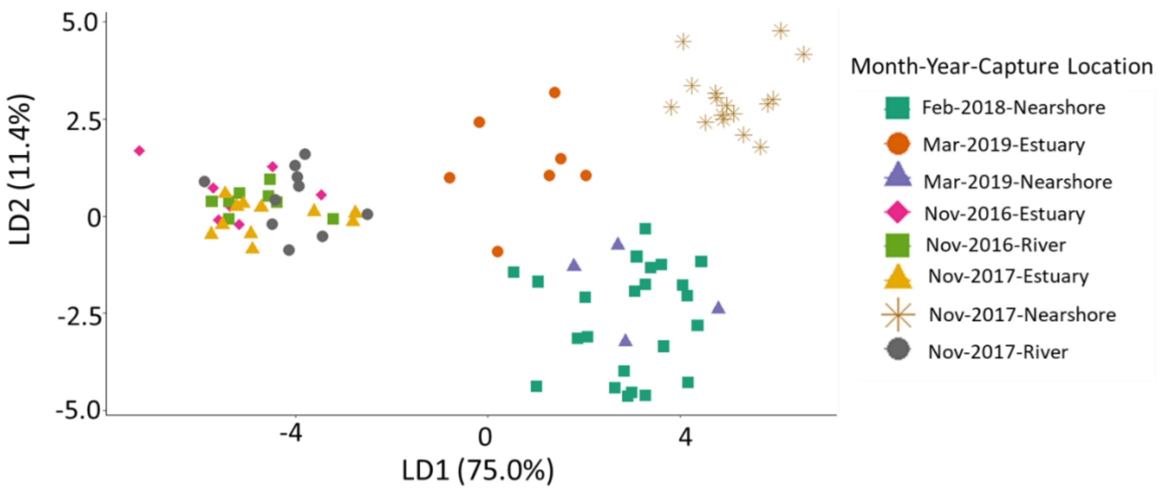

Figure 29. Linear discriminant analysis of major and trace element concentrations determined in prawn muscle tissue collected in Flinders estuary and nearshore environment.

3.5 Objective 5 – Modelling prawn fisheries and flow

Develop a prawn population model and examine different scenarios of flow, including climate change related, on prawn fisheries catch.

See accepted paper (Appendix 3).

Andrew Broadley, Ben Stewart-Koster, Christopher J. Brown, Rob A. Kenyon, Michele A. Burford. Predicted impacts of reduced river flows on the catch of a commercial marine fishery. *Ecosphere*.

4. Conclusions and recommendations

In conclusion, this study has demonstrated:

- There were many similarities in the characteristics of the Mitchell, Gilbert and Flinders River estuaries, climatic drivers and water quality. However, the Mitchell River has more consistent flow year-to-year, and a more extended period of flow each year compared with the other two rivers. Conversely, on the other end of the spectrum, the Flinders has the most extreme conditions, with lowest rainfall, highest evaporation and highest year-to-year variability in flow.
- In the wet season, when salinities in the estuaries decreased due to freshwater flows, total nitrogen and phosphorus concentrations only increased in short term spikes, and for much of the wet season do not increase above dry season values. The large volumes of water discharged from the estuaries in the medium to large wet seasons in our study resulted in substantial loads of nutrients into the nearshore area, directly and indirectly driving coastal productivity. There were no consistent differences in the nutrient loads between the estuaries with the scale of the freshwater flow from year-to-year being the major driver.
- There was no consistent difference in water column or benthic algal biomass, or benthic primary productivity rates between the estuaries. Rates and biomasses were comparable with other tropical estuaries. However, in contrast to other tropical estuaries, respiration rates and the organic carbon content of sediments was low suggesting limited organic carbon availability from sources other than primary production on the mudflats. By inference, mangrove detritus is not a major contributor to mudflat productivity. There is little evidence for major organic carbon inputs from freshwater flows in the wet season.
- We tested experimentally whether the input of nutrients to the mudflats was important for stimulating primary production on the mudflats. Primary productivity rates increased in all three estuaries in response to nutrient inputs in both the dry and wet season. The inference is the estuaries are chronically nutrient limited, and therefore, wet season inputs of nutrients are critical to maintain primary productivity. This has flow-on effects to food availability for animals within the system.
- Juvenile banana prawns (*Penaeus merguiensis*) use Gulf estuaries each year for some months as feeding and refuge areas. This study found that the densities and the total number of juvenile banana prawns in each estuary varied substantially between years, with no statistical differences between estuaries, with the exception of the Gilbert River estuary in November 2017. This suggests that all three estuaries are important to the fishery, with the relative importance varying from year to year.
- The study confirmed previous studies in other Gulf rivers showing that during the wet season, most banana prawn juveniles leave the estuaries. Prawns continued to be captured in lower densities in the nearshore area, highlighting that not all prawns are migrating to the offshore fisheries.
- A spatio-temporal Bayesian model was used to quantify the relationship between low, medium and high-level flows, and banana prawn catch in the offshore fishery. This model incorporated novel climatic measures. The effect of loss of flow, due to water extraction or diversion, on the prawn catch was examined. Three water development scenarios were tested. One of the most important findings of this study was the predicted proportional decline in banana prawn catch with decreasing flow-levels due to water extraction. Catch

was most impacted by water extraction during low flows, with all three rivers predicted to impact catch. The impact of water extraction was greatest for a scenario with dam construction on the Mitchell River, where during low river years predicted a 53% reduction in catch. Overall, our results imply that maintenance of low-level flows is a crucial requirement for sustained fishery yields.

This study had a number of new and important findings with implications for water planning.

- Firstly, given the importance of nutrient inputs to fuelling primary productivity, maintenance of flow in low and medium flow years is critical if estuarine productivity is to be maintained. Additionally, first flush flows at the start of the wet season are critical to ensure there is sufficient food for fisheries and other species. The first flush is also important to reducing salinity, which is typically hypersaline and highly stressful for the plants and animals living in the estuaries. The Flinders River estuary is likely to be the system most vulnerable to loss of first flush, due to the longer period of no flow each year compared with the Gilbert and Mitchell Rivers.
- In low to medium flow years, reduction of flow from water extraction will keep salinities high, and as a result, prawns will be less likely to emigrate from estuaries into the offshore fisheries. As prawns are a shortlived species and because prawns in estuaries are predated at a rapid rate, prawns that do not move out of estuaries are unlikely to contribute to the next generation. Therefore, fisheries catch will be affected in both the short and long term. The scale of impact in the short term has been quantified via a model of flow and fisheries catch, with significant effects on catch.
- Water extraction in a year after multiple years of little or no flow will have major impacts. The scenario is not unusual, particularly for the Flinders River which has the highest interannual variability in flow, and can have multiple consecutive years of no flow. Therefore, species will be highly vulnerable to additional years of no or little flow. It is not clear what impact climate change, and resulting changes of weather patterns will have as there is too much uncertainty in current models for this area of Australia.

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Appendix 1: Hydrographs

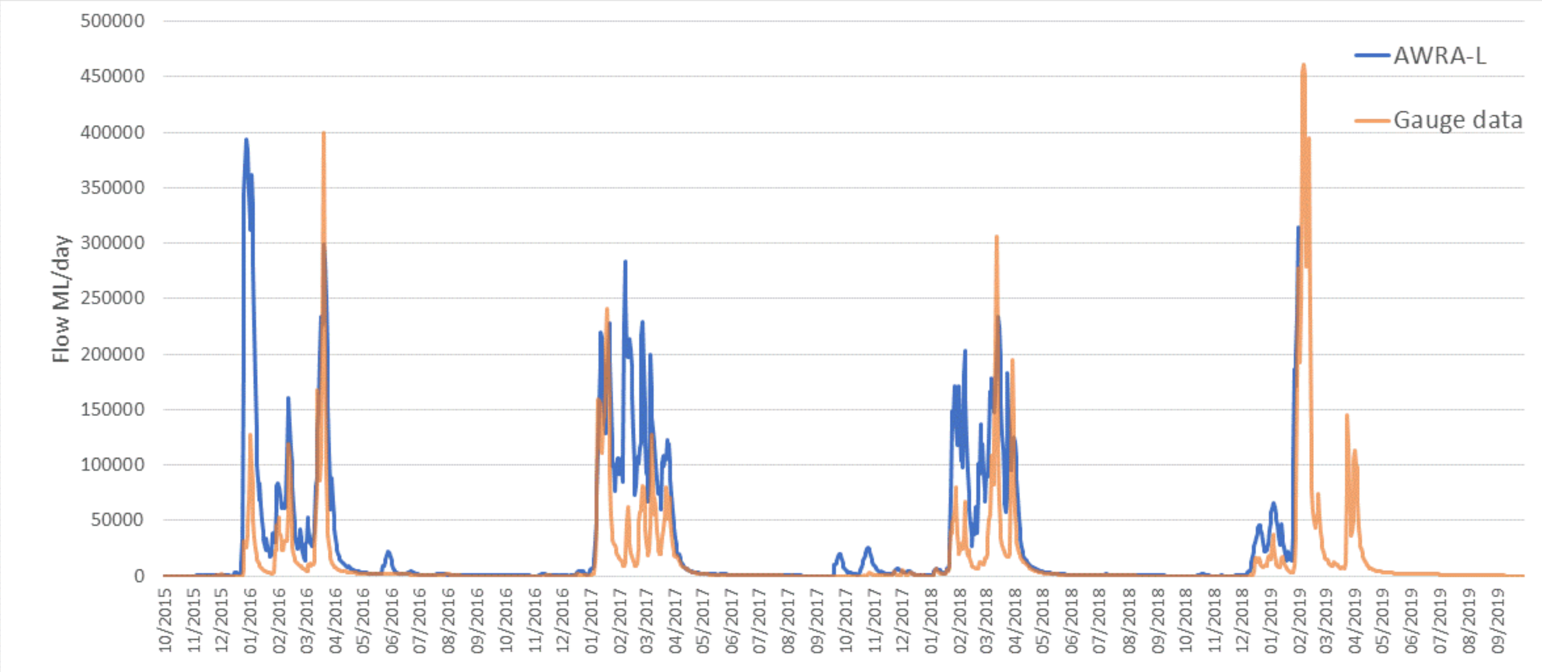

Figure A1-1. Hydrographs for the end-of-system flow for the Mitchell River using 1. Gauge data from Dunbar (139 km from Mitchell River mouth), 2. CSIRO modelled data, i.e. AWRA-L model.

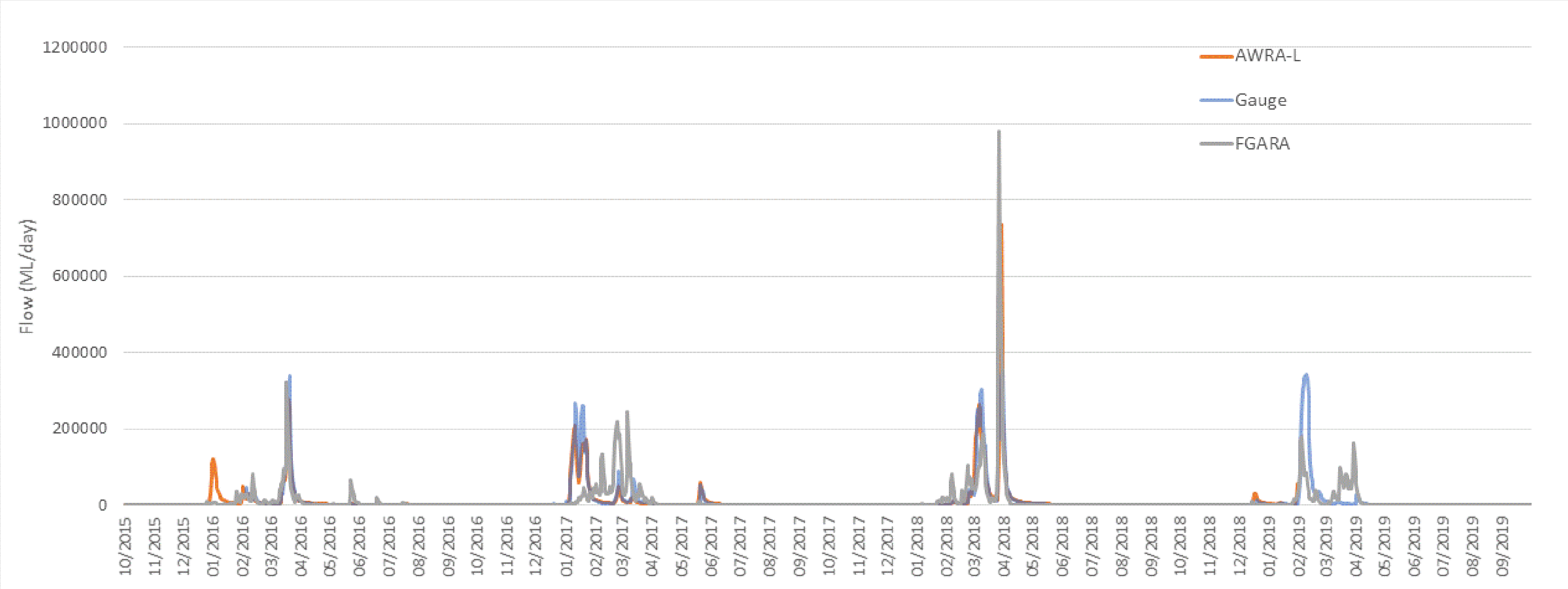

Figure A1-2. Hydrographs for the end-of-system flow for the Gilbert River using 1. CSIRO modelled data, i.e. AWRA-L model, 2. Gauge data from Burke Development Rd (102 km from Gilbert River mouth), 3. CSIRO modelled data, i.e. FGARA model.

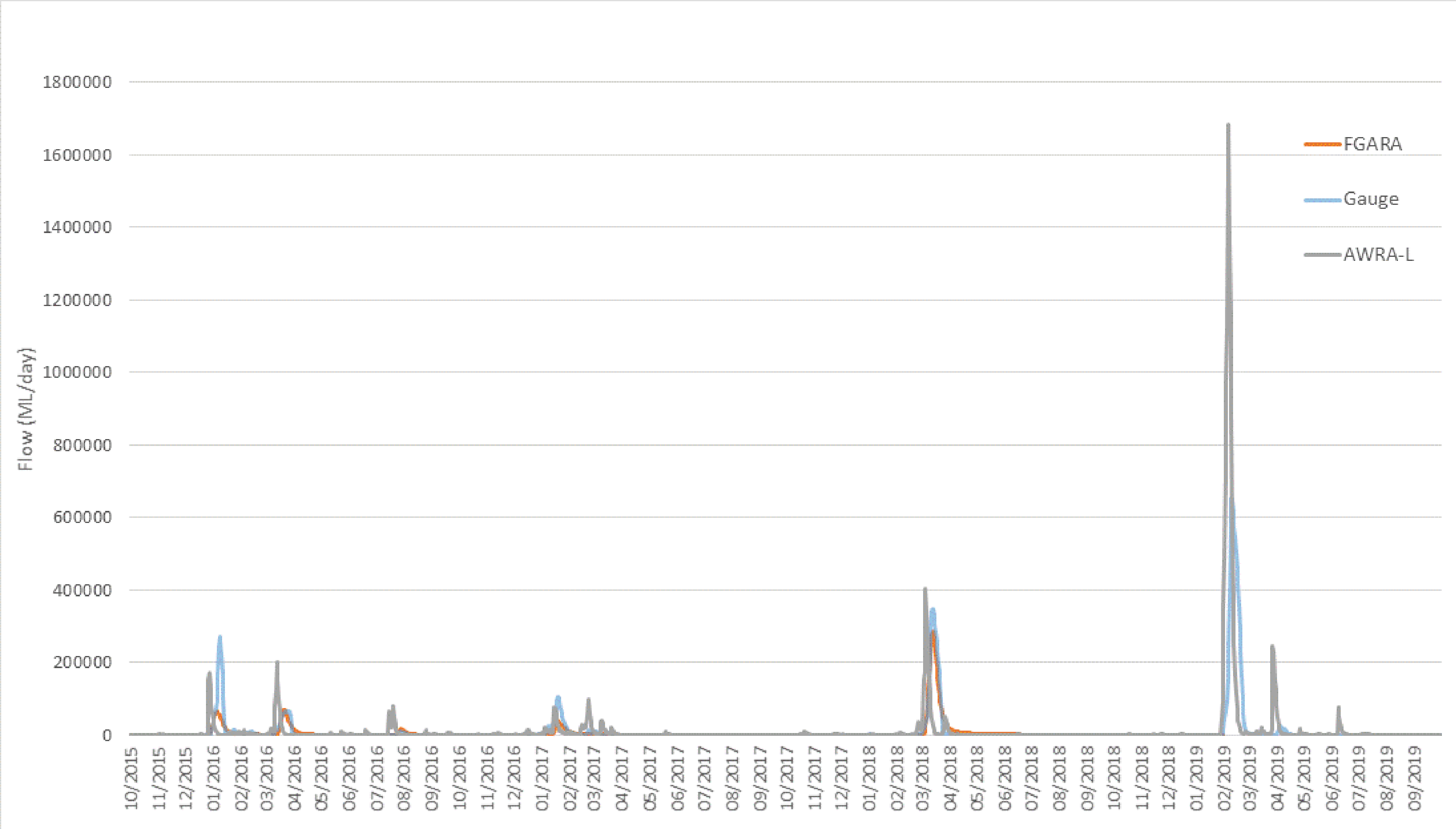

Figure A1-3. Hydrographs for the end-of-system flow for the Flinders River using 1. CSIRO modelled data, i.e. FGARA model, 2. Gauge data from Walkers Bend (103 km from Flinders River mouth) 3. CSIRO modelled data, i.e. AWRA-L model.

