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The vulnerability of food supplies for migratory shorebirds to altered flow in the southern Gulf of Carpentaria

Final report

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CLCAC
CARPENTARIA LAND COUNCIL ABORIGINAL CORPORATION

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Contents

Acknowledgements iv

Executive summary 1

1. Introduction 4

1.1 Background 4

1.2 Objectives 5

1.3 Characterisation of study sites 6

2. Methodology 9

2.1 Food supply and productivity studies 9

2.2 Shorebird surveys 14

3. Results and discussion 18

3.1 Identify areas of high productivity within the river estuaries and adjacent mudflats 18

3.2 Quantify and compare food availability across three rivers potentially subject to flow alteration, and assess how flow affects food sources 20

3.3 Undertake shorebird surveys to determine comparative densities of migratory shorebirds at each estuary and, in the Flinders estuary, determine how this changes seasonally 25

4. Conclusions and recommendations 30

References 32

Appendix 1: Burford & Faggotter, 2021 paper published in Marine Pollution Bulletin 34

Appendix 2: Lowe et al. paper submitted to Estuarine, Coastal and Shelf Science 78

Appendix 3: Venarsky et al. paper submitted to Estuarine, Coastal and Shelf Science 80

Appendix 4: Queensland Wader Study Group shorebird surveys 82

Appendix 5: Carpentaria Land Council Aboriginal Corporation shorebird surveys 92

Figures

Figure 1.1. (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 Meteorology data).....7

Figure 1.2. Annual flow (GL) from 1984 to 2011, based on modelled end-of-system flow (adapted from Broadley et al., 2020). Red dashed line represents mean annual flow across the years. 8

Figure 2.1. Hydrograph (ML day^{-1}) in the 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. 9

Figure 2.2. Mitchell River mudflat and sandflat sampling sites for primary productivity (Google Earth). 12

Figure 2.3. Gilbert River mudflat and sandflat sampling sites for primary productivity (Google Earth). 12

Figure 2.4. Flinders River mudflat and sandflat sampling sites for primary productivity (Google Earth). 13

Figure 2.5. Photos showing examples of intertidal mudflats (left) and sandflats (right) at the mouth an estuary. Photos: Stephen Faggotter. 13

Figure 2.6. Shorebird counting from land and boat (Photos: Queensland Wader Study Group). 15

Figure 2.7. Low tide survey sites at the Mitchell, Gilbert and Flinders estuaries and nearshore environments done by the Queensland Wader Study Group (QSWG). Coloured regions show each survey track.....16

Figure 2.8. High tide roost sites at or near mouth of Flinders River regularly surveyed by the Carpentaria Land Council Aboriginal Corporation (CLCAC). 17

Figure 3.1. Effect of nutrient additions on primary production (mg O_2 m^{-2} h^{-1}) in bioassays using mud from mudflats of the three estuaries across all sampling trips. *P<0.05, **P<0.01, ***P<0.005. 19

Figure 3.2. Mean intertidal macrobenthos abundances (density ind m^{-2} ± SD) at three estuarine intertidal flats (sites 1–3) and three nearshore intertidal flats (sites 4–6) sampled at the Flinders River estuary during the end-dry season (2016–17), early-dry period (2018) and end-flood period (2019). No nearshore intertidal flats were sampled during the 2016 end-dry season. Dry season 1: 2016; dry season 2: 2017. 22

Figure 3.3. Intertidal macrobenthos relative abundance (% of total), stacked by major taxonomic groups within a) estuarine intertidal flats (sites 1–3) and b) nearshore intertidal flats (sites 4–6) sampled during the end-dry season (2016–17), early-dry period (2018) and end-flood period (2019) in the Flinders River estuary. No nearshore intertidal flats were sampled during the 2016 end-dry season.....23

Tables

Table 2.1. Summary of sampling trips to the Mitchell, Gilbert and Flinders River estuaries, and parameters measured. 11

Table 2.2. Details of shorebird surveys undertaken throughout study. 15

Table 3.1. Summary of characteristics and key findings for three estuaries in this study during the dry season, showing relative rankings for values. TP = total phosphorus, TN = total nitrogen. 20

Table 3.2. Abundance measures of intertidal macrobenthos reported in intertidal flats across Asia and Australia. Koppen Climate classification system used. Am = Tropical, monsoonal, Aw = Tropical, savanna, dry winter; BSh = Arid, Steppe, hot; BWh = Arid, desert, hot; Cfa = Temperate, without dry season, hot summer; Cwa = Temperate, dry winter, hot summer; Dwa = Continental, dry winter, hot summer. For details of references see Appendix 2. 24

Table 3.3. Comparison of dominant shorebird species and maximum counts in the three river systems. Count data in red exceed 1% threshold for international importance (Hansen et al., 2016). 26

Table 3.4. Summary of all counts from Flinders high tide roost sites. Species in red are listed as threatened under the EPBC Act 1999. Count data in red exceed the 1% threshold for international importance (Hansen et al. 2016). Boxes shaded blue denote migratory species.....29

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Executive summary

The Queensland Government has identified three river systems – the Flinders, Gilbert and Mitchell 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 is needed to ensure that water development is done in a sustainable way, and that economic and social trade-offs between agriculture and the downstream environment are well understood and made transparent.

The southern Gulf has been identified as a key Australian site for migratory shorebirds (Garnett, 1989; Driscoll, 1997, 2001, 2014). Migratory shorebirds use the Gulf intertidal flats for feeding on macrobenthos during summer months. However, there have been very few surveys of shorebirds in the Gulf (Driscoll, 2014). Additionally, little is known of the scale of the macrobenthic food supply, and the likely impact of water development on the sustainability of this food supply.

This National Environmental Science Program (NESP) project therefore examined the links between freshwater flow and estuarine and coastal productivity as a mechanism for understanding how changes in flow may impact shorebirds and their food supply in estuaries and adjacent coastal environments. A range of approaches were used, including measuring coastal and estuarine primary productivity and macrobenthos densities, based on sampling during a number of field trips. The premise is that this productivity is the fundamental underpinning of the resource needs of shorebirds. Additionally, shorebird surveys were conducted to assess the importance of the Flinders, Gilbert and Mitchell estuaries and nearshore as feeding sites for birds. This study complemented NESP Northern Australia Environmental Resources (NAER) Hub project 1.4 (Burford et al., 2020) which examined freshwater inputs to the three Gulf estuaries in the context of fisheries species, and some productivity data overlaps with outputs from project 1.4.

The primary productivity and macrobenthos components of the research are presented as published (Burford & Faggotter, 2021) and submitted papers (Lowe et al., submitted ECSS; Venarsky et al., submitted ECSS).

This study showed that freshwater flows had a number of impacts on primary productivity in the Flinders, Gilbert and Mitchell river estuaries and nearshore environment. In the short term, when wet season flooding was occurring, chlorophyll *a* concentrations in the water column and intertidal flats decreased as salinities decreased. This is because low salinity has negative effects on the physiology of the marine algal species in estuaries. However, low salinity water also contributed significant nutrient loads to estuaries and the nearshore. In our *in-situ* experiments, addition of nutrients stimulated mudflat primary production in all estuaries at multiple sampling times, suggesting chronic nutrient limitation. Therefore, we conclude that catchment nutrients are critical to promoting primary productivity across all three estuaries.

The Flinders estuary was the most productive of the three estuaries, compared to the Gilbert and Mitchell estuaries. This is despite the fact that the Flinders estuary typically has the shortest period of freshwater flow each year (i.e. longest cease-to-flow period) and more variable flows from year to year, compared with the other estuaries. This makes the Flinders highly vulnerable to excessive water development. It is hypothesised that the shallower

coastal waters beyond the mouth of the Flinders estuary increase the connectivity between the coastal waters and estuary, resulting in more nutrients being retained locally.

Macrobenthic diversity and abundance was also determined in all three estuaries, and adjacent coastal intertidal environments. There were two components to this study. One examined the effect of freshwater flow on intertidal macrobenthic (>0.5 mm mesh size) assemblages in the Flinders estuary and nearshore habitats. The other compared dry-season macrobenthos assemblages across the three estuaries. For the Flinders estuary study, macrobenthic fauna on the intertidal flats were sampled on four occasions spanning the late dry (two consecutive years), post-flood, and immediately following the wet season (i.e. early-dry) across four years. Assemblages had strong seasonal responses to salinity changes, driven by changes in freshwater inputs.

Total macrofaunal abundances were significantly lower during the post-flood period, when salinity was low, while abundances reached a maximum in the late dry season, under hypersaline conditions. The dominant faunal group in the estuarine intertidal flats was polychaetes. In contrast, in the nearshore intertidal flats, bivalves dominated in the late dry season, and in the early-dry. The nearshore intertidal flats experienced almost complete defaunation of bivalves during the post-flood, while polychaetes were less impacted by the freshwater inputs, presumably due to their burrowing abilities. Although flow had short-term negative effects on macrobenthic abundance, it is clear that recruitment back into the system occurred quickly once the tide re-established in the early-dry.

The other study comparing two dry seasons of data on macrobenthos in the three estuary systems showed that the number of days of cease-to-flow during the preceding dry season best explained inter- and intra-annual patterns in benthic community composition. Specifically, this suggests that the dry-season river flow regime dictated the salinity regime of each estuary, which in turn influenced benthic community composition. However, neither the differences in the salinity regime nor community composition influenced total abundance or biomass of the benthic community, indicating that the regional taxa pool currently contains enough functional redundancy to maintain abundances and biomasses under a range of physicochemical conditions. This, in turn, provides consistent resources for higher trophic levels, such as migratory shorebirds.

Two studies focussed on shorebird numbers and diversity. One of the studies, led by the Queensland Wader Study Group (QWSG; a non-government organisation), compared the shorebirds at and near the mouths of the three estuaries. They undertook low-tide counts at sites where birds were feeding. There were two surveys – March and December 2019 – undertaken at the same time and from the same boat as primary productivity measurements and macrobenthos sampling. A key finding was that all three river mouths had significant numbers of shorebirds, including endangered and critically endangered species. This provides important new information for management and protection of these species, particularly for the understudied Gilbert and Mitchell estuaries. The shorebird species, the Black-tailed Godwit, was present in the highest numbers compared with other species in all three systems. Numbers of birds in the Flinders region in March 2019 were relatively low compared with other sampling occasions, possibly due to the major flood in the Flinders River system, which removed much of the food supply, as determined in the study of macrobenthos. In particular, numbers of Great Knot declined coincidentally with a major reduction in their major food source, bivalves.

Carpentaria Land Council Aboriginal Corporation (CLCAC) undertook a seasonal comparison of shorebirds in the Flinders system by surveying previously identified high tide roost sites. They found a predominance of Great and Red Knots, and Black-tailed Godwits. A number of endangered and critically endangered species were present in significant numbers. The highest densities of Great Knot and Black-tailed Godwits were in mid-summer (January), compared with August and September, suggesting that many birds are resident over summer rather than using this region as a staging area for southward migration. Other species (e.g. Red Knot) had higher numbers in August and September, suggesting that the Flinders region was a staging area before migrating south for the summer.

Overall, this study has a number of new and important findings with implications for water planning:

- Given the importance of nutrient inputs in 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 for contributing nutrients which fuel productivity, ensuring there is sufficient food for shorebirds. The first flush is also important for reducing salinity slightly. Typically, estuaries are hypersaline in the late dry season which may become stressful for the plants and animals living in the estuaries. The Flinders 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.
- Water extraction in a year after multiple years of little or no flow is likely to have major impacts on productivity. 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 vulnerable to an increase in years of little or no 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.
- The study also provided important new information in terms of management and protection of migratory shorebird species. The first on-ground surveys of the Gilbert and Mitchell estuaries were completed and significant densities of birds were found, including critically endangered species. Additionally, the importance of the Flinders estuary for migratory shorebirds throughout the summer was established. The extensive intertidal flats combined with significant food resource re-enforces that the Gulf is a critical site for migratory shorebirds. It also means that it is important to manage water development so that productivity of the intertidal flats is not compromised to ensure that Australia meets its international obligations to protect migratory shorebirds.
- Although the link between flows, food supply and migratory shorebirds was established, further work is needed to quantify tipping points for the productivity implications of long-term changes in flow magnitude, frequency and timing. A precautionary approach to water planning should be taken given that tipping points have not been established. Different shorebird species have different diet preferences, so it is likely that some species will be more affected than others by changes in flow. However, the degree to which this would occur could not be ascertained during our study due to insufficient data.

1. Introduction

1.1 Background

Sustainable water development in northern Australia requires information on the current 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 region in northern Australia have been earmarked for water development: the Flinders, Gilbert and Mitchell rivers (DNRME, 2017, 2018a, 2018b).

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 and 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). 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 (Queensland Government regional rankings). There are proposed or potential applications for water development in three rivers in the southern Gulf of Carpentaria region (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.

In this project, the focus is on the effect of flow on food supplies for migratory shorebirds in the East Asian-Australasian flyway. These birds migrate annually from the extreme northern hemisphere latitudes, where they breed in the northern summer, through Asia to Australia and New Zealand where they feed during the Austral summer months. The macrobenthos living on intertidal flats are an important prey item for larger species, such as fish and shorebirds, throughout the flyway (Herman et al., 1999; Nebel et al., 2008). However, these habitats are under pressure, with approximately 16% of the habitat lost globally between 1984 and 2016 (Murray et al., 2019).

The southern Gulf is known to be an important area for feeding by migratory shorebirds, with a number of endangered and critically endangered species using this area either as they migrate north or south each year, or for feeding throughout the summer (Garnett, 1989; Driscoll, 1997, 2001, 2014). The southern Gulf has been recognised by, and included in, the International East Asian-Australasian Flyway Site Network as a site of great importance within Australia (EAAFP, 2018). However, estuaries and adjacent areas have not been a specific focus.

Some species that frequent the Gulf, such as the Great Knot (*Calidris tenuirostris*), Red Knot *(Calidris canutus)*, Eastern Curlew (*Numenius madagascariensis*), and Bar-tailed Godwit (*Limosa lapponica menzbieri*), are now classified as critically endangered. Further stress on such populations could result in extinction (Hansen et al., 2016). Protection of staging, resting and breeding sites is crucial for the survival of these birds. A report by Driscoll (2014) confirmed that vulnerable, endangered and critically endangered species rely upon the sand and mudflats of the Gulf for staging and feeding.

A Canadian study has shown that counts of shorebirds were lower when the discharge from the Fraser River was higher, and they propose that this is due to a reduction in the intertidal biofilm (Canham et al., 2021). Therefore, as seen in our study, freshwater flows can have negative short-term effects on shorebirds, but this is counterbalanced by the positive effects of increased primary and secondary production post-flow.

Given that water development is occurring in the Gulf, this study sought to understand the importance of freshwater flows to shorebird feeding in the Flinders, Gilbert and Mitchell rivers, and to learn more about species and numbers present in the Mitchell and Gilbert estuaries. Specifically, this study is focused on:

- How are flow alterations due to water extraction likely to impact of the food supply for the shorebirds?
- How important are the mouths of the Mitchell and Gilbert estuaries for shorebird feeding, and what species frequent these areas?
- What are the seasonal changes in shorebird numbers in the Gulf? This is important as birds may use the Gulf as a staging site for travels north and south, or as an over-summer site for feeding during the austral summer.

1.2 Objectives

Based on the key knowledge gaps, the objectives for Project 3.6 are outlined below:

This project aimed to:

1. Identify areas of high productivity within the river estuaries and adjacent mudflats
2. Quantify the importance of a range of river flows to threatened migratory shorebirds by quantifying and comparing food availability across three rivers potentially subject to flow alteration, and assess how flow affects food sources
3. Undertake shorebird surveys for each estuary to determine comparative densities of migratory shorebirds at each estuary (Queensland Wader Study Group) and, in the case of the Flinders R estuary, determine how this changes seasonally (Carpentaria Land Council Aboriginal Corporation)

1.3 Characterisation of study sites

The Mitchell, Gilbert and Flinders rivers are located in the Gulf of Carpentaria catchments 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 for the Mitchell, Gilbert and Flinders rivers are 71,670 km^2, 46,406 km^2 and 109,000 km^2, 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 1.1). 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.

The Flinders River starts in the Great Dividing Range, extends westward into gulf savannah country towards Julia Creek, then heads north to drain through a delta into the Gulf of Carpentaria. 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.

Modelled end-of-system flows are available for the three rivers from 1984 to 2011 (CSIRO data; Figure 1.2). Annual flow was typically highest in the Mitchell River estuary compared with the other two rivers. The 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 other two river systems.

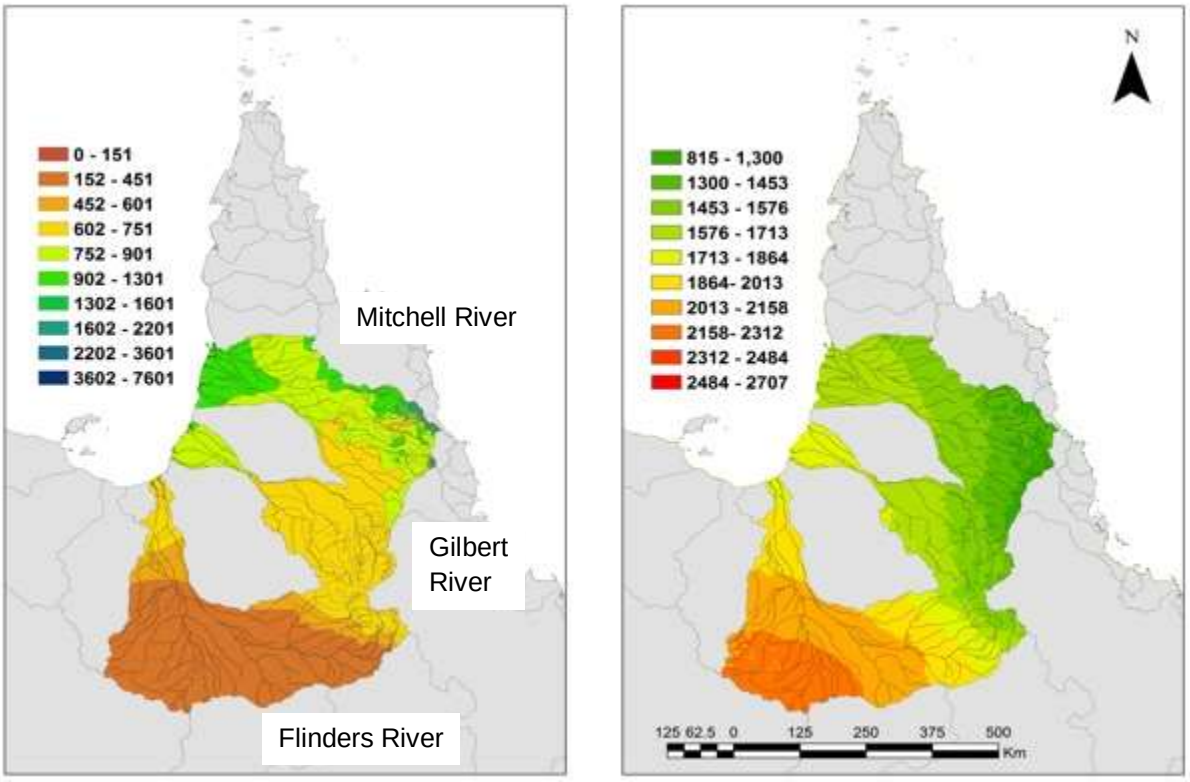

Figure 1.1. (a) Mean annual rainfall (mm) and (b) evaporation (mm) in the three study catchments – Mitchell, Gilbert and Flinders Rivers (generated by J. Coates-Marnane, Bureau of Meteorology data).

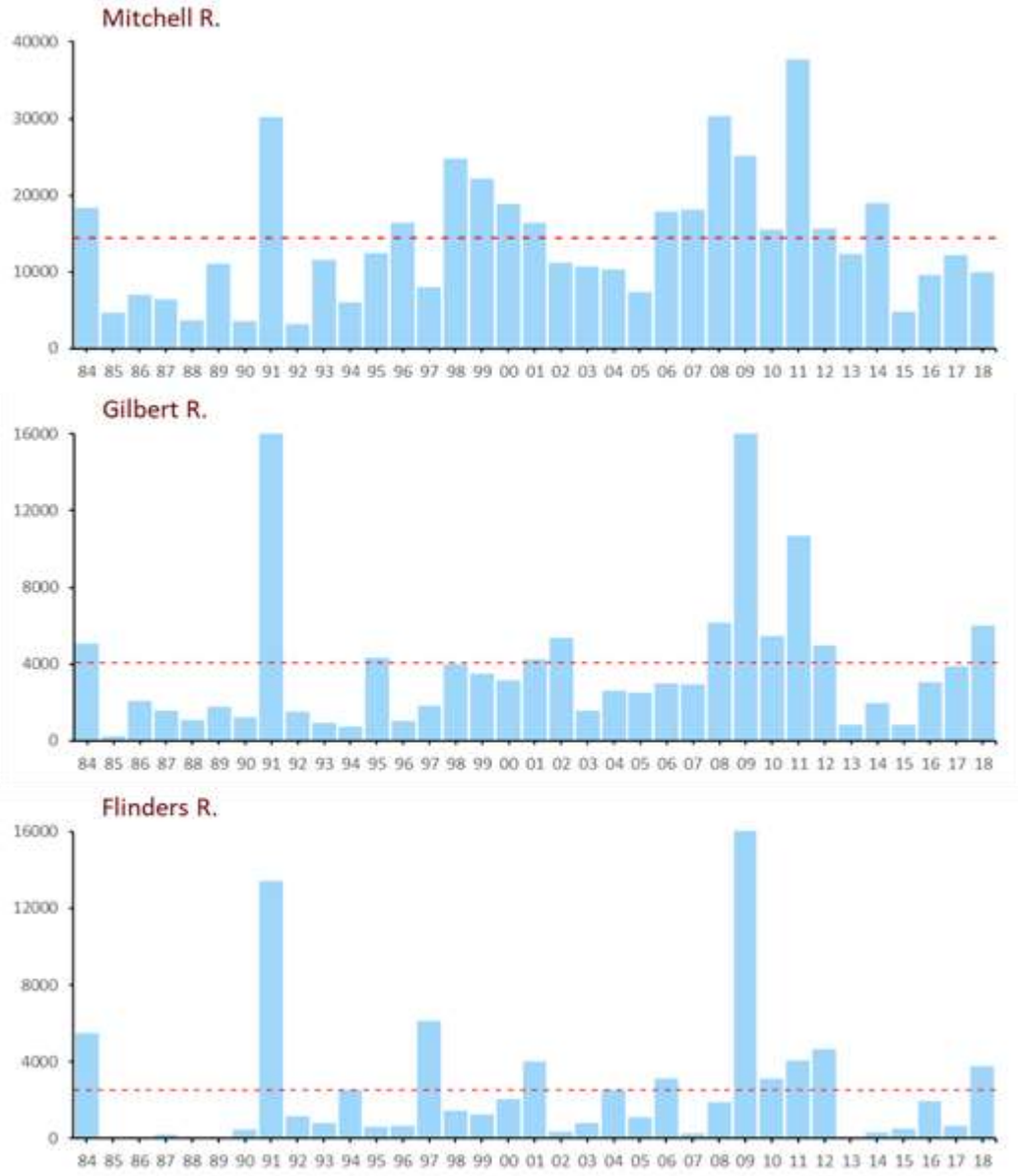

Figure 1.2. Annual flow (GL) from 1984 to 2011, based on modelled end-of-system flow (adapted from Broadley et al., 2020). Red dashed line represents mean annual flow across the years.

2. Methodology

2.1 Food supply and productivity studies

This study involved a series of field sampling trips to study the estuaries of the Flinders, Gilbert and Mitchell rivers. Field trips were done concurrently with NESP NAER project 1.4 to maximise the data collected on each trip. The field trips were designed to capture both wet and dry season conditions (Figure 2.1). Additional sampling was done in the Flinders estuary, due to the proximity of the port at Karumba and increased ease of accessibility.

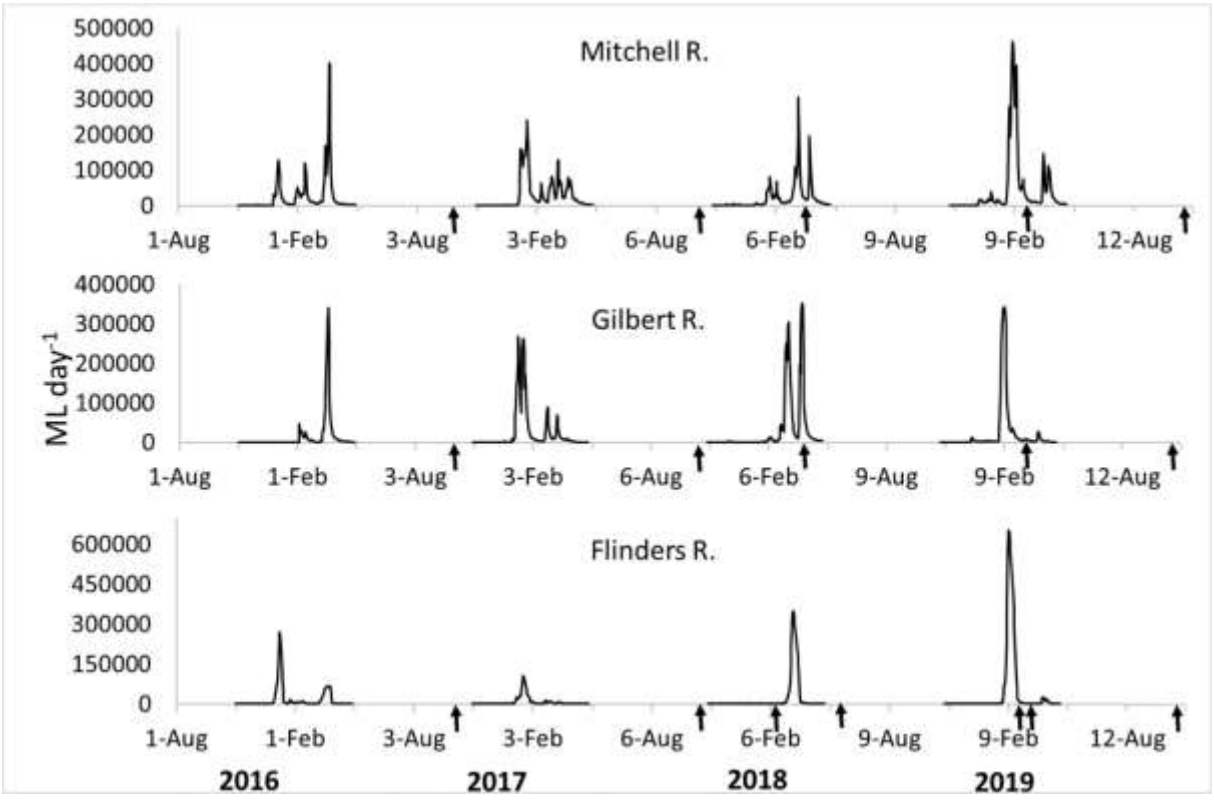

Figure 2.1. Hydrograph (ML day^{-1}) in the three rivers over the period of the study, based on DNRM gauging station data at Dunbar (139.4 km from Mitchell River mouth), Burke Development Rd (102.5 km from Gilbert River mouth) and Walkers Bend (103 km from Flinders River mouth). Arrows show sampling times.

Field trips were conducted to the estuaries of the three rivers on the catamaran, MV Eclipse D or monohull, RV CSIRO One (Table 2.1; Figure 2.1). 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. Helicopter sampling was also conducted at the height of the wet season (April 2018 for the Gilbert and Mitchell, and February 2019 for the Flinders), but only surface water samples could be collected.

There were three sampling sites within the estuaries on or near the intertidal mudflats that were sampled on all boat trips (Figure 2.2, 2.3, 2.4, 2.5). Sandflats beyond the mouth of the estuaries were also sampled on most trips. A wide range of physicochemical conditions, nutrient and chlorophyll *a* concentrations, macrobenthos, primary productivity measures and sediment characteristics were sampled (Table 2.1). Details of all the parameters measured, sampling methods, and analysis methods are given in Burford and Faggotter (2021), Lowe et al. (submitted), Venarsky et al. (submitted; see Appendices 1, 2, 3, respectively).

Table 2.1. Summary of sampling trips to the Mitchell, Gilbert and Flinders River estuaries, and parameters measured.