Appendix 2: Sampling sites

Figure A2-1. Mitchell River mudflat and sandflat sampling sites for primary productivity. Google Earth.

Figure A2-2. Gilbert River mudflat and sandflat sampling sites for primary productivity. Google Earth.

Figure A2-3. Flinders River mudflat and sandflat sampling sites for primary productivity. Google Earth.

Figure A2-4. Mitchell River prawn trawling sites. Google Earth.

Figure A2-5. Gilbert River prawn trawling sites. Google Earth.

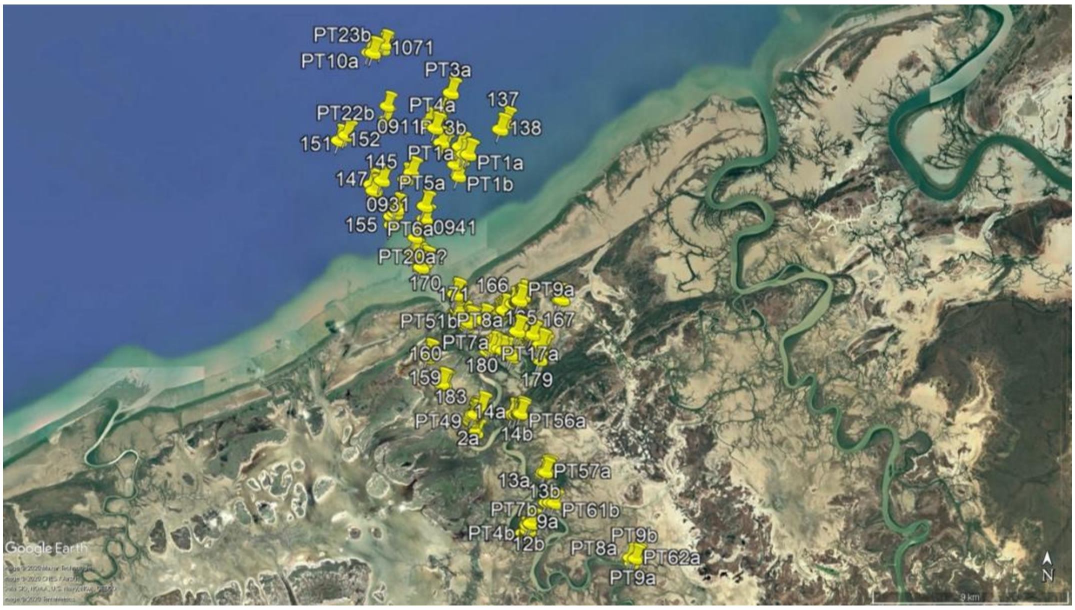

Figure A2-6. Flinders River prawn trawling sites. Google Earth.

Appendix 3: Broadley et al, paper modelling fisheries catch with flow alterations

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Impact of water development on river flows and the catch of a commercial marine fishery

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Abstract

The growing demand for freshwater resources has led to dam construction and water diversions in a majority of the world's large rivers. With an increasing demand for freshwater, trade-offs between water allocations and the preservation of ecological connections between terrestrial and marine ecosystems are inevitable. The ecological links formed by rivers flowing into the ocean benefit many commercially fished species. The degree to which different species and the livelihoods of fishers are impacted by changes in river flows due to water extraction or diversion is important for management across terrestrial and marine boundaries. Our objective was to predict how changes in freshwater flows from three wet-dry tropical rivers in northern Australia, the Mitchell, Gilbert and Flinders Rivers, affect the commercial banana prawn (*Penaeus merguiensis*) catch. We used a spatio-temporal Bayesian model to quantify the relationship between low, medium and high-level flows and banana prawn catch. We then predicted how the loss of flow due to water extraction or diversion affected prawn catch. Our analyses of three water development scenarios found that catch was most negatively impacted by water extraction during low flows. The impact of water extraction was greatest for a scenario with dams on the Mitchell River, where we predicted catch would decline by 53% during a year with low flow. Overall, our results imply that maintenance of low-level flows is a crucial requirement for sustained fishery yields. We suggest that water managers must balance agricultural demand for water during dryer years against the impact of water extraction on prawn fisheries during low-flow years. Protecting low-level flows during dry years is a priority for maintaining terrestrial-marine linkages for adjacent marine fisheries.

Keywords coastal ecology, estuaries, estuarine ecology, fisheries dynamics, fisheries management

Introduction

The connections between terrestrial and marine ecosystems are a critical interface for ecological dynamics and have important implications for fishery management (Hughes et al, 2015; Brown et al, 2019). Productivity of the world's coastal fisheries is dependent on ecological links to freshwater and terrestrial ecosystems, such as nutrient inputs from floods that boost primary production (e.g. Bianchi, 2007; Saeck et al, 2013) and altered physio-chemical environments (e.g. MacCready & Geyer, 2001; Stacey et al, 2001). The disturbance of terrestrial freshwater pathways from changes in climate, river flows and land-use has led to habitat destruction and loss of biodiversity in recipient coastal marine ecosystems (Vörösmarty & Sahagian, 2000; Oczkowski et al, 2009). However, it is often difficult to distinguish between human and natural sources of variability in coastal ecosystems, because of the confounding nature of environmental change on ecological processes (Brown et al, 2019). Despite these difficulties there is mounting evidence that accounting for changes in the environment may improve fish stock predictability and contribute to better management of commercial fisheries (Szuwalski et al, 2015).

Environmental factors affecting coastal wild capture fish stocks extend far beyond the management boundaries of fisheries (Oczkowski et al, 2009; Szuwalski et al, 2015). The absence of integrated management across terrestrial-marine boundaries has seen the decline and collapse of fish stocks from the construction of dams and water diversions (Oczkowski et al, 2009). The Australian government is currently investigating opportunities for water resource development in northern Australia (Petheram et al, 2018). However, unlike most tropical rivers that have distinctive seasonal patterns of flow, wet-dry tropical rivers like those in northern Australia have highly variable flows (Warfe et al, 2011). In the wet-dry tropics rivers may only flow for short periods of time during the wet season and are often followed by long periods of low flow or cease to flow in the dry season (Warfe et al, 2011). The extreme climatic variability of the region raises concerns about how water extraction in low flow years will impact marine fisheries. It is important to evaluate the scale of impacts of proposed water resource development projects on river flows and their effects on the catch and effort of adjacent coastal marine fisheries.

Both spatial and temporal changes in freshwater flows are known to have important implications for fish and invertebrate species in coastal, estuarine or freshwater habitats, particularly in Northern Australia (Vance et al, 1985; Robins et al, 2005). For example, the construction of the Ord River dam in northern Australia led to a reduction in the banana prawn (*Penaeus merguiensis*) population by changing the river's flow regime from wet-dry tropical to a perennial flow system (Warfe et al, 2011). Similar to the banana prawn many other marine species respond to changes in freshwater flows by shifting their location to avoid unfavourable conditions such as changes in salinity, while others may take advantage of changed conditions to reproduce or search for prey (Grimes & Kingsford, 1996). This behaviour is reflected in a species distribution in space and time and is often constrained by their physiological adaption to environmental changes that have occurred throughout their life history (Vance et al, 1985; Taylor & Loneragan, 2019). Species that spawn or spend their early life stages in estuarine or freshwater habitats are particularly vulnerable to changes in the timing and magnitude of freshwater flows (Vance et al, 1985). Fluctuations in seasonal patterns of freshwater flows are known to affect the survival, growth, migration and recruitment to fisheries of many commercially important marine fish and invertebrates (e.g. Drinkwater & Frank, 1994; Hilborn et al, 2003; Duggan et al, 2014). Changes in freshwater flows can either directly affect an individual's physiology through variations in salinity and temperature, or indirectly from changes in habitat or food availability, but regardless of the mechanism, changes in flow are expected to influence fishery yields (Drinkwater & Frank, 1994).

In the Australian Northern Prawn Fishery, changes in the osmoregulation capability of juvenile banana prawns combined with reduced salinities from seasonal freshwater flows is an important mechanism forcing banana prawns to emigrate from estuarine nurseries to coastal waters (Vance et al, 1985; Vance and Rothlisberg, in press). There is concern that growing development pressure on freshwater flows, particularly in low flow years, will reduce the emigration cue and thus impact the fishery. One of the first stages in the process of planning for major water resource development involves using simulation models to evaluate the impact of upstream development on downstream needs, such as the water needs of fisheries species (Gippel et al, 2009). Predicting the impact of such water resource development on fishery catch requires a modelling framework that can simultaneously account for the natural spatial and temporal variability in the environment that also affects catch. The aims of this research were to: (1) characterise inter-annual flow variability for three wet-dry tropical rivers in northern Australia, the Mitchell, Gilbert and Flinders Rivers; (2) determine how climate and environmental variables affect prawn catch; and (3) predict how scenarios for water extraction and diversion from the three rivers may affect the commercial banana prawn catch. We examined the influence of river flows on the annual catch using a spatio-temporal Bayesian model. The model development process considered different climate covariates and river flow scenarios over a 28-year period and the impact of flow extraction and diversion on the banana prawn fishery.

Method

Study area

Situated in northern Australia the Gulf of Carpentaria is a large semi-enclosed body of water covering an area of approximately 400,000 km^2 (Figure1). The Gulf of Carpentaria's open boundary extends into the Arafura Sea and is connected to the Coral Sea across the Torres Strait (Condie, 2011). The bathymetry of the entire region is relatively flat and shallow with water depths ranging from 20 m near the coast to 70 m toward the centre (Rothlisberg & Burford, 2016). The focus of this study was on the south-eastern region covering around 150,000 km^2 of coastal waters (Figure1). Within this region, the Mitchell, Gilbert and Flinders Rivers drain vast catchment areas that remain largely undisturbed from human impact (Petheram et al, 2008; Rothlisberg & Burford, 2016).

Northern Prawn Fishery

The Northern Prawn Fishery has operated within some sections of the Gulf of Carpentaria from the late 1960's (Kompas et al, 2010). Since this time, it has expanded to become Australia's largest multi-species prawn fishery covering an area of around 900,000 km^2 in the coastal waters around northern Australia (Kompas et al, 2010). The banana prawn is one of the most commercially important species targeted by fishers in Northern Prawn Fishery. Adult banana prawns spawn offshore, generally in the warmer tropical and sub-tropical waters. The resultant larvae are then transported by currents toward settlement locations in shallow water habitats within estuarine and coastal areas. After growing for a period of 4 to 6 months, ontogenetic changes in their osmoregulation combined with reduced salinities from wet season river flows cue their emigration offshore. Once in the ocean banana prawns continue to grow, mature, spawn and recruit to the fishery (Vance & Rothlisberg, in-press).

A majority of the banana prawn catch was harvested in the south-eastern region of the Gulf of Carpentaria, where 80% of the catch was usually taken within the first few weeks of the season opening that normally begins at the transition from wet to dry seasons in April. At the beginning of the season banana prawns form large aggregations and fishers look for discoloration in sediments as a guide for large schools of banana prawns. Light aircraft are also used to identify and direct the location of banana prawn aggregations to fishers (Die & Ellis, 1999). The aggregating behaviour of the banana prawn and its influence on fisher behaviour meant catch had strong influence on effort. This was evidenced by both a strong correlation between catch and effort, r=0.77, and from the majority of the trawl tows being under 3 hours (Die & Ellis, 1999).

Weekly catch and effort data for the banana prawn fishery from 1984 to 2011 on a 6 nautical mile (~11 km^2) grid resolution covering the entire study area was obtained from the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The catch and effort data were based on information recorded by fishers in daily log sheets (Dichmont et al, 2014). When the catch and effort data were analyzed spatially some areas of low catch and very low effort were found. These areas produced a high catch per unit effort (CPUE) that was comparable to areas of much larger catch and higher effort. Targeting banana prawn aggregations early in the season meant CPUE was likely to be decoupled from the true abundance distribution, with short trawls able to yield very low or very high catch, depending on the size of the aggregation. We also did not have access to individual trawler location data and were therefore unable to verify fishing effort. We assumed catch data were correct because fishers logged the location of each shot of the net, which is verified with landed weights from processing companies and trawler owners (Bishop & Die, 2001). For these reasons, we decided that using catch data only would provide a better spatial representation of banana prawn distribution than CPUE.

Regional climate and weather

The Gulf of Carpentaria is an area of extreme climatic variability that is characterised by wet and dry seasons (Petheram et al, 2009). In this study the wet season was defined as the months between October to April, and the dry season from May through to September based on gauged river flow data. Each season was influenced by global scale changes in atmosphere-ocean circulation patterns that generate substantial modes of climate variability (Wheeler & Hendon, 2004; Ghelani et al, 2017). The influence of different climate modes on regional rainfall flux provided an opportunity to analyze how substantial interannual changes in river flows related to the catch of banana prawns. The relationship between river flow regimes and banana prawn catch was used to infer how altered flows from water extraction, i.e. water diversion or construction of dams, might impact the fishery.

The long-term average rainfall in the Gulf of Carpentaria showed a strong north-south gradient with most rain falling in the northern catchments. The Mitchell River located in the northern most catchment of the study had the highest average annual flow of 13,000 GL/year. Average annual flows in the Gilbert (5,304 GL/year) and Flinders (1,982 GL/year) rivers were considerably less than the Mitchell River. The large difference in size of the Flinders catchment (109,000 km^2) compared to the Gilbert and Mitchell (46,354 and 73,230 km^2, respectively) did not appear to be an important factor influencing river flows in this study.

The variation in climate is mainly caused by interactions between shifts in phase of the El Niño Southern Oscillation (ENSO) and the strength of activity from the Madden Julian Oscillation (MJO) (Ghelani et al, 2017). The ENSO is the dominant mode of climate variability measured on interannual timescales, and the MJO operates intra-seasonally approximately every 30 to 80 days (Wheeler & Hendon, 2004). Changes in the ENSO and MJO have been linked to the frequency and severity of tropical storms and cyclones occurring in northern Australia (Ghelani et al, 2017).

We captured the interannual effects of El Niño, La Niña and neutral phases of ENSO by calculating the average Southern Oscillation Index (SOI) for each wet season from 1984 to 2011 using data from the Australian Bureau of Meteorology (BOM). An SOI value below -8 indicated an El Niño, above +8 La Niña, or values between -8 and +8 implied neutral conditions.

In the Gulf of Carpentaria tropical cyclones have an important role in contributing to extreme changes in weather conditions (Klingaman et al, 2013). During the wet season each year it is common for more than one tropical cyclone to form or make landfall in north-eastern Australia (Ramsay et al, 2008). As cyclones move across the coast and into the Mitchell, Gilbert and Flinders catchments they have the potential to cause floods or overbank flows that occur over very short periods of time (Klingaman et al, 2013). A composite index based on each cyclone's mean wind speed (km/h), representing its severity, and the day of year it first appeared in the region, including catchment areas, was created using Principal Components Analysis (PCA). The first component of the PCA was used as the index, which accounted for 75.8% of the variation in the wind speed and timing of all cyclones. Information on tropical cyclone wind speed, track and timing used in this study were obtained from the Australian BOM.

Both the SOI and cyclone index captured important large-scale and local elements of annual climate variability. We accounted for additional regional scale climate effects by creating an index of the outgoing longwave radiation (OLR) measured at 850 hPa in the atmosphere directly above the Gulf of Carpentaria. The index was developed from daily interpolated 1º latitude by 1º longitude OLR data from the Physical Sciences Division of the National Oceanic and Atmospheric Administration (NOAA). The mean OLR between 138º to 144º east and -13º to -20º south was computed for each wet season from 1984 to 2011. Lower values of the OLR index indicated greater convection in the atmosphere above the Gulf of Carpentaria's coastal and river catchment areas.

The SOI, cyclone and OLR indices were created to capture the non-linear effects of environmental conditions in the ocean and atmosphere that influence the catch of banana prawns. The SOI represented large-scale changes in ocean water temperatures and rainfall that are known to affect spawning patterns and migration of many marine species (Meynecke & Lee, 2012). The cyclone index was created because the timing of severe weather events can positively or negatively affect catch from increased river flows, damage to habitat or reduced fishing effort from fishers seeking safe harbor (Callaghan 2011; Loneragan et al, 2013). The OLR index captured the effects of both the ENSO and cyclones by focussing on atmospheric conditions directly above the Gulf of Carpentaria. OLR has been used in many climate studies and forms the basis of indices such as the MJO (Wheeler & Hendon, 2004).

Rivers

The end of system (EOS) river flow data were available for the Mitchell, Gilbert and Flinders Rivers from the CSIRO using river models configured in the eWater Source software (Lerat et al, 2013). The modelled CSIRO flow data covered a period in time from 1900 to 2011. Annual wet season flows for each river were created by summing daily EOS flow data between October to April. Because the annualised wet season flows crossed years they were associated with the end of wet season year that aligned with the fishing season. All of the flow data were standardised.

Collinearity between river flows was investigated using a Pearson correlation test in R (R Core Team, 2018). The results of the Pearson test identified a strong correlation between the Flinders and Gilbert rivers (86.3%), and the Gilbert and Mitchell rivers (74.6%). Evidence of collinearity does not always present issues for model stability or prediction, but early testing of our model indicated collinearity was causing instability and spurious results. To reduce model instability a PCA was used in R (R Core Team, 2018) to create two new variables (PC's 1 and 2) that each accounted for 79.8% and 17.5% of the variability for all river flows. The results of the PCA were verified with a biplot (Supplementary data A: Figure1). The parameter values of PC1 and PC2 were not directly interpretable and had to be back-transformed by projecting onto the PCA coordinate system using the same rotation matrix as the observed river flows.

Model development

Modelling approach

The model development process considered the life history of the banana prawn with particular focus on how changes in river flows influence the spatial distribution of commercial catch. Exploratory analysis revealed the banana prawn catch had a distinct spatial structure with a high concentration of banana prawns found near the coast (Figure2). It was also evident that the extreme interannual variability in climate meant there was little temporal autocorrelation between seasonal river flows (Supplementary data A: Figure2). The development of an appropriate model would need to account for the spatial dependency of banana prawn catch, seasonal changes in river flows and non-linearities associated with interannual changes in climate.

Model structure

We used a hierarchical spatio-temporal Bayesian model to predict how changes in the distribution of the banana prawn catch vary with annual freshwater flows from the Mitchell, Gilbert and Flinders Rivers. A gamma distribution was chosen because the banana prawn catch data only contains positive values. Following the integrated nested Laplace approximation (INLA) modelling framework (www.r-inla.org) the gamma function $\Gamma(\cdot)$, was parameterised in terms of its mean μ, a fixed scaling parameter $s > 0$ and hyperparameter ϕ (Rue et al, 2009; Lindgren et al, 2011):

$$y_{ij} \mid \mu_{ij}, \theta \sim \Gamma(\mu_{ij}, s\phi)$$

Where, y_{ij} represents banana prawn catch at location i in year j that depends on an unobserved process μ_{ij} with hyperparameters θ. A log-link was used to link the linear predictor to μ. The unobserved process μ_{ij} was modelled by:

$$\log(\mu_{ij}) = \eta_{ij} = \beta_0 + \beta_1 \mathrm{PC1}_{ij} + \beta_2 \mathrm{PC2}_{ij} + \sum_{l=1}^{L} f_l(climate_{jl}) + x_i$$

where η_{ij} is the linear predictor, β_0 is the intercept, both β_1 and β_2 are coefficients used to quantify the effect of river flows represented by $\mathrm{PC1}_{ij}$ and $\mathrm{PC2}_{ij}$ from the PCA axes for flows, *L* refers to the total number of $climate$ covariates, $f_l(\cdot)$ were first order random walks on $climate_{jl}$ used to evaluate the temporal trends of SOI, OLR and cyclones on the fit and predictive power of the model, and x_i refers to a Gaussian Random Field (GRF) with a zero mean and Matérn covariance matrix, $x_i \sim GRF(0, \Sigma)$. Using a GRF enabled any latent factors, such as the availability of habitat or coastal primary productivity, influencing the spatial distribution of the banana prawn catch to be represented in the covariance structure of the model.

The spatial effect was modelled using INLA's stochastic partial differential equation (SPDE) approach. Here, the smoothness, range and marginal variance of the Matérn function were parameterised for use with the Penalized Complexity (PC) prior framework (see Fuglstad et al, 2019). INLA's finite element method was used to approximate the solution of the SPDE (Lindgren et al, 2011). The spatial domain of the banana prawn catch was divided into a constrained refined Delaunay triangulation or mesh of non-intersecting triangles (Supplementary data A: Figure3). The vertices within the mesh were mapped to basis functions with an associated weighting factor for linear interpolation of values in each of the triangles (Lindgren et al, 2011):

Priors

Bayesian priors were assigned to regression coefficients and hyperparameters. We used the default Gaussian prior distributions with 0 mean and precision 0.0001 for the coefficients that were associated with river flows. PC priors were incorporated into the Gamma distribution, random walk and Matérn GRF components of the model (see Simpson et al, 2017; Fuglstad et al, 2019). PC priors are weakly informative priors that shrink model components from more flexible to simpler base models and so are useful to avoid over-fitting the model to the data

(Simpson et al, 2017). Probability statements were used to specify parameters of the PC priors, thus setting the magnitude (λ) of the penalty for deviating from base models. PC priors for the precision (τ) of the Gamma distribution and random walks were set to have a high probability their standard deviation would be between 0 and 1, $P(\sigma > 1) = 0.01$, calculated as:

$$\lambda = -\frac{\ln(0.01)}{1},$$

$$\pi(\tau) = \frac{\lambda}{2}\tau^{-3/2}\exp(-\lambda\tau^{-1/2})$$

A joint PC prior for the range and variance was used to shrink the Matérn GRF toward a base model of infinite range and 0 marginal variance (Fuglstad et al, 2019). This approach avoids overfitting of the Matérn GRF by using the range and variance parameters to control the correlation and magnitude of the spatial field. In this setting and because many penaeid species are mobile and able to move distances over 100 km, we assumed there was a low probability the spatial range parameter would be smaller than 10 km, $P(\rho < 10 \text{ km}) = 0.01$ (García, 1988; Dall et al, 1990). We also set the standard deviation of the spatial field so it was unlikely to exceed 1.5, $P(\sigma > 1.5) = 0.01$. The joint prior for the Matérn GRF with a fixed smoothness $\upsilon = 1$ and dimensions $d = 2$ was calculated as:

$$\tilde{\lambda}_1 = -\log(0.01)10^{d/2} \text{ and } \tilde{\lambda}_2 = -\frac{\log(0.01)}{1.5},$$

$$\pi(\sigma,\rho) = \frac{d}{2}\tilde{\lambda}_1\tilde{\lambda}_2\rho^{-d/2-1}\exp(-\tilde{\lambda}_1\rho^{-d/2}\tilde{\lambda}_2\sigma)$$

Model comparison and cross-validation

In order to compare the fit and predictive quality of different combinations of SOI, OLR and cyclones on the model we used the widely applicable information criterion (WAIC), logarithm of the pseudo marginal likelihood (LPML). We also ran out-of-sample cross-validation using the root mean square error (RMSE) as the evaluation metric to compare models. The WAIC was calculated by INLA during model runs with lower values indicating improved model performance. The LPML summarises the Conditional Predictive Ordinate (CPO) that was computed by INLA into a single value, a greater number indicates better predictive quality of the model,

$$LPML = \sum_{i=1}^{n_{obs}} \log(\text{CPO}_i)$$

We conducted the cross-validation process by randomly dividing data into training and test sets, with randomisation stratified by year. This process tests the ability of the model to predict catch across years, assuming the fixed spatial structure is known. Each training set contained 22 years or ~80% of data and the remaining 6 years of data became the test set. Each model was initially fitted to the training data while omitting the test data. The fitted model was then used to predict catch in each location and year from the previously omitted test data. RMSE was calculated to measure the quality of fit between the observed data and predicted values for each model run, smaller values indicated a better fit,

$$RMSE = \sqrt{\frac{1}{n_{obs}}\sum(obs - pred)^2}$$

The cross-validation process was repeated 100 times for each model and the mean RMSE values from the training and test data sets were used to compare different models. We evaluated the sensitivity of the RMSE to the hold-out set by stratifying the cross-validation by flow scenarios. The flow covariates were included in all model comparisons. Testing flow would be a trivial null hypothesis because its importance in the lifecycle of banana prawns was already well established (Vance et al, 1985). Once we found which environmental covariates were important, we applied the model to different flow scenarios to predict the catch of banana prawns under changed river flows.

Predicting catch from changes in river flows

We used the fitted Bayesian model to predict annual catch when the flow of each river was reduced according to three water extraction scenarios (Table 1). Water extraction scenarios were based on recent Queensland Government Water Resource Plans and Assessments for the Flinders, Gilbert and Mitchell catchment areas. Scenario A had the least extraction of any scenario and assumed that all surface water entitlements granted as part of the water planning process were fully utilised (DNRME, 2017). These included extractions for town, indigenous and industrial use. Scenario B assumed current and future allocations were fully utilised (DNRME, 2018a; DNRME, 2018b). Scenario C had the greatest water extraction from the potential development of major in-stream dams in the Mitchell catchment (Petheram et al, 2018).

To account for covariance in river flows, we ran the extraction scenarios for multiple flow regimes. The EOS flow data from 1900 to 2011 were analyzed to determine a common set of flow-level patterns for the Flinders, Gilbert and Mitchell Rivers. Flow-level patterns were identified using *k*-means cluster analysis by classifying annual wet season flows for each river into low, medium, high and very high categories using the Cluster package in R (Maechler et al, 2018; R Core Team, 2018). We then predicted catch when each river's flow was altered for each flow-level pattern and water extraction scenario.

Results

Climatic context

Here we consider the environmental context throughout the 28-year study period and examine potential confounding influences between climate predictors. These results were an important component of model development and were used to better understand model limitations and behaviour.

A majority of cyclones (59%) appeared in the region during neutral ENSO conditions (Fig 3a,b). The number of cyclones in both El Niño and La Niña years were much lower with 9 cyclones occurring in each phase. The average intensity of cyclones was 25% stronger during El Niño years compared to those in La Niña. Similar to the difference in intensity was the average timing of cyclones where during El Niño years cyclones first appeared in January, while in La Niña they appeared later in February. There was also a noticeable shift in the timing of cyclones between 1990 and 1998, in neutral to El Niño conditions, where most cyclones first appeared in early December.

Regional-scale atmospheric processes represented by the OLR index showed that five of the lowest OLR years had values ranging from 245 to 250 watts/m^2 that occurred in neutral to La Niña conditions (Figure3a,c). Out of the five lowest OLR years three recorded an OLR of 245 watts/m^2, which coincided with the presence of at least one category 3 or higher cyclone in the region. More generally, the observed trends in OLR reflected cycles of ENSO where La Niña conditions had an average OLR of 250 watts/m^2, neutral years averaged 255 watts/m^2 and El Niño years had the highest average OLR of 260 watts/m^2. When comparing OLR and SOI at 10- to 15-year time scales there was a small difference, 256 watts/m^2 from 1984 to 1998, compared to 253 watts/m^2 from 1999 to 2011. The difference in OLR did match a similar scale shift in SOI, from -4.2 to 4.3, over the same periods of time. Along with the possible existence of a low frequency cycle associated with OLR there also was evidence of a higher frequency 3- to 7-year cycle.

The temporal patterns found in the ENSO and OLR climate predictors were also evident in the observed river flows. In the last 13 years of the study there was a 30% increase in total river flows, from 244,949 to 349,757 GL. The increase in total flow could be attributed to above average flows in all three rivers that only occurred during neutral or La Niña phases of ENSO. There were also some notable patterns at shorter time scales between rivers and OLR. For instance, the 3- to 7-year periods of below average flows mostly occurred when OLR was above 255 watts/m^2. A similar threshold existed when OLR was below 253 watts/m^2 with at least one of the rivers having above average flows.

The strength and number of cyclones did not always translate into years of good river flows. For example, both 2005 and 2006 were seasons influenced by strong category 3 to 5 cyclones but generated very different patterns in river flows. Despite the presence 2 cyclones in 2005 the total flow of freshwater was around 50% below average, 10,960 GL. Below average flows were more likely to associate with El Niño type conditions, an SOI of -8.3, and the absence of convective conditions in the atmosphere for a majority of the wet season, shown by a high OLR of 262 watts/m^2. In 2006 the presence of 2 cyclones coincided with close to La Niña conditions, SOI 7.1, and a very low OLR of 245 watts/m^2, indicating strong convection in the atmosphere throughout the wet season. These conditions were associated with above average flows in the Flinders (3,104 GL) and Mitchell (17,883 GL), and below average in the Gilbert (3,015 GL).

Overall these environmental patterns indicated some, but not complete, covariance between each climate predictor, which may confound model interpretation. So below we focus on identifying which subset of climate predictors provided the most accurate predictions of catch.

Classification of river flows

There were some common patterns of flow found with the *k*-means classification of the river flow time series of the three rivers (Table 2). Less than half (n=29) of all 64 possible combinations of low, medium, high and very high flows occurred between 1900 to 2011 (Table 3). When only considering the 28-year study period the number of river flow combinations was reduced to 16. Within the study period, the top six flow patterns occurred more than once, and these accounted for 64% of all study years. Low flows in all three rivers (flow-level pattern 1) was the most frequently occurring pattern, found in 18% of study years and 22% of all years. The number of medium flow (flow-level pattern 4) years during the study period was nearly half, 7%, that of all years, 12%. Whereas flow-level pattern 3 (low, medium and high), occurred more frequently, 11%, during the study period compared to 6% in all years.

Model comparison, verification and fit

The performance of each model was evaluated using different combinations of climate predictors (Table 4). The WAIC did not vary greatly between most models except that models 1 (no climate covariates) and 4 (cyclones) had higher (worse) values. There was less difference among the predictive quality of models measured by the LPML, with all models except 1 and 4 ranging from -12,406 to -12,415. The top three models having the smallest difference between the observed annual catch versus the fitted training data (Figure4a,d,g), and the observed annual catch versus predictions from the hold-out data (Figure4b,e,h) were models 1 (24.6 t/year), 3 (134.3 t/year), and 4 (120.8 t/year). Further analysis revealed that throughout the cross-validation, model 3 (OLR) had produced the best predictive performance (Figure4f) having the lowest variance in catch predictions of 223 t/year.