Date	Vessel	Estuary	Water column chlorophyll	Nutrients	Sediment chlorophyll	Sediment primary productivity	Physicochem measures	Macrobenthos measures
7–13 Nov 2016 (dry season)	Boat: MV Eclipse D	Mitchell, Gilbert, Flinders	Yes	Yes	Yes	Yes	Yes	Yes
7–15 Nov 2017 (dry season)	Boat: MV Eclipse D	Mitchell, Gilbert, Flinders	Yes	Yes	Yes	Yes	Yes	Yes
28 Feb 2018 (wet season)	Boat: RV CSIRO One	Flinders	Yes	Yes	No	No	Yes	No
13 Apr 2018 (wet season)	Helicopter	Mitchell, Gilbert	Yes	Yes	No	No	Yes	No
23 May 2018 (post-wet season)	Boat: RV CSIRO One	Flinders	Yes	Yes	Yes	Yes	Yes	Yes
23 Feb 2019 (wet season)	Helicopter	Flinders	Yes	Yes	No	No	Yes	No
8–16 Mar 2019 (wet season)	Boat: MV Eclipse D	Mitchell, Gilbert, Flinders	Yes	Yes	Yes	Yes	Yes	Yes
12–17 December 2019 (dry season)	Boat: MV Eclipse D	Mitchell, Gilbert, Flinders	Yes	Yes	Yes	Yes	Yes	No

Figure 2.2. Mitchell River mudflat and sandflat sampling sites for primary productivity (Google Earth).

Figure 2.3. Gilbert River mudflat and sandflat sampling sites for primary productivity (Google Earth).

Figure 2.4. Flinders River mudflat and sandflat sampling sites for primary productivity (Google Earth).

Figure 2.5. Photos showing examples of intertidal mudflats (left) and sandflats (right) at the mouth an estuary. Photos: Stephen Faggotter.

2.2 Shorebird surveys

In addition to the studies of the food supply for migratory shorebirds, a number of surveys were conducted to determine the numbers and species of shorebirds (Table 2.2; Figure 2.6). Detailed reports are given in Appendices Appendix 4 and Appendix 5.

There were two types of surveys:

1. Low-tide surveys of feeding areas in the estuary and around the mouth of the three river systems, conducted twice in March and December 2019 (Figure 2.7). These were designed with consistent methodology for direct comparisons of species and numbers of shorebirds in each river system. These surveys were led by the Queensland Wader Study Group (QWSG).
2. High-tide roost site surveys at the Flinders estuary and adjacent areas to determine seasonal differences in species and numbers of shorebirds (Figure 2.8). The Flinders was chosen due to its proximity to Karumba, meaning that a helicopter could be quickly and cost-effectively deployed. Additionally, previous surveys had identified the Flinders and Karumba region as being a shorebird 'hotspot'. These surveys were led by the Carpentaria Land Council Aboriginal Corporation (CLCAC) with input from Roger Jaensch (Jaensch Ornithology & Conservation).

The QWSG lead low tide surveys were done in conjunction with sampling for primary and secondary productivity, and other studies for NESP NAER project 1.4. These surveys were conducted simultaneously with sampling for macrobenthos and primary productivity, from the MV Eclipse, a catamaran. The shorebird surveys were primarily carried out from one of the tenders associated with the catamaran. The second trip in December 2019 was problematic, as the daytime tides were not ideal for counting. This meant that surveys were incomplete. The QWSG count sites at the Flinders occurred at sites originally identified by Driscoll (2014) and enhanced by previous surveys by CLCAC. The counts on the Gilbert and Mitchell were conducted at low tide and on the rising tide at identified shorebird feeding and shoreline roosting areas.

The CLCAC high tide surveys at the Flinders were done on the land after being transported by helicopter from Karumba. The roost sites for counting had been identified from previous studies (Driscoll, 2014). The final survey in 2020 was incomplete due to COVID restrictions on the number of people who could be transported in a helicopter.

It was not possible to directly compare low tide counts (conducted by QWSG) with high tide counts (conducted by CLCAC) and it is likely that low tide counts were an underestimate, due to the difficulties of surveying large areas. However, low tide spanned the daylight hours during the QWSG surveys so it was not possible to do high tide counts.

Table 2.2. Details of shorebird surveys undertaken throughout study.

Dates of surveys	Sites	Stage of tide/habitat	Organisation
15–18 Jan 2019	Flinders	High tide roosts	CLCAC
8–16 Mar 2019	Mitchell, Gilbert, Flinders	Low tide feeding areas	QWSG
29, 30 Mar, 1, 2 Apr 2019	Flinders	High tide roosts	CLCAC
30, 31 Aug, 2, 3 Sep 2019	Flinders	High tide roosts	CLCAC
12–17 Dec 2019*	Mitchell, Gilbert, Flinders	Low tide feeding areas	QWSG/CLCAC
2, 3 Apr 2020**	Flinders	High tide roosts	CLCAC

**Incomplete at Gilbert and Flinders due to access issues.*
***Incomplete at Flinders due to restrictions on number of people doing survey during COVID.*

Figure 2.6. Shorebird counting from land and boat (Photos: Queensland Wader Study Group).

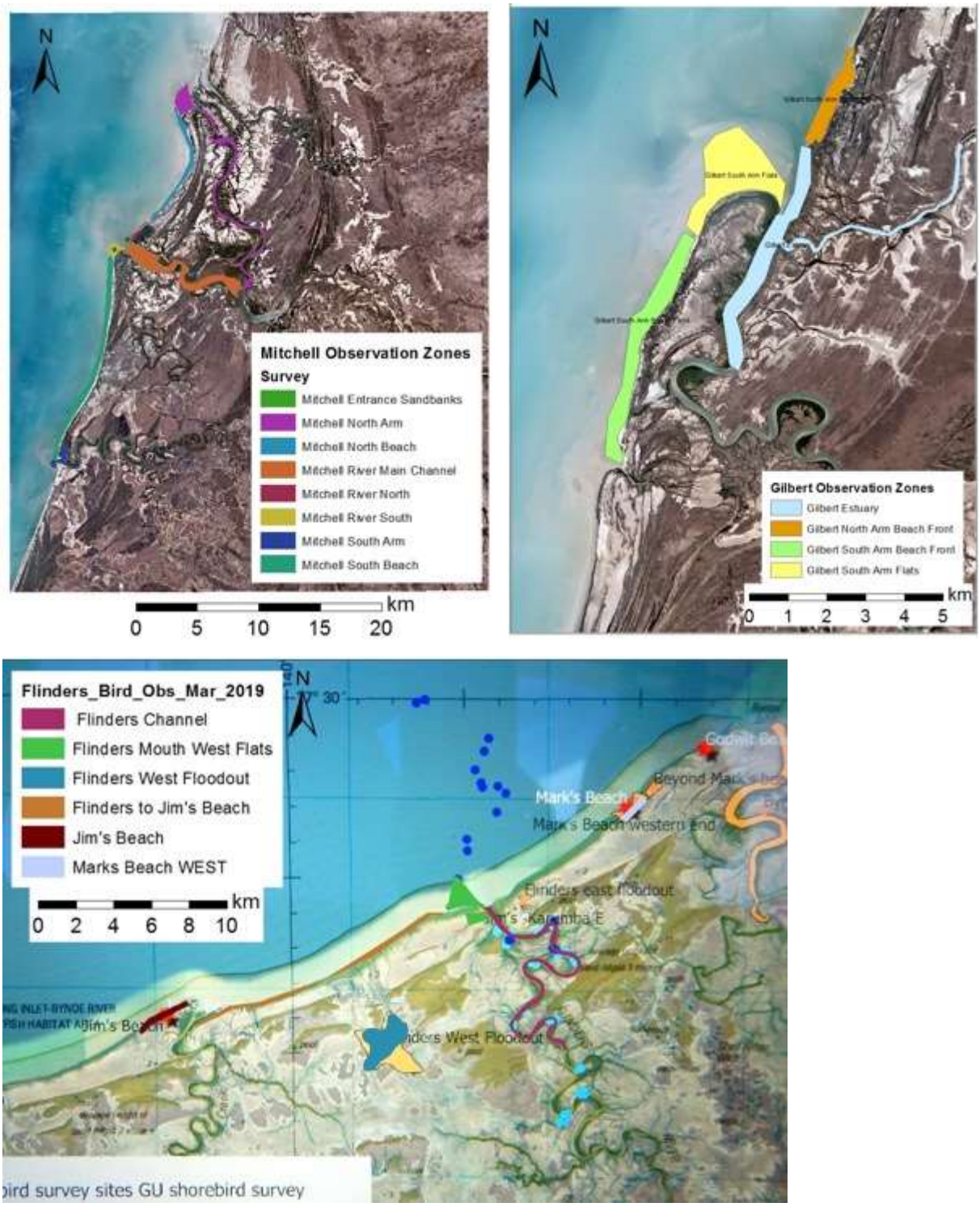

Figure 2.7. Low tide survey sites at the Mitchell, Gilbert and Flinders estuaries and nearshore environments done by the Queensland Wader Study Group (QSWG). Coloured regions show each survey track.

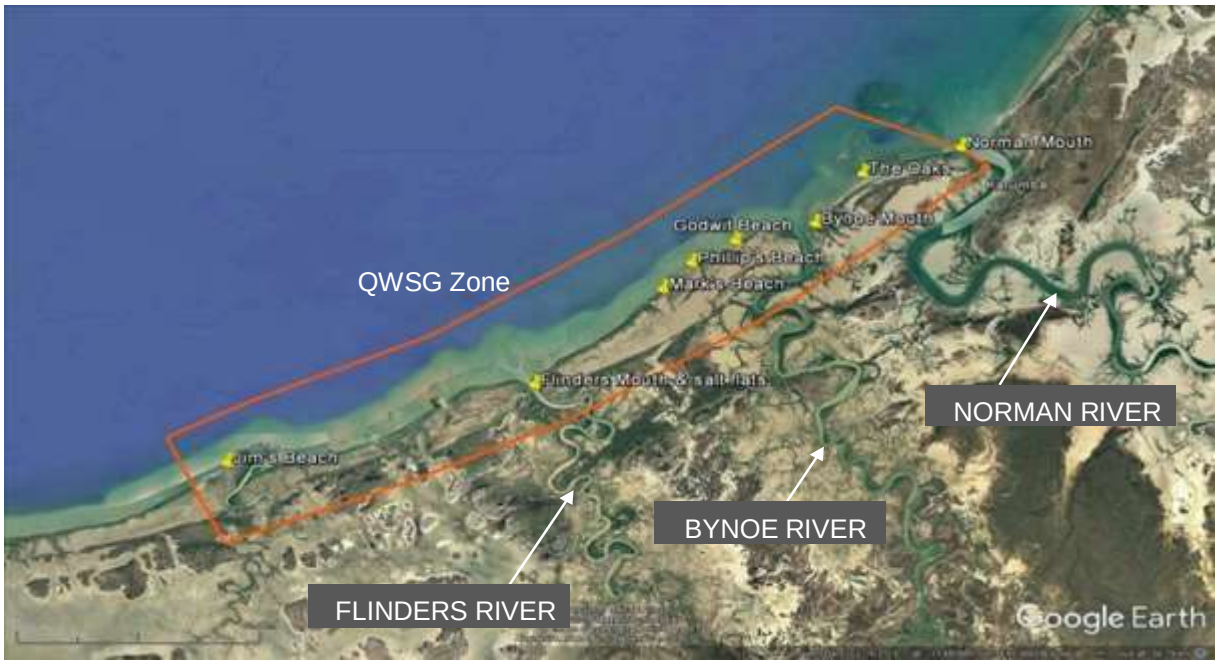

Figure 2.8. High tide roost sites at or near mouth of Flinders River regularly surveyed by the Carpentaria Land Council Aboriginal Corporation (CLCAC).

3. Results and discussion

3.1 Identify areas of high productivity within the river estuaries and adjacent mudflats

Published as: Burford, M.A., & Faggotter, S.J. (2021). Comparing the importance of freshwater flows driving primary production in three tropical estuaries. *Marine Pollution Bulletin 169*, 112565 (see Appendix 1).

This study showed that freshwater flows had a number of impacts on primary productivity in the Flinders, Gilbert and Mitchell river estuaries and nearshore environment. In the short term, when flooding was occurring, chlorophyll *a* concentrations decreased as salinities decreased. This is likely because low salinity has negative effects on the physiology of the marine algal species in estuaries. This is consistent with findings of a previous study in the adjacent Norman River estuary (Duggan et al., 2014).

However, low salinity water also contributes nutrients, as demonstrated in our study. In our *in-situ* experiments in the Flinders, Gilbert and Mitchell, addition of nutrients stimulated mudflat primary production in all estuaries on multiple sampling times, suggesting chronic nutrient limitation (Figure 3.1). A previous study in an adjacent estuary, the Norman estuary, has also shown that the water column is nutrient limited (Burford et al., 2012). The Flinders estuary was the most productive of the three estuaries, compared to the Gilbert and Mitchell estuaries (Table 3.1). This is despite the fact that the Flinders estuary has the shortest period of freshwater flow each year, and more variable flows from year-to-year, compared with the other estuaries. Therefore, the findings coupled with the hydrological characteristics suggest that the Flinders system is highly vulnerable to excessive water development. It is proposed that the shallower coastal waters beyond the mouth of the Flinders estuary increase the connectivity between the coastal waters and estuary, causing more nutrients to be retained locally. Therefore, water development which significantly reduces freshwater flows, and associated nutrient loads, is likely to negatively impact on primary productivity in the Gulf estuaries, in the longer term. The interannual variability in flow may mean that it takes some years to quantitatively measure the impacts.

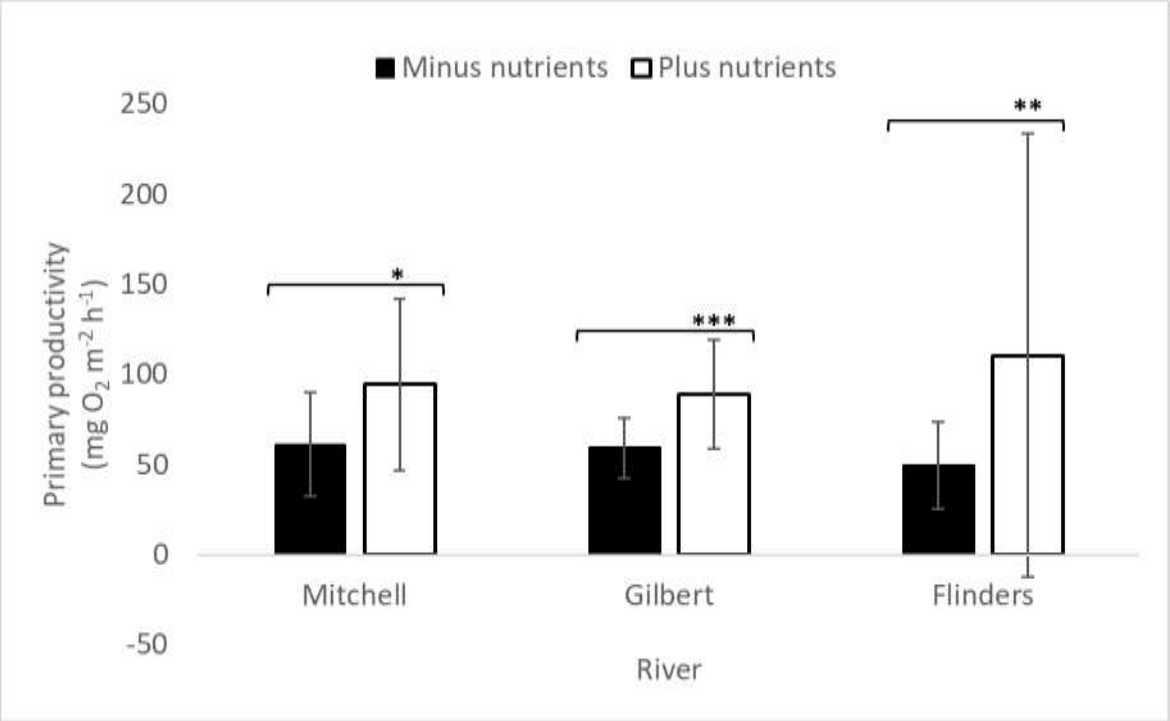

*Figure 3.1. Effect of nutrient additions on primary production (mg O_2 m^{-2} h^{-1}) in bioassays using mud from mudflats of the three estuaries across all sampling trips. *P<0.05, **P<0.01, ***P<0.005.*

Table 3.1. Summary of characteristics and key findings for three estuaries in this study during the dry season, showing relative rankings for values. TP = total phosphorus, TN = total nitrogen.

Parameter	Flinders estuary	Gilbert estuary	Mitchell estuary
Long-term mean annual flow volumes	Low	Medium	High
Interannual flow variability	High	Medium	Low
Annual cease to flow period	High	Medium	Low
Mudflat areal extent	Medium	Low	High
Mangrove areal extent	Medium	Low	High
Supratidal saltflat extent	High	Low	Medium
Open water area	Medium	Low	High
Salinity	High	Medium	Low
Turbidity	High	Medium	Low
w/c total nitrogen and phosphorus conc.	High	Medium	Low
Mudflat nutrient conc.	High TP No differences in TN between estuaries	Low TP	Low TP
Mudflat prim. prod.	High	High	Low
Nutrient addition effects on mudflat prim. prod.	Stimulation of prim. Prod.	Stimulation of prim. Prod.	Stimulation of prim. Prod.
w/c chlorophyll *a* conc.	High	Low	Low
Mudflat respiration rates	High	Low	Low

3.2 Quantify and compare food availability across three rivers potentially subject to flow alteration, and assess how flow affects food sources

Submitted as: Lowe, V., Frid, C. L. J., Venarsky, M., & Burford M. A. (submitted). Responses of a macrobenthic community to seasonal freshwater flow in a wet-dry tropical estuary. *Estuarine Coastal and Shelf Science* (see Appendix 2).

Venarsky, M. P., Lowe, V., Frid, C. L. J., & Burford, M. A. (submitted). Flow regimes among rivers influences benthic biota biodiversity, but not abundance or biomass, in intertidal mudflats and sandflats in wet-dry tropical estuaries. *Estuarine Coastal and Shelf Science* (see Appendix 3).

Sampling was conducted in all three estuaries and nearshore intertidal habitats to determine macrobenthos diversity and abundance. There were two components of this: one examined the effect of freshwater flow on intertidal macrobenthic (>0.5 mm mesh size) assemblages in

the Flinders estuary and nearshore habitats, the other compared dry season macrobenthos across the Flinders, Gilbert and Mitchell estuaries. The macrobenthos in these estuaries are an important food source for endangered migratory shorebirds.

For the Flinders estuary study, macrobenthic fauna on the intertidal flats were sampled on four occasions spanning the late dry (two consecutive years), post-flood, and immediately following the wet season (i.e. early-dry across four years). Assemblages had strong seasonal responses to the physico-chemical variation, driven by changes in freshwater inputs. Total macrofaunal abundances were significantly lower during the post-flood period, when salinity was low, and reached a maximum in the late dry season, under hypersaline conditions. Abundances were highest in the late dry season, coinciding with highest benthic chlorophyll *a* concentrations, and lower in the post-flood and early-dry (Figure 3.2).

The dominant faunal group in the estuarine intertidal flats was polychaetes (Figure 3.3). In contrast, in the nearshore intertidal flats, bivalves dominated in the late dry season, and in the early-dry. The nearshore intertidal flats experienced almost complete defaunation of bivalves during the post-flood. Although flow had short-term negative effects on macrobenthos abundance, it is clear that macrobenthos recruitment back into the system occurred once the tide re-established in the early-dry. Primary productivity was likely to be enhanced by increased nutrient loads from the catchment during the dry season. Flow variability is a key feature of the Flinders River, and therefore alteration of flow, via proposed water extraction, is likely to negatively affect macrobenthos via a reduction in a key food supply (i.e. benthic microalgae).

In the study of dry season macrobenthos in the Flinders, Gilbert and Mitchell rivers, benthic macrobenthic species composition, abundance and biomass were examined on intertidal mudflats and sandflats on two sequential dry seasons. The study found that the number of consecutive days of zero river flow during the preceding dry season best explained inter- and intra-annual patterns in benthic community composition. Specifically, this suggests that the dry season river flow regime dictated the salinity regime of each estuary, which in turn influenced benthic community composition. However, neither the differences in the salinity regime or community composition influenced total abundance or biomass of the benthic community, indicating that the regional taxa pool currently contains enough functional redundancy to maintain abundances and biomasses under various physicochemical conditions. This in turn provides consistent resources for higher trophic levels, such as birds and fish.

A comparison of macrobenthic densities on the intertidal mudflats in the three estuaries during the dry season, compared with published studies in other Australian and Asian tropical estuaries found that densities were generally higher in current study (Table 3.2). The exceptions were Shenzhen, China (Cai et al., 2001) and Darwin Harbour, Australia (K Reeds, unpubl. data), which had higher densities. Therefore, our study shows that the estuaries of all three estuaries are highly productive, and therefore provide an important food source for migratory shorebirds and fisheries species. It is likely that if the food supply for the macrobenthos, (i.e. benthic microalgae), is affected by reduced flows, the macrobenthic abundance will ultimately be affected as well.

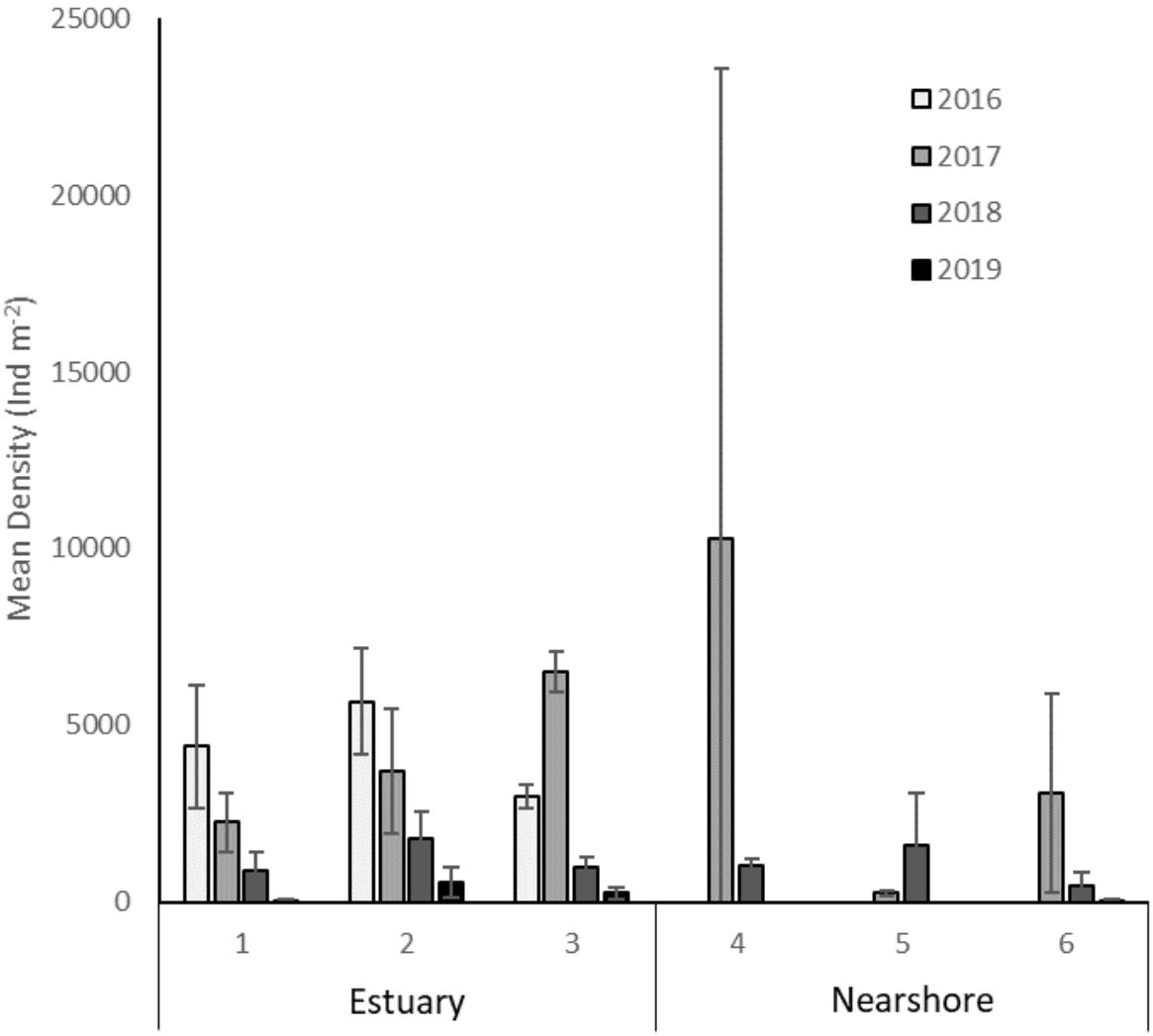

Figure 3.2. Mean intertidal macrobenthos abundances (density ind m^{-2} ± SD) at three estuarine intertidal flats (sites 1–3) and three nearshore intertidal flats (sites 4–6) sampled at the Flinders River estuary during the end-dry season (2016–17), early-dry period (2018) and end-flood period (2019). No nearshore intertidal flats were sampled during the 2016 end-dry season. Dry season 1: 2016; dry season 2: 2017.

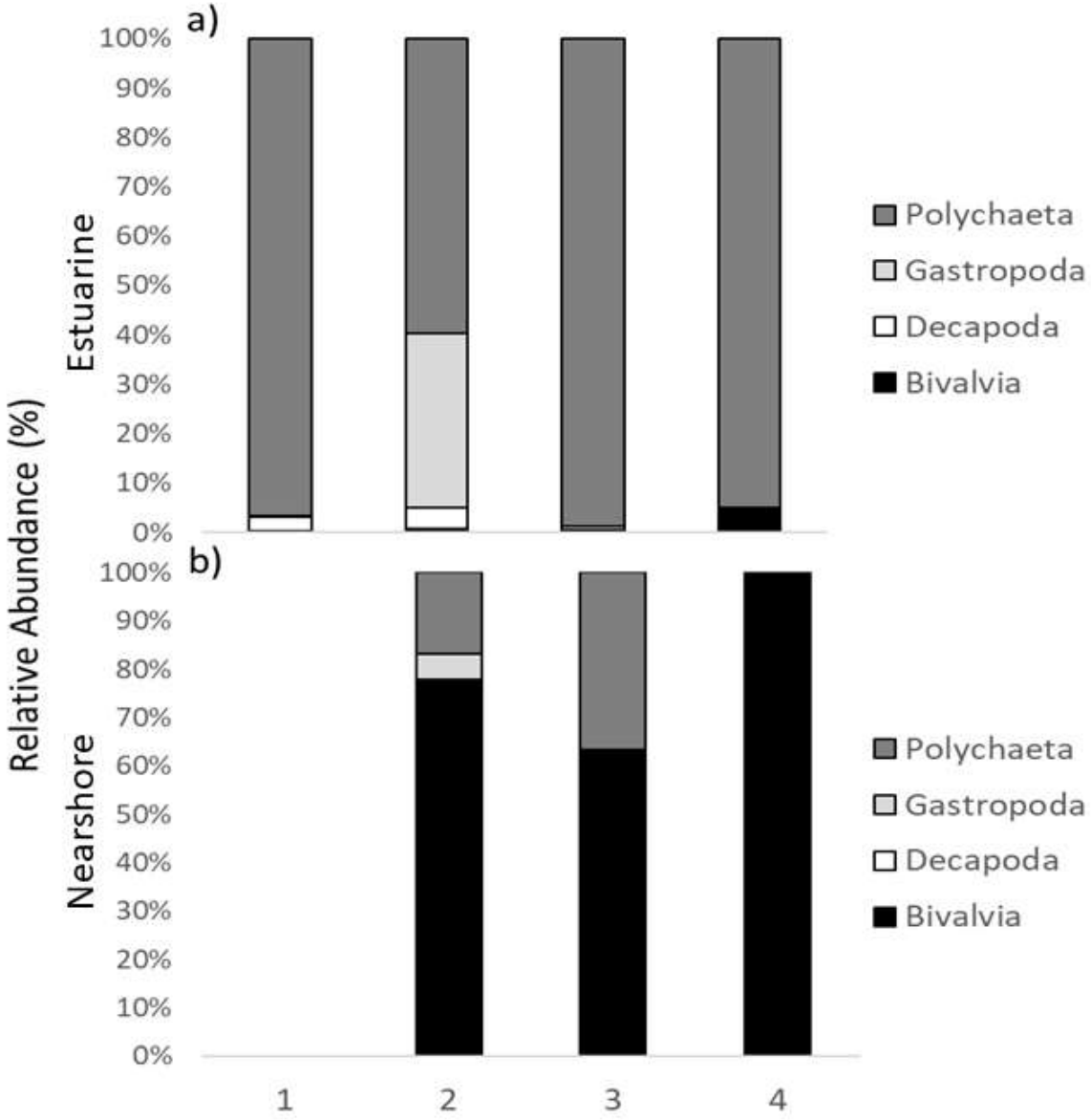

Figure 3.3. Intertidal macrobenthos relative abundance (% of total), stacked by major taxonomic groups within a) estuarine intertidal flats (sites 1–3) and b) nearshore intertidal flats (sites 4–6) sampled during the end-dry season (2016–17), early-dry period (2018) and end-flood period (2019) in the Flinders River estuary. No nearshore intertidal flats were sampled during the 2016 end-dry season.

Table 3.2. Abundance measures of intertidal macrobenthos reported in intertidal flats across Asia and Australia. Koppen Climate classification system used. Am = Tropical, monsoonal, Aw = Tropical, savanna, dry winter; BSh = Arid, Steppe, hot; BWh = Arid, desert, hot; Cfa = Temperate, without dry season, hot summer; Cwa = Temperate, dry winter, hot summer; Dwa = Continental, dry winter, hot summer. For details of references see Appendix 2.

Region	Location	Climate	Season	Abundance (ind m^{-2})			Sed. core depth (m)	Sieve size (mm)
				Mean (SD)	Min	Max		
Australia	Bay of Rest, NW Australia[1]	BWh	Dry	922 (± 722)	356	4,183	0.05	2.0
	Roebuck Bay, Western Australia[2]	BSh	Dry	1,287 (-)	40	16,280	0.05	1.0
	Hinchinbrook Channel, NE Queensland, Australia[3]	Am	Dry	1,363 (-)	57	8,531	0.2	0.25
	Haughton Estuary, NE Queensland, Australia[4]	Aw	Dry	1,811 (-)	20	26,150	0.2	0.25
	Gladstone Harbour, NE Queensland[5]	Aw	Dry to wet	-	196	5,905	0.2	0.5
	Darwin Harbour, N Australia[6]	Am	Dry	-	2,548	12,739	0.4	0.5
	This study, Flinders River estuary[7]	**Aw**	**Dry**	**4,594 (± 2,103)**	**2,252**	**7,684**	**0.2**	**0.5**
	This study, Gilbert River estuary[7]	**Aw**	**Dry**	**2,497 (± 918)**	**1,169**	**3,659**	**0.2**	**0.5**
	This study, Mitchell River estuary[7]	**Aw**	**Dry**	**3,082 (± 1,886)**	**693**	**5,478**	**0.2**	**0.5**
Asia	Ximen Island, China[8]	Cfa	All*	1,365 (-)	-	-	0.3	0.5
	Saemangeum, Korea[9]	Dwa	All^	1,948 (-)	-	-	0.3	1.0
	Borneo[10]	Am	Drier (wet all year)	3,462 (-)	27	451	0.15	0.5
	Shenzhen, China[11]	Cwa	All^	-	7,834	25,605	0.2	0.5

[1] Wells, (1983), [2] Pepping et al., (1999), [3] Dittmann, (2002), [4] Dittmann, (1995), [5] Choi et al., (2017), [6] K. Reeds, (unpubl. data), [7] This study, nematodes and foraminifera excluded, [8] Liao et al., (2018), [9] Kim et al., (2020), [10] Zakirah et al., (2019), [11] Cai et al., (2001).
***** *There was no statistical difference between seasons, so mean (SD) is reported as an annual value.*
^ *Results presented as a mean of all sampling events.*

3.3 Undertake shorebird surveys to determine comparative densities of migratory shorebirds at each estuary and, in the Flinders estuary, determine how this changes seasonally

Mitchell, Gilbert and Flinders estuary surveys to compare shorebird numbers and diversity (Qld Wader Study Group; see Appendix Appendix 4 for full details)

The surveys showed that the Mitchell and Gilbert River mouths and estuaries were important migratory shorebird feeding sites. This is important new information demonstrating the importance of these sites either as staging sites for birds moving north and south on their migration, or as over-summer feeding sites.

The dominant species in all three sites was the Black-tailed Godwit (Table 3.3). A previous study has highlighted the dominance of this species in the southern Gulf (Driscoll, 2014). In the Gilbert system, the Red-necked Stint was also dominant. There were mixed flocks of Red-necked Stints and sandplovers that could not be differentiated in the Mitchell, meaning that it was not possible to get complete count data for the Red-necked Stint in the Mitchell. Great Knot was prevalent in the Flinders and Gilbert systems, while the Bar-tailed Godwit was relatively more important in the Mitchell.

Table 3.3. Comparison of dominant shorebird species and maximum counts in the three river systems. Count data in red exceed 1% threshold for international importance (Hansen et al., 2016).

FLINDERS RIVER		GILBERT RIVER		MITCHELL RIVER	
SPECIES & NUMBERS >1000	**N**	**SPECIES & NUMBERS >1000**	**N**	**SPECIES & NUMBERS >1000**	**N**
Black-tailed Godwit	1470	Black-tailed Godwit	4301	Black-tailed Godwit	3434
				Mixed (sandplover/Red-necked Stint)	2370
SPECIES AND NUMBERS 500-999		**SPECIES AND NUMBERS 500-999**		**SPECIES AND NUMBERS 500-999**	
		Red-Necked Stint	759		
SPECIES AND NUMBERS 100-499		**SPECIES AND NUMBERS 100-499**		**SPECIES AND NUMBERS 100-499**	
Great Knot	346	Great Knot	363	Bar-tailed Godwit	407
Black-winged Stilt	211	Greater Sandplover	298	Red -neck Stint	388
Terek Sandpiper	150	Lesser Sandplover	162	Lesser Sandplover	237
		Bar-tailed Godwit	154	Black-winged Stilt	129
				Sharp-tailed Sandpiper	124
SPECIES AND NUMBERS 50-99		**SPECIES AND NUMBERS 50-99**		**SPECIES AND NUMBERS 50-99**	
Common Greenshank	63	Black-winged Stilt	75	Greater Sandplover	78
Eastern Curlew	55	Whimbrel	69	Whimbrel	67

3.3.2 Flinders River seasonal shorebird surveys (CLCAC; for more details see Appendix Appendix 5)

The Carpentaria Land Council Aboriginal Corporation Normanton Ranger team conducted shorebird surveys focused on areas along the coastline from the Norman River mouth to a point west of the Flinders River estuary (the 'Flinders-Bynoe coast'), on the country of the Gkuthaarn-Kukatj People. The Normanton Rangers of CLCAC implemented the survey program with planning, technical, and in- field support from Jaensch Ornithology & Conservation (JOC).

Fieldwork over four days was conducted on four occasions by the Normanton Rangers with JOC support (Table 2.2). Surveys of up to 13 high tide roosts were carried out in January and August-September (Figure 2.8), but coverage was reduced in April 2020, due to limitations as a result of the COVID-19 pandemic. Conditions were conducive to effective surveys, with maximum high tides over 3.6 m.

A total of 20 species of migratory shorebirds and 4 resident shorebird species were recorded during the surveys (Table 3.4). Seven species that are listed as threatened under the EPBC Act 1999 were recorded. Five of the species were recorded in numbers of at least 100 with the exception of the Greater Sandplover and Lesser Sandplover. The most abundant species were Great Knot (max. count 7,496; Jan. 2019), Black-tailed Godwit (4,990; Jan. 2019) and Red Knot (2,860; Aug–Sep. 2019). No other species exceeded 1,000 birds and 11 species occurred only in numbers of less than 100 birds. Three species were recorded in numbers above 1% of the estimated population size in the East Asian – Australasian Flyway (EAAF): the Great Knot, Black-tailed Godwit and Red Knot (Hansen et al., 2016). More than 10,000 migratory shorebirds were documented twice.

It was not possible to directly compare low tide counts (conducted by QWSG) with high tide counts (conducted by CLCAC) and it is likely that low tide counts were an underestimate due to the difficulties of surveying large areas.

In terms of seasonal comparisons of high tide roost counts (i.e. comparing January 2019 with August-September 2019), there were a number of key findings:

- Though numbers of Great Knot and Black-tailed Godwit were high in both instances, they were much higher in January.
- Red Knot was scarce in January, but relatively abundant in August and September. Curlew Sandpiper exhibited a similar result but at a smaller scale.
- Numbers of Eastern Curlew in January were almost twice the number in August and September.

The lower number of Great Knot in March 2019 coincided with a period of low salinity and associated low densities of bivalves on the nearshore intertidal sandflats (see Appendix 2). Bivalves are a preferred food source for Knots (Dekinga & Piersma, 1993; Zhang et al., 2011). In contrast, numbers of the other dominant species, Black-tailed Godwit, did not decrease to the same degree. Their preferred food supply is polychaetes (Perez-Hurtado et al., 1997), which also did not decrease in abundance to the same degree as bivalves (see Appendix 2). Further work is needed to confirm the potential relationship.

Significant decreases in maximum count for a species and in totals for roost sites and the Flinders coast overall, were recognised, compared with a previous study (Driscoll, 2001).

Four of the seven threatened species – including two of the Critically Endangered species, Eastern Curlew and Curlew Sandpiper – showed a similar maximum count whereas three (Bar-tailed Godwit, Greater Sandplover and Lesser Sandplover) showed a decrease. This was probably due mainly to external factors in the EAAF. Nevertheless, the importance of this coast in terms of numbers of shorebirds remains high. The historically dominant, most abundant species on the Flinders Coast (Black-tailed Godwit and both knots) remain unchanged and proportionately their numbers were similar to those in the past. Although short-term natural events (cyclone and flood) impacted shorebird numbers in the short-term, there was evidence of strong recovery within several months.

Table 3.4. Summary of all counts from Flinders high tide roost sites. Species in red are listed as threatened under the EPBC Act 1999. Count data in red exceed the 1% threshold for international importance (Hansen et al. 2016). Boxes shaded blue denote migratory species.

Survey dates	Asian Dowitcher	Australian Pied Oyster-catcher	Bar-tailed Godwit	Beach Stone-curlew	Black-fronted Dotterel	Black-tailed Godwit	Black-winged Stilt	Broad-billed Sandpiper	Common Greenshank	Common Sandpiper	Curlew Sandpiper	Eastern Curlew	Great Knot
1% threshold:	140		3250			1600		300	1100	1900	900	350	4250
16-18 Jan-19	1	10	199			**4990**	27		40		21	195	**7496**
29-Mar to 2-Apr 19	6	9	42			1347	170		11		17	66	105
30-Aug to 3-Sep 19	1	13	7			**2747**	303	2	39		392	100	**4940**
2 & 3 April 2020		8	5			99	93		6			18	600
maximum value:	**6**	**13**	**199**	**0**	**0**	**4990**	**303**	**2**	**40**	**0**	**392**	**195**	**7496**

Survey dates	Greater Sand Plover	Grey Plover	Grey-tailed Tattler	Lesser Sand Plover	Little Curlew	Marsh Sandpiper	Masked Lapwing	Oriental Plover	Pacific Golden Plover	Red Knot	Red-capped Plover	Red-necked Avocet	Red-necked Stint
1% threshold:	2000	800	700	1800	1100	1300		2300	1200	1100			4750
16-18 Jan-19	5	28	5	12		17	2		16	314	2		81
29-Mar to 2-Apr 19	5	43	1	49		88				24	27		45
30-Aug to 3-Sep 19	24	11		55		4				**2860**	108		210
2 & 3 April 2020		1				14				30			10
maximum value:	**24**	**43**	**5**	**55**	**0**	**88**	**2**	**0**	**16**	**2860**	**108**	**0**	**210**

Survey dates	Ruddy Turnstone	Sanderling	Sharp-tailed Sandpiper	Sooty Oyster-catcher	Terek Sandpiper	Whimbrel	Unident. sand plover	Unident. small shorebirds	Unident. shorebirds	All shorebirds	**Total migratory shorebirds**
1% threshold:	300	300	850		500	650					
16-18 Jan-19	4		48		84	197	300	1037		15131	**15090**
29-Mar to 2-Apr 19	6		49		29	117	170	49	244	2719	**2513**
30-Aug to 3-Sep 19			46		1	50	18	510	150	12591	**12167**
2 & 3 April 2020					2	14	47		284	1231	**1130**
maximum value:	**6**	**0**	**49**	**0**	**84**	**197**	**300**	**1037**	**284**	**15131**	**15090**

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.
- 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.
- Macrobenthic abundance was comparable between the three river systems, and relatively high compared with other Australian tropical systems. The dominant species in the intertidal mudflats were polychaetes, with bivalves also prevalent in the sandy intertidal flats. Short term reductions in macrobenthic abundance occurred when salinity decreased but animals recruited back once the salinity increased at the end of the wet season. The differences in the cease-to-flow period between the three river systems appeared to affect macrobenthic species composition, with differences in the abundance of polychaetes, ostracods, bivalves and gastropods.
- Significant numbers of shorebirds were found at the mouths of the Gilbert and Mitchell estuaries and adjacent intertidal habitats. This is the first on-ground survey of these sites. Seasonal differences in shorebird species and abundances were also observed in a more detailed study of the Flinders estuary. There were a number of endangered and critical endangered species identified at all three river systems. The Black tailed Godwit was a dominant species overall. This species is less well studied than many other shorebird species, but it is known to feed on polychaetes, a dominant macrobenthic group on the intertidal flats.

Overall, 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 for contributing nutrients which fuel productivity, ensuring there is sufficient food for shorebirds. The first flush is also important for reducing salinity, which is typically hypersaline and may become stressful for the plants and animals living in the estuaries. The Flinders 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.
- Water extraction in a year after multiple years of little or no flow is likely to have major impacts on productivity. 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 vulnerable to an increase in years of little or

no 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.

- The study also provided important new information in terms of management and protection of migratory shorebird species. The first on-ground surveys of the Gilbert and Mitchell estuaries were done, and significant densities of birds were found, including critically endangered species. Additionally, the importance of the Flinders estuary for migratory shorebirds throughout the summer was established. The extensive intertidal flats combined with significant food resource re-enforces that the Gulf is a critical site for migratory shorebirds. It also means that it is important to manage water development so that productivity of the intertidal flats is not compromised to ensure that Australia meets its international obligations to protect migratory shorebirds.

References

Broadley, A, Stewart-Koster, B, Kenyon, RA, Burford, MA and Brown, CJ (2020) Impact of water development on river flows and the catch of a commercial marine fishery. *Ecosphere,* 11: e03194.

Burford, MA, Webster, IT, Revill, AT, Kenyon, RA, Whittle, M and Curwen, G. (2012) Controls on phytoplankton productivity in a wet-dry tropical estuary. *Estuarine, Coastal and Shelf Science,* 113:141-151.

Burford, MA, Faggotter, SJ and Kenyon., R (2020) *Project 1.4: Contribution of rivers to the productivity of floodplains and coastal areas of the southern Gulf of Carpentaria – Component 1: NESP Northern Australia Environmental Resources Hub final report*, Northern Australia Environmental Resources Hub

Burford, MA and Faggotter, SJ (2021) Comparing the importance of freshwater flows driving primary production in three tropical estuaries. *Marine Pollution Bulletin* 169: 112565.

Cai, LZ, Lin, JD and Li, HM (2001) Macroinfauna communities in an organic-rich mudflat at Shenzhen and Hong Kong, China. *Bulletin of Marine Science*, 69:1129-1138.

Canham, R, Flemming, SA, Hope, DD and Drever, MC (2021) Sandpipers go with the flow: Correlations between estuarine conditions and shorebird abundance at an important stopover on the Pacific Flyway. *Ecology and Evolution* 11:2828-2841.

Commonwealth of Australia (2015) *Our north, our future: white paper on developing Northern Australia.* Department of Infrastructure and Regional Development, Department of the Prime Minister and Cabinet, Commonwealth of Australia.

Crowley et al NERP (2014a) *Environmental Research Plan for Natural Resource Management Organisations and Regional Development Australia Boards in Northern Australia.*

Crowley et al NERP (2014b) *Environmental Research Plan for Natural Resource Management Organisations and Regional Development Australia Boards in Northern Australia Supplementary Report.*

Dekinga, A and Piersma, T (1993) Reconstructing diet composition on the basis of faeces in a mollusc-eating wader, the Knot *Calidris canutus*. *Bird Study* 40:144-156.

DNRME (Department of Natural Resources, Mines and Energy) (2017) *Water Resource (Gulf) Plan, Sale of general reserve unallocated water: tender assessment report.* Department of Natural Resources, Mines and Energy, Queensland Government, Brisbane, Australia.

DNRME (2018a). *Minister's Performance Assessment Report, Water Plan (Gulf) 2007.* Department of Natural Resources, Mines and Energy, Queensland Government, Brisbane, Australia.

DNRME (2018b). *Minister's Performance Assessment Report, Water Plan (Mitchell) 2007.* Department of Natural Resources, Mines and Energy, Queensland Government, Brisbane, Australia.

Driscoll, PV (1997). 'The distribution of shorebirds along the Queensland coastline' in Straw, P (ed) *Shorebird Conservation in the Asia-Pacific Region*, Australasian shorebirds Studies Group of Birds Australia, Melbourne.

Driscoll, PV (2001) *Gulf of Carpentaria Wader Surveys 1998-9,* report prepared on behalf of QWSG with assistance from AWSG for the Queensland Environmental Protection Agency.

Driscoll, PV (2014) *Shorebird surveys in the south east Gulf of Carpentaria*, report for Shorebirds 2020, Queensland and Australasian Wader Study Groups.

DSITIA (Department of Science, Information Technology, Innovation and the Arts) (2014) *Targeted review of Water Resource (Gulf) Plan 2007.* Environmental Assessment. Department of Science, Information Technology, Innovation and the Arts. Queensland Government.

Duggan, M, Connolly, RM, Whittle, M, Curwen, G and Burford, MA (2014) Effects of freshwater flow extremes on intertidal biota of a wet-dry tropical estuary. *Marine Ecology Progress Series,* 502:11-23.

Garnett, ST (1989). *Wading Bird Abundance and Distribution - South-eastern coast of the Gulf of Carpentaria,* RAOU Report No. 58, report to the Queensland National Parks and Wildlife Service.

Hansen, B, Fuller, RA, Watkins, D, Rogers, D, Clemens, RS, Newman, M and Woehler, E (2016) *Revision of the East Asian – Australasian Flyway Population Estimates for 37 listed Migratory Shorebird Species*, unpublished report for the Department of the Environment, BirdLife Australia, Melbourne.

Herman, PMJ, Middelburg, JJ, van de Koppel, J, and Heip, CHR, (1999) Ecology of Estuarine Macrobenthos, *Advances in Ecological Research*, 29:195-240, doi:10.1016/S0065-2504(08)60194-4.

Murray, NJ, Phinn, SR, DeWitt, M, Ferrari, R, Johnston, R, Lyons, MB, Clinton, N, Thau, D and Fuller, RA (2019) The global distribution and trajectory of tidal flats. *Nature* 565:222-225.

Nebel, S, Porter, JL and Kingsford, RT (2008) Long-term trends of shorebird populations in eastern Australia and impacts of freshwater extraction. *Biological Conservation* 141:971–980, doi:10.1016/j.biocon.2008.01.017.

Perez-Hurtado, A, Goss-Custard, JD and Garcia, F (1997) The diet of wintering waders in Cadiz Bay, southwest Spain. *Bird Study* 44:45 – 52.

Waltham N, Burrows, D, Butler, B, Wallace, J, Thomas, C, James, C and Brodie, J (2013) Waterhole ecology in the Flinders and Gilbert. catchments. *A technical report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy*, CSIRO Water for a Healthy Country and Sustainable Agriculture flagships, Australia.

Zhang, X, Hua, N, Ma, Q, Xue, W, Feng, X, Wu. W, Tang, C and Ma, Z (2011) Diet of Great Knots (*Calidris tenuirostris*) during spring stopover at Chongming Dongtan, China. *Chinese Birds* 2:27-32.

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Comparing the importance of freshwater flows driving primary production in three tropical estuaries

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Abstract

Estuaries in the tropical Gulf of Carpentaria (GOC) in Australia are under increasing pressure from catchment water development, potentially affecting productivity. We examined the potential effect of changes in freshwater inputs on the primary productivity of three estuaries (Flinders, Gilbert and Mitchell Rivers). The addition of nutrients stimulated mudflat primary production in all estuaries at multiple sampling times, suggesting chronic nutrient limitation. All three estuaries were productive with the Flinders estuary being the most productive of the three estuaries, compared to the Gilbert and Mitchell estuaries. This is despite the fact that the Flinders estuary has the shortest period of freshwater flow and more variable flows from year-to-year compared with the other estuaries. This makes the Flinders highly vulnerable to excessive water development. This study suggests that water extraction which significantly reduce freshwater inputs and associated nutrients, has the potential to impact on productivity within these estuaries.

Keywords (max 6): respiration, primary production, intertidal, mudflat, nutrients

1. Introduction

Estuaries have been described as biogeochemical hotspots with high rates of primary productivity (Cloern et al., 2014). However, this study also showed that of the 1148 reported values of phytoplankton primary production globally, 958 come from sites between latitudes of 30 and 60°N; with only 36 for sites south of 20°N, and even less from the tropics. Despite the limited information for comparisons, they propose that tropical estuaries are more productive than temperate estuaries. In a review comparing eutrophic, temperate estuaries and low-nutrient, tropical estuaries, Vieillard et al. (2020) showed that there was also a strong literature bias toward heavily eutrophied estuaries in the Northern Hemisphere, with relatively little data available from tropical and low-nutrient systems.

Tropical/subtropical river systems account for 68% of Australian estuaries, meaning that these climatic regions are important contributors to the productivity of estuarine and coastal systems (Bucher and Saenger, 1994). Tropical rivers in northern Australia flow into some of the most pristine coastal habitats and estuaries in the world (Halpern et al., 2019). This contrasts with southeast Asia and central/south America, where there is major human development and environmental degradation, including major loss of intertidal flats from coastal development, reduced catchment sediment delivery to estuaries, coastal erosion and sea level rise (Murray et al., 2019). Within Australia, a study in the coastal areas adjacent at the mouth of the Murray River, one of the most overexploited water resources in the southern region of Australia (Maheshwari et al., 1995), has shown that water development can have major impacts on productivity (Auricht et al., 2017).

The significant rainfall and runoff in the wet-dry tropics of Australia provides a potential resource for water development in the catchments, e.g. irrigated agriculture. There has, for example, already been significant water development in catchments in the wet-dry tropics adjacent to the Great Barrier Reef (e.g. Howley et al., 2018). There are plans for significant water development in three rivers in the Gulf of Carpentaria region, the Flinders, Mitchell and Gilbert Rivers (DNRME, 2018a, b). The downstream estuaries support commercial fisheries, and endangered migratory shorebirds and a suite of other plant and animal species that are poorly characterized (Garnett, 1989; Robins et al., 2005). Increased water extraction and building dams will reduce freshwater flow to estuaries, but the scale of the likely effect on secondary productivity in estuaries and nearshore environments is poorly understood.

Previous studies have shown that higher wet season freshwater flows correlate with catches of estuarine fish and crustaceans, but the underlying mechanism has not been determined (Robins et al., 2005). Other studies have suggested that primary productivity and densities of juvenile crustaceans may be affected with long term flow alterations (Kenyon et al., 2004; Burford et al., 2011).

In the short term, flow events change water residence times, increase turbidity, and reduce the salinity in estuaries which can have negative effects on phytoplankton and benthic algal production (Burford et al., 2012; Duggan et al., 2014). In the longer term, i.e. weeks to months, once flows and turbidity have decreased and salinity has increased, nutrient inputs during the wet season fuel primary production, (Mallin et al., 1993; Gillanders and Kingsford, 2002; Murrell et al., 2007; Auricht et al., 2017).

Given the pressures of water development, and the desire to learn from the negative social, environmental and economic consequences of water overallocation in other Australian rivers (Maheshwari et al., 1995), a study was undertaken in river earmarked for water development in the Gulf of Carpentaria. The study examined the effect of freshwater flows on nutrient inputs, primary production, respiration and biomass of primary producers in three wet-dry tropical estuaries (Mitchell, Gilbert and Flinders). These three rivers provide contrasts in seasonal and interannual flow, with the Mitchell River having the most consistent year-to-year flow and a low rate of base flow in the dry season. The Flinders River is the other extreme with highly variable interannual flow and long cease-to-flow periods each dry season.

2. Materials and methods

2.1 Study site

The Mitchell, Gilbert and Flinders Rivers are located in the Gulf of Carpentaria catchments in the Australian wet-dry tropics (Fig. 1). They are all classified as Class 10 rivers, i.e. unpredictable summer flow which is highly intermittent (Fig. 1, Kennard et al., 2010). The catchment areas are 71 670, 46 406 and 109 000 km^2, for Mitchell, Gilbert and Flinders Rivers respectively. All the catchments are dominated a mixture of low-intensity cattle grazing, with some improved pasture or crop production. Mining activities also occur in the catchments. In the case of the Mitchell River catchment, soil gully erosion has been shown to be very high compared with other rates in Australia, mostly impacted by cattle grazing in riparian areas (Shellberg et al., 2016). Another study of the Flinders River catchment showed that gully and channel erosion are significant contributors to sediment loads in the Flinders River (Caitcheon et al. 2012).

During the dry season, the Gilbert and Flinders Rivers become a series of disconnected waterholes (Faggotter et al., 2013), whilst the Mitchell flows slowly. During the wet season, the floodplains become inundated for periods of days to weeks (Ndehedehe et al., 2020a, b).

The Gilbert and Flinders estuaries are characterized as having simple meandering river channels with some small tidal creeks, fringed with a relatively narrow line of mangroves, behind which are extensive saltflats. These saltflats are only inundated during the wet season or at the highest astronomical tides. The Mitchell estuary has many of the same characteristics, but is a deltaic fan with multiple estuary mouths.

All three estuaries are characterized as tide-dominated deltas due to the relatively high tidal energy compared to wave energy at the mouth, and high freshwater discharges in the wet season (Heap et al., 2001). The tidal range is <1 m on the neap tide, and 2.5 – 4 m on the spring tide. There is typically only one tide per day. In the nearshore area adjacent to the estuaries, ephemeral sandflats extend seaward from the estuary mouth, the size and shape of which varies with season, tidal and wind action. The coastal currents along the Gulf trap coastal water in these shallow environments (1-3 m deep) within a coastal (< 20 m)

boundary layer (Wolanski and Ridd, 1990). The outflowing estuarine water during times of high flow mix with this entrained coastal water to produce a turbid coastal water column (Wolanski, 1993).

The areal extent of intertidal mudflats, mangroves and supratidal (shallow coastal habitats only infrequently tidally inundated) mudflats for each estuary was measured using low-tide maps (Google Earth). This area was estimated to be 1.4, 0.4 and 1.1 km^2 for the Mitchell, Gilbert and Flinders/Bynoe (the Bynoe estuary is included in the estimations as it is a bifurcation of the Flinders near the mouth) estuaries respectively. The nearshore sandflat area was also determined using the same approach. It was estimated to be 0.5, 2.0 and 3.8 km^2 for the Mitchell, Gilbert and Flinders/Bynoe estuaries respectively. Additionally, the mangrove area was estimated to be 56.9, 7.2 and 24.5 km^2 for the Mitchell, Gilbert and Flinders/Bynoe estuaries respectively. The area of open water was 51.2, 8.8 and 26.7 km^2 for the Mitchell, Gilbert and Flinders estuaries respectively. The supratidal mudflat area behind the mangroves was estimated to be 112 km^2 for the Mitchell, 40 km^2 for the Gilbert, 213 km^2 for the Mitchell, Gilbert and Flinders/Bynoe estuaries respectively.

2.2 Hydrology

Gauging station data was used to generate hydrographs for the three river systems. Data from the gauging stations lowest in the catchments were used, i.e. Dunbar (139 km from Mitchell mouth), Burke Development Rd (102 km from Gilbert mouth) and Walkers Bend (103 km from Flinders mouth) (https://water-monitoring.information.qld.gov.au/) (Fig. 2). There were no gauging stations near the mouth of the rivers. No nutrient data exists from the gauging station sites.