Model 3 (OLR) was selected due to its consistent performance across evaluation measures compared to other models. The OLR model performed well compared to other models having similar WAIC and LPML scores (Table 4), and importantly a consistently lower variance in prediction accuracy during cross-validation (Figure4f). The performance of the OLR model was related to how the OLR index captured changes in atmospheric conditions that were confounded with elements of both the SOI and the presence of cyclones (Figure3a,b,c). The confounded elements of the SOI were linked to large-scale changes in ocean-atmospheric circulation patterns, whereas the effects of cyclones were more likely confounded at a much smaller catchment scale. Overall, the OLR model demonstrated it would provide the most reliable predictions of banana prawn catch from changes in flow.

The cross-validation process was sensitive to the mix of low, medium, high and very high flows included in the training data. Sensitivity analyses revealed a range in $RMSE_{Test}$, for all 8 models, from 223 to 1,083 t/year (Supplementary data A: Figure4). In general, the $RMSE_{Test}$ was lower when the training data included the rare years with very high river flows (200 to 500 t/year). When the training data excluded high and very high flow years, the $RMSE_{Test}$ was higher (500 and 650 t/year), because these models were extrapolating catch predictions to high flow years.

A review of marginal posterior parameters for all models (Supplementary data A: Table 2), showed the fixed, random and spatial effects were all important to explain the variability in catch. Back-transforming PC1 and PC2 for each model (Supplementary data A: Table 3), revealed similar parameter values for each river, ranging from 2,457 to 2,794 GL/year in the Flinders, 4,642 to 4,819 GL/year for Gilbert and 17,011 to 19,146 in the Mitchell. The ρ (range) of the spatial field indicated the distance where spatial correlation was reduced to around 0.13. All of our models had a similar value of ρ from between 99 to 113 km, indicating a diminishing spatial autocorrelation of catch for distances over 113 km.

Model predictions for water extraction scenarios

The following results show catch predictions from the OLR model for each of the three water extraction scenarios, (A) granted entitlements, (B) planned allocations and (C) Mitchell instream dams. For each water extraction scenario, the predicted decline in catch was shown for the four most common flow-level patterns (patterns 1 to 4), with the addition of rare patterns 8 (all rivers high) and 10 (all rivers very high). These six flow-level patterns accounted for 56% of all possible combinations of low to very high categories of flow that occurred in the three rivers over a 112-year period (Table 4).

In scenario A we assumed that all surface water entitlements granted as part of the water planning process were fully used and therefore flow reductions were minimal (Figure5a,d). The predicted change in catch for all flow-level patterns was less than 5%. Flow patterns 1 to 4 had a decline in catch of between 34 to 57 t (95% CI, 30 to 65 t). The decline in catch was lower for the higher flows associated with patterns 8 and 10, with a predicted reduction in catch of between 5 and 22 t (95% CI, 3 to 35 t).

The planned allocations scenario B assumed full use of all future planned surface water allocations including those entitlements already granted (Figure5b,e). Model predictions indicated water extracted during low to medium flow years (patterns 1 to 4) at the level of planned allocations could potentially reduce catch from between 12.4 to 17.3% or from 178 to 226 t (95% CI, 155 to 257 t). Changes in flow during high and very high flow years (patterns 8 and 10) appeared to have little effect on catch, 1.2% (39 t) and 0.7% (26 t), respectively.

Scenario C included the construction of multiple major instream dams in the Mitchell River that would have had a major impact on EOS flows (Figure5c,f). During low flow conditions (pattern 1) the model predicted a decline in catch of 53.2% or 568 t (95% CI, 498 to 646 t). The modelled decline in catch across flow patterns 2 to 4 were similar, ranging from 371 to 426 t (95% CI, 313 to 482 t). During high and very high flows the predicted catch was lower in terms of percentage, 9%, but the larger observed catch associated with years of high flows meant predicted catch declined between 305 and 349 t (95% CI, 223 to 524 t), respectively.

Discussion

We investigated the potential impact of water extraction scenarios on the commercial catch of banana prawns in the economically important Northern Prawn Fishery. The scenarios modelled water extraction induced-changes in seasonal river flows within three catchments in a wet-dry tropical region. We found a greater decline as measured by both percent and quantity in banana prawn catch across all extraction scenarios in years with low to medium river flows than those with high and very high flows. Previous research in this region has linked the variation in catch by using rainfall as proxy for flow or modelled temporal changes in flow from only one or two rivers (e.g. Vance et al, 1985; Staples & Maliel, 1994; Vance et al, 2003; Venables et al, 2011; Duggan et al, 2019). Despite differences in statistical approaches between previous studies and our Bayesian spatio-temporal model, we found some similarities in results. For example, a technical report that focussed only on the Flinders and Gilbert rivers and a larger geographical catch area found that a reduction in total flows of 852 GL resulted in a decline in catch from 3 to 13% (Bayliss et al, 2014). We predicted a decline in catch from between 0.7% (high flows) to 17.3% (low flows) in scenario B when a total 825 GL of water was extracted from the Mitchell, Gilbert and Flinders Rivers. Overall, our results show that managing water extraction during periods of extended low flows or drought conditions, like those seen in the region from 1985 to 1990, will be particularly challenging for ensuring sustained fishery yields.

Flow and catch

One of the most important findings of this study was the predicted proportional decline in banana prawn catch with decreasing flow-levels due to water extraction. In this fishery, annual profits are closely tied to the quantity of banana prawn catch, because market prices for banana prawns are exogenous to the fishery (Kompas et al, 2010). Our analyses of six flow-level patterns, delineating low, medium, high and very high flows showed that proportionally, catch was most impacted by water extraction during low flows (Figure5d,e,f). Low catch years are when the economic viability of the fishery may be most sensitive to catch reductions (Kompas et al, 2010). For instance, we predicted that extracting water during low flows would see a year of already poor catch (~1070 t) and a potential revenue drop of 53%. With the current 52 licensed vessels fishing in the NPF, a predicted catch of less than 10 t per vessel would adversely impact the livelihoods of many fishers.

We also found the catch of banana prawns was driven by different patterns in wet-season river flows both across years and across the three rivers (Table 3). When two or more rivers had medium to very high flows regional catch was higher. The current understanding is that in years with high flows, combined with the Gulf of Carpentaria’s shallow coastal bathymetry, salinity levels are reduced to below the physiological tolerance for banana prawns both within in estuarine and near-shore areas (Staples & Vance, 1986; Vance et al, 1998). It is also possible that periods of sustained low salinity due to high freshwater flows may prevent recently emigrated juvenile banana prawns from returning to their preferred near-shore habitats. The food supply for banana prawns (benthic animals) in the estuaries is also impacted by low salinity, resulting in major reductions in food availability (Duggan et al, 2014, 2019). The estuarine benthic community is only re-established as salinity increases during the dry season. These conditions are likely to force banana prawns to grow and mature in deeper waters where they are available to the fishery. High flows may also benefit banana prawns by stimulating coastal production at the base of the food-web and protection from many predators from increased levels of turbidity, enhancing banana prawn growth and survival (Griffiths et al, 2007; Burford et al, 2009). The opposite was also true, low flows in two or more rivers produced lower catch. Within marine-equivalent estuaries, it is likely that without a low salinity mechanism triggering or forcing emigration, banana prawns remained in estuarine or near-shore coastal areas or were simply inaccessible to the fishery (Haywood and Staples, 1993; Wang et al, 1999; Burford et al, 2010).

The predicted decline in catch in scenario C (Mitchell instream dams) was surprising because many years of catch data have consistently shown relatively low catch in the vicinity of the Mitchell River, suggesting that flow from the Mitchell River had a limited influence on catch (Laird, 2018). Past analyses have had difficulty demonstrating a relationship between Mitchell River flow and adjacent banana prawn catch or have shown a low contribution of flow (using rainfall as a proxy) to eventual commercial catch (Vance et al, 1985, 2003). Alternatively, it could also be a sign of the Mitchell's considerable importance in the hydrodynamics of the Gulf of Carpentaria. In the south-eastern region, seasonal river flows produce large jets of freshwater that interact with Coriolis forces, tidal and wind driven currents, and generate salinity driven currents that move and mix lower salinity water in a southerly direction (Wolanski, 1993). We hypothesise that juvenile banana prawns emigrating from the Mitchell River were forced toward the Gulf of Carpentaria's southern coastal boundary as a result of a low salinity water mass moving south. Thus, banana prawn catch near the Mitchell estuary will be low because juvenile banana prawns that used it as a nursery are potentially recruited to the fishery over 100 km away. Further research is required to fully understand the effect of river flows on regional hydrodynamics, the migration of juvenile banana prawns and the spatial distribution of catch.

Management implications

In the Gulf of Carpentaria, it is common for years of higher flows to be separated by 4 to 7 years of low flows or periods of drought (Figure 3d,e,f). This variability in river flow has considerable management implications in balancing the needs of upstream agricultural development and downstream users like the Northern Prawn Fishery. Under all of the modelled water resource development scenarios water extraction from wet season high and very high flows would have minimal impact on banana prawn catch. Extracting water during periods high flows could sustain the needs of upstream agriculture if there was enough storage capacity to last through periods of low flows or drought. The protection of low flows, in conjunction with water extraction from high flows has the capacity to serve the needs of both current users of catchment flows (such as fisheries) and irrigated agriculture should it become established within the catchments. One of the methods used to protect low flows is to set a minimum flow or trigger level below which water extraction must reduce or cease (Kenyon et al, 2018). Trigger levels should be set quantitatively, deploying the latest empirical studies and modelling to define a rigorous flow level that supports ecosystem stability in each river and catchment (see Bayliss et al, 2014; Petheram et al, 2018; Pollino et al, 2018a, b; Duggan et al, 2019).

Model testing and limitations

A novel component of this study was the use of SOI, cyclones and OLR climate indices as non-linear predictors of ocean-atmosphere interactions that influence banana prawn catch. We compared multiple models with different climate covariates, but in general, there was little difference between these models (Supplementary data A: Figure4, Table 2). The relatively small difference in model performance indicated possible confounding between climate predictors (Figure3a,b,c). Confounded climate predictors could also explain the poor predictive performance of models with two or more climate covariates from increased model instability. The main source of confounding was likely related to climate patterns operating at local and regional scales, captured by the cyclones and OLR indexes, and the ENSO (SOI) oscillating over larger spatial scales. We found some evidence of a 10- to 15-year oscillation where a negative SOI was correlated with a 25% increase in the intensity of cyclones that occurred one month earlier in the season, and a decrease in regional atmospheric convection measured by an increase in OLR of 10 W/m^2.

The frequent presence of cyclones and tropical storms in the Gulf of Carpentaria was another potential source of confounding from changes in fisher behaviour influencing catch. The effects of changes in fishing effort due to cyclones and tropical storms was largely minimised by the banana prawn fishing season starting at the transition from wet to dry seasons, which meant extreme weather events at this time of year are rare (Figure3b). Though cyclones occur less frequently at this time of year there were two fishing seasons, 1984 and 2006 that were interrupted by cyclones. In late March 1984 severe winds from cyclone Kathy caused damage to some boats in the fishing fleet from the Sir Edward Pellow group of islands in western region of the Gulf of Carpentaria. Similarly, during the peak banana season in late April 2006, cyclone Monica caused some of the fleet to stop fishing and seek sheltered waters. Both the 1984 and 2006 fishing seasons were included in our models because cyclone Kathy and Monica were tracked over 400 km away from our study region and had a lower impact on fishing in the south-eastern Gulf of Carpentaria (BOM, 2020).

Including flow from other major rivers should improve the model's predictive power and reduce the variability associated with predictions. Using catch data only instead of CPUE was not ideal and unfortunately obtaining better data was not possible due its commercial sensitivity. We also did not consider the possibility of population collapse resulting from one or more years of low flows. Future studies would benefit from a more complete data set where spatial discrepancies with fishing effort could be accurately resolved.

Future directions

Further exploring the links between climate and the spatio-temporal dynamics of banana prawn populations may be an area of future research that could provide valuable insights into the impact of climate change on fisheries in the region. The model could also be extended to other fishing areas, species and environmental covariates. While these points identify avenues for future research, this current modelling provides managers and decision makers with substantial information about the implications of potential development that can be integrated into water planning processes.

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Table 1. Summary of the water extraction scenarios used to model the effect of changes in river flows on the commercial prawn catch.

Scenario	Description	Flinders	Gilbert	Mitchell
		Water extracted (GL)		
A Granted entitlements	Full use of all surface water entitlements that have been granted as part of the water planning process. In this scenario surface water is mainly pumped to locations throughout each catchment.	206	126	20
B Planned allocations	Full use of all future planned surface water allocations including those licenses already granted. Surface water could be extracted by either pumping or building instream dams.	266	489	70
C Mitchell instream dams	The construction of multiple major instream dams in the Mitchell River could release 2,800 GL of water for consumption. Water extraction at this level would see total EOS flows reduced by around 3,425 GL. This scenario includes the full use of all planned and granted water allocations.	266	489	3,425

Table 2. Descriptive statistics generated from the *k*-means classification of the Flinders, Gilbert and Mitchell river flows from 1900 to 2011.

River	Category	Range (GL)	Mean (GL)	Median (GL)
Flinders	Low	0 – 1,602	540	335
	Medium	1,743 – 4,216	2,883	2,758
	High	5,120 – 9,772	7,113	6,876
	Very high	13,435 – 24,918	18,234	16,349
Gilbert	Low	55 – 2,410	1,221	1,399
	Medium	2,506 – 5,689	3,734	3,591
	High	6,131 – 10,966	8,231	7,915
	Very high	16,167 – 34,735	22,716	17,246
Mitchell	Low	2,095 – 8,503	4,975	4,691
	Medium	9,262 – 16,654	12,946	12,525
	High	17,049 – 25,130	21,022	20,642
	Very high	30,220 – 54,255	38,467	38,282

Table 3. Categorised flow patterns identified by using *k*-means clustering on the 1900 to 2011 EOS flow data set for the Flinders, Gilbert and Mitchell Rivers. The number of years each flow pattern occurred, and percentage of total years are shown for flow data from 1900 to 2011 and the study period from 1984 to 2011.

Flow pattern	Flinders	Gilbert	Mitchell	All Years 1900-2011	%	Study Years 1984-2011	%
1	low	low	low	25	22	5	18
2	low	low	medium	11	10	4	14
3	low	medium	high	7	6	3	11
4	medium	medium	medium	13	12	2	7
5	low	medium	low	6	5	2	7
6	medium	medium	high	5	4	2	7
7	low	medium	medium	9	8	1	4
8	high	high	high	5	4	1	4
9	low	high	medium	2	2	1	4
10	very high	very high	very high	2	2	1	4
11	medium	low	low	1	1	1	4
12	high	low	low	1	1	1	4
13	medium	high	medium	1	1	1	4
14	very high	very high	high	1	1	1	4
15	medium	high	very high	1	1	1	4
16	medium	very high	very high	1	1	1	4
				91	81	28	100

Table 4. Comparison of model statistics to assess each model's performance with different combinations of random walks on SOI, OLR or cyclone covariates using WAIC, LPML and RMSE. All of the models include PCA transformed river flows.