Two hydrological models were used to generate annual end-of-river system (EOS) flow data for the three rivers: the FGARA (Lerat et al., 2013; Petheram and Yang, 2013), and NAWRA models (Fig. 2, Table S1, Philip et al., 2018). The river models developed for the Assessment were built within the eWater Source modelling platform (Welsh et al., 2012). Note that only the NAWRA data was available for the EOS flow for the Mitchell River. The difference between the FGARA and NAWRA model outputs was that the NAWRA model built on the FGARA model, with some bias correction applied to more closely matched gauge data.

The field trips are outlined below. The aim of the field trips was to compare the algal biomass and primary production of each estuary, and assess the effect of freshwater flow on nutrient inputs and primary production. Sampling was undertaken for water column physico-chemical parameters, nutrients, chlorophyll *a* concentrations, and sediment nutrients, chlorophyll *a* concentrations, primary productivity and respiration.

2.3 Field trips

Five field trips were conducted to the estuary systems of the three rivers on either the catamaran, MV Eclipse D (~ 16 m in length) or the monohull, RV CSIRO One (~ 7 m in length, Flinders only, May 2018) (Table S2). Three trips were conducted in the dry season (November 2016 and 2017, December 2019) when there was little or no river flow, and one in the wet season (March 2019). It was not possible to undertake all sampling in consecutive seasons due to resourcing issues, and this is acknowledged as a limitation in data interpretation. In the case of the MV Eclipse D trips, small boats (~5 m in length) were deployed from the mother boat to access sampling sites within each estuary.

Two additional trips were undertaken in the height of the wet season (April 2018 for Gilbert and Mitchell, and February 2019 for Flinders, Fig. 2b). It was not possible to access the estuaries by boat for logistical reasons. Therefore, helicopter sampling was conducted by lowering bottles into the surface waters mid-estuary and in the floodplume.

2.2.1 Physico-chemical and water column sampling and analyses

There were three routine sampling sites to each estuary sampling water above representative intertidal estuarine mudflats (Fig. 1). These sites were sampled in November 2016 and 2017, May 2018 (Flinders only), March and December 2019 (Table S2). Physico-chemical parameters were measured in the overlying water of the intertidal mudflats typically on the ebbing tide using a small boat. 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 which ensured a similar phase of the tide for the dry season sampling. In the wet season there was little tidal influence.

Water samples were also taken from the water surface above the estuarine mudflats for nutrients and chlorophyll *a* analyses. For nutrients, triplicates of surface water were also collected in separate buckets, then subsampled for total nitrogen (TN) and phosphorus (TP). Subsamples were also filtered in situ 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 analyzed. For chlorophyll *a* concentrations, known volumes of water were filtered through GF/F glass fibre filters (Whatman, nominal pore size 0.7 µm), then the filters were kept on ice until frozen at -80°C in the laboratory.

Sampling was also conducted in the height of the wet season by helicopter. This involved lowering a bottle three times into the surface waters at each site (Table S2). A transect was taken from the mouth of each estuary out into the floodplume in the nearshore environment. Replicated samples were processed for nutrient and chlorophyll *a* concentrations in situ using the methods outlined above.

To further assess the effect of freshwater nutrients on the estuary systems, 24 h sampling was done in March 2019 (wet season) and December 2019 (dry season) on board the MV Eclipse D when moored in each estuary. Sampling was conducted every 2 h in the wet season and less frequently, i.e. every 3 h, in the dry season. The reduced frequency in the dry season was because parameters did not change markedly over the tidal cycle in the dry season. Surface water samples were taken with a bucket, and bottom samples with a van Dorn sampler (1 m from the bottom). Processing followed protocols outlined above. Physico-chemical parameters were also measured with a datalogger (Hydrolab) at the same time.

Nutrients were analyzed using standard colorimetric approaches and an autoanalyzer (Seal analytical AA500HR, APHA, 2005). Total N and P, and total dissolved nitrogen and phosphorus were digested using the persulfate method prior to colorimetric analysis (Hosomi and Sudo, 1986). Samples were also run using the Kjeldahl digestion method (APHA, 2005) prior to colorimetric analysis to confirm that the persulfate digestion method was sufficient to convert TN to nitrate for colorimetric analysis in samples with high turbidity. Detection limits were 0.5 mg L^{-1} for DOC, 0.002 mg L^{-1} for ammonia, 0.001 mg L^{-1} for nitrate and phosphate, 0.4 mg L^{-1} for Kjeldahl TN, 0.2 mg L^{-1} for Kjeldahl TP, and 0.1 mg L^{-1} for persulfate TN. Filters for chlorophyll *a* analyses were sonicated in 90% acetone to extract the pigments, samples were kept in the fridge overnight to allow additional extraction, then the extract was filtered to remove glass filter 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.

In order to provide an estimate of TN and TP loads during the wet season in each estuary, TN and TP concentration data from the wet season trips (April 2018, February 2019, March 2019) were used multiplied by the gauging station flow rate data (Section 2.1). Gauging station data was used rather than modelled EOS flows because data was available for more years (Table S2).

2.2.2 Sediment chlorophyll and nutrient measurements

At the same times and sites as the routine water quality sampling was done at three sites in each estuary (Fig. 1), sediment samples on the estuarine mudflats were also taken for chlorophyll *a,* primary production, TN, TP, organic carbon and grain size analyses. Early in the day at low tide or close to low tide, three replicate sediment samples were collected from the intertidal zone. In the case of sediment chlorophyll *a* and total nutrient and organic carbon 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 analyzed.

For sediment total nutrient analyses, the Kjedahl method was used, and for organic carbon, the combustion method was used (APHA, 2012). For grain size analysis, sediment samples were dried in an oven at 60°C for 24 h. Dried samples were analyzed for grain size distribution according to Thorburn and Shaw (1987).

Sediment chlorophyll *a* concentrations were determined using the same analysis method as for the water column chlorophyll *a* concentrations (Jeffrey and Welshmeyer, 1997). A known weight of sediment was used. In summary, cold acetone (90%) was added to sediment, and samples were sonicated with a probe sonicator, left to extract overnight in the fridge, then filtered through GF/G glass fibre filters prior to absorbance measurements

On the December 2019 trip, porewater nutrients were also measured in the estuarine mudflats at the same sites as for total nutrients. This was done by pushing PVC tubes with small screen holes along the sides into the intertidal mud and leaving for 1-2 h at low tide. Then a syringe was used to remove the porewater which was subsequently filtered through 0.45 µm membrane filters, and then frozen until analyzed.

In addition to the sampling of the estuarine mudflats, in the second year and subsequent years, samples were also taken on the intertidal nearshore sandflats. Cores were taken for chlorophyll *a* concentrations, using the same sampling and analysis protocol as for the estuarine mudflats. This was done at half tide to minimize risks from crocodiles.

2.2.3 Sediment primary productivity and respiration

For primary production measurements on the intertidal estuarine mudflats, replicated cores (4.5 cm dia.) with a standardized sediment depth of 3 cm were collected at the same sites as the chlorophyll *a* samples using acrylic tubes and rubber bungs. These cores, with overlying estuarine water, were then used for incubations to measure oxygen fluxes. These incubations were done on the boat adjacent to the sampling points within a few hours of collecting samples. Primary production cores were equilibrated open to the air for a few hours prior to the experiment. The experiment commenced once full sunlight became available. Cores were then completely filled with water so no air remained, then capped so they were completely sealed. A Presens® fiber-optic oxygen sensor (FIBOX) was used to measure oxygen-sensitive optode patches glued to the inside wall of each core (Presens) (Duggan et al. 2014). This allowed measurements of oxygen concentrations in each core over time without needing to open up the cores. 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 to provide more statistically robust information on respiration rates. All sealed cores were placed in a rank in a bin with in situ seawater flowing over the sealed cores to maintain temperature in situ, and were kept in full sunlight. Cores for 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 the overlying water to oxygen fluxes.

The oxygen levels in the cores were read periodically 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. Experiments were stopped before non-linearity occurred. Oxygen production (and consumption in the dark treatments) was calculated based on the rate of

change of oxygen concentrations, standardized to the area of sediment, and expressed per unit time. Water column primary production was accounted for using cores containing only water. The method was too inaccurate to get meaningful water column productivity rates.

In addition to the incubations outlined above, estuarine mudflat samples were also taken at the same sites on November 2017, May 2018 (Flinders only) and December 2019 to determine the effect of nutrient additions on oxygen fluxes. This was designed to be a simulation of nutrient inflows from wet season flow. Oxygen fluxes were chosen, rather than chlorophyll *a* concentrations, because preliminary analyses showed that the time available for incubations, i.e. two days, was insufficient for a statistically significant increase in chlorophyll *a* concentrations. At each site, one dark and four light replicate cores were incubated with and without nitrogen and phosphorus addition. Ammonium chloride solution, to give a final concentration of 0.924 mg N L^{-1}, was added to overlying water of each core. Ammonium was chosen, rather than nitrate, because previous research using phytoplankton in an adjacent estuary in the Gulf showed that ammonium was present at similar concentrations as nitrate and assimilated preferentially (Burford et al. 2012). Sodium dihydrogen phosphate solution, to give a final concentration of 0.127 µg P L^{-1}, was also added. Open cores with overlying water but kept separated from other cores were kept in tubs with flowing seawater surrounding the cores in full sun for two days. After this, all cores were filled with estuarine water early in the day, capped and incubated. Primary production measurements were then done using the same protocol outlined above for sediment core samples.

2.4 Statistical analyses

Statistical comparisons between rivers and sampling occasions for sediment 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 Welsh's test.

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

3. Results

3.1 Hydrological conditions during study

During the study, the Mitchell typically had a longer period of flow during each wet season, based on gauging station data, compared with the Gilbert, followed by the Flinders (Fig. 2b). In the final wet season of the study, in February/March 2019, the Flinders system had the highest daily flow since records began in the 1970's. The annual cease-to-flow periods during the study (2016-2019), based on flow at the gauging stations, were shortest in the Mitchell, typically with no days of cease-to-flow (Fig. 3). This was followed by the Gilbert, and then the Flinders, which had a cease-to-flow period of 150 to over 200 days per year. These cease-to-flow periods are representative of long-term differences between the river systems.

The flow data from the gauging stations was used to estimate annual water year (July – June) flows over the study and compared with data from two models of end-of-system (EOS) flow, the NAWRA and FGARA models (Table S1). The modelled EOS annual flow volume using the NAWRA model was substantially higher than the gauging station data for the Mitchell, but not the Gilbert and Flinders. The FGARA model data for the Gilbert was also substantially higher than the gauging station data for the same river. However, values for both models were typically similar to the gauging station data for the Flinders.

It would be expected that EOS flows would be higher than those in the gauging stations, given that the gauging stations are more than 100 km upstream. Some rivers, e.g. Mitchell

River, have additional tributaries downstream from the gauging station that would change flow estimates. Additionally, there could be localized rainfall with associated runoff downstream of the gauging stations. An additional source of difference between modelled and gauging station data occurs in high flow years, such as the 2019 floods in the Flinders (Ndehedehe et al., 2020a), where overbank flow and floodplain inundation may be significant. This flow may not be captured by the gauging station.

Conversely, there are likely to be errors in model estimates, due to the low typographic relief of much of the downstream floodplains of these rivers. This means that during years with extensive flooding, catchment boundaries cannot be differentiated and water from floodplains may move through more than one river system in an unpredictable manner.

3.2 Intertidal estuarine mudflat chlorophyll a concentrations and primary production

Across all sampling occasions and combining nearshore sand (at the mouth of rivers) and estuarine mudflat data, there were no statistical differences in chlorophyll *a* concentrations between the three estuaries. However, comparing the nearshore sand and estuarine mudflat sites across all sampling occasions, the sandflats had higher chlorophyll *a* concentrations than the mudflat in the Flinders ($P<0.001$) and the Mitchell estuaries ($P<0.05$), while for the Gilbert estuary, the mudflats had higher chlorophyll *a* concentrations than the sandflats ($P<0.05$) (Fig. 4).

Comparing sampling times within each estuary, chlorophyll *a* concentrations were higher in the first two dry season sampling occasions (November 2016, 2017) than the wet season or transition period in the Flinders estuary (Table S3). The Gilbert and Mitchell estuaries also had higher chlorophyll *a* concentrations in November 2016 compared with the other sampling occasions.

Overall, primary production (only measured on estuarine mudflat sites) was statistically higher in the Flinders and Gilbert estuaries than the Mitchell estuary (Table 1). Respiration rates on the estuarine mudflat sites (measured on the last two trips) were also statistically higher on the Flinders estuary than the other two estuaries. Rates were also compared between sampling occasions. The estuarine mudflats on the Flinders and Gilbert estuaries had higher primary production than the Mitchell estuary in both November 2016 and 2017, but not in December 2019 (Table 2). The estuarine mudflats on the Gilbert estuary had higher primary production in March 2019 compared with the other two estuaries.

Primary production in the Flinders estuarine mudflats were higher in the dry season in November 2016 and December 2019 than the other sampling occasions (Table S3). However, in the case of the Gilbert and Mitchell estuaries, rates were highest in November 2016 and the wet season, March 2019. Rates were also higher in December 2019 in the Mitchell estuary. Respiration rates were higher in the wet season than the dry season in the Flinders, but the same was not true in the Gilbert and Mitchell estuaries.

3.3 Estuarine intertidal mudflat nutrient addition experiments

Experiments were also conducted on multiple trips to determine the effect of nutrient additions, at concentrations of ~0.924 mg N L^{-1} as ammonium, and 0.127 mg P L^{-1} as phosphate, on primary production in the estuarine mudflats. Overall, the addition of nutrients resulted in statistically higher mudflat primary production compared with no addition (Fig. 6). The Flinders estuary had double the primary productivity rates with the addition of nutrients, while in the Gilbert it was 60% higher, and the Mitchell was 54% higher. There was a high level of variation between sampling sites and replicates meaning that primary production was not enhanced on all occasions, sites and rivers. However, there was no consistent differences in the responses.

3.4 Sediment nutrients and grain size

There were no statistical differences in the TN or total organic carbon concentrations in mudflat sediments between estuaries (Table 1). Total P concentrations in the estuarine mudflat sediments were statistically higher in the Flinders estuary than the other two estuaries. Porewater ammonium, nitrate/nitrite and phosphate concentrations were only measured in the Flinders and Gilbert estuaries in December 2019. Concentrations were highly variable, but ammonium concentrations were typically higher than nitrate/nitrite and phosphate concentrations across estuaries. Percentage mud was similar at the estuarine mudflat sites in each estuary, i.e. 80-84% (Table 1).

3.5 Water column chlorophyll a concentrations and primary production

Comparing rivers within each sampling occasion, water column chlorophyll *a* concentrations in the Flinders was statistically higher than the Mitchell estuary in November 2017, March 2019 and December 2019 (Table 3). The Gilbert estuary was typically intermediate between the other two estuaries. Comparing sampling occasions within each river, the Flinders estuary had the highest water column chlorophyll *a* concentrations in March 2019 compared with November 2016 and May 2018 (Table S3). There were no statistical differences between sampling occasions in the Gilbert estuary, while in the Mitchell estuary, values were statistically higher in December 2019.

Primary production in the water column was only measured on the final trip in December 2019 (Table 3). Depth-integrated primary production was highest in the Mitchell estuary, and lowest in the Gilbert estuary. The euphotic depth was less than 0.5 m.

3.6 Water column nutrients

The Flinders estuary had statistically higher water column TN and TP concentrations than the other two estuaries in the three dry season sampling occasions (Table 4). In the wet season, the Mitchell estuary had statistically higher TN concentrations than the other two estuaries. There were no consistent differences in ammonium, nitrate/nitrite and phosphate concentrations between the three estuaries on different sampling occasions. Across the study, dissolved organic nitrogen concentrations were 58 ± 15%, 72 ± 13% and 62 ± 20% of the TN concentrations in the Flinders, Gilbert and Mitchell estuaries, respectively. Dissolved organic phosphorus could not be determined accurately due to the lack of sensitivity of the method. The log(TN:TP) ratios were calculated as per Isles (2000). Log(TN:TP) ratios varied considerably and were sometimes higher than balanced Redfield (1958) ratios, i.e. 1.2, and sometimes lower, with no consistency.

There was no evidence of increased total or dissolved inorganic nutrient concentrations during the March 2019 wet season sampling, compared with the dry season sampling for either the Flinders or the Glibert R estuaries (Table S4). The Mitchell estuary had higher TN, TP and ammonium concentrations in the wet season compared with the dry seasons. Despite the lack of statistical differences between the sampling occasions, other sampling in March over a 24 h tidal cycle provided evidence of higher concentrations of TN, ammonium and nitrate/nitrite flowing downstream during the wet season in the Flinders estuary. This was based on a correlation (R^2 = 0.75 – 0.8) between salinity and TN, ammonium and nitrate/nitrite, as measured over a tidal cycle in March 2019 (Fig. 5a-c). Additionally, when data from sampling all estuary floodplumes was combined and compared with salinity during the wet season sampling in March 2019, salinity explained approximately 50% of the variation in TN concentrations (Fig. 5d).

Estimates were made of the potential TN and TP wet season loads to estuaries using measured data from wet season trips multiplied by gauging station flow volumes (Table S1). TN loads varied from 797 to 3605 t, and TP loads varied substantially more, i.e. 45 to 2849 t. There was a high level of interannual variability driven largely by differences in flow volumes. It should be acknowledged that only one branch of the Mitchell River, and one of Flinders/Bynoe was sampled which would have affected the accuracy of load calculations.

3.7 *Water column physico-chemical parameters*

Typically, the Flinders and Gilbert estuaries were hypersaline in the dry season during the study (Table 4). The salinity in the Mitchell estuary was statistically lower than these two rivers, and was close to seawater salinity. Salinities in all estuaries were lower in the wet season with the scale of salinity reduction dictated by the timing of flow events in each river compared with the time of sampling.

Water temperatures were generally similar between estuaries being >30°C most of the time in the late dry and wet season (Table 4). The only exception was in the transition period in May 2018, when the water temperature in the Flinders estuary was considerably lower, i.e. 18.2°C. Dissolved oxygen concentrations, pH and turbidity typically did not vary statistically between rivers, although the Flinders typically had a much higher, but highly variable turbidity (Tables 4, S4).

3.8 Summary of results

In summary, estimated nutrient loads to the end of the catchments from wet season flow were highly variable from year-to-year, with no obvious differences between the three river systems. The Flinders estuary had higher rates of primary production and respiration on the estuarine mudflats in the dry season than the Mitchell estuary, with the Gilbert estuary intermediate between the two (Table 5). Addition of nutrients to estuarine mudflat samples stimulated primary productivity in all three estuaries, but the scale of response varied between sampling trips, sites and estuaries. Primary productivity was a more sensitive measure of differences between estuaries than chlorophyll *a* concentrations. Water column chlorophyll *a,* and nutrient concentrations, as well as salinities and turbidity were also higher on the Flinders in the dry season than the other estuaries (Table 5). It was more difficult to directly compare estuaries in the wet season as the timing of sampling did not always coincide with the peak of the flow. However, 24 h sampling showed that higher nutrient concentrations enter the estuaries during the wet season.

4. Discussion

4.1 Comparison with other estuaries

Nutrient and chlorophyll *a* concentrations in the three estuaries in our study during the wet season were comparable with concentrations measured in studies of other tropical estuaries in northern Australia (Burford et al. 2011, 2012; Howley et al., 2018). Primary production in the water column (December 2019 only) was also comparable with other measured rates in northern Australia (Burford et al., 2008, 2012; Smith et al., 2012). However, rates were lower than in a tropical estuary in Costa Rica (Soria-Piriz et al., 2017). Rates were also lower than those typically reported in a global comparison of studies (Cloern et al., 2014). The high turbidity in the estuaries in our study, which would have limited light availability, is likely to be a key reason why depth-integrated primary production was relatively low. This turbidity was the result of inorganic, rather than organic particles. High turbidity was also found in adjacent Norman estuary in the Gulf of Carpentaria (Burford et al., 2012).

Interestingly, estuaries did not become more turbid in the wet season. This suggests that wind and tidal action, rather than catchment inputs were the main driver of high estuarine turbidity (Wolanski, 1990). The highest turbidity was in the Flinders estuary. This is despite the fact that a previous study has highlighted globally significant erosion in the Mitchell catchment (Shellberg et al., 2016). However, Caitcheon et al. (2012) proposed that at least for the Flinders, much of the eroded material is deposited before it reaches the estuary. Given the low topographic relief of much of the lower sections of the three rivers, it is likely that there is significant deposition on all three rivers.

Mudflat chlorophyll *a* concentrations (9-182 mg m^{-2}) and primary production (2.0-2.9 mmol O_2 m^{-1} h^{-1}) in the estuaries in our study were within the range of other reported studies

globally. This is despite the fact that many other systems were more impacted by anthropogenic inputs than our study (10-200 mg chlorophyll *a* m^{-2}, Gomez-Ramirez et al., 2019; 10-100 mg chlorophyll *a* m^{-2}, primary production 0.8-7.5 mmol O_2 m^{-1} h^{-1}, Kwon et al., 2020).

There have been limited studies of primary production on intertidal mudflats in northern Australia for comparison, but a study in Darwin Harbour showed that chlorophyll *a* concentrations and primary production were similar to our study (Burford et al., 2008). Conversely, mudflat respiration rates in the Darwin Harbour study were considerably higher than in our study (102.2 ±38.4 mg O_2 m^{-2} h^{-1} versus 3.8 – 13.8 mg O_2 m^{-2} h^{-1} respectively) and in the Darwin Harbour study, respiration exceeded primary production. However, in our study, respiration rates were substantially lower than primary production rates.

Primary production on the estuarine mudflats appeared to be a more sensitive measure of differences between estuaries than chlorophyll *a* concentrations. Although chlorophyll *a* is a proxy for biomass, it is also varies per unit carbon with many factors such as light conditions, nutrient conditions, and type and size of species present (Jeffrey and Vesk, 1997). Additionally, if faunal grazing rates are high, biomass of benthic algae may be low while productivity remains high. Other research on estuarine mudflats in the Gulf of Carpentaria has shown that benthic animal densities, including macrofauna and penaeid prawns, are relatively high (Staples and Vance, 1987; Lowe et al., submitted). Therefore, grazing impacts may be high.

The differences may relate to differences in the ratio of mangrove to estuary area, with Darwin Harbour having extensive dense mangrove forests while in our study mangroves were typically smaller plants limited to a narrow margin along the creeks. As a result, it is likely that less organic matter and nutrients would be contributed from mangroves to the adjacent aquatic environment in our study compared with Darwin Harbour. A study by Chen et al. (2019) in three subtropical estuaries also proposed that increased intensity in agricultural land use can shift benthic metabolism from net autotrophy to net heterotrophy.

4.2 Implications of flow alterations

Experiments within this study showed that nutrient inputs stimulate growth of estuarine mudflat algae in all three rivers. This highlights the importance of nutrient inputs to the estuary in fuelling estuarine productivity. This productivity is critical to supporting higher trophic levels, including fisheries species and endangered migratory shorebirds, which are a significant component of these estuary systems (Garnett, 1989; Robins et al., 2005; Vance and Rothlisberg, 2020). These species feed on the abundant benthic organisms on the mud- and sandflats, which in turn rely on primary production (Duggan et al., 2014; Lowe et al. submitted).

Water entitlements have been allocated for the Gulf rivers which range from 20 to 206 GL per year across rivers (DNRME, 2017). There are plans for a significant increase in water development in the three rivers (DNRME, 2018a, 2018b). In the case of the Mitchell River this may include major dams in the upstream reaches (Petheram, et al., 2018). While the impact of proposed water allocations on freshwater species has been identified using an ecohydrological approach (DSITIA, 2014), this assessment has not been undertaken for estuarine habitats and their species. The most immediate effect of flow regulation and/or extraction, is likely to be a reduction in loads of nutrients (and sediment) reaching estuaries in the wet season. A study of the Mitchell River catchment showed which areas of the catchment have the highest nutrient loads and hence are likely to be the greatest potential contributors to nutrient loads downstream (Rustomji et al., 2010). Similar studies have not been done on the Flinders or Gilbert River catchments. It is clear that this information is crucial to more accurately determining the scale of impact of water development plans throughout the catchment.

A few key attributes of flow are likely to be most critical to productivity: first flush for a wet season; and flow during years with medium to low flow. The first flush each season is likely to input the highest nutrient concentrations to estuaries, while salinity has not decreased to the level where primary productivity is adversely affected (Duggan et al., 2014). Medium to low flow years are those for which water extraction as a proportion of total flow will be at its highest, and may result in substantially lower nutrient (and sediment loads) transported into the estuary. While the effects may not be seen immediately, consecutive years of low to medium flow will mean ultimately mean nutrient depletion in estuaries via processes such as advection, burial and denitrification. Therefore, protecting estuarine and nearshore productivity is best achieved by ensuring that first flushes continue to occur. Additionally, water extraction should be highly controlled in low to medium flow years.

The effect of flow alteration on freshwater habitats and species is more well studied than for estuarine systems (e.g. Poff and Zimmerman, 2010; Rytwinski et al., 2020). Poff and Zimmerman (2010) showed that 92% of flow alteration studies found negative ecological changes in freshwater in response to a variety of types of flow alteration, with fish measures consistently showing a negative response. However, they acknowledge that information was lacking on primary production and nutrient retention measures. Rytwinski et al. (2020) show that much of the knowledge of ecological effects of flow alteration is focussed on the impact of dam construction. In terms of water extraction, however, there are far fewer studies, with an emphasis on fish abundance and diversity.

Studies on the effect of flow alteration on estuarine and marine habitats is much more limited. Brookes et al. (2015) found ecological impacts of an extreme drought combined with over-allocation of water resources on a southern Australian estuary. During their study, as the drought conditions progressed, food web complexity and productivity declined, including a decrease in fish abundance, lower nutrient loads and lower primary productivity.

Comparing the long-term hydrographs of the three river systems, the Flinders estuary has the most variable flow inputs from year to year, as well as the longest cease-to-flow period each year. Cease-to-flow duration gives an indication of the period of time each year when new sources of nutrients and sediment are not being contributed from the catchment. Therefore, internal nutrient sources or sources from tidal incursion must be accessed for primary producers to continue to grow. As a result, the Flinders system is likely to be more susceptible than either the Gilbert or Mitchell systems to changes in water extraction on low to medium flow years. The effects of water extraction may not be seen immediately, as these river systems are highly adapted to variable flow, but multiple years of sustained water extraction is likely to impact productivity in the longer term.

In the longer term, an increased number and intensity of irrigated agricultural activities could result in significant nutrient inputs, from fertilizers to Gulf rivers. In the Great Barrier Reef, a number of catchments have relatively high dissolved inorganic nutrient loads which are transported through estuaries into the nearshore zone, with adverse ecological effects (Bainbridge et al., 2009). This is the result of agricultural activities such as sugarcane and banana production.

4.3 Comparison of estuaries

This study found that the Flinders estuary was typically more productive than the Mitchell estuary, with the Gilbert estuary intermediate between the two. This was based on higher rates of primary production on the estuarine mudflats, and higher chlorophyll *a* concentrations in the water column, irrespective of sampling occasion (Table 5). In the dry season, water column nutrient concentrations were also higher in the Flinders estuary compared with the other estuaries.

These results are surprising given that the Flinders estuary typically had the longest cease-to-flow period of the three estuaries each year, resulting in the more pronounced hypersaline

conditions than the other two estuaries. This estuary also had lower freshwater flow volumes, on average, compared with the Mitchell estuary, and more variable year-to-year flow.

Three alternative hypotheses are proposed for the primary production ranking of the three estuaries:

1. Loads of nutrients entering the Flinders estuary during the wet season were higher than the other two estuaries;
2. Mangroves and supratidal (shallow coastal habitats only infrequently tidally inundated) estuarine mudflats contributed more nutrients to the Flinders estuary than the other two estuaries;
3. The nearshore environment in the Flinders system was more conducive to greater nearshore-estuary coupling, such that a higher proportion of floodplume nutrients in coastal waters re-enter the estuary fuelling productivity.

Hypothesis 1: Wet season nutrient loads higher in the Flinders estuary than other estuaries

The first hypothesis states that wet season nutrient loads into the Flinders estuary are typically higher than those in the other estuaries. It also assumes that primary production in the estuary is driven by nutrient availability and hence higher nutrient loads would equate to higher productivity. The in-situ experiments conducted throughout our study showed that nutrient additions can stimulate primary production, at least on the estuarine mudflats in all three estuaries (Table 5). Although the potential for nutrient stimulation of water column primary production was not measured, a previous bioassay study in a similar nearby Gulf estuary, the Norman R estuary, showed that nutrient addition consistently stimulated water column primary production (Burford et al., 2012). A previous study also showed that the deeper waters of the Gulf are nutrient limited, and unlikely to be a substantial source of nutrients to coastal areas (Burford et al., 2009).

There was no statistical difference in the water column ammonium and phosphate concentrations between the three estuaries in the wet season. However, the Flinders estuary had statistically highly nitrate concentrations, indicative of freshwater inputs. The volume of flow in the Flinders estuary was always lower than the Mitchell estuary throughout the study. This is despite the larger catchment area. The estimated nutrient load from each river, albeit based on limited information on nutrient concentrations during wet season flows, suggests that interannual variability in flow volumes was the most important factor driving nutrient loads. There was no evidence that any one river had consistently higher inputs. These combined findings suggest that there is no evidence to support the hypothesis that the total wet season nutrient load was consistently higher in the Flinders estuary than the other two estuaries. So nutrient loads alone do not appear to explain the higher primary production in the Flinders.

Use of nutrient measurements in our study to compare estuaries was challenging, especially as it is logistically not possible to sample at the peak of flow, or during first flush of wet season flow in all estuaries. Therefore, statistical comparisons of nutrient concentrations measured during the study should be treated with caution. The 24 h sampling during the wet season gave a better indication of the higher nutrient concentrations as a result of freshwater inputs, since salinity was negatively correlated with nutrient parameters. A previous study in an estuary adjacent to the Flinders estuary, Norman R estuary, where fortnightly sampling of water column nutrients was conducted over two consecutive wet seasons showed that nutrient concentrations increased relative to the dry season in one wet season but not the other, again highlighting the highly variable nature of nutrient inputs associated with freshwater flow (Burford et al., 2012). The lack of river models quantifying freshwater flows, and associated nutrients, is a major impediment to interpretation of results, and requires further work.

An additional challenge with measuring nutrient concentrations is that concentrations can give a distorted view of the relative productivity of estuaries, particularly in systems with relatively low nutrient concentrations. Nutrient uptake rates by phytoplankton may result in turnover rates of minutes to hours (e.g. Burford et al., 2008, 2012). Other studies have shown that low-nutrient estuaries can be highly productive (e.g. Cook et al. 2004a, b), with a higher proportion of bioavailable nitrogen assimilated rather than denitrified and therefore being retained with the system compared with estuaries with higher nutrient concentrations (Vieillard et al., 2020). Therefore, factors that integrate the effect of nutrient inputs, such as algal production or faunal production, may provide better indicators.

Hypothesis 2: Adjacent mangroves and supratidal saltflats were important nutrient contributors

This hypothesis assumes that larger mangrove and supratidal saltflat extent could contribute significantly more nutrients to fuel primary production in the Flinders estuary compared with the other estuaries. Typically, in estuaries with significant mangrove forests, carbon and nutrient inputs from the forests are an important driver of primary production on adjacent mudflats (Alongi, 2002). Conversely, studies have shown that runoff from mangrove forests can also inhibit production due to the leaching of humic substances (Rivera-Monroy et al., 1998). However, the mangrove areal extent in the Mitchell estuary was greater than the Flinders estuary (Table 5). This suggests that the nutrient contribution to the Flinders from this source should be lower, not higher than the Mitchell. Additionally, organic carbon levels and respiration rates in the intertidal mudflat sediment in the wet season were low in all three estuaries compared with other studies (Alongi, 2002; Burford et al., 2008). This indicates that mangrove carbon (and nutrients) is unlikely to be a major contributor.

The areal extent of the supratidal saltflats on the Flinders estuary was higher than the Mitchell, followed by the Gilbert (Table 5). These areas are only inundated during the highest astronomical tides, or during the wet season flooding. Previous research on the supratidal saltflats of the nearby Norman R estuary which has saltflats contiguous with the Flinders estuary, has shown that these saltflats can contribute substantial nutrient (and sediment from erosion processes) loads to the estuary as flooding recedes (Burford et al., 2016). The estimated annual releases based on this previous study were 166, 54 and 1.3 t for ammonium, nitrate/nitrite and phosphate respectively. While these loads were not insignificant, they were still considerably less than the estimated catchment loads in our study or the previous study (Table S2, Burford et al., 2016). Therefore it would be expected that in the Flinders estuary, nutrients from saltflats would be an important, but not major contributor to primary production.

The nutrients releases from the saltflats are the result of previous inundation periods fuelling benthic cyanobacterial growth, which subsequently desiccate and decompose. Upon wetting, decomposed algae result in nutrients (and carbon) release. It is therefore possible that the saltflat nutrient release played a significant role in fuelling greater productivity in the Flinders estuary compared with the other estuaries. A previous study in a tropical estuary in northern Australia showed the importance of linkages between saltflats and estuaries, highlighting erosion of these habitats over geological timeframes (Crosswell et al., 2020).

Estuarine mudflats themselves can also be a source of nutrients for algal growth. Measurements of porewater nutrients in the final sampling trip (December 2019) showed that ammonium concentrations, in particular, were high relative to water column concentrations. However, there was insufficient data to demonstrate whether concentrations were higher in the Flinders estuary. Certainly addition of nutrients to the mudflats of all three estuaries stimulated primary production, suggesting porewater nutrients alone were not sufficient for maximum primary productivity. Total N concentrations in estuarine mudflat sediments were also comparable between the three estuaries, although total phosphorus concentrations were higher in the Flinders estuary.

Hypothesis 3: Greater connectivity between nearshore and estuary in Flinders system

The third hypothesis states that the Flinders estuary and nearshore waters are more closely linked than in the other estuaries, resulting in material in floodplumes ultimately having a greater influence on the estuarine environment. There was evidence during our study that the mouth of the Flinders estuary had more shallow nearshore sandflat area, and was generally shallower than the Gilbert or Mitchell systems (Fig. S1). Nitrate concentrations were also higher in the Flinders than the other two estuaries in the dry season, suggesting greater conservation of nitrogen in this system.

The southern Gulf, which includes the Flinders estuary, shows long-term evidence of progradation and accretion as a result of terrestrial sediment inputs (Rhodes, 1980). Therefore, during the wet season, when nutrient plumes enter the nearshore environment, there is less dilution and dispersal of nutrients than would occur in the Mitchell. The coastal boundary zone in the shallower waters of the Gulf ensures that freshwater and associated nutrients are trapped in this zone, rather than being transported out to sea (Short et al., 2020). As tides re-establish in the dry season, resuspended material from biological productivity nearshore is transported into estuaries. Another study in a northern Australia estuary/floodplume demonstrated tidal resuspension of carbon and nutrients from floodplumes influencing an estuary (Crosswell et al., 2020).

It should also be noted that the Flinders system, including the Bynoe which bifurcates at the lower end of the Flinders and the Norman River, all discharge within a distance of 28 km of each other. Therefore, all three estuary mouths are likely to share discharge nutrient loads. A previous study estimated significant nutrient discharge load from the Norman River over two wet seasons (Burford et al., 2012). Additionally, preliminary data from a study of release of ammonium as a result of chemical desorption and biological activity in floodplumes in these three Gulf rivers suggests that this could also be an important driver of primary productivity (A. Garzon Garcia, unpublished data). This potentially provides a more sustained source of nitrogen for primary productivity than dissolved inorganic nutrients discharged directly from the river.

There is evidence for higher chlorophyll *a* concentrations in the floodplume out from the Flinders estuary in March 2019, compared with the other two systems. Chlorophyll *a* concentrations in the Flinders floodplume just after the peak of flooding was as high as 11.02 µg L^{-1} in the outer edges of the floodplume. Concentrations were comparable with those in the Princess Charlotte Bay floodplume in the Great Barrier Reef lagoon (Howley et al., 2018). The concentrations in the Flinders estuary were substantially higher than the Mitchell (3.49 µg L^{-1}) and the Gilbert floodplumes (0.92 µg L^{-1}) on the same sampling trip. The concentrations in the Michell and Gilbert floodplumes were comparable with floodplume chlorophyll *a* concentrations in the Tully coastal region of the Great Barrier Reef lagoon, Australia (Devlin and Schaffelke, 2009).

Additionally, water column chlorophyll *a* concentrations in the Flinders estuary at this time were statistically higher (18.4 µg L^{-1}) than other sampling times, pointing to the stimulatory effects of nutrient inputs during the wet season. A review of tropical and low nutrient estuaries suggested that in these systems a far greater proportion of the bioavailable nitrogen is assimilated rather than denitrified, resulting in a net retention of nitrogen within the system, compared with more eutrophic systems (Vieillard et al., 2020).

Therefore there is evidence to support Hypothesis 3, although more research in needed on the hydrodynamics of the coastal environment in the Gulf to support the hypothesis.

4.4 Conclusions

In conclusion, this study compared the productivity of three estuary systems (Flinders, Gilbert, Mitchell) in the wet-dry tropics. The Flinders estuary was found to be the most productive of the three estuaries. This is despite the fact that the Flinders estuary had the

most extreme climate with a shorter period of freshwater flow, and highly variable flow from year-to-year, compared with the other two rivers. The addition of nutrients stimulated estuarine mudflat primary production in all three estuaries suggesting chronic nutrient limitation. The higher rates of productivity in the Flinders estuary appear to be the result of closer coupling between the estuary and nearshore compared with the other estuaries. Proposed water extraction may therefore significantly impact estuarine productivity especially during first flush periods at the start of the wet season, and in years with low to medium flow.

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References

Alongi, D.M., 2002. Present state and future of the world's mangrove forests Environ. Conserv. 29, 331–349

American Public Health Association (APHA), 2005. Standard Methods for the Examination of Water and Wastewater. 21st Edn. Greenburg, A.E., Clesceri, L.S., Eaton, A.D. (Eds.) American Public Health Association, Washington, D.C.

Auricht, H.C.C., Clarke, K.D., Lewis, M.M., Mosley, L.M., 2017. Have droughts and increased water extraction from the Murray River (Australia) reduced coastal ocean productivity? Mar. Freshw. Res. 69, 343-356.

Bainbridge, Z.T., Brodie, J.E., Faithful, J.W., Sydes, D.A., Lewis, S.E. Identifying the land-based sources of suspended sediments, nutrients and pesticides discharged to the Great Barrier Reef from the Tully–Murray Basin, Queensland, Australia. Mar. Freshw. Res. 60, 1081-1090

Brookes, J.D., Aldridge, K.T., Bice, C.M., Deegan, B., Ferguson, G.J., Paton, D.C., Sheaves, M., Ye, Q., Zampatti, B.P., 2015. Fish productivity in the lower lakes and Coorong, Australia, during severe drought. Trans. Royal Soc. South Australia. 139, 189-215.

Bucher, D., Saenger, P., 1994. A classification of tropical and subtropical Australian estuaries. Aquat. Conserv. 4, 1-19.

Burford, M.A., Alongi, D.M., McKinnon, A.D., Trott, L.J., 2008. Primary production and nutrients in a tropical macrotidal estuary, Darwin Harbour, Australia. Est. Coast. Shelf Sci. 79, 440-448.

Burford, M.A., Rothlisberg, P.C., Revill, A. T., 2009. Sources of nutrients driving production in the Gulf of Carpentaria, Australia – a shallow tropical shelf system. Mar. Freshw. Res. 60, 1044-1053.

Burford, M. A., Revill, A.T., Palmer, D.W. Clementson, L., Robson, B.J., Webster, I.T., 2011. River regulation alters drivers of primary productivity along a tropical river-estuary system. Mar. Freshw. Res. 62, 141-151.

Burford, M., Webster, I., Revill, A., Kenyon, R., Whittle, M., Curwen, G., 2012. Controls on phytoplankton productivity in a wet-dry tropical estuary. Est. Coast. Shelf Sci. 113, 141-151.

Burford, M., Valdez, D., Curwen, G., Faggotter, S., Ward, D., O'Brien, K., 2016. Inundation of saline supratidal mudflats provides an important source of carbon and nutrients in an aquatic system. Mar. Ecol. Prog. Ser. 545, 21–33.

Caitcheon, G.G., Olley, J.M., Pantus, F., Hancock, G., Leslie, C., 2012. The dominant erosion processes supplying fine sediment to three major rivers in tropical Australia, the Daly (NT), Mitchell (Qld) and Flinders (Qld) Rivers. Geomorphology 151, 188-195.

Chen, J-J., Wells, N.S., Erler, D.V., Eyre, B.D., 2019. Importance of habitat diversity to changes in benthic metabolism over land-use gradients: evidence from three subtropical estuaries. Mar. Ecol. Prog. Ser. 631, 31-47.

Cloern, J.E., Foster, S.Q., Kleckner, A.E., 2014. Phytoplankton primary production in the world's estuarine-coastal ecosystems. Biogeosciences 11, 2477–2501.

Cook, P. L. M., Revill, A. T., Butler, E. C. V., Eyre, B. D., 2004a. Carbon and nitrogen cycling on intertidal mudflats of a temperate Australian estuary. II. Nitrogen cycling. Mar. Ecol. Prog. Ser. 280, 39–54.

Cook, P. L. M., Revill, A. T., Clementson, L. A., Volkman, J. K., 2004b. Carbon and nitrogen cycling on intertidal mudflats of a temperate Australian estuary. III. Sources of organic matter. Mar. Ecol. Prog. Ser. 280, 55–72.

Crosswell, J. R., Carlin, G., & Steven, A. (2020). Controls on carbon, nutrient, and sediment cycling in a large, semiarid estuarine system; princess Charlotte Bay, Australia. J. Geophys. Res.: Biogeosciences, 125, e2019JG005049.

Devlin, M., Schaffelke, B. 2009. Spatial extent of riverine flood plumes and exposure of marine ecosystems in the Tully coastal region, Great Barrier Reef. Mar. Freshw. Res. 60, 1109-1122.

DNRME [Department of Natural Resources, Mines and Energy]. 2017. Water Resource (Gulf) Plan, Sale of general reserve unallocated water: tender assessment report. Department of Natural Resources, Mines and Energy, Queensland Government, Brisbane, Australia.

DNRME [Department of Natural Resources, Mines and Energy]. 2018a. Minister's Performance Assessment Report, Water Plan (Gulf) 2007. Department of Natural Resources, Mines and Energy, Queensland Government, Brisbane, Australia.

DNRME [Department of Natural Resources, Mines and Energy]. 2018b. Minister's Performance Assessment Report, Water Plan (Mitchell) 2007. Department of Natural Resources, Mines and Energy, Queensland Government, Brisbane, Australia.

DSITIA. 2014. Targeted review of Water Resource (Gulf) Plan 2007. Environmental Assessment. Department of Science, Information Technology, Innovation and the Arts, Queensland Government, Brisbane.

Duggan, M., Connolly, R.M., Whittle, M., Curwen, G., Burford, M.A., 2014. Effects of freshwater flow extremes on intertidal biota of a wet-dry tropical estuary. Mar. Ecol. Prog. Ser. 502, 11-23.

Faggotter, S.J., Webster, I.T., Burford, M.A., 2013. Factors controlling primary productivity in a wet-dry tropical river. Mar. Freshw. Res. 64, 585-598.

Garnett, S.T., 1989. Wading Bird Abundance and Distribution - South-eastern coast of the Gulf of Carpentaria. RAOU Report No. 58. Report to the Queensland National Parks and Wildlife Service.

Gomez-Ramirez, E.H., Corzo, A., Garcia-Robledo, E., Bohorquez, J., Aguera-Jaquemet, A., Bibbo-Sanchez, F., Soria-Piriz, S., Jimenez-Arias, J.L., Morales, A., Papaspyrou, S., 2019. Benthic-pelagic coupling of carbon and nitrogen along a tropical estuarine gradient (Gulf of Nicoya, Costa Rica). Est. Coast. Shelf Sci. 228, 106362.

Gillanders B.M., Kingsford M. J., 2002. Impact of changes in flow of freshwater on estuarine and open coastal habitats and the associated organisms. Oceanogr. Mar. Biol. 40, 233-309.

Halpern, B.S., Frazier, M., Afflerbach, J., Lowndes, J.S., Micheli, F., O'Hara, C., Scarborough, C., Selkoe, K.A., 2019. Recent pace of change in human impact on the world's ocean. Sci. Reports 9, 11609.

Heap, A., Bryce, S., Ryan, D., Radke, L., Smith, C., Smith, R., Harris P., Heggie, D., 2001. Australian Estuaries & Coastal Waterways: A geoscience perspective for improved and integrated resource management. Australian Geological Survey Organisation, Record 2001/07.

Howley, C., Devlin, M., Burford, M., 2018. An assessment of water quality from a tropical river to coastal flood plumes on the northern Great Barrier Reef, Australia. Mar. Freshw. Res, 69, 859-873.

Hosomi, M., Sudo, R., 1986. Simultaneous determination of total nitrogen and total phosphorus in freshwater samples using persulfate digestion. Int. J. Environ. Stud. 27, 267–275.

Isles, P.D.F., 2020. The misuse of ratios in ecological stoichiometry. Ecology 101, 10.1002/ecy.3153

Jeffrey, S.W., Vesk, M. 1997. Introduction to marine phytoplankton and their pigment signatures. In: Jeffrey, S.W., Mantoura, R.F.C., Wright, S.W. (Eds.), Phytoplankton Pigments in Oceanography (Monographs on Oceanographic Methodology). UNESCO Publication, pp. 37-84.

Jeffrey, S.W., Welshmeyer, N.A., 1997. Spectrophotometric and fluorometric equations in common use in oceanography. In: Jeffrey, S.W., Mantoura, R.F.C., Wright, S.W. (Eds.), Phytoplankton Pigments in Oceanography (Monographs on Oceanographic Methodology). UNESCO Publication, pp. 597–615.

Kennard, M.J., Pusey, B.J., Olden, J.D., Mackay, S.J., Stein, J.L., Marsh, N., 2010. Classification of natural flow regimes in Australia to support environmental flow management. Freshw. Biol. 55, 171−193.

Kenyon, R.A., Loneragan, N.R., Manson, F.J., Vance, D.J., Venables, W.N., 2004. Allopatric distribution of juvenile red-legged banana prawns (*Penaeus indicus* H. Milne Edwards, 1837) and juvenile white banana prawns (*Penaeus merguiensis* De Man, 1888), and inferred extensive migration, in the Joseph Bonaparte Gulf, northwest Australia. J. exp Mar. Biol. Ecol. 309, 79-108

Kwon, B-O., Kim, H., Noh, J., Lee, S.Y., Nam, J., Khim, J.S., 2020. Spatiotemporal variability in microphytobenthic primary production across bare intertidal flat, saltmarsh, and mangrove forest of Asia and Australia. Mar. Poll. Bull. 151, 110707.

Lerat, J., Egan, C., Kim, S., Gooda, M., Loy, A., Shao, Q., Petheram, C., 2013. Calibration of river models for the Flinders and Gilbert catchments. In: A technical report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy. CSIRO Water for a Healthy Country and Sustainable Agriculture flagships, Australia.

Lowe, V., Frid, C.L.J., Venarsky, M., Burford, M.A. Responses of a macrobenthic community to seasonal freshwater flow in a wet-dry tropical estuary. Est. Coast. Shelf Sci., submitted

Maheshwari, B. L., Walker, K. F., and McMahon, T. A. 1995. Effects of regulation on the flow regime of the River Murray, Australia. Regul. Rivers: Res. *Manage*. 10, 15–38.

Mallin, M.A., Paerl, H.W., Rudek, J., Bates, P.W., 1993. Regulation of estuarine primary production by watershed rainfall and river flow. Mar. Ecol. Prog. Ser. 93, 199-203.

Murray, N.J., Phinn, S.R., DeWitt, M., Ferrari, R., Johnston, R., Lyons, M.B., Clinton, N., Thau, D., Fuller, R.A., 2019. The global distribution and trajectory of tidal flats. Nature 565, 222-225.

Murrell, M.C., Hagy, J.D., Lores, E.M., Greene, R.M., 2007. Phytoplankton production and nutrient distributions in a subtropical estuary: Importance of freshwater flow. Estuaries Coast. 30, 390-402.

Ndehedehe, C., Burford, M.A., Stewart-Koster, B., Bunn, S.E., 2020a. Predicting hot spots of aquatic plant biomass in a large floodplain river catchment in the Australian wet-dry tropics. Ecol. Indic. 117, 106616.

Ndehedehe, C., Burford, M.A., Stewart-Koster, B., Bunn, S.E., 2020b. Satellite-derived changes in floodplain productivity and freshwater habitats in northern Australia (1991-2019). Ecol. Indic. 114, 106320.

Petheram, C., Yang, A., 2013. Climate data and their characterisation for hydrological and agricultural scenario modelling across the Flinders and Gilbert catchments. In: A technical report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy. CSIRO Water for a Healthy Country and Sustainable Agriculture flagships, Australia.

Petheram, C., Watson, I., Bruce, C., Chilcott, C. 2018. Water resource assessment for the Mitchell catchment. A report to the Australian Government from the CSIRO Northern Australia Water Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments. CSIRO, Canberra, Australia.

Philip, S., Davies, P., Hughes, J., Karim, F., Marvanek, S., Petheram, C., Taylor, A., Ticehurst, C., Vanderzalm, J., Wang, B., Watson, I., 2018. Chapter 2: Physical environment of the Mitchell catchment. In: Petheram C, Watson I, Bruce C and Chilcott C (eds) (2018) Water resource assessment for the Mitchell catchment. A report to the Australian Government from the CSIRO Northern Australia Water Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments. CSIRO, Australia.

Poff, N.L., Zimmerman, J.K.H., 2010. Ecological responses to altered flow regimes a literature review to inform the science and management of environmental flows. Freshw. Biol. 55, 194-205.

Redfield A.C., 1958. The biological control of chemical factors in the environment. American Science 46, 205-222.

Rhodes, E.G., 1980. Modes of Holocene coastal progradation, Gulf of Carpentaria. PhD thesis, Australian National University, Canberra.

Rivera-Monroy, V.H., Madden, C.J., Day, J.W., Twilley, R.R., Vera-Herrara, F., Alvarez-Guillen, H., 1998. Seasonal coupling of a tropical mangrove forest and an estuarine water column: enhancement of aquatic primary productivity. Hydrobiol. 379, 41-53.

Robins J.B., Halliday I.A., Staunton-Smith J., Mayer D.G., Sellin M.J., 2005. Freshwater-flow requirements of estuarine fisheries in tropical Australia: a review of the state of knowledge and application of a suggested approach. Mar. Freshw. Res. 56, 343-360.

Rustomji, P., Shellberg, Jeffrey, Brooks, Andrew, Spencer, John, Caitcheon, G. 2010. A catchment sediment and nutrient budget for the Mitchell River Queensland. A report to the Tropical River and Coastal Knowledge (TRaCK) research program. CSIRO. http://hdl.handle.net/10072/38127

Rytwinski, R., Harper, M., Taylor, J.J., Bennett, J.R., Donaldson, L.A., Smokorowski, K.E., Clarke, K., Bradford, M.J., Ghamry, H., Olden, J.D., Boisclair, D., Cooke, S.J., 2020. What are the effects of flow-regime changes on fish productivity in temperate regions? A systematic map. Environ. Evidence 9, 7.

Short, A.D., 2020. Chapter 9: Gulf of Carpentaria Division. In: Australian Coastal Systems, Coastal Research Library 32, Springer Nature Switzerland AG, pp. 279-290.

Shellberg, J.G., Spencer, J., Brooks, A.P., Pietsch, T.J. 2016. Degradation of the Mitchell River fluvial megafan by alluvial gully erosion increased by post-European land use change, Queensland, Australia. Geomorphology 266, 105-120

Smith, J., Burford, M.A., Revill, A.T., Haese, R.R., Fortune, J., 2012. Effect of nutrient loading on biogeochemical processes in tropical tidal creeks. Biogeochemistry 108, 359- 380.

Soria-Piriz, S., Garcia-Robledo, E., Papaspyrou, S., Aguilar, V., Seguro, I., Acuna, J., Morales, A., Corzo, A., 2017. Size fractionated phytoplankton biomass and net metabolism along a tropical estuarine gradient. Limnol. Oceanogr. 62, S309-S326.

Staples, D.J., Vance, D.J., 1987. Comparative recruitment of the banana prawn, *Penaeus merguiensis* in five estuaries in the southeast Gulf of Carpentaria, Australia. Aust. J. Mar. Freshw. Res. 38, 29-45

Thorburn, P.J., Shaw, R.J., 1987. Effects of different dispersion and fine-fraction determination methods on the results of routine particle-size analysis. Aust. J. Soil Res. 25, 347.

Vance, D.J., Rothlisberg, P.C., 2020. The Biology and Ecology of the Banana Prawns *Penaeus merguiensis* De Man and *P. indicus* H. Milne Edwards. Adv. Mar. Biol. 86, 1-139.

Vieillard, A.M., Newell, S.E., Thrush, S.F., 2020. Recovering from bias: A call for further study of underrepresented tropical and low-nutrient estuaries. J. Geophys. Res.: Biogeosciences, 125, e2020JG005766.

Welsh, W.D., Vaze, J., Dutta, D., Rassam, D., Rahman, J.M., Jolly, I.D., Wallbrink, P., Podger, G.M., Bethune, M., Hardy, M.J. 2012. An integrated modelling framework for regulated river systems. Environ. Model. Softw. 39, 81-102.

Wolanski, E., 1993. Water circulation in the Gulf of Carpentaria. J. Mar. Syst. 4, 401–420.

Wolanski, E., Ridd, P., 1990 Mixing and trapping in Australian coastal waters. In Coastal and Estuarine Studies, Vol. 38, Cheng, R. T. (Ed.), Springer-Verlag, New York, pp. 165–183.

Figure Legends

Figure 1: Map of sampling sites in the Flinders, Gilbert and Mitchell estuaries in the Gulf of Carpentaria, Australia.

Figure 2 a. Long term annual flow (GL) based on modelled EOS flow (Lerat et al., 2013; Petheram and Yang, 2013; Philip et al., 2018), and b) hydrograph (ML day^{-1}) based on DNRM gauging station data at Dunbar (139 km from Mitchell mouth), Burke Development Rd (102 km from Gilbert mouth) and Walkers Bend (103 km from Flinders mouth) (https://water-monitoring.information.qld.gov.au/). Arrows show sampling times.

Figure 3: Number of cease-to-flow days each year of the study using DNRM gauging station data at Dunbar (Mitchell River), Burke Development Rd (Gilbert River) and Walkers Bend (Flinders River) (https://water-monitoring.information.qld.gov.au/).

Figure 4: Comparison of chlorophyll *a* concentrations (mg m^{-2}) on the estuarine mudflats in the estuaries, and nearshore sandflats in the three estuaries across all sampling occasions. *P<0.05, ***P<0.005.

Figure 5: a) Correlation between salinity and TN, b) salinity and nitrate/nitrite, and c) salinity and ammonium (NH4) in Flinders estuary during 24 h sampling across the tidal cycle during wet season (March 2019), and d) correlation between salinity and TN in the floodplumes when data from all rivers was combined in wet season (March 2019).

Figure 6: Effect of nutrient additions on primary production (mg O_2 m^{-2} h^{-1}) in bioassays using mud from mudflats of the three estuaries across all sampling trips. *P<0.05, **P<0.01, ***P<0.005.

Table 1: Comparisons of mean (SD) mudflat chlorophyll *a* concentrations, production, respiration, and sediment nutrients and percentage mud across the three estuaries. Porewater only sampled on December 2019. TN = total nitrogen, TP = total phosphorus, TOC = total organic carbon, NS = not significant, nd = no data. Bolded text shows statistically highest values.

Estuary	**Primary Production (mg O_2 m^{-2} h^{-1})**	**Respiration (mg O_2 m^{-2} h^{-1})**	**TN %dw**	**TP %dw**	**TOC %dw**	**% mud**	**Porewater ammonium (mg N L^{-1})**	**Porewater nitrate/nitrite (mg N L^{-1})**	**Porewater phosphate (mg P L^{-1})**
	(F 4.84, P < 0.01)	*(F 8.48, P < 0.01)*	*NS*	*(F 19.46, P<0.001)*	*NS*	*NS*	*NS*	*NS*	*NS*
Flinders	**93.12 (69.19) a****	**-10.21 (6.40) a****	0.057 (0.016)	**0.025 (0.004)a*****	0.588 (0.213)	82 (6)	8.395 (2.200)	0.120 (0.121)	0.081 (0.053)
Gilbert	**94.62 (50.19) a**	-5.93 (5.83) b	0.075 (0.017)	0.021 (0.002)b	0.637 (0.183)	84 (7)	4.482 (4.284)	0.047 (0.025)	0.047 (0.020)
Mitchell	65.48 (48.76) b	-6.02 (5.36) b	0.064 (0.038)	0.015 (0.008)b	0.554 (0.280)	80 (9)	nd	nd	nd

Table 2: Comparisons of mean (SD) sediment chlorophyll *a* concentrations, production and respiration between the mudflats of three estuaries on each sampling occasion. NS = not significant, nd = no data. Bolded text shows statistically highest values. [a] and [b] denote statistical differences.