Model	Climate covariates	WAIC	LPML	RMSE	$RMSE_{Train}$	$RMSE_{Test}$
				(t/year prawn catch)		
1	None	24,949.6	-12,469.8	503.5	502.3	526.9
2	SOI	24,831.1	-12,415.6	320.4	336.1	511.0
3	OLR	24,819.6	-12,409.8	326.2	344.4	478.7
4	Cyclones	24,885.2	-12,442.6	442.4	426.6	547.4
5	SOI + OLR	24,814.6	-12,407.3	300.2	317.0	503.1
6	SOI + Cyclones	24,825.4	-12,412.7	311.8	322.9	516.1
7	OLR + Cyclones	24,817.7	-12,408.9	316.5	329.3	500.9
8	SOI + OLR + Cyclones	24,813.9	-12,406.9	295.0	308.1	580.6

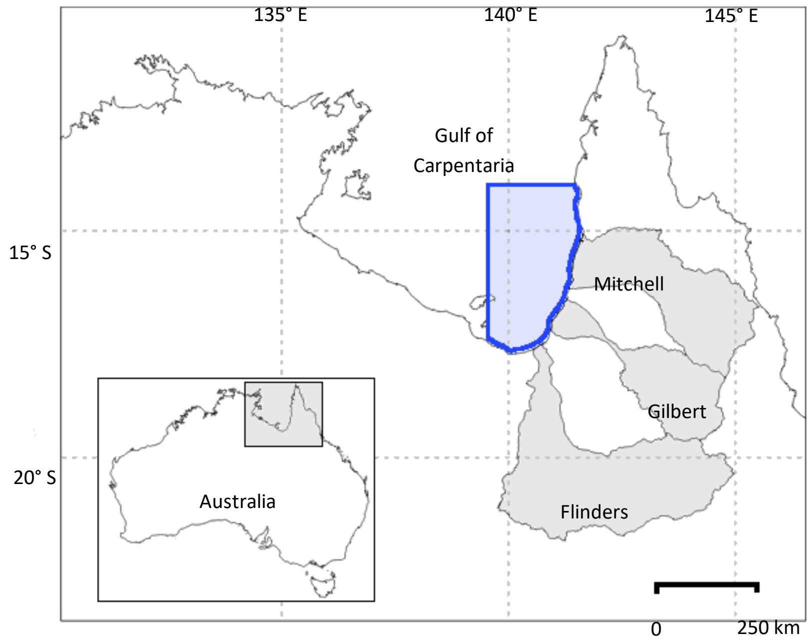


Figure 1. Map of the Gulf of Carpentaria with the Mitchell, Gilbert and Flinders catchments shown in the grey shaded areas and the blue shaded area shows the region of the study.

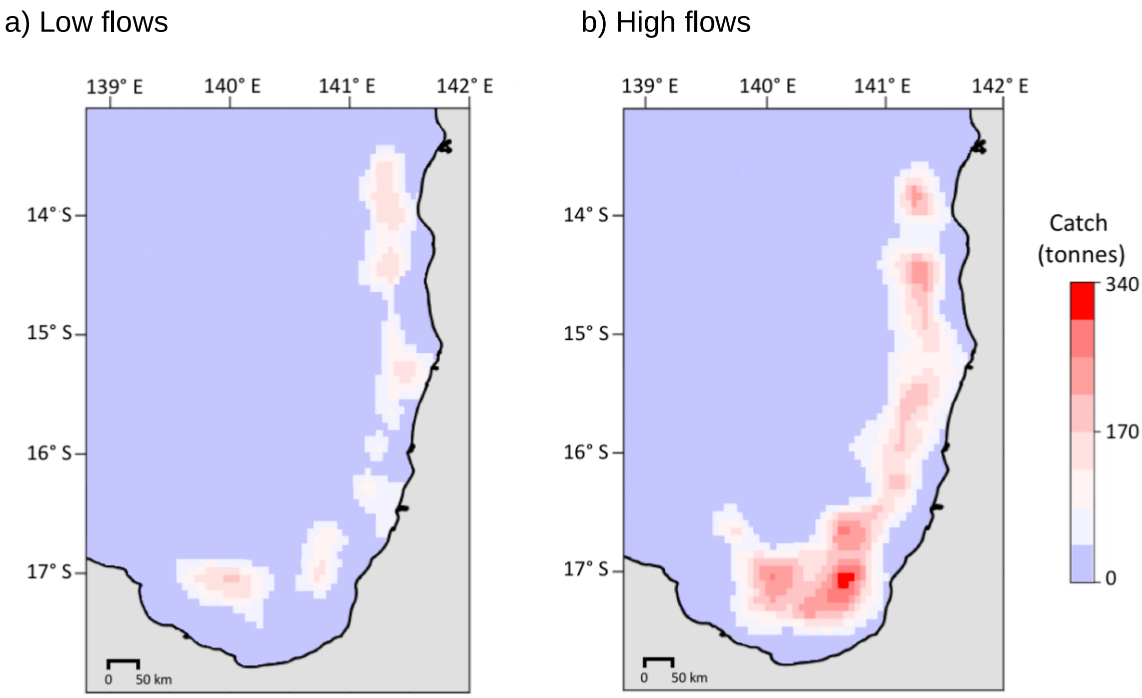


Figure 2. Spatial distribution of the mean banana prawn catch with discharge from the Mitchell, Gilbert and Flinders rivers for years grouped by a) low flows, and b) high flows .

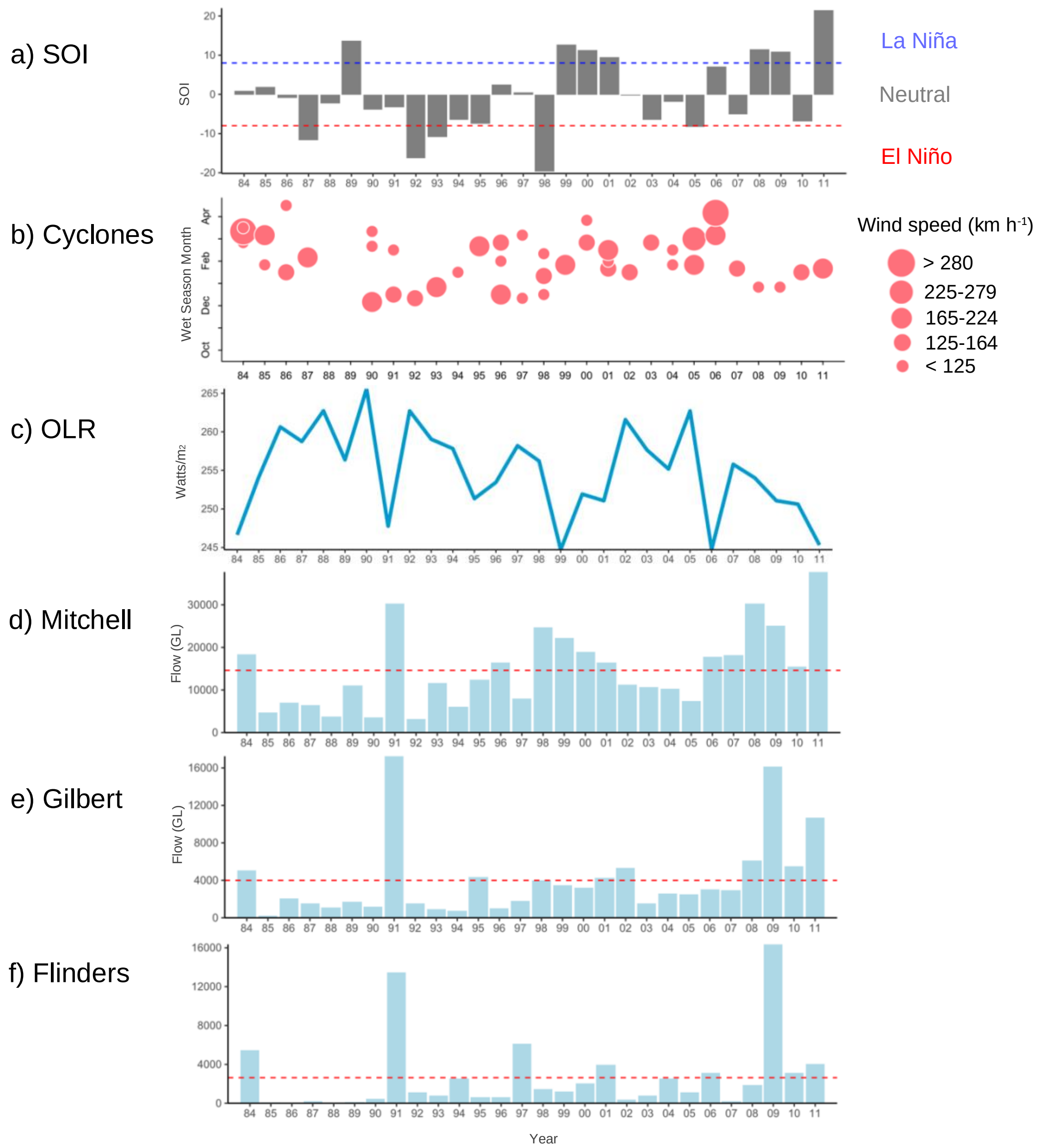


Figure 3. Interannual variability in climate and river flows during the wet season from October to April from 1984 to 2011. a) the average Southern Oscillation Index was categorised into El Niño, Neutral or La Niña phases of the ENSO cycle, b) cyclones that were found to occur within and around the Gulf of Carpentaria and river catchments, c) the average outgoing longwave radiation represents atmospheric convection above the region, lower values indicate greater convection. The modelled end of system flow for each year and average annual flow, indicated by the red dashed line, for the d) Mitchell, e) Gilbert, and f) Flinders Rivers.

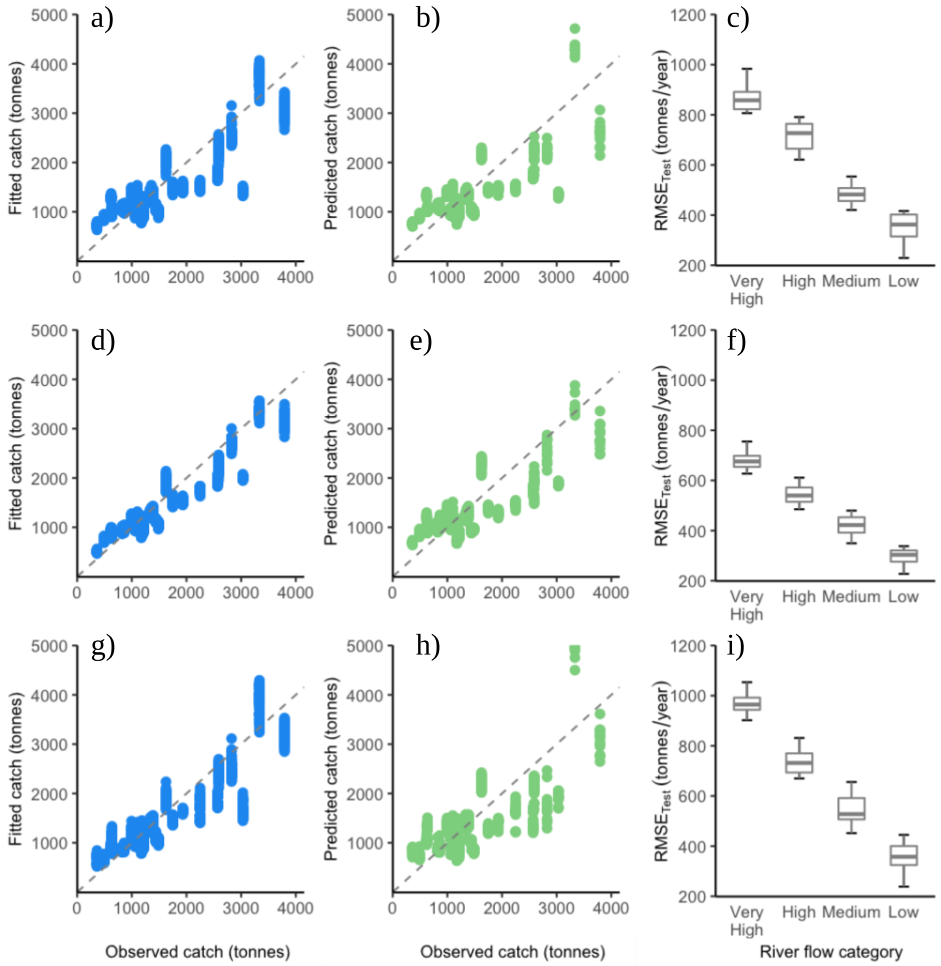


Figure 4. Comparison of observed versus fitted annual catch, observed versus predicted annual catch, and boxplots representing model sensitivity, from 100 cross-validation runs for: a,b,c) Model 1 (no climate covariates); d,e,f) Model 3 (OLR); and g,h,i) Model 4 (cyclones). For a, d and g, observed annual catch versus the fitted training data; b,e,h) Observed annual catch versus model predictions from the hold out data; c,f,i) The box plots show the distribution of predictive performance of specific years grouped as low, medium, high and very high flows. Those box plots with smaller ranges and a lower mean value of $RMSE_{Test}$ were less sensitive to the combination of flow categories that were present in each training data set.

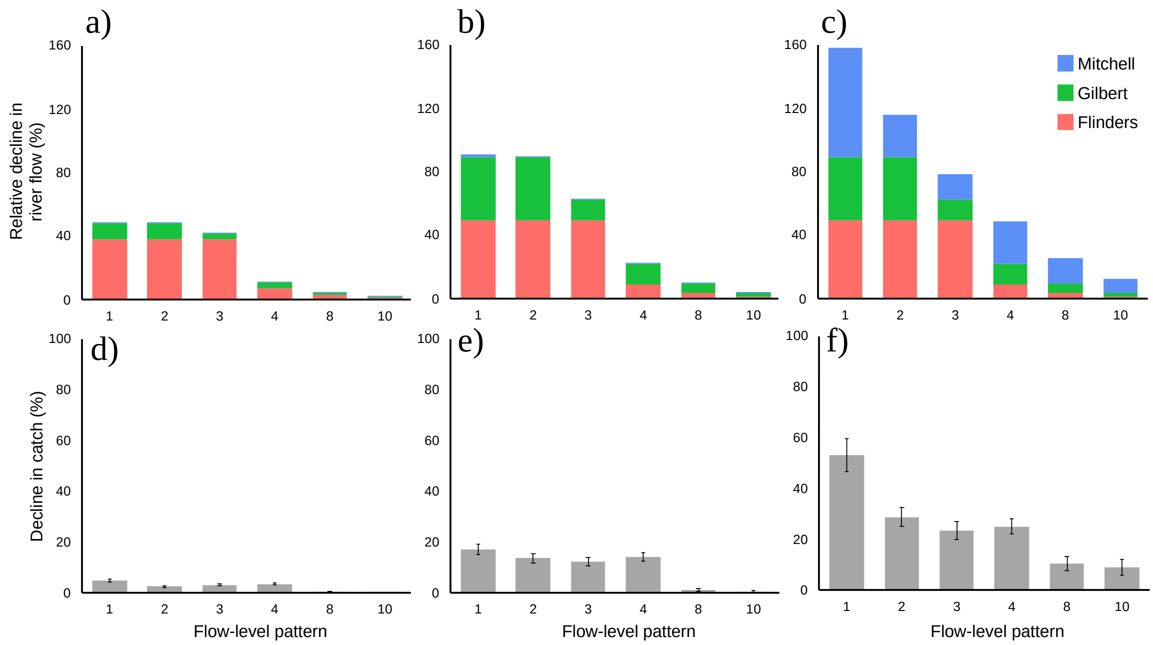


Figure 5. The relative decline in flow as a percentage of mean end of system flow for the Flinders (red), Gilbert (green) and Mitchell (blue) rivers, and the predicted change in catch for flow-level patterns 1-4, 8 and 10 for water extraction scenarios: a,d) Scenario A - flow was reduced by 206 GL, 126 GL and 20 GL, respectively; b,e) Scenario B - flow was reduced by 266 GL, 489 GL and 70 GL, respectively; c,f) Scenario C - flow was reduced by 266 GL, 489 GL and 3,425 GL, respectively. The predicted decline in total banana prawn catch as a percentage of total catch with 95% confidence intervals (CI) are shown in d,e and f.