	Date	**Estuary**	**Chlorophyll *a* conc (mg m^{-2})**	**Primary Production (mg O_2 m^{-2} h^{-1})**	**Respiration mg O_2 m^{-2} h^{-1}**
Estuarine mudflat	Nov-16 (Dry)		*NS*	(*F* 7.02, *P* < 0.05)	
		Flinders	66.88 (31.26)	**148.46 (81.69)[a]**	nd
		Gilbert	80.50 (35.28)	**108.28 (62.38)[a]**	nd
		Mitchell	73.97 (20.24)	81.65 (56.22)[b*]	nd
	Nov-17 (Dry)		*NS*	*(F 12.91, P <0.001)*	
		Flinders	70.99 (22.82)	**50.52 (29.55)[a]**	nd
		Gilbert	66.25 (22.79)	**59.51 (26.07)[a]**	nd
		Mitchell	182.15 (254.15)	22.42 (21.72)[b*]	nd
	May-18 (Transition)	Flinders	17.76 (15.19)	48.11 (41.73)	nd
	Mar-19 (Wet)		*(F 5.09, P <0.05)*	(*F* 12.30, *P* < 0.01)	*NS*
		Flinders	10.19 (2.47)[b]	89.74 (43.76)[b]	-13.82 (5.88)
		Gilbert	14.11 (7.70)[b]	**139.86 (29.31)[a**]**	-3.82 (6.51)
		Mitchell	**34.40 (23.07)[a*]**	84.53 (46.16)[b]	-6.04 (5.78)
	Dec-19 (Dry)		*(F 12.47, P <0.001)*	*NS*	NS
		Flinders	**18.19 (7.83)[a]**	119.21 (68.89)	-6.83 (4.96)
		Gilbert	9.25 (3.06)[b**]	69.42 (19.4)	-8.04 (4.31)
		Mitchell	**23.19 (8.60)[a]**	72.4 (27.76)	-5.99 (4.99)
Nearshore sandflat	Nov-17 (Dry)		*NS* 144.59 (66.69)	nd	nd

		Flinders	nd	nd	nd
		Gilbert	111.07 (63.78)	nd	nd
		Mitchell			
	May-18 (Transition)	Flinders	53.39 (24.44)	nd	nd
	Mar-19 (Wet)		*(F 11.00, P <0.01)*		
		Flinders	15.56 (7.60)[b]	nd	nd
		Gilbert	30.74 (9.29)[ab]	nd	nd
		Mitchell	**57.95 (31.44)[a*]**	nd	nd

Table 3: Mean (SD) water column chlorophyll *a* concentrations and primary production across each estuary for each sampling occasion. NS = not significant, nd = no data. Bolded text shows statistically highest values. [a] and [b] denote statistical differences.

Date	Estuary	Chlorophyll *a* (µg L^{-1})	Primary production (mg C m^{-2} h^{-1})
Nov-16 (Dry)		*NS*	
	Flinders	4.5 (1.9)	nd
	Gilbert	3.7 (0.8)	nd
	Mitchell	3.9 (1.2)	nd
Nov-17 (Dry)		*(F 6.02, P<0.05)*	
	Flinders	**9.7 (1.9)[a]***	nd
	Gilbert	4.5 (2.8)[b]	nd
	Mitchell	5.1 (1.0)[a,b]	nd
Feb-18 (Wet)	Flinders	3.7 (1.2)	nd
April-18* (Wet) Helicopter	Gilbert	8.8 (0.2)	nd
	Mitchell	2.7 (0.3)	nd
May-18 (Transition)	Flinders	4.2 (1.7)	nd
Feb-19* (Wet) Helicopter	Flinders	2.8 (1.7)	nd
Mar-19 (Wet)		(*F* 51.67, *P*<0.001)	
	Flinders	**18.4 (3.0)[a]*****	nd
	Gilbert	3.5 (0.3)[b]	nd
	Mitchell	4.3 (1.8)[b]	nd
Dec-19 (Dry)		(F 6.26, *P*<0.05)	
	Flinders	**13.2 (1.0)[a]***	15.59 (0.92)[c]
	Gilbert	10.8 (4.0)[ab]	30.22 (0.87)[b]
	Mitchell	6.6 (0.7)[b]	**42.20 (1.29)[a]*****

Table 4: Statistical comparison of mean (SD) nutrient concentrations, and physico-chemical parameters in the water column of 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. ^^Log total nitrogen (TN):total phosphorus (TP) based on Isles (2020). NS = not significant, nd = no data. Bolded text shows statistically highest values. [a] and [b] denote statistical differences.

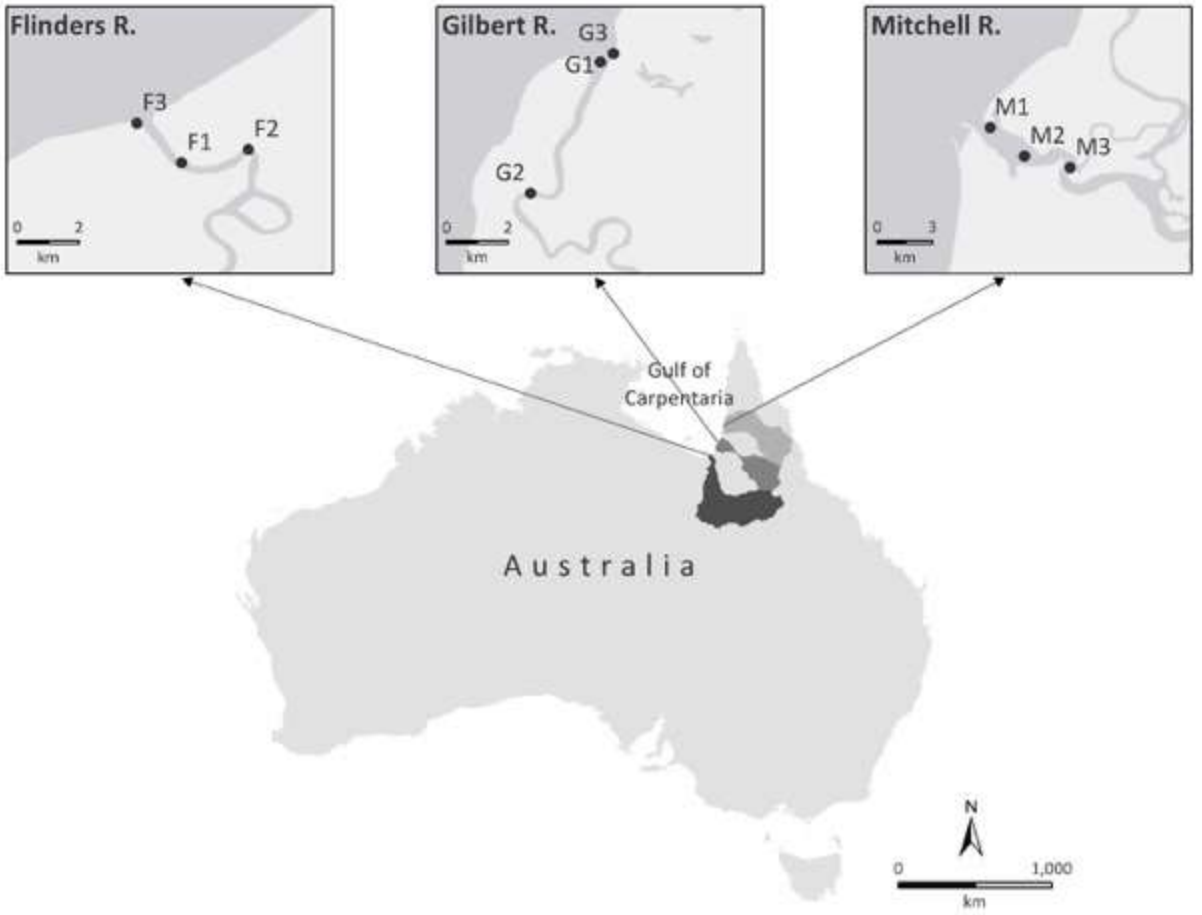
Date	Estuary	Total nitrogen (mg N L^{-1})	Total phosphorus (mg P L^{-1})	Ammonium (mg N L^{-1})	Nitrate/nitrite (mg N L^{-1})	Phosphate (mg P L^{-1})	Log TN:TP ratio^^	Temp. (°C)	Salinity	Turbidity (ntu)
Nov-16 (Dry)		*F 19.99, P<0.01*	*F 19.37, P<0.01*	*NS*	*F 13.25, P<0.01*	*NS*		*NS*	*F 10.72, P<0.05*	*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)	1.53	33.12 (0.21)	40.39 (0.13)[b]	349.4 (271.3)
	Gilbert	0.237 (0.038)[b]	0.008 (0.000)[b]	0.019 (0.012)	0.014 (0.011)[b]	0.012 (0.001)	2.02	33.38 (0.90)	40.23 (0.24)[b]	95.7 (24.8)
	Mitchell	0.193 (0.020)[b]	0.006 (0.001)[b]	0.013 (0.007)	0.003 (0.002)[b]	0.009 (0.006)	1.93	31.65 (0.84)	37.15 (1.65)[a*]	36.1 (12.2)
		F 21.65, P<0.001	*F 7.90, P<0.05*	*F 7.94, P<0.05*	*NS*	*NS*		*F 9.78, P<0.05*	*F 55.62, P<0.001*	

Nov-17 (Dry)	Flinders	**0.897 (0.173)[a]***	**0.052 (0.008)[a]***	**0.057 (0.028)[b]**	0.030 (0.006)	0.016 (0.001)	0.74	29.05 (0.15)[b]	39.21 (0.05)[b]	nd
	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)	2.33	29.96 (0.58)[a,b]	37.29 (0.49)[b]	nd
	Mitchell	0.227 (0.031)[b]	0.005 (0.000)[b]	0.006 (0.006)[a]*	0.009 (0.001)	<0.002 (0.000)	2.00	30.97 **(0.70)[a*]**	31.12 **(1.63)[a***]**	nd
Feb-18 (Wet)	Flinders	0.462 (0.010)	0.048 (0.013)	0.069 (0.004)	0.033 (0.001)	0.020 (0.001)	1.33	31.25	4.62	190.0
April-18^ (Wet)	Gilbert	0.357 (0.050)	0.017 (0.005)	0.013 (0.013)	0.007 (0.003)	0.004 (0.005)	1.52	30.90	2.30	39.5
	Mitchell	0.287 (0.042)	0.008 (0.006)	0.013 (0.014)	0.004 (0.004)	0.002 (0.003)	1.88	29.85	8.82	30.2
May-18 (Transition)	Flinders	0.322 (0.113)	0.018 (0.015)	0.004 (0.005)	0.021 (0.021)	0.007 (0.007)	1.92	18.24 (0.80)	29.55 (1.42)	261.4 (245.0)
Feb-19^ (Wet)	Flinders	0.477 (0.051)	0.377 (0.022)	0.022 (0.009)	0.102 (0.009)	0.063 (0.004)	0.24	30.50	0.01	110.0

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*		*NS*	*F 34.72, P<0.001*	*NS*
	Flinders	0.285 (0.044)^{b}	0.115 (0.072)^{a*}	0.018 (0.010)	**0.021 (0.005)^{a*}**	0.005 (0.002)^{b}	1.20	29.74 (0.72)	**12.17 (0.76)^{a**}**	291.0 (213.2)
	Gilbert	0.222 (0.058)^{b}	0.022 (0.008)^{b}	0.027 (0.009)	0.011 (0.004)^{b}	**0.012 (0.002)^{a*}**	1.09	31.13 (0.56)	4.53 (1.28)^{b}	40.2 (30.3)
	Mitchell	**0.515 (0.093)^{a*}**	0.120 (0.038)^{b}	0.042 (0.010)	0.010 (0.001)^{b}	0.001 (0.000)^{c}	1.15	30.72 (1.16)	5.93 (1.44)^{b}	42.6 (35.3)
Dec-19 (Dry)		F 6.10, *P*<0.05	F 6.50, *P*<0.05	F 7.01, *P*<0.05	F 15.17, *P*<0.01	F 185.93, *P*<0.001		*F 14.62*, P<0.01	*F 119.4*, *P*<0.001	*F 8.55*, *P*<0.05
	Flinders	**0.387 (0.050)^{a*}**	**0.270 (0.168)^{a*}**	0.007 (0.004)^{ab}	**0.048 (0.011)^{a*}**	**0.019 (0.001)^{a**}**	0.62	**33.68 (0.51)^{a**}**	**41.09 (0.92)^{a**}**	**751.7 (378.2)^{a*}**
	Gilbert	**0.365 (0.069)^{a*}**	0.078 (0.059)^{ab}	**0.009 (0.010)^{a*}**	0.022 (0.010)^{ab}	0.007 (0.002)^{ab}	0.92	32.70 (0.35)^{a,b}	40.72 (0.45)^{a,b}	145.0 (94.5)^{b}
	Mitchell	0.265 (0.021)^{b}	0.024 (0.021)^{b}	0.026 (0.007)^{b}	0.013 (0.003)^{b}	0.002 (0.001)^{b}	1.35	31.70 (0.47)^{b}	36.70 (0.48)^{b}	51.4 (14.4)^{b}

Table 5: Summary of characteristics and key findings for three estuaries in this study during the dry season, showing relative rankings for values. TP = total phosphorus, TN = total nitrogen.

Parameter	Flinders estuary	Gilbert estuary	Mitchell estuary
Long term mean annual flow volumes	Low	Medium	High
Interannual flow variability	High	Medium	Low
Annual cease to flow period	High	Medium	Low
Mudflat areal extent	Medium	Low	High
Mangrove areal extent	Medium	Low	High
Supratidal saltflat extent	High	Low	Medium
Open water area	Medium	Low	High
Salinity	High	Medium	Low
Turbidity	High	Medium	Low
w/c total nitrogen and phosphorus concs	High	Medium	Low
Mudflat nutrient concs	High TP No differences in TN between estuaries	Low TP	Low TP
Mudflat prim. prod.	High	High	Low
Nutrient addition effects on mudflat prim. prod.	Stimulation of prim. Prod.	Stimulation of prim. Prod.	Stimulation of prim. Prod.
w/c chlorophyll *a* conc.	High	Low	Low
Mudflat respiration rates	High	Low	Low


Flinders R.
F3
F1
F2
0 2
km
Gilbert R.
G3
G1
G2
0 2
km
Mitchell R.
M1
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km
Gulf of
Carpentaria
Australia
N
0 1,000
km

Figure 1

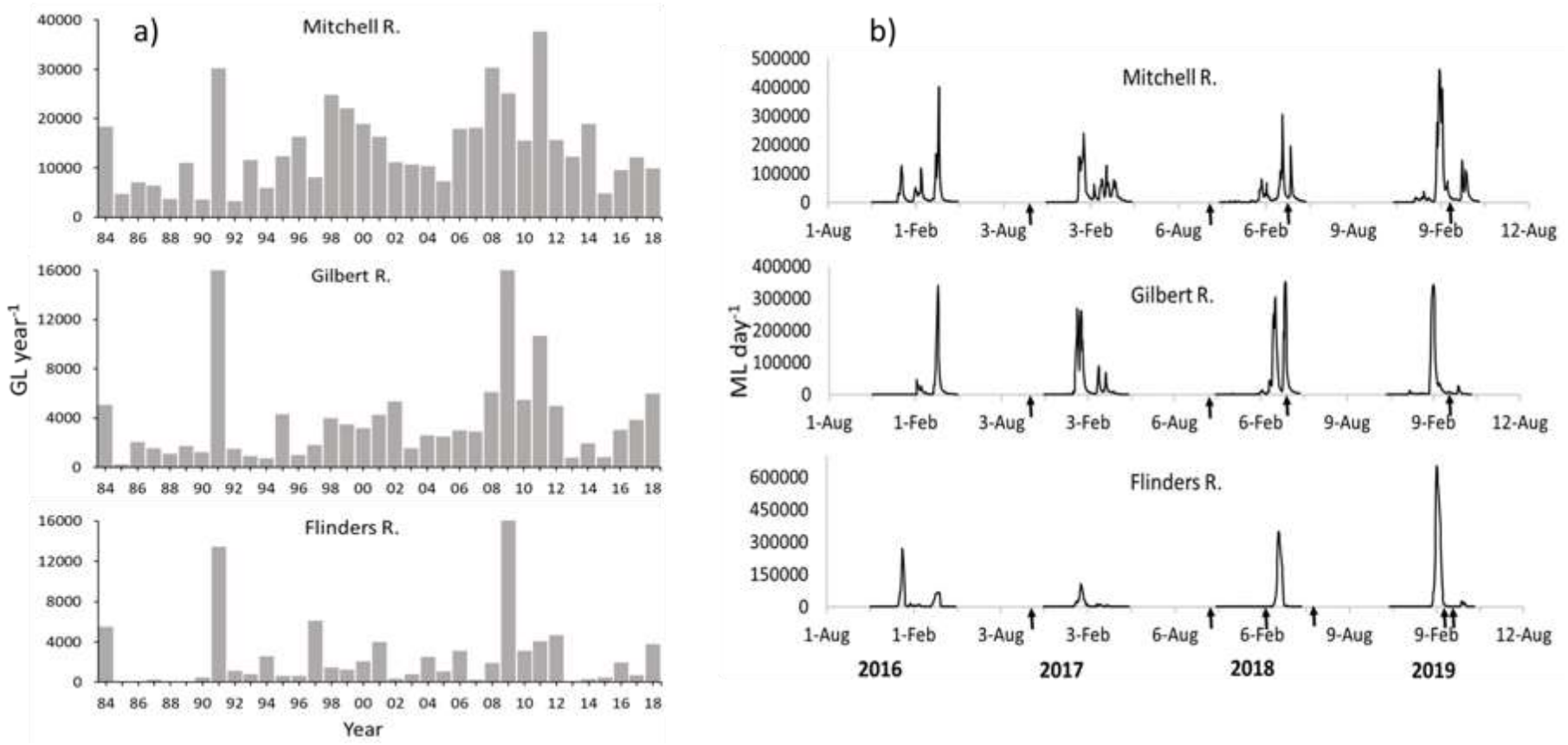
a)
Mitchell R.
Gilbert R.
Flinders R.
GL year-1
Year
b)
ML day-1
1-Aug
1-Feb
3-Aug
3-Feb
6-Aug
6-Feb
9-Aug
9-Feb
12-Aug
2016
2017
2018
2019

Figure 2

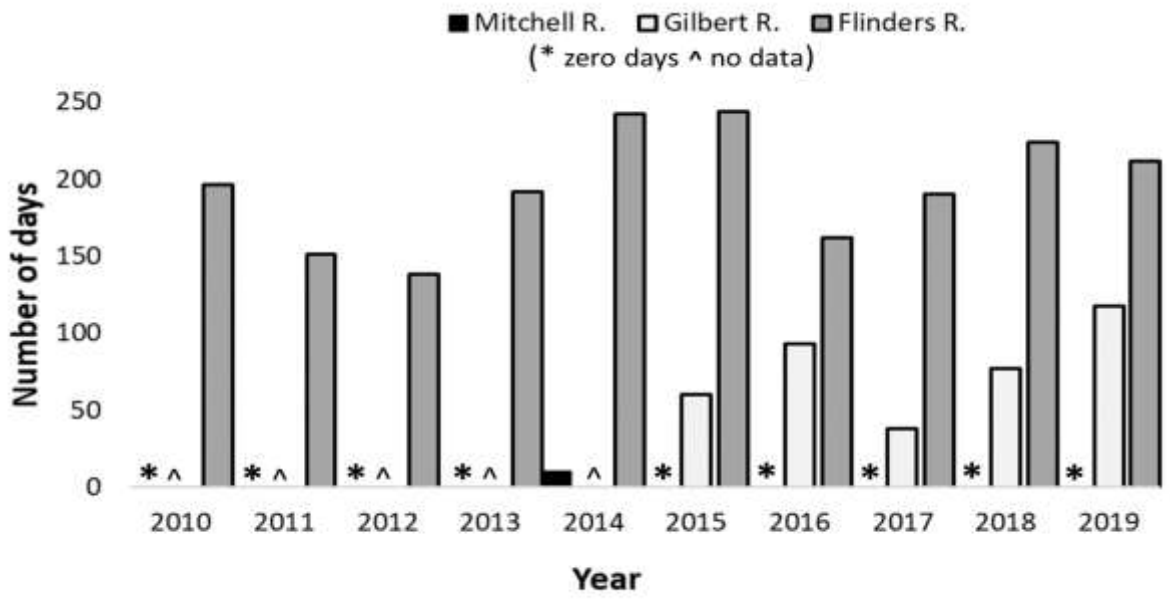
Mitchell R.
Gilbert R.
Flinders R.
(* zero days ^ no data)
Number of days
250
200
150
100
50
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Year

Figure 3

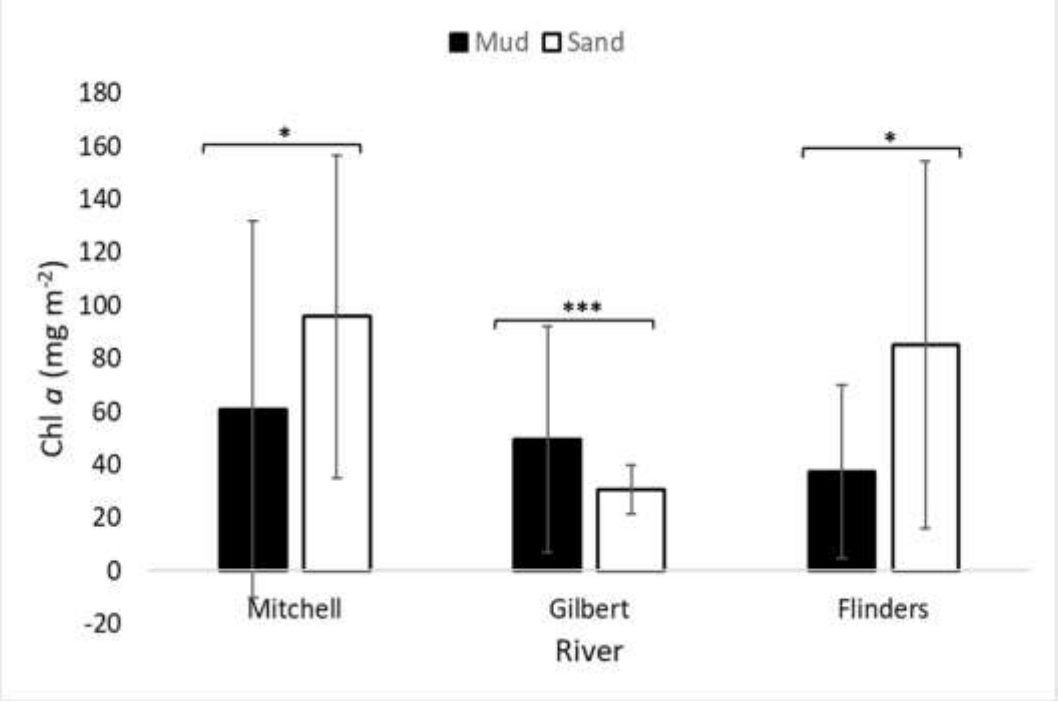
Mud
Sand
180
160
140
120
100
80
60
40
20
0
-20
Chl a (mg m-2)
*
***
*
Mitchell
Gilbert
Flinders
River

Figure 4

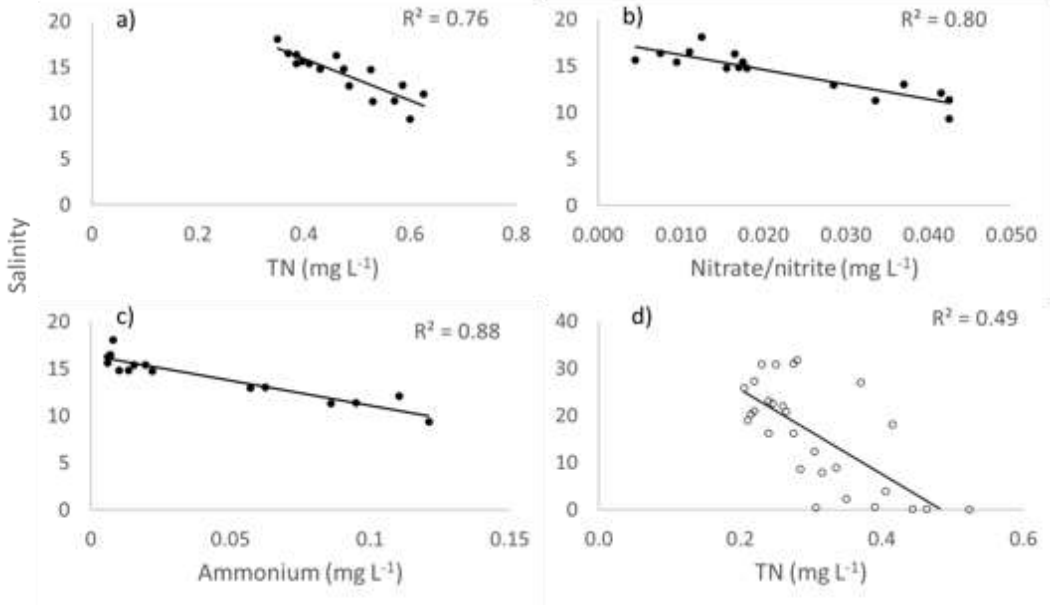
a)
R² = 0.76
TN (mg L⁻¹)
b)
R² = 0.80
Nitrate/nitrite (mg L⁻¹)
c)
R² = 0.88
Ammonium (mg L⁻¹)
d)
R² = 0.49
TN (mg L⁻¹)
Salinity

Figure 5

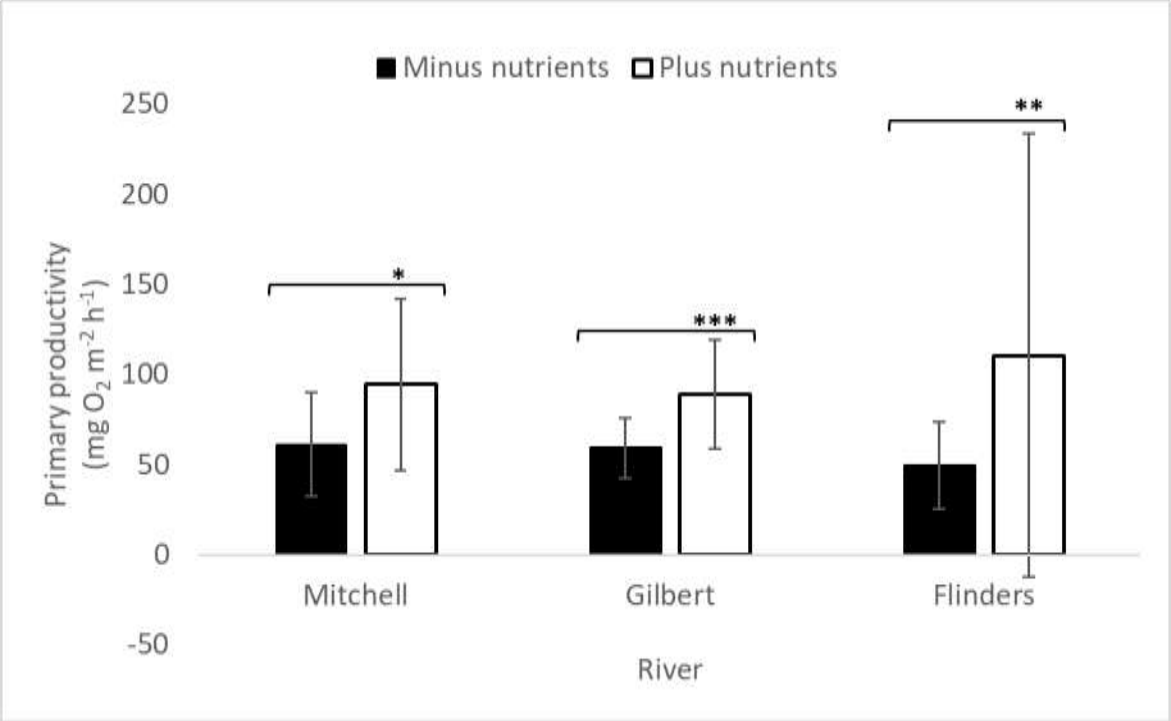
Minus nutrients
Plus nutrients
250
200
150
100
50
0
-50
Primary productivity (mg O_2 m^{-2} h^{-1})
*
***
**
Mitchell
Gilbert
Flinders
River

Figure 6

Supplementary material

Table S1: Annual flow volumes for each river at the gauging stations (DNRM) compared with modelled end-of-system (EOS) flows (NAWRA, Philip et al. (2018), and FGARA, Lerat et al. (2013); Petheram and Yang, (2013)). Water years are from July to June to capture entire wet season flows which are typically from December – April. Total nitrogen (TN) and total phosphorus (TP) loads (t) are estimated using wet season data from sampling trips (both February and March 2019 data was used) and flow volumes from gauging station data. Gauging station data was used as data for more years was available.