Supplementary data

PCA of river flows

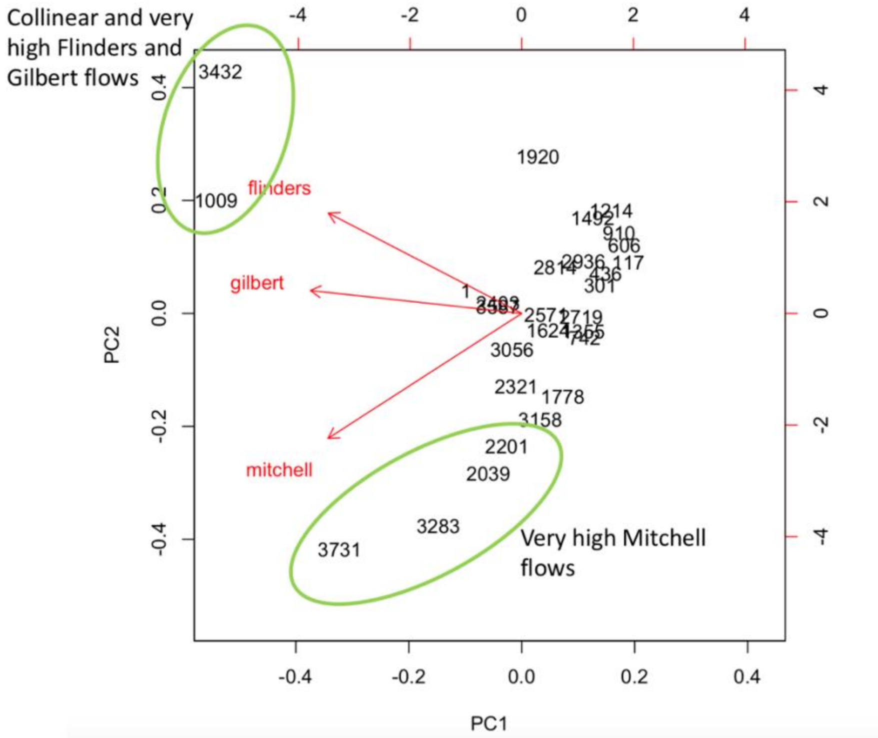


Figure 1. Principal Components Analysis (PCA) was used to transform Flinders, Gilbert and Mitchell river flows. The bi-plot shows the Flinders and Gilbert rivers are strongly correlated and they all have greater influence over PC1.

Table 1. The proportional and cumulative variance explained by each component of the PCA.

	PC1	PC2	PC3
Standard deviation	1.4630	0.6850	0.2671
Proportion of Variance	0.7984	0.1750	0.0266
Cumulative Proportion	0.7984	0.9734	1.0000

Test for temporal autocorrelation

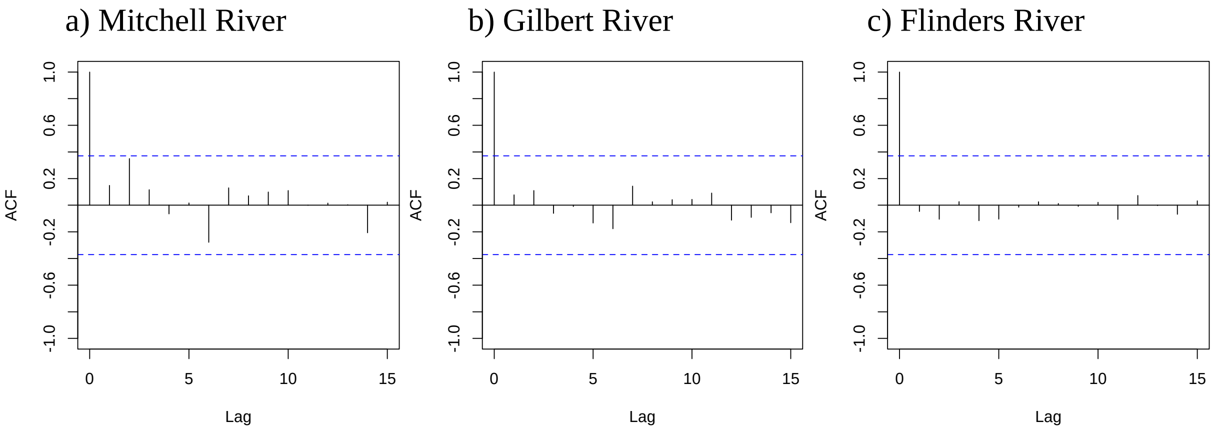


Figure 2. Autocorrelation for time lags up to 15 years for the end of system river flows from 1984 to 2011 in a) Mitchell River, b) Gilbert River and c) Flinders River. The blue dashed horizontal lines indicate the level that correlations are significantly different from zero. Correlations below the lines and closer to zero are not significant. Time lag 0 will always have a correlation of 1 and is plotted as a reference point.

Model spatial domain

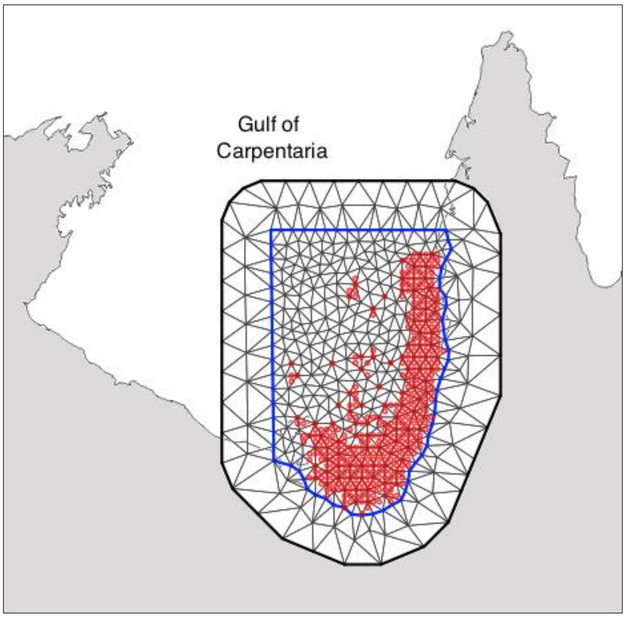
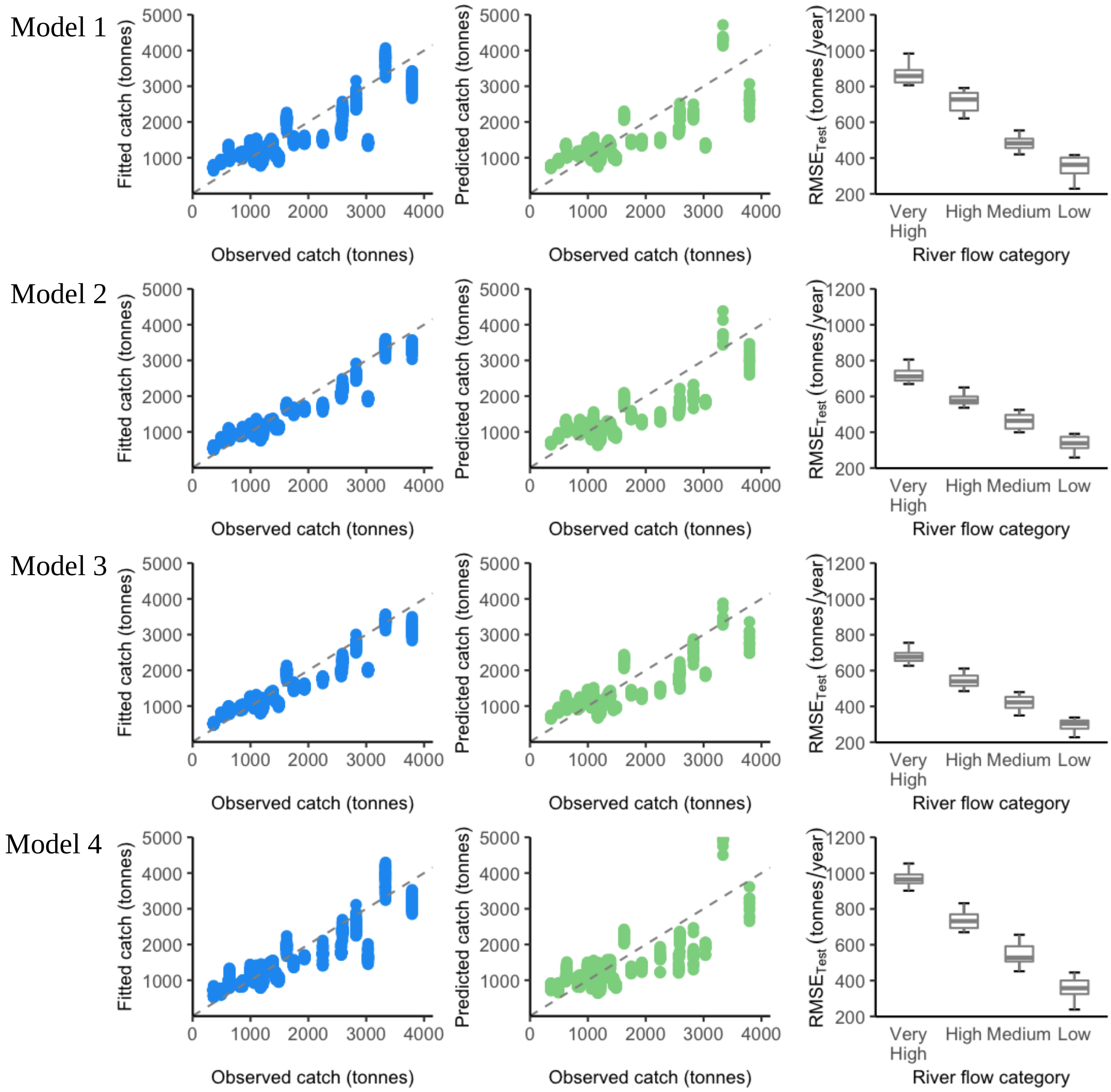


Figure 3. Constrained refined Delaunay triangulation of the banana prawn catch used for linear approximation in the spatial Bayesian model.

Results of cross validation



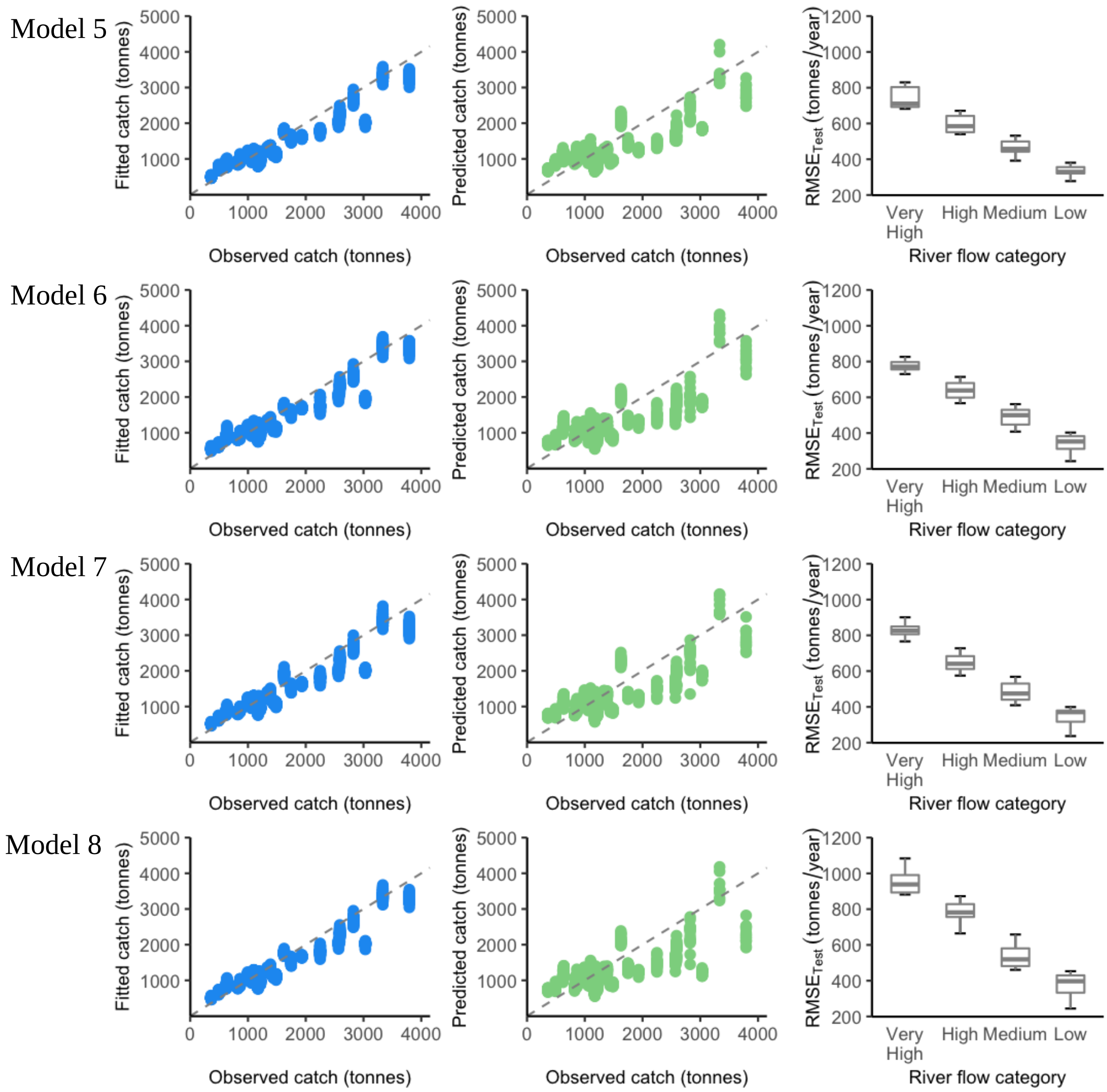


Figure 4. Comparison of observed versus fitted annual catch, observed versus predicted annual catch, and boxplots representing model sensitivity, from 100 cross-validation runs for model1 to 8. For the first column (blue), observed annual catch versus the fitted training data; The second column (green) observed annual catch versus model predictions from the hold out data; The box plots show the distribution of predictive performance of specific years grouped as low, medium, high and very high flows. Those box plots with smaller ranges and a lower mean value of $RMSE_{Test}$ were less sensitive to the combination of flow categories that were present in each training data set.

Posterior parameters

Table 2. Summary of model parameters for each model.

Model	Parameter	Mean	Sd	CI 95%	
				0.025	97.5
1 (No climate covariates)	Intercept	0.8360	0.4186	-0.1108	1.5652
	PC1	-0.1607	0.0143	-0.1889	-0.1329
	PC2	-0.1671	0.0314	-0.2290	-0.1056
	ρ (km)	99.70	29.67	54.91	170.70
	σ	1.204	0.1459	0.9433	1.519
	ϕ_{Gamma}	1.2837	0.0124	1.2593	1.3077
2 (SOI)	Intercept	0.8049	0.4254	-0.1665	1.5370
	PC1	-0.2673	0.0441	-0.3576	-0.1835
	PC2	-0.3899	0.1155	-0.6341	-0.1787
	$RW1_{SOI}$	0.4865	0.0842	0.3429	0.6706
	ρ (km)	103.60	33.99	52.79	185.00
	σ	1.1610	0.1577	0.8210	1.5010
	ϕ_{Gamma}	1.2651	0.1220	1.2413	1.2892
3 (OLR)	Intercept	0.8230	0.4030	-0.0803	1.5329
	PC1	-0.1766	0.0301	-0.2356	-0.1172
	PC2	-0.2849	0.0636	-0.4117	-0.1614
	$RW1_{OLR}$	0.9916	0.1804	0.6858	1.3876

	ρ (km)	102.50	29.59	57.33	172.70
	σ	1.1430	0.1416	0.8956	1.4520
	ϕ_{Gamma}	1.2647	0.0123	1.2410	1.2890
4 (Cyclones)	Intercept	0.7799	0.4008	-0.1198	1.4832
	PC1	-0.1762	0.0315	-0.2400	-0.1161
	PC2	-0.2073	0.0460	-0.2991	-0.1182
	$RW1_{Cyclones}$	1.1005	0.1950	0.7614	1.5201
	ρ (km)	99.58	30.02	55.67	172.20
	σ	1.1490	0.1358	0.9128	1.4470
	ϕ_{Gamma}	1.2655	0.0123	1.2416	1.2896
5 (SOI+OLR)	Intercept	0.8270	0.3875	-0.0298	1.5161
	PC1	-0.2137	0.0502	-0.3228	-0.1266
	PC2	-0.3072	0.0833	-0.4818	-0.1522
	$RW1_{SOI}$	0.1120	0.1140	0.0227	0.2492
	$RW1_{OLR}$	0.8390	0.1855	0.5399	1.2584
	ρ (km)	101.00	30.95	55.40	175.60
	σ	1.1490	0.1406	0.9034	1.4550
	ϕ_{Gamma}	1.2644	0.0123	1.2402	1.2882
6 (SOI+Cyclones)	Intercept	0.7299	0.4385	-0.2425	1.5120
	PC1	-0.1864	0.0453	-0.2808	-0.1020
	PC2	-0.2027	0.0768	-0.3657	-0.0620
	$RW1_{SOI}$	0.2002	0.0770	0.0885	0.3722

	$RW1_{Cyclones}$	0.8167	0.2151	0.4779	1.3057
	ρ (km)	110.40	31.29	58.87	182.00
	σ	1.185	0.1626	0.8927	1.5310
	ϕ_{Gamma}	1.2642	0.0123	1.2396	1.2878
7 (OLR+Cyclones)	Intercept	0.7663	0.4437	-0.2340	1.5484
	PC1	-0.2281	0.0474	-0.3215	-0.1347
	PC2	-0.2318	0.0618	-0.3548	-0.1114
	$RW1_{OLR}$	0.3234	0.1410	0.1309	0.6082
	$RW1_{Cyclones}$	0.5255	0.1871	0.2564	0.9457
	ρ (km)	113.00	32.40	59.45	185.80
	σ	1.1950	0.1738	0.8771	1.5580
	ϕ_{Gamma}	1.2639	0.0123	1.2399	1.2880
8 (SOI+OLR+Cyclones)	Intercept	0.7243	0.5795	-0.5604	1.7003
	PC1	-0.2185	0.0500	-0.3238	-0.1276
	PC2	-0.2760	0.0811	-04433	-0.1215
	$RW1_{SOI}$	0.0728	0.0695	0.0182	0.2551
	$RW1_{OLR}$	0.8676	0.1799	0.5554	1.2490
	$RW1_{Cyclones}$	0.0527	0.0429	0.0712	0.9050
	ρ (km)	100.60	44.85	28.51	195.00
	σ	1.1690	0.2676	0.6585	1.6780
	ϕ_{Gamma}	1.2636	0.0122	1.2398	1.2877

Back-transformation of flow covariates

Table 3. Back-transformed values of PC1 and PC2 by projecting onto the PCA coordinate system using the same rotation matrix as the observed river flows.

Model	PC1	PC2	Flinders	Gilbert	Mitchell
			GL/year		
1	-0.1607	-0.1671	2,781.51	4,673.71	17,011.35
2	-0.2673	-0.3899	2,457.39	4,826.99	19,146.88
3	-0.1766	-0.2849	2,516.61	4,642.22	17,931.59
4	-0.1762	-0.2073	2,714.40	4,690.98	17,377.39
5	-0.2137	-0.3072	2,545.26	4,731.07	18,281.77
6	-0.1864	-0.2027	2,794.75	4,722.30	17,397.31
7	-0.2281	-0.2318	2,771.63	4,819.57	17,819.62
8	-0.2185	-0.2760	2,636.25	4,764.48	18,084.56

Model predictions for water extraction scenarios

Table 4. The predicted change in catch for water extraction scenario A, granted entitlements. The mean flow of the Flinders, Gilbert and Mitchell rivers for flow-level patterns 1-4, 8 and 10 was reduced by 206 GL, 126 GL and 20 GL, respectively. The predicted decline in total banana prawn catch as a percentage of total catch and in tonnes with 95% confidence intervals (CI) are shown.

Flow-level pattern	Flinders		Gilbert		Mitchell		Decline in catch	
	Flow	Change in mean flow (GL)	Flow	Change in mean flow (GL)	Flow	Change in mean flow (GL)	%	Tonnes (CI 95%)
1	Low	540-	Low	1,221-	Low	4,975-	4.9	52.2 (45.3-59.9)

		334		1,100		4,955		
2	Low	540-334	Low	1,221-1,100	Medium	12,946-12,926	2.7	34.7 (30.4-39.5)
3	Low	540-334	Medium	3,734-3,613	High	21,022-21,002	3.2	51.6 (44.7-59.1)
4	Medium	2,883-2,677	Medium	3,734-3,613	Medium	12,946-12,926	3.6	56.7 (49.4-65.2)
8	High	7,113-6,907	High	8,231-8,110	High	21,022-21,002	0.7	22.5 (16.7-35.4)
10	Very high	18,234-18,028	Very high	22,716-22,595	Very high	38,467-38,447	0.1	5.2 (3.4 -15.9)

Table 5. The predicted change in catch for water extraction scenario B, granted entitlements. The mean flow of the Flinders, Gilbert and Mitchell rivers for flow-level patterns 1-4, 8 and 10 was reduced by 206 GL, 126 GL and 20 GL, respectively. The predicted decline in total banana prawn catch as a percentage of total catch and in tonnes with 95% confidence intervals (CI) are shown.

Flow-level pattern	Flinders		Gilbert		Mitchell		Decline in catch	
	Flow	Change in mean flow (GL)	Flow	Change in mean flow (GL)	Flow	Change in mean flow (GL)	%	Tonnes (CI 95%)
1	Low	540-334	Low	1,221-1,100	Low	4,975-4,955	4.9	52.2 (45.3-59.9)
2	Low	540-334	Low	1,221-1,100	Medium	12,946-12,926	2.7	34.7 (30.4-39.5)
3	Low	540-334	Medium	3,734-3,613	High	21,022-21,002	3.2	51.6 (44.7-59.1)
4	Medium	2,883-2,677	Medium	3,734-3,613	Medium	12,946-12,926	3.6	56.7 (49.4-65.2)

8	High	7,113-6,907	High	8,231-8,110	High	21,022-21,002	0.7	22.5 (16.7-35.4)
10	Very high	18,234-18,028	Very high	22,716-22,595	Very high	38,467-38,447	0.1	5.2 (3.4 -15.9)

Table 6. The predicted change in catch for water extraction scenario C, granted entitlements. The mean flow of the Flinders, Gilbert and Mitchell rivers for flow-level patterns 1-4, 8 and 10 was reduced by 266 GL, 489 GL and 3,425 GL, respectively. The predicted decline in total banana prawn catch as a percentage of total catch and in tonnes with 95% confidence intervals (CI) are shown.

Flow-level pattern	Flinders		Gilbert		Mitchell		Decline in catch	
	Flow	Change in mean flow (GL)	Flow	Change in mean flow (GL)	Flow	Change in mean flow (GL)	%	Tonnes (CI 95%)
1	Low	540-274	Low	1,221-732	Low	4,975-1,550	53.2	568.5 (498.8-646.3)
2	Low	540-274	Low	1,221-732	Medium	12,946-9,521	28.8	373.5 (323.8-430.1)
3	Low	540-274	Medium	3,734-3,245	High	21,022-17,597	23.4	371.4 (313.3-436.8)
4	Medium	2,883-2,617	Medium	3,734-3,245	Medium	12,946-9,521	27.0	425.7 (376.1-482.0)
8	High	7,113-6,847	High	8,231-7,742	High	21,022-17,597	9.4	305.3 (223.3-414.4)
10	Very high	18,234-17,968	Very high	22,716-22,227	Very high	38,467-35,042	9.0	348.7 (227.2-524.2)

Appendix 4: Maps of nutrient concentrations in three rivers

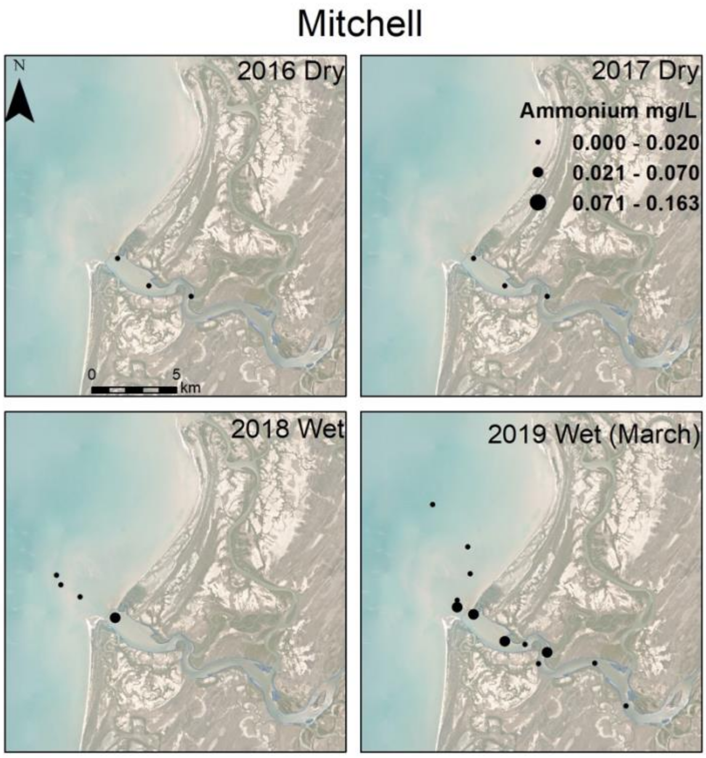


Figure A4-1. Ammonium concentrations (mg L^{-1}) in transects in Mitchell River estuary and nearshore.

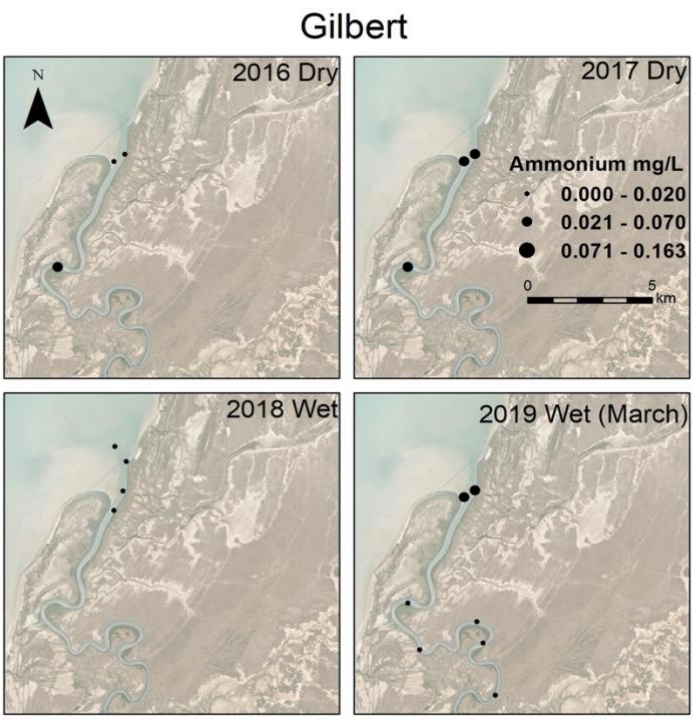


Figure A4-2. Ammonium concentrations (mg L^{-1}) in transects in Gilbert River estuary and nearshore.

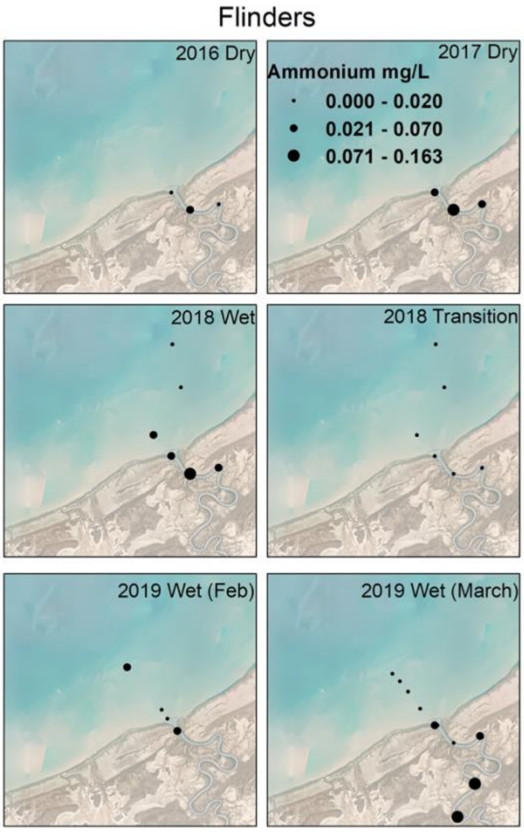


Figure A4-3. Ammonium concentrations (mg L^{-1}) in transects in Flinders River estuary and nearshore.

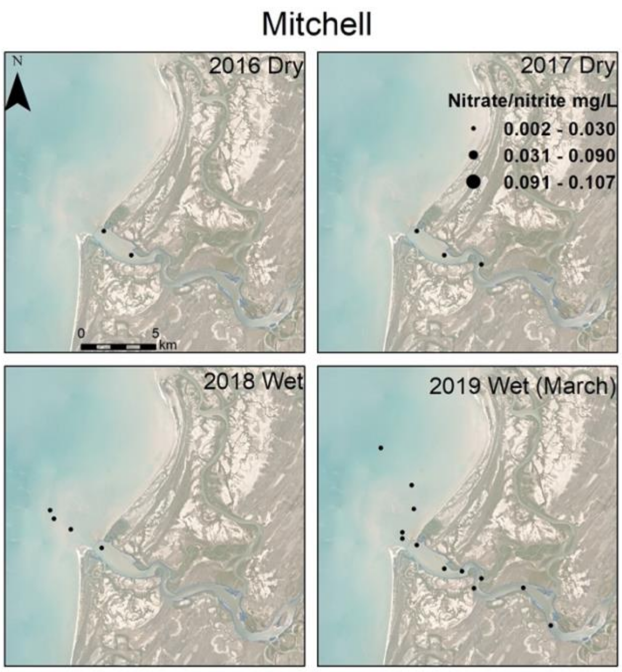


Figure A4-4. Nitrate/nitrite concentrations (mg L^{-1}) in transects in Mitchell River estuary and nearshore.

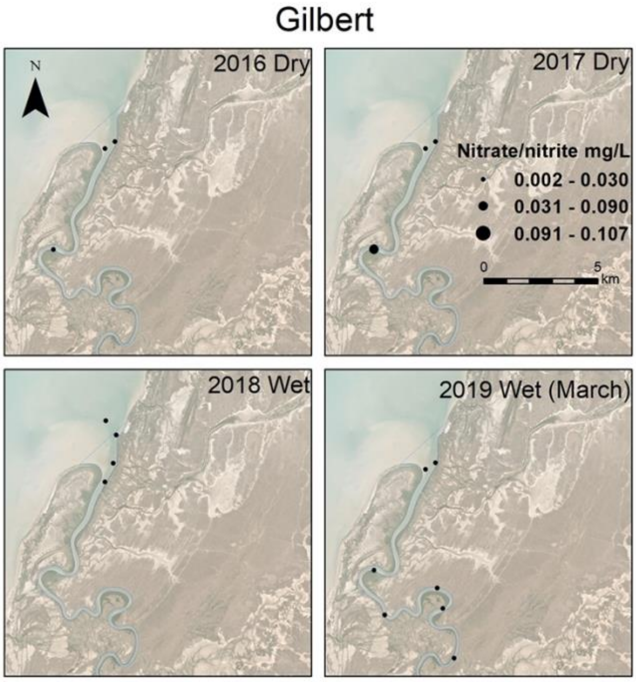


Figure A4-5. Nitrate/nitrite concentrations (mg L-1) in transects in Gilbert River estuary and nearshore.