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	TP loads (t) using gauge data
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	nd	nd	-	-
	2018-19	8,057	n/a	n/a	0.29	0.01	1144	45
Gilbert	2015-16	2,165	3,169	7,717	0.35	0.07	2833	588
	2016-17	4,640	3,469	7,740	nd	nd	-	-
	2017-18	5,653	5,664	7,807	nd	nd	-	-
	2018-19	3,949	n/a	3,997	0.36	0.02	2035	92
Flinders	2015-16	2,989	2,926	1,814	0.26	0.01	1017	39
	2016-17	1,335	634	1,545	nd	nd	-	-
	2017-18	3,768	3,542	2,537	0.6	0.22	797	294

	2018-19	7,564	n/a	13,278	0.46	0.05	1739	182
					0.48 (Feb)	0.38 (Feb)	3605	2849
					0.47 (Mar)	0.09 (Mar)	3583*	697*

Table S2: Sampling occasions, sites and parameters measured throughout the study.

Date	**Estuary**	**Sites**	**Mode of sampling**	**Water column chlorophyll**	**Nutrients**	**Sediment Chlorophyll**	**Sediment primary production**	**Physicochem measures**
7 – 13 Nov 2016	Mitchell, Gilbert, Flinders	3 estuarine mudflat, 3 nearshore sandflat	Boat	Yes	Yes	Yes	Yes	Yes
7 - 15 Nov 2017	Mitchell, Gilbert, Flinders	3 estuarine mudflat, 3 nearshore sandflat	Boat	Yes	Yes	Yes	Yes	Yes
13 Apr 2018	Mitchell, Gilbert	Transect of 4 sites	Helicopter	Yes	Yes	No	No	Yes
23 May 2018	Flinders	3 estuarine mudflat, 3 nearshore sandflat	Boat	Yes	Yes	Yes	Yes	Yes
23 Feb 2019	Flinders	Transect of 4 sites	Helicopter	Yes	Yes	No	No	Yes

8 Mar 2019	Mitchell, Gilbert, Flinders	3 estuarine mudflat, 3 nearshore sandflat, 24 h tidal sampling, floodplume transect	Boat	Yes	Yes	Yes	Yes	Yes
11 - 17 December 2019	Mitchell, Gilbert, Flinders	3 estuarine mudflat, 3 nearshore sandflat, 24 h tidal sampling	Boat	Yes	Yes	Yes	Yes	Yes

Table S3: Comparison of mean (SD) water column and mudflat chlorophyll *a*, primary production and respiration in each estuary across multiple sampling trips. NS = not significant, nd = no data. Bolded text shows statistically highest values. [a] and [b] denote statistical differences.

Date	**Estuary**	**Water column**		**Mudflat**		
		Chlorophyll *a* (mg m^{-3})	**Primary production (mg C m^{-2} h^{-1})**	**Chlorophyll *a* (mg m^{-2})**	**Primary production (mg O_2 m^{-2} h^{-1})**	**Respiration (mg O^2 m^{-2} h^{-1})**
		(*F* 12.65, *P* < 0.01)		(*H* 38.00, *P* < 0.001)	*(H 27.13, P < 0.001)*	(*Wilcoxon* 38, *P* < 0.001)
Nov-16	Flinders	4.5 (1.9)[b]	nd	**66.88 (31.36)[a***]**	**148.45 (81.69)[a*]**	nd
Nov-17	Flinders	9.7 (1.9)[ab]	nd	**70.99 (22.82)[a***]**	50.51 (29.55)[b]	nd
May-18	Flinders	4.2 (1.7)[b]	nd	17.76 (15.19)[b]	48.11 (41.73)[b]	nd
Mar-19	Flinders	**18.4 (3.0)[a]**	nd	10.19 (2.47)[b]	89.73 (43.76)[b]	**-13.82 (5.88)[***]**
Dec-19	Flinders	13.2 (1.0)[ab]	30.22 (1.19)	18.19 (7.83)[b]	**119.21 (68.89)[a]**	-6.83 (4.96)
		NS		(*H* 30.59, *P* < 0.001)	(*H* 27.81, *P* < 0.001)	(*Wilcoxon* 165, *P* < 0.05)
Nov-16	Gilbert	3.7 (0.8)	nd	**80.50 (35.28)[a*]**	**108.28 (62.38)[a*]**	nd
Nov-17	Gilbert	4.5 (2.7)	nd	66.24 (22.79)[ab]	59.50 (26.07)[b]	nd
Mar-19	Gilbert	3.5 (0.3)	nd	14.11 (7.70)[b]	**139.86 (29.31)[a]**	-3.82 (6.51)
Dec-19	Gilbert	10.8 (4.0)	15.59 (1.67)	9.25 (3.06)[b]	69.42 (19.40)[b]	-8.04 (4.31)
		(H 8.64, P < 0.05)		(*H* 24.62, *P* < 0.001)	(*H* 21.19, *P* < 0.001)	

Nov-16	Mitchell	3.902[b]	nd	**73.97 (20.24)[a**]**	**81.65 (56.22)[a*]**	nd
Nov-17	Mitchell	5.060[ab]	nd	182.20 (254.15)[ab]	22.42 (21.72)[b]	nd
Mar-19	Mitchell	4.307[ab]	nd	34.40 (23.07)[b]	**84.53 (46.16)[a]**	-6.04 (5.78)
Dec-19	Mitchell	**6.625[a]**	42.20 (2.93)	23.19 (8.60)[b]	**72.40 (27.76)[a]**	-5.99 (4.99)

Table S4. Physico-chemical data comparing sampling occasions in each estuary. Sampling was conducted b the mornings. TN = total nitrogen, TP = total phosphorus. NS = not significant, nd = no data. Bolded text shows statistically highest values. [a] and [b] denote statistical differences.

Date	Estuary	TN (mg L^{-1})	TP (mg L^{-1})	Ammonium (mg L^{-1})	Nitrate/nitrite (mg L^{-1})	Phosphate (mg L^{-1})	pH	Dissolved oxygen (mg L^{-1})
		(H 13.289, P < 0.05)	(*F 13.77*, *P* < 0.01)	*(H 12.94, P < 0.05)*	*NS*	*NS*	(*F* 149.8, *P* < 0.001)	(*F* 4.90, *P* < 0.05)
Nov-16	Flinders	0.457 (0.085)^{a,b}	0.033 (0.010)^{a,b}	0.022 (0.018)^{a,b}	0.043 (0.013)	0.017 (0.002)	**8.02 (0.08)^{a*}**	6.45 (2.02)^{a*}
Nov-17	Flinders	**0.897 (0.173)^{a*}**	0.052 (0.008)^{a,b}	0.057 (0.028)^{a,b}	0.030 (0.006)	0.016 (0.001)	**8.18 (0.02)^{a}**	5.52 (0.20)^{a}
May-18	Flinders	0.322 (0.010)^{a,b}	0.018 (0.015)^{b}	0.004 (0.005)^{b}	0.021 (0.021)	0.007 (0.007)	9.35 (0.08)^{b}	**7.96 (0.26)^{b}**
Mar-19	Flinders	0.285 (0.044)^{b}	0.115 (0.072)^{a,b}	0.018 (0.010)^{a,b}	0.021 (0.005)	0.005 (0.002)	8.79 (0.06)^{c}	7.63 (0.31)^{a}
Dec-19	Flinders	0.387 (0.050)^{a,b}	**0.270 (0.168)^{a*}**	0.007 (0.004)^{a,b}	0.048 (0.011)	0.019 (0.001)^{a}	nd	nd
		(H 8.01, P < 0.05)	NS	*(H 8.85, P < 0.05)*	NS	NS	(*F* 77.96, *P* < 0.001)	(*F* 10.96, *P* < 0.01)
Nov-16	Gilbert	0.237 (0.038)^{a,b}	0.008 (0.001)	0.019 (0.012)^{a,b}	0.014 (0.011)	0.012 (0.001)	7.96 (0.05)^{b}	**6.05 (0.54)^{b*}**
Nov-17	Gilbert	**0.482 (0.129)^{a*}**	0.031 (0.024)	**0.049 (0.003)^{a*}**	0.026 (0.016)	0.024 (0.019)	7.97 (0.13)^{b}	4.66 (0.91)^{a}
Mar-19	Gilbert	0.222 (0.058)^{b}	0.022 (0.008)	0.027 (0.009)^{a,b}	0.011 (0.004)	0.012 (0.002)	**8.72 (0.04)^{a***}**	**7.20 (0.46)^{b}**
Dec-19	Gilbert	0.365 (0.069)^{a,b}	0.078 (0.059)	0.009 (0.010)^{b}	0.022 (0.010)	0.007 (0.002)	nd	nd
		(H 10.28, P < 0.05))	*(H 9.46, P < 0.05)*	*(H 9.31, P < 0.05)*	(H 8.19, P < 0.05)	*(H 10.8, P < 0.05)*	(*F* 18.8 *P* < 0.01)	*NS*
Nov-16	Mitchell	0.193 (0.020)^{b}	0.006 (0.001)^{a,b}	0.013 (0.007)^{a,b}	0.003 (0.002)^{b}	**0.009 (0.006)^{a*}**	7.83 (0.15)^{b}	6.23 (1.54)
Nov-17	Mitchell	0.227 (0.031)^{a,b}	0.005 (0.001)^{b}	0.006 (0.006)^{a,b}	0.009 (0.001)^{a,b}	0.001 (0.001)^{b}	8.02 (0.06)^{b}	6.06 (0.75)
Mar-19	Mitchell	**0.515 (0.093)^{a*}**	**0.120 (0.038)^{a*}**	**0.042 (0.011)^{a*}**	0.010 (0.001)^{a,b}	0.001 (0.001)^{b}	**8.34 (0.07)^{a*}**	7.03 (0.59)
Dec-19	Mitchell	0.265 (0.021)^{a,b}	0.024 (0.021)^{a,b}	0.026 (0.007)^{b}	**0.013 (0.003)^{a}**	0.002 (0.001)^{a,b}	nd	nd

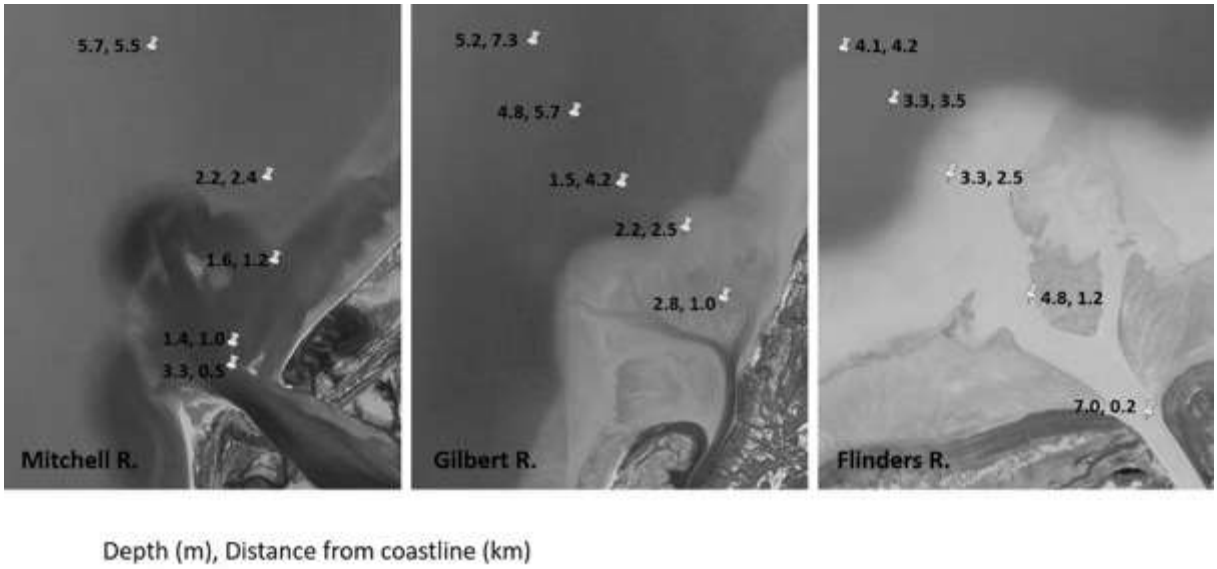

Figure S1: Satellite maps showing mouths of the three estuaries, and sites were water depth and distance from coastline was calculated.

Appendix 2: Lowe et al. paper submitted to Estuarine, Coastal and Shelf Science

Responses of a macrobenthic community to seasonal freshwater flow in a wet-dry tropical estuary

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Abstract

Wet-dry tropical estuaries are extreme environments driven by wet season rainfall and runoff events. The biota associated with these systems are highly adapted to large fluctuations in salinity, but extraction of freshwater for human development may reduce this variability, with negative implications for estuarine species. This study examined the effect of unregulated freshwater flow on intertidal macrobenthic (>0.5 mm mesh size) assemblages in a pristine wet-dry tropical estuary and nearshore environment. The macrobenthos in this estuary are an important food source for endangered migratory shorebirds and fisheries species. Macrobenthic fauna on the intertidal flats were sampled on four occasions spanning the late dry, post-flood, and immediately following the wet season, i.e. early-dry across four years. Assemblages had strong seasonal responses to the physico-chemical variation, driven by changes in freshwater inputs. Total macrofaunal abundances were significantly lower during the post-flood period, when salinity was low, and reached a maximum in the late dry season, under hypersaline conditions. Infaunal abundances were highest in the late dry season, coinciding with highest benthic chlorophyll *a* concentrations, and lower in the post-flood and early-dry. The dominant faunal group in the estuarine intertidal flats was polychaetes. In contrast, in the nearshore intertidal flats, bivalves dominated in the late dry season, and in the early-dry. The nearshore intertidal flats experienced almost complete defaunation of bivalves during the post-flood. Although flow had short-term negative effects on macrobenthos abundance, it is clear that macrobenthos recruitment back into the system occurred quickly once the tide re-established in the early-dry. Primary productivity was likely to be enhanced by increased nutrient loads from the catchment during the dry season. Flow variability is a key feature of this estuary and its biota, and therefore alteration of flow, via proposed water extraction, is likely to have unintended consequences for macrobenthos.

Keywords: Gulf of Carpentaria, resource management, infauna, flow regulation, waders

Appendix 3: Venarsky et al. paper submitted to Estuarine, Coastal and Shelf Science

Flow regimes among rivers influences benthic biota biodiversity, but not abundance or biomass, in intertidal mudflats and sandflats in wet-dry tropical estuaries

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Key words: Productivity, macrofauna, community structure, abundance, presence/absence, hypersaline, no-flow.

Abstract

Flow is a fundamental driver of ecological processes in river networks and estuaries. In estuaries, river flow interacts with tidal and wave energy to structure the physiochemical environment and the relative strength of these interactions changes in space and time. Thus, ecological processes in estuaries are best understood within the context of these physical processes. In this study, we explore how changes in river flow regime influence the structure of benthic communities in three estuaries in northern Australia's Gulf of Carpentaria. This region resides in the wet-dry tropics and the rivers have among the most variable flow regimes in the world. During two sequential dry seasons, we compared measures of benthic macroinvertebrate biodiversity, abundance, and biomass in intertidal mudflats and sandflats among three estuaries with differing river flow regimes. We found that the number of consecutive days of zero river flow during the preceding dry season best explained inter- and intra-annual patterns in benthic community composition. Specifically, we suggest that the dry season river flow regime dictated the salinity regime of each estuary, which in-turn influenced benthic community composition. However, neither the differences in the salinity regime or community composition influenced total abundance or biomass of the benthic community, indicating that the regional taxa pool currently contains enough functional redundancy to maintain abundances and biomasses under various physicochemical conditions. This in turn provides consistent resources for higher trophic levels such as birds and fish.

Appendix 4: Queensland Wader Study Group shorebird surveys

SHOREBIRD SURVEY REPORT

MITCHELL, GILBERT AND FLINDERS ESTUARIES, GULF OF CARPENTARIA

MARCH AND DECEMBER 2019

Robert Bush, David Edwards

Queensland Wader Study Group

With

Carpentaria Land Council Aboriginal Corporation

Background

This report contains summary tables of two surveys conducted on the Flinders, Gilbert and Mitchell River estuaries and adjacent shorelines in the Gulf of Carpentaria in March and December, 2019.

There were three key objectives: 1). To set up and document survey sites for this and future shorebird surveys; 2). To compare the species and numbers of birds at the three estuaries, and 3). The determine the prevalence and species diversity of shorebirds, particularly birds migrating north (March) and during summer (December).

The first survey was conducted between 8 and 16 March, 2019, and the second survey between 12 and 17 December 2019.

Surveys were conducted by Robert Bush and David Edwards from the Queensland Wader Study Group (QWSG) while on board the MV Eclipse (Fig. 1). Surveys were done from tenders with counting of birds in feeding grounds on the lower end of the tide. On occasion, surveying was done by foot on sand islands and coastal sandy areas where it was safe to do so. Overall total coverage of sites within the estuaries, i.e. intertidal mudflats, and sites adjacent to the estuaries, typically intertidal sandflats was attempted. It was not always possible to identify birds to species level due to the difficult conditions. The same protocols for each estuary were used on both trips to allow direct comparison of results, as much as possible. However, differences in the tides from one trip to the next made this challenging.

The December 2019 sampling period was particularly problematic as the phase of the tide made it difficult to get to sites that were surveyed in the March 2019 trip.

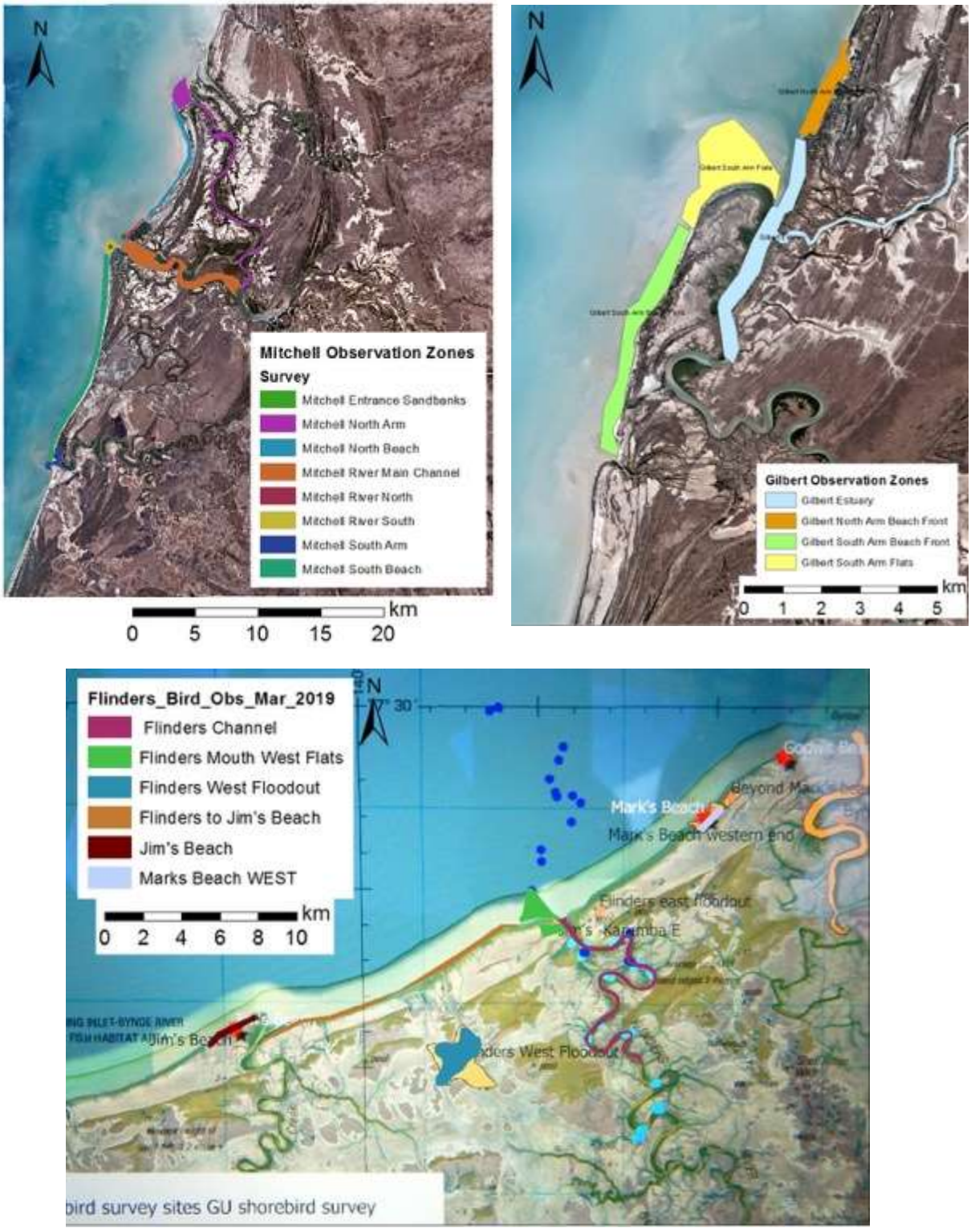

Figure 1: Maps showing survey locations in Mitchell, Gilbert and Flinders estuaries and nearby habitats.

Survey outcomes

These were the first reported ground surveys of the Mitchell and Gilbert River estuaries and related shorelines. The survey sites were also mapped for future field research.

The species diversity and counts of resident and migratory shorebirds has been documented across two surveys in a single year. The March survey was conducted at the interface of the non-breeding period and the start of the northern migration period. The December survey was conducted during the non-breeding period.

The Finders River Survey in March replicated roost site surveys conducted in earlier surveys.[1] The December Flinders River survey was a low tide survey undertaken on the river entrance sandbanks and mudflats and within the river estuary.

Black-tailed Godwits were the most dominant species on all three estuaries overall (Table 1). Small short-billed waders (Greater and Lesser Sandplovers and Red-necked Stints) were also numerous on the Mitchell and common on the Gilbert but much less so on the Flinders. Great Knots were present on the Flinders and the Gilbert but not on the Mitchell. Great Knots were in much lower numbers on the Flinders than in past surveys conducted before January 2019.[1]

The critically endangered Far Eastern Curlew is found across all three river systems on shorelines and in the river channels. Whimbrels also make use of both the shoreline and the inland river channels and wetlands. The Black-winged Stilt is the dominant resident shorebird.

There is a considerable diversity of migratory shorebirds that make use of wetland habitats and are usually found in the wet margins of the river channels.

[1] Driscoll, P.V. 2014. Shorebird surveys in the south east Gulf of Carpentaria. Report for Shorebirds 2020, Queensland and Australasian Wader Study Groups.

TABLE 1. Species by ranked maximum counts across survey periods (March and December, 2019) for the Flinders, Gilbert and Mitchell estuaries and nearshore. Red shows critically endangered species, blue shows endangered species. Italicised names and counts show species exceeding 1% threshold for international importance.[2]

FLINDERS RIVER		GILBERT RIVER		MITCHELL RIVER	
SPECIES >1000	**N**	**SPECIES >1000**	**N**	**SPECIES >1000**	**N**
Black-tailed Godwit	*1470*	*Black-tailed Godwit*	*4301*	*Black-tailed Godwit*	*3434*
				Mixed (Greater and Lesser Sandplover/ Red-necked Stint)	2370
SPECIES 500-999		**SPECIES 500-999**		**SPECIES 500-999**	
		Red-necked Stint	759		
SPECIES 100-499		**SPECIES 100-499**		**SPECIES 100-499**	
Great Knot	346	Great Knot	363	Bar-tailed Godwit	407
Black-winged Stilt	211	Greater Sandplover	298	Red-necked Stint	388
Terek Sandpiper	150	Lesser Sandplover	162	Lesser Sandplover	237
		Bar-tailed Godwit	154	Black-winged Stilt	129
				Sharp-tailed Sandpiper	124
SPECIES 50-99		**SPECIES 50-99**		**SPECIES 50-99**	
Terek Sandpiper	92	Black-winged Stilt	75	Greater Sandplover	78
Common Greenshank	63	Whimbrel	69	Whimbrel	67
Far Eastern Curlew	55				
SPECIES <49		**SPECIES <49**	40	**SPECIES <49**	
Lesser Sandplover	45	Far Eastern Curlew	31	Terek Sandpiper	46
Whimbrel	32	Terek Sandpiper	16	Marsh Sandpiper	28
Bar-tailed Godwit	19	Marsh Sandpiper	13	Far Eastern Curlew	25
Red-neck Stint	15	Common Greenshank	10	Common Greenshank	20
Marsh Sandpiper	15	Pied Oystercatcher	4	Pacific Golden Plover	17
Greater Sandplover	6	Grey Plover	2	Curlew Sandpiper	13
Curlew Sandpiper	5	Masked Lapwing	2	Grey Plover	9
Pied Oystercatcher	4	Sharp-tailed Sandpiper	1	Pied Oystercatcher	7
Common Sandpiper	3	Curlew Sandpiper		Broad-billed Sandpiper	2
Red Knot	3			Beach Stone-curlew	2
Grey Plover	2				
Pacific Golden Plover	2				
Asian Dowitcher	1				

[2] Hansen, B., Fuller, R.A., Watkins, D., Rogers, D., Clemens, R.S., Newman, M., Woehler, E., 2016. Revision of the East Asian – Australasian Flyway Population Estimates for 37 listed Migratory Shorebird Species (Unpublished report for the Department of the Environment). BirdLife Australia, Melbourne.

Summary of Flinders surveys

In March 2019, Black tailed Godwits were the most dominant shorebird species in the Flinders region (Tables 2, 3). This was followed by the Great Knot with numbers considerably lower that previous surveys by Driscoll (2001)[3] and the CLCAC surveys of the Flinders (Appendix 5). Numbers were comparable with low counts found by CLCAC earlier in March 2019. At this time there was significant wet season flooding, and studies by Lowe et al. (submitted, Appendix 2) showed that macrobenthos densities declined, especially bivalves which are a favoured food supply for Great Knot.

TABLE 2. Flinders River estuary and adjacent beachfront total shorebird count (N), percentage abundance (%) and species diversity in March 2019 summed across nine designated count sites (main habitats identified).

SPECIES (N=19)	N	%	MAIN HABITAT
Black-tailed Godwit	1470	65	Estuary/Beach Mudflats
Pied Stiltt	211	9	Estuary/Beach Mudflats
Great Knot	205	9	Beach Mudflats
Terek Sandpiper	92	4	Estuary
Common Greenshank	63	3	Estuary
Far Eastern Curlew	55	2	Estuary/Beach Mudflats
Lesser Sandplover	45	2	Beach Mudflats
Whimbrel	32	1	Estuary/Beach Mudflats
Bar-tailed Godwit	19	1	Beach Mudflats
Red-necked Stint	15	0.7	Beach Mudflats
Marsh Sandpiper	12	0.5	Estuary
Greater Sandplover	6	0.3	Beach Mudflats
Curlew Sandpiper	5	0.3	Estuary/Beach Mudflats
Pied Oystercatcher	4	0.3	Beach Mudflats
Common Sandpiper	3	0.2	Estuary
Sharp-tailed Sandpiper	3	0.2	Estuary/Beach Mudflats
Red Knot	3	0.2	Beach Mudflats
Grey Plover	2	0.01	Beach Mudflats
Pacific Golden Plover	2	0.01	Beach Mudflats
Asian Dowitcher	1	0.005	Beach Mudflats
TOTAL	**2244**		

[3] Driscoll, P.V., 2001. Gulf of Carpentaria Wader Surveys. 1998-9 prepared on behalf of QWSG with assistance from AWSG for the Queensland. Environmental Protection Agency, July 2001.