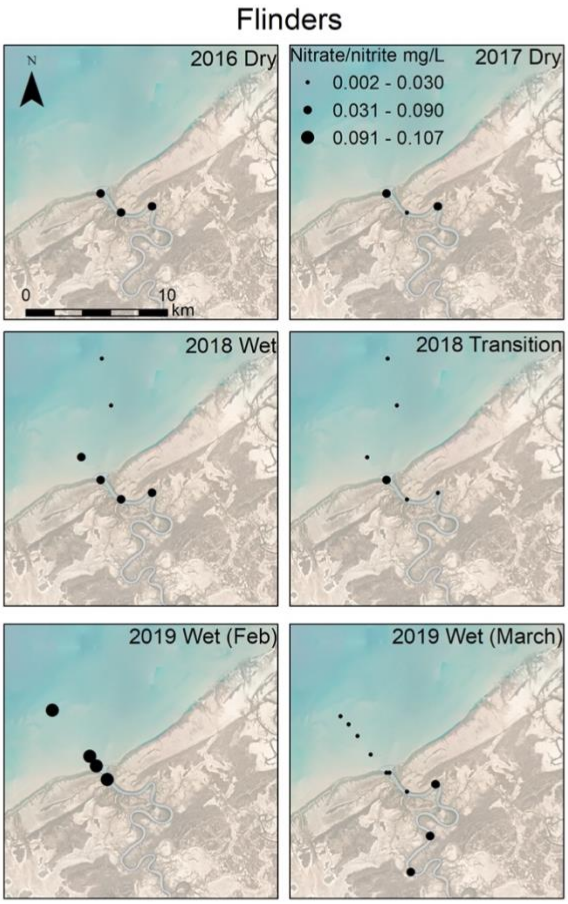


Figure A4-6. Nitrate/nitrite concentrations (mg L-1) in transects in Flinders River estuary and nearshore.

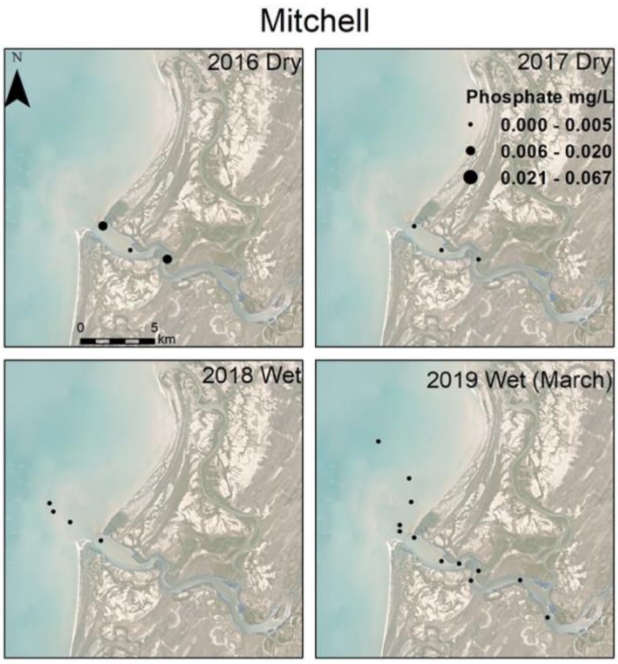


Figure A4-7. Phosphate concentrations (mg L-1) in transects in Mitchell River estuary and nearshore.

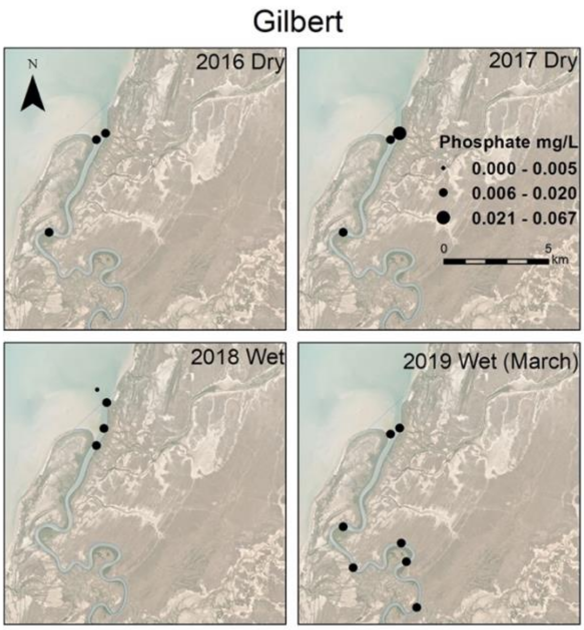


Figure A4-8. Phosphate concentrations (mg L-1) in transects in Gilbert River estuary and nearshore.

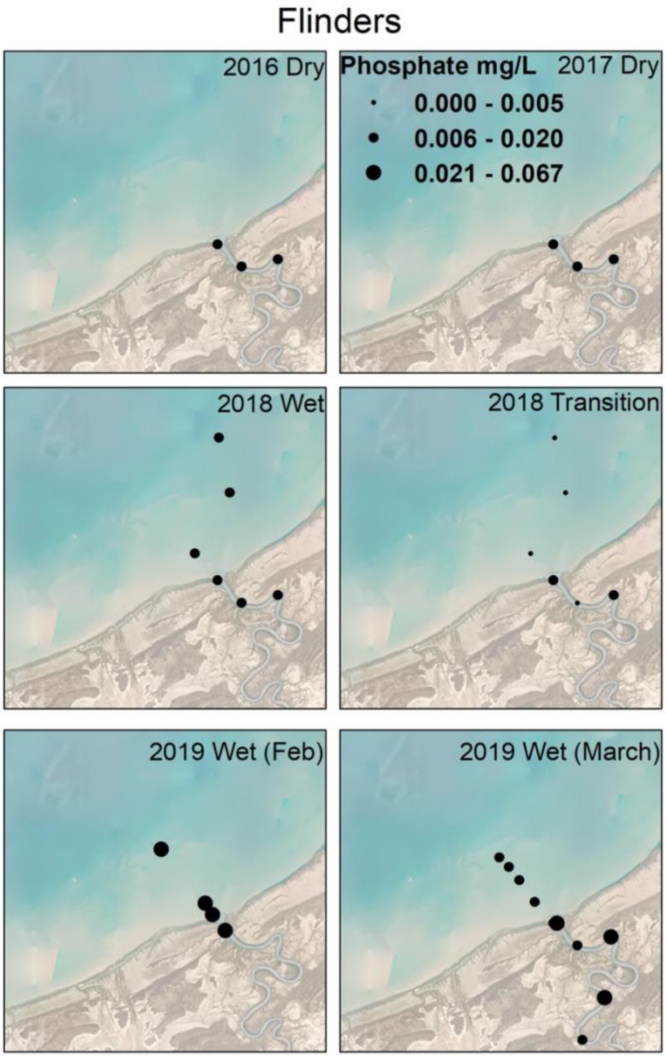


Figure A4-9. Phosphate concentrations (mg L-1) in transects in Flinders River estuary and nearshore.

Appendix 5: Mudflat and sandflat grain size analysis

Table A5-1. Grain size analysis for samples collected at routine sediment sampling sites in mudflat and sandflat in each estuary system.

Date	River		0-2µm (%)	2-10µm (%)	10-63µm (%)	63-200µm (%)	200-2000µm (%)	>2000µm (%)
Nov-16 (dry)	Mitchell	mudflat	4.8 (2.0)	35.5 (13.4)	29.8 (6.9)	20.9 (12.3)	8.7 (10.1)	0.05 (0)
	Gilbert	mudflat	10.5 (5.2)	42.2 (9.5)	34.4 (4.5)	11.6 (10.7)	1.2 (2.1)	0.05 (0)
	Flinders	mudflat	25.8 (8.8)	27.6 (5.9)	29.9 (6.8)	15.6 (9.3)	1.5 (3.8)	0.05 (0)
Nov-17 (dry)	Flinders	mudflat	n/a	47.3 (12.4)	35.5 (10.6)	12.4 (7.9)	0.4 (0.5)	0.05 (0)
	Flinders	sandflat	n/a	0.9 (0.7)	1.3 (1.1)	20.7 (2.3)	76.3 (2.5)	0.05 (0)
	Gilbert	mudflat	n/a	45.3 (1.2)	39.0 (6.2)	11.0 (7.5)	0.1 (0)	0.05 (0)
	Gilbert	sandflat	n/a	1.0 (0.9)	0.8 (0.6)	51.3 (25.5)	46.7 (26.0)	0.05 (0)
	Mitchell	mudflat	n/a	36.0 (12.0)	34.3 (5.5)	12.5 (5.2)	14.2 (12.2)	0.05 (0)
	Mitchell	sandflat	n/a	3.3 (4.7)	6.0 (10.4)	43.0 (15.1)	46.7 (28.0)	0.05 (0)
Mar-19 (wet)	Mitchell	sandflat	n/a	0.01 (0)	0.1 (0)	31.3 (7.4)	68.0 (7.2)	0.05 (0)
	Gilbert	sandflat	n/a	12.5 (13.9)	19.7 (20.7)	38.0 (16.8)	28.7 (32.3)	0.05 (0)
	Gilbert	mudflat	n/a	43.3 (10.0)	33.3 (4.0)	17.7 (13.5)	1.9 (1.6)	0.05 (0)
	Flinders	sandflat	n/a	9.8 (9.9)	6.9 (5.7)	14.5 (17.8)	67.0 (21.0)	0.05 (0)
	Flinders	mudflat	n/a	34.3 (9.1)	25.3 (7.4)	27.0 (13.5)	4.7 (3.4)	0.05 (0)

Appendix 6: Size distribution of prawns

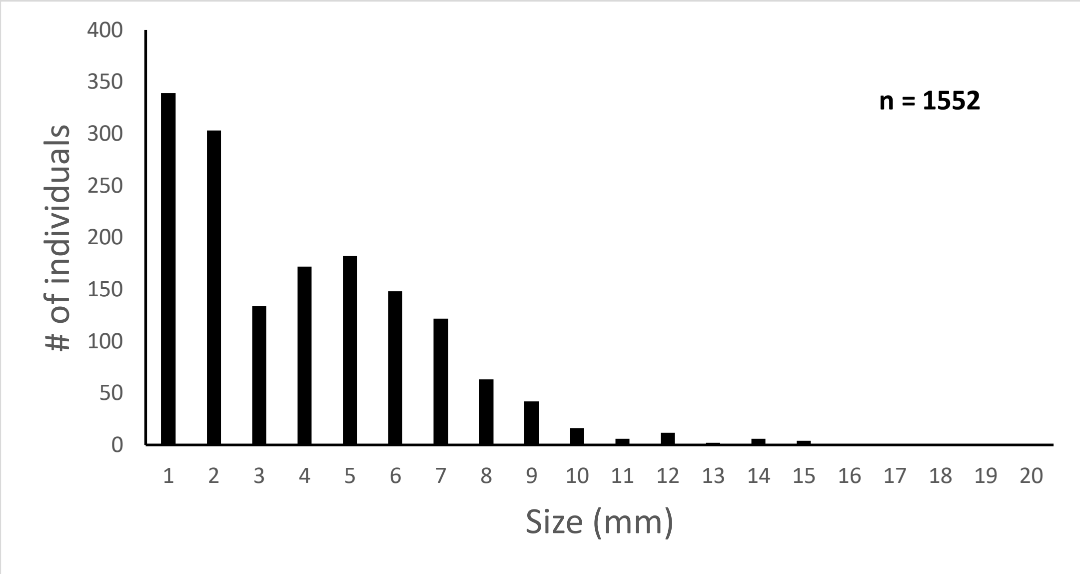


Figure A6-1. Length frequency (mm) of juvenile banana prawns (black columns) in the Mitchell River estuary in 2017.

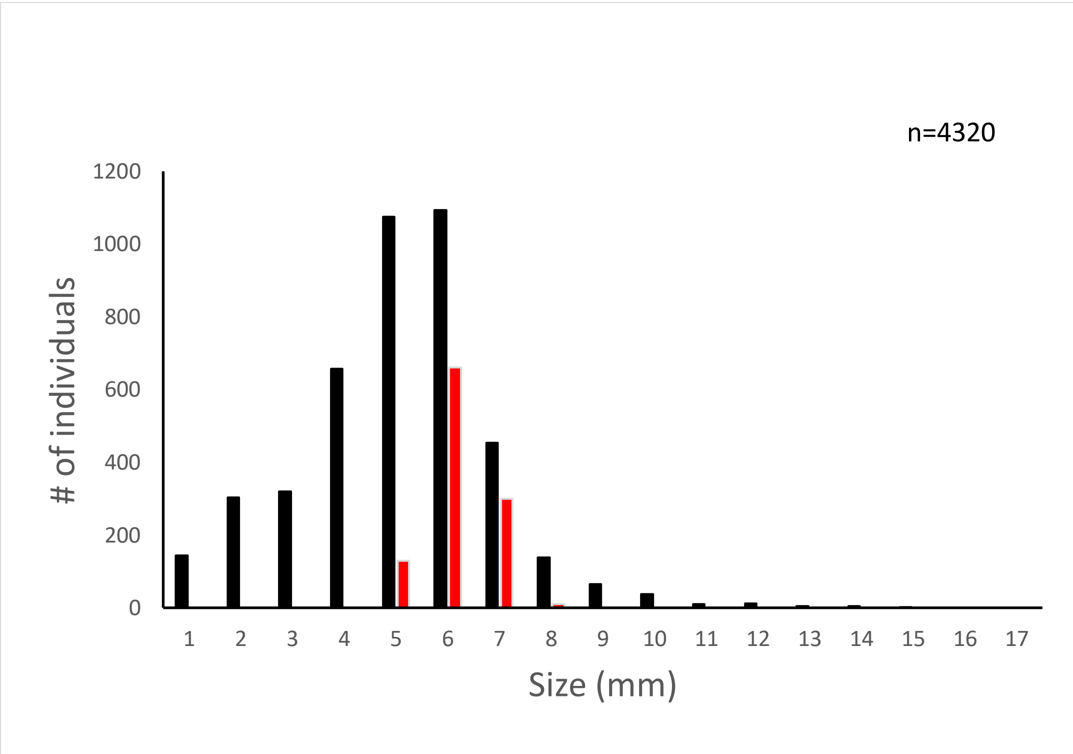


Figure A6-2. Length frequency (mm) of juvenile banana prawns (black columns) resident in the Gilbert River estuary and emigrant prawns (red columns) from the estuary in 2017.

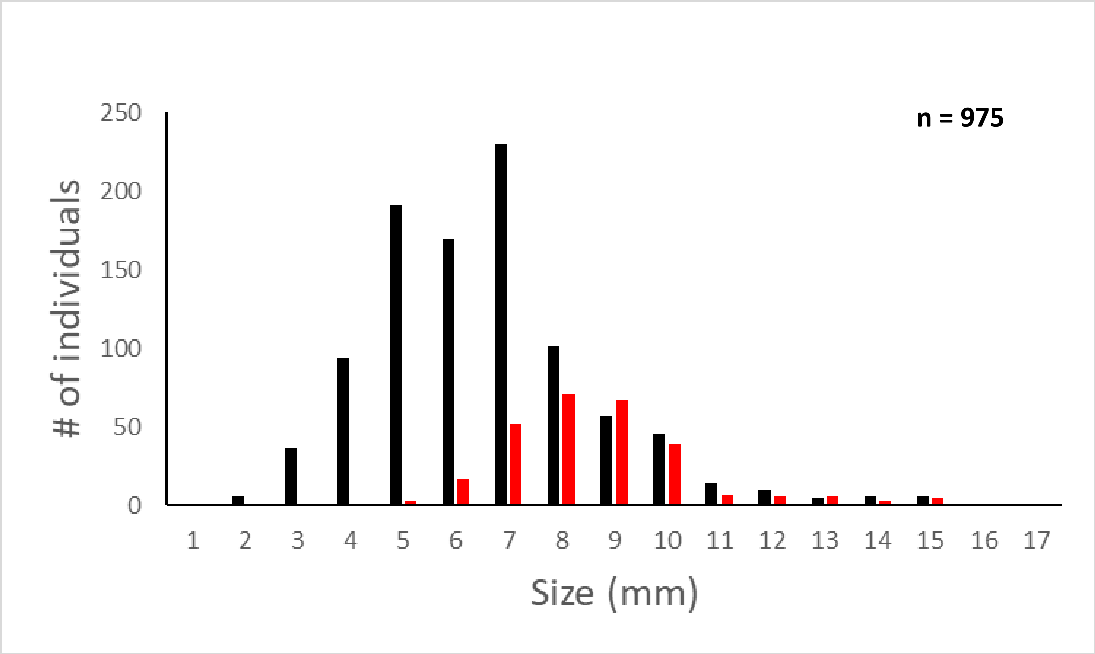


Figure A6-3. Length frequency (mm) of juvenile banana prawns (black columns) resident in the Flinders River estuary and emigrant prawns (red columns) from the estuary in 2017.

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