Surveys in December 2019 were problematic due to the tide. This meant that many sites could not be adequately counted (only the river mouth and estuary was counted) and hence why counts were so low (Table 3).

TABLE 3. Flinders River low tide count of the river mouth mud and sandbanks and the river estuary in December, 2019.

Species (14 species)	River mouth banks	Estuary
	N	N
Great Knot	346	
Black-tailed Godwit	304	
Terek Sandpiper		150
Marsh Sandpiper	15	
Whimbrel		12
Far Eastern Curlew	5	5
Bar-tailed Godwit		4
Grey Plover		2
Greater Sandplover		2
Common Greenshank		2
Pied Stilt		1
Common Sandpiper		1
Sharp-tailed Sandpiper		1
Red-neck Stint		1
TOTALS	670	181

Summary of Gilbert surveys

The on-ground survey of the Gilbert demonstrated that this is an important shorebird site. This is new and important information with respect to shorebird habitat protection and future water development. The dominant species on the Gilbert River system was the Black-tailed Godwit across both surveys (Table 4). The December 2019 survey numbers are based on one less count site than the March 2019 survey. In December, this site could not be reached due to hazardous weather conditions. This site had a large number of Black-tailed Godwit in the March survey.

Given this, the relative abundance of species is approximately similar across the two survey periods.

TABLE 4. Gilbert River estuary and adjacent beachfront total shorebird count (N), percentage abundance (%) and species diversity in March and December 2019 summed across four designated count sites in March and three designated sites in December (main habitats identified).

	MARCH 2019		DECEMBER 2019		
Species (N = 18)	**Number**	**%**	**Number**	**%**	**Habitat**
Black-tailed Godwit	4301	81	1550	49	Beachfront Mudflats
Great Knot	363	7	277	9	Beachfront Mudflats
Lesser Sandplover	162	3	5	0.2	Beachfront Mudflats
Greater Sandplover	142	3	298	9	Beachfront Mudflats
Black-winged Stilt	75	1	28	0.9	Beachfront Mudflats/Estuary
Whimbrel	69	1	29	0.9	Beachfront Mudflats/Estuary
Red-necked Stint	53	1	759	24	Beachfront Mudflats
Terek Sandpiper	31	0.5	4	0.1	Beachfront Mudflats/Estuary
Common Greenshank	28	0.5	5	0.1	Estuary
Marsh Sandpiper	16	0.3	1	0.03	Estuary
Common Sandpiper	13	0.3	3	0.1	Estuary
Pied Oystercatcher	10	0.3	11	0.3	Beachfront Mudflats
Eastern Curlew	8	0.1	40	1.3	Beachfront Mudflats/Estuary
Grey Plover	4	0.08	0	0	Beachfront Mudflats
Bar-tailed Godwit	4	0.08	154	5	Beachfront Mudflats
Masked Lapwing	2	0.04	0	0	Estuary
Sharp-tailed Sandpiper	2	0.04	0	0	Estuary
Curlew Sandpiper	0	0	1	0.03	Beachfront Mudflats
Total	**5283**		**3165**		

Summary of Mitchell survey

The on-ground survey of the Mitchell system demonstrated that this is an important shorebird site. This is new and important information with respect to shorebird habitat protection and future water development. The Mitchell survey had some challenges. In December, the large mixed flock of sandplovers and Red-necked Stints was observed from a vessel in rough seas making it difficult to determine the proportion of specific species. However, this proportion of mixed species is approximately proportionate in relative abundance terms to a combined total of these species in the March survey 2019, although in numbers observed is considerably higher in December 2019.

There were considerably more Black-tailed Godwit in the December survey than the March survey (Table 5). However, both survey findings suggest the Mitchell River is an important site for Black-tailed Godwit. The survey showed that the wet margins of the river estuaries and inland wetlands are valuable sites for shorebirds that favour marsh environments.

TABLE 5. Mitchell River estuary and abjacent beachfront total shorebird count (N), percentage abundance (%) and species diversity in March and December 2019 summed across eight designated count sites (main habitats identified).

	MARCH	MARCH	DECEMBER	DECEMBER	
SPECIES (N=18)	**N**	**%**	**%**	**N**	**Main habitat**
Red-necked Stint	388	38	5	347	Estuary/beachfront
Black-tailed Godwit	183	18	47	3434	Estuary/beachfront
Black-winged Stilt	83	8	2	129	Estuary
Greater Sandplover	78	8	0.7	48	Beachfront
Lesser Sandplover	77	7	3	237	Beachfront
Terek Sandpiper	34	3	0.7	46	Estuary
Bar-tailed Godwit	33	3	6	407	Estuary/beachfront
Eastern Curlew	25	2	0.3	23	Estuary/beachfront
Marsh Sandpiper	24	2	0.3	28	Estuary
Common Greenshank	20	2	0.1	9	Estuary
Whimbrel	20	2	0.9	67	Estuary/beachfront
Sharp-tailed Sandpiper	17	2	2	124	Estuary
Curlew Sandpiper	13	1	0.1	5	Estuary/beachfront
Grey Plover	9	1	0.1	6	Estuary
Pied Oystercatcher	7	0.6	0.1	7	Beachfront
Pacific Golden Plover	6	0.6	0.3	17	Estuary
Broad-billed Sandpiper	2	0.2	0.02	1	Beachfront
Beach Stone Curlew	2	0.2	0	0	Beachfront
Mix Small Waders (Sandplovers Red-necked Stints)			33	2370	Beachfront
TOTAL NUMBERS	**1021**			**7255**	

Appendix 5: Carpentaria Land Council Aboriginal Corporation shorebird surveys

CLCAC CARPENTARIA LAND COUNCIL ABORIGINAL CORPORATION | *United we stand.*

Final Report

Collaborative Research Project – NESP NAER Project 7.3
Indigenous and Regional Engagement

Links between Gulf Rivers and food for migratory shorebirds

June 2020

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EXECUTIVE SUMMARY

The Carpentaria Land Council Aboriginal Corporation (CLCAC) Normanton Ranger Team is a collaborator in the project 'Links between Gulf rivers and food for migratory shorebirds', led by Griffith University (GU). The project is linked to the Northern Australia Environmental Resources Hub, funded under the Australian Government's National Environmental Science Program (NESP). The project occurred through two financial years 2018-19 and 2019-20. As part of this project GU commissioned CLCAC to conduct surveys of migratory shorebirds in the South-East Gulf of Carpentaria in 2019 and 2020. The survey focused on areas along the coastline from the Norman River mouth to a point west of the Flinders River estuary ('the Flinders-Bynoe coast'), on the country of the Gkuthaarn-Kukatj People. The Normanton Rangers of CLCAC implemented the survey program with planning, technical, and in- field support from Jaensch Ornithology & Conservation (JOC).

Shorebirds that migrate between Australia and the northern hemisphere were the subject of the project, because on the Flinders-Bynoe coast, they feed on invertebrates living amongst intertidal flats, which may be impacted by future changes to river flows. The broad objective of the project was to provide GU with estimates of shorebird abundance and diversity that would enable it to place its research work, including study of shorebirds feeding in the Flinders estuary at low tide, into perspective. Migratory shorebirds are a Matter of National Environmental Significance under Commonwealth legislation and the subject of several international agreements.

The CLCAC-GU Flinders Coast Shorebird Project began with collation of historical counts of migratory shorebirds in the study area, from surveys at high tide roosts. Fieldwork over four days was conducted onfour occasions by the Normanton Rangers with JOC support: 15 to 18 January 2019; 29 & 30 March and1 & 2 April 2019; 30 & 31 August and 2 & 3 September 2019; and 2 & 3 April 2020. Surveys of up to 13 high tide roosts were carried out in January and August-September, but coverage was reduced inApril 2020 due to the COVID-19 pandemic. Conditions were conducive to effective surveys, with maximum high tides over 3.6 metres.

Twenty of the 24 migratory species known on this coast were recorded in 2019-20, including all seven species presently listed as threatened in Australia. More than 15,000 migratory shorebirds were accounted for in January 2019, a little above the historical highest tally, and over 12,000 in August- September. Six roosts each held over 1,000 birds at some time; the largest aggregation was over 10,000at The Oaks beach. As in the past, the most abundant species were Great Knot (up to 7,496 birds), Black- tailed Godwit (4990) and Red Knot (2860). Numbers of all species were very low in March-April 2019 dueto persistent effects of a passing cyclone and a major flood in the Flinders River, only weeks earlier.

Significant decreases in maximum count for a species and in totals for roost sites and the Flinders coastoverall, were recognised, all probably due mainly to external factors in the East Asian – Australasian Flyway (EAAF). Nevertheless, the importance of this coast in terms of numbers of shorebirds remains high. The historically dominant, most abundant species on the Flinders Coast (Black-tailed Godwit and both knots) remain unchanged and proportionately their numbers were similar to those in the past. Although short-

term natural events impacted shorebird numbers in the short-term, there was evidence of strong recovery within several months.

CONTENTS

EXECUTIVE SUMMARY 2
Introduction 4
METHODS 5
The study area 5
Existing data 8
2019 – 2020 Survey methods 8
RESULTS 11
Historical data 11
2019 to 2020 data 11
January 2019 11
March-April 2019 12
April 2020 12
Leg flag re-sightings 12
DISCUSSION 12
Comparison within the survey period 2019-20 12
Comparison of historical and 2019-2020 results 13
By Species 13
By roost site 14
CONCLUSIONS 15
Total numbers and the use of roosts 15
Shorebird species 16
REFERENCES 17
Annex 1. Survey data for shorebirds & terns, January 2019 18
Annex 2. Survey data for shorebirds & terns, March – April 2019 19
Annex 3. Survey data for shorebirds & terns, August-September 2019 20
Annex 4. Survey data for shorebirds & terns, April 2020 21
Annex 5. Summary of shorebird counts for Zone E in 2019 and 2020 from the four survey events 22
Annex 6. Comparison between 2019-2020 and previous surveys 23

Introduction

During 2019 and 2020, Griffith University collaborated with Carpentaria Land Council Aboriginal Corporation (CLCAC), Queensland Wader Study Group (QWSG) and Jaensch Ornithology & Conservation (JOC) to document migratory shorebirds in part of the South-East Gulf of Carpentaria. Thefocus of this effort was estuaries of the Flinders, Gilbert and Mitchell Rivers, to build improved understanding of how proposed future changes to the flows of some of these rivers could impact wildlife and natural resources downstream. Rivers discharge fresh water, sediment and nutrients to the sea, which impact invertebrates such as worms and bivalves living in the intertidal mud and sand flats where shorebirds feed.

Changes to land and sea country including its wildlife are a concern to many stakeholders in the Lower Gulf of Carpentaria. One stakeholder group, the Gkuthaarn-Kukatj People, have traditional association with coastline from the mouth of the Norman River west to far beyond the Flinders River mouth. Accordingly, the Normanton Rangers facilitated participation in documenting the present biodiversity in terms of migratory shorebirds, along this 'Flinders-Bynoe coast' in order to protect wildlife, including shorebirds, for future generations. Migratory species are a Matter of National Environmental Significance (MNES) under the *EPBC Act 1999* (Commonwealth) and of state significance under Queensland legislation. Additionally, seven species of migratory shorebird that occurin the Gulf are listed as threatened species (also a MNES) under the Act, largely due to loss of habitat and hunting elsewhere in the East Asian – Australasian Flyway. To address these matters, CLCAC and Traditional Owners in the Lower Gulf have already supported the designation of three sections of the Gulfcoast as Flyway Network Sites under the Partnership for the East Asian – Australasian Flyway and are considering additional nominations.

The Normanton Ranger team's role in the project is to collect data that will support interpretation of resultsthat the GU research team will obtain on invertebrates—many of which are crucial food items of the shorebirds—presently occurring in intertidal mud-flats and sand-flats associated with river mouths of theGulf coast. Specifically, the Normanton Ranger team—with technical assistance from leading ornithologist Roger Jaensch—are recording migratory shorebird counts at roosts used by shorebirds at high tide, closest to the GU study sites. Counting at high tide is the standard and most effective approach,as opposed to counts of widely dispersed shorebirds feeding at low tide. Principal roosts have been identified along the Gulf coast by past QWSG expeditions.

Volunteers from QWSG worked separately with GU to document shorebirds at low tide feeding habitats in the areas where GU has been intensively researching the hydrology, sediments and invertebrate fauna living in the intertidal zone. The broad objective of CLCAC contributions to the project was to develop a contemporary understanding of shorebird composition, numbers and seasonality near the estuaries in order to place the results of GU/QWSG feeding studies in context, i.e. to give a wider (bigger picture) perspective.

This report provides a compilation of the project results for all surveys undertaken during this project andconclusions drawn solely from the migratory shorebird data. The first year progress report (CLCAC, 2019) provides comprehensive information on historical records of shorebirds on the Flinders coast, the resultsfrom surveys in the first two surveys and descriptions and images of each of the main roost sites.

METHODS

The study area

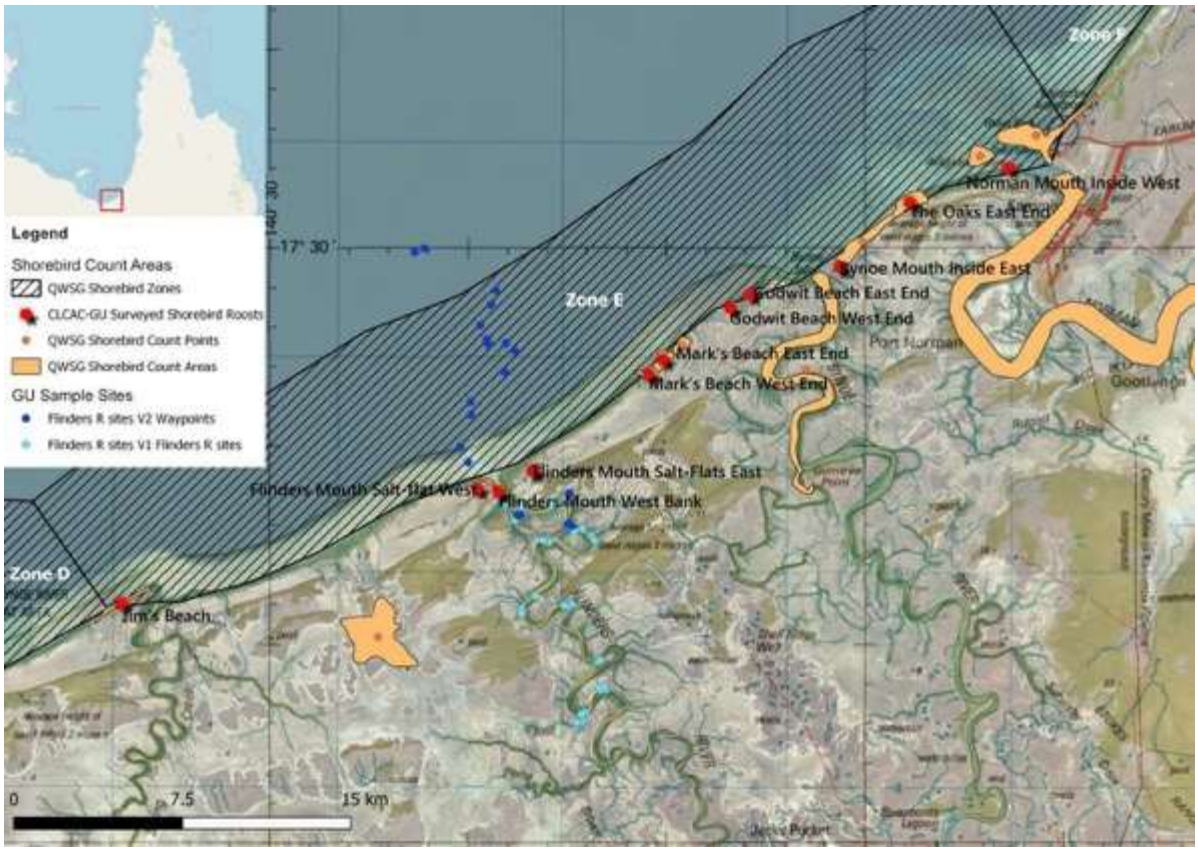
The study area for the CLCAC component of the project is the Flinders-Bynoe Coast from the mouth of the Norman River to the area of beach immediately west of the mouth of an un-named creek, a distanceof 50 kilometres (Map 1). The project study area fell within and is a little smaller than Zone E as definedby QWSG for shorebird surveying and adopted nationally as a component of the shorebird area known as 'South-East Gulf of Carpentaria'.

In this project, three rivers—the Flinders, Gilbert and Mitchell—were studied, given the future prospect ofwater damming and/or harvesting in those systems. As the Mitchell catchment is outside the CLCAC region, and because the Gilbert River Estuary is remote and expensive to access, the CLCAC surveys concentrated on the Flinders River Estuary. Further investigation of the Gilbert River area is targeted forfuture survey efforts. By helicopter, parts of the Flinders Coast are within 10 minutes flight from the port and tourist town of Karumba whereas the Gilbert River can require over 1 hour of flight time each direction.

Map 2 shows the location of major roosts close to the Flinders estuary, noting that this river splits well upriver of the coast, into the Flinders and Bynoe Rivers. 'Mark's Beach' (QWSG site name, code GE01)and 'Godwit Beach' (name coined by Roger Jaensch; no QWSG code) are the two roost sites closest tothe mouth of the Flinders Estuary, where GU has concentrated its research (for maps and photos of thesetwo roosts see pg. 38-41 in Year 1 Progress Report CLCAC 2019). The roosts are known to support moderate but not overwhelming numbers of shorebirds, thereby being countable with reasonableaccuracy. They occur on relatively small beaches (less than 1 km long) of shell fragments, landward of the seaward edge of the mangroves and with open areas immediately in front of the beach. Other majorroosts known as 'The Oaks' and 'Jim's Beach' are farther from the GU patch and much longer, which means that roosting shorebirds, if disturbed, can readily shift well beyond the vision and access of the observer team.

Map 1 below illustrates the study area and high-tide roosts identified through previous surveys. The eleven (11) roosts surveyed by the Normanton Rangers and Roger Jaensch for the purposes of this project are indicated in red.

Map 1. The study area and shorebird roosts



Map 2. Location of shorebird high tide roosts (yellow pins) in Zone E (red outline) based on historical and recent knowledge of QWSG, CLCAC and/or JOC.

Note: names of roosting sites are not official & were designed simply for survey purposes.

Annex 10 in the first-year report (CLCAC, 2019) provides details on all roosts except Phillip's Beach (which is similar to Mark's and Godwit Beach roosts), with oblique aerial or ground-level photos, satelliteimages and/or notes on how birds typically use the roost.

All coastlines are dynamic, changing with weather patterns and sea currents seasonally and/or year-to- year and especially from major events such as cyclones, river floods and sea-level rise. During the project, CLCAC and JOC noted an ongoing increase in cover and size of small mangroves across the mouths and on the frontal flats of some beach roosts.

Existing data

To aid in survey planning and in analysis of the results to provide meaningful conclusions, JOC was requested to collate existing data on shorebirds for the study area. The data sources and summary of existing data is provided in the year 1 progress report (CLCAC, 2019).

2019 – 2020 Survey methods

Dates for surveys for the project were chosen as result of multiple influences: key weeks/months for migration of shorebirds; weather conditions; tide predictions; fieldwork by GU; and availability of rangers and JOC in view of other commitments. Data on predicted tide times and heights at Karumba from the Bureau of Meteorology and other websites were used to identify suitable dates for surveys. The ideal circumstance was a peak of high tide well after sunrise or before sunset, of a height exceeding 2.5 metres. The survey dates, highest high tides, and number of roosts surveyed are shown below in Table 1.

Table 1: Survey dates, highest high tide and number of roosts surveyed during each survey period.

Survey dates	Highest high tide	Number of roosts surveyed
15-18 Jan 2019	3.91 m at 18:18 on 18 January.	12 Roosts (Mark's beach West End was surveyed twice).
29 & 30 Mar 1 & 2 Apr 2019	3.83 m at 14:30 on 30 March.	8 roost sites were surveyed, 4 of themtwice.
30 & 31 Aug 2 & 3 Sep 2019	3.65 m at 07:17 on 30 August.	13 roost sites surveyed, 11 of them (e.g. The Oaks) more than once.
2 & 3 Apr 2020	3.9 m at 14:23 on 3 April.	Three roost sites were surveyed: Godwit Beach (West & East) & Phillip's Beach.

Shorebird counts at the accessed roost sites followed standard methods used by QWSG and BirdLife Australia's Shorebirds 2020 program. A first estimate of total numbers was obtained, then species identified and either counted separately or assigned percentages where flocks were large and dense. This procedure was repeated many times to improve accuracy, especially also to account for changes due to arrival of more birds as the tide rose higher, covering intermediate roosts located nearby. Where circumstances allowed, terns also were documented, mainly because terns commonly roost withshorebirds and can include some migratory species.

JOC, Rangers and occasionally other CLCAC staff participated in each survey. Whereas four days of surveys were possible in the first three survey events, in April 2020, restrictions due to the COVID-19 pandemic limited operations in terms of number of days (only 2) and observers (only 2 per day). JOC was prevented from participating in the fourth

survey event due to travel restrictions made by the government and to decisions made by CLCAC to protect remote communities. Instead, the Rangers conducted surveys independently and JOC reviewed results and photos and suggested adjustments where needed, remotely.

Weather conditions were good or reasonable in all four survey events. However, major flooding in the Flinders and other rivers in the 2019 wet season (February) and passage of Severe Tropical Cyclone Trevor close to the South-East part of the Gulf on 21-23 March 2019 [1], only six days before the first shorebird survey, undoubtedly impacted shorebirds and thus the survey results in March-April 2019 (seeCLCAC 2019, and Results below).

Before the start of the project, no major roost for shorebirds was known at the mouth of the Flinders River itself, partly because of extensive mangroves on both sides [2]. Hence, the original plan for choice of rooststo be surveyed by CLCAC and JOC on the Flinders-Bynoe coast was to focus on the two roosting beaches closest to the Flinders River mouth: Mark's Beach and Godwit Beach. Both were known to be relatively good for approaching and counting shorebirds at rising and high tide. Initially, the plan was to conduct replicate surveys of these roosts alone. However, because different heights of tide on subsequent days of a survey event impacted how shorebirds used any particular roost, it was realised during the first eventthat repeats would have limited value. Instead it would be more beneficial to GU if surveys covered as many roosts in Zone E as possible at the time. Photograph representations of some of the sites which were surveyed are shown in Figure 1 below.

Across the four survey events, the scope of roosts visited, and surveys conducted was inevitably and overwhelmingly controlled by factors beyond the influence of CLCAC and JOC. This meant thatcomparability of results between survey events is limited; however, in most cases a core set of sites wassurveyed, as reflected in the tables of results.

Access to the coast was provided by helicopter chartered from Cloncurry Mustering out of Karumba Point. This arrangement was cost-efficient and minimised risk because flying time to roosts was mostly in the order of only 5 to 10 minutes. On some occasions, more than three Rangers could be brought to the roost. Mobile phone reception was possible at many roosts and one or more satellite phones were alwayscarried. The helicopter also enabled more distant roosts to be accessed, as far as Jim's Beach, on some survey events. Restrictions due to COVID-19 limited the scope of flying and survey work in April 2020.

[1] http://www.bom.gov.au/announcements/sevwx/nt/nttc20190311.shtml

[2] In January 2019, a flock of several thousand knots was recorded on a small beach inside the estuary,on the west bank (birds later transferring to salt flat a kilometre to the west), but few shorebirds were at that site on the next two survey events.

The Oaks – east end

Godwit Beach – east end

Figure 1: Examples of high-tide roost sites for migratory shorebirds on the Flinders-Bynoe coast

RESULTS

Historical data

Data on shorebird usage of the Flinders Coast before 2019 were collated from sources such as Driscoll (2001) at the project start and reported in Annex 1 and 2 in the Year 1 Progress Report (CLCAC, 2019). Historical data were collected from 1998 to 2015 across 16 surveys. Survey coverage of roost sites was variable. Across the surveys 24 migratory shorebird species were recorded; 18 of which were regularly occurring across surveys. Seven of these species are listed as nationally threatened under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). The most abundant species was the Great Knot (up to 7,880 birds). The roosts where highest numbers of shorebirds generally occurred was Jim's Beach and/or The Oaks. The highest total for all migratory shorebirds from ground counts was 14,602 birds on 3 April 2013 (3 roosts included). More than 10,000 migratory shorebirds were recorded in Zone E in each of seven surveys; four were in the period 1998-99 and three in the period 2013-15. Three species—Black-tailed Godwit, Great Knot and Red Knot—occurred in numbers exceeding 1% of their estimated Flyway population. The results are broadly comparable to two other QWSG shorebird survey zones in the South-East Gulf of Carpentaria: Zone C (north of Burketown) and Zone F (north of Karumba).

2019 to 2020 data

Data from each survey period in 2019 and 2020 are presented in Annex 1 to 4. A total of 20 species of migratory shorebirds and 4 resident shorebird species were recorded during the surveys. All 7 species that are listed as threatened under the *EPBC Act 1999* were

recorded. Five of the species were recordedin numbers of at least 100 with exception of the Greater Sand Plover and Lesser Sand Plover. The mostabundant species were Great Knot (max. count 7,496, Jan. 2019), Black-tailed Godwit (4990, Jan. 2019)and Red Knot (2860, Aug-Sep. 2019). No other species exceeded 1,000 birds and 11 species occurred only in numbers of less than 100 birds. Three species were recorded in numbers above 1% of the estimated population size in the East Asian – Australasian Flyway: Great Knot, Black-tailed Godwit and Red Knot (Hansen *et al*. 2016). More than 10,000 migratory shorebirds were documented, twice.

In terms of individual roost sites for shorebirds on the Flinders Coast 6 roosts each held at least 1,000 migratory shorebirds at some time. Highest numbers were at The Oaks East End (10,637 migratory shorebirds, August-September 2019; based on max. counts from three surveys), Flinders Mouth West Bank (4,551, 18 January 2019) and Jim's Beach (1,664, 17 January 2019).

A brief outline of survey results is provided below for each survey period.January 2019
Results for this survey event are presented in Annex 1. A total of 15,090 migratory shorebirds were
recorded, comprising 18 species. Four resident shorebird species were additionally recorded. All 7 species that are listed as threatened under the *EPBC Act 1999* were recorded, with good numbers of Eastern Curlew (195) and Bar-tailed Godwit (199). The most abundant species were Great Knot (7,496 birds) [3] and Black-tailed Godwit (4,990) and to a lesser extent, Red Knot (314).

March-April 2019

Results for this survey event are presented in Annex 2. A total of 2,719 migratory shorebirds were recorded[4], comprising 18 species. Three resident shorebird species were additionally recorded. All 7 species that are listed as threatened under the *EPBC Act 1999* were recorded. The most abundant species was Black-tailed Godwit (1,347 birds). Numbers of the normally abundant knots were very low: only 105 Great Knot and 24 Red Knot.

August-September 2019

Results for this survey event are presented in Annex 3. A total of 12,591 migratory shorebirds were recorded, comprising 17 species. Three resident shorebird species were additionally recorded. Of the 13roosts that were surveyed, 6 sites had no birds present at the time the surveys occurred. All 7 species listed as threatened under *EPBC Act 1999* were recorded, two species were recorded in thousands (e.g.Red Knot, 2,860) and two in hundreds (e.g. Curlew Sandpiper, 392). The most abundant species were Great Knot (4,940 birds) and Black-tailed Godwit (2747)

April 2020

Results for this survey event are presented in Annex 4. A total of 1,130 migratory shorebirds were recorded [5], comprising 11 species. Four resident shorebird species were additionally recorded. Four species that are listed as threatened under the *EPBC Act 1999* were recorded, including 30 Red Knots. The most abundant species was Great Knot (600-800 birds).

Leg flag re-sightings

Despite scanning thousands of birds, only one leg-flagged individual was detected in the project: a Red Knot that had been flagged in south-eastern Australia, possibly Victoria, re-sighted at The Oaks East Endon 31 August 2019. This bird may have been intending to again continue to south-eastern Australia and/or New Zealand.

At some roosts, such as those with huge dense flocks of knots, there were relatively few opportunities toget close enough to shorebirds to scan for leg flags.

[3] *Some large flocks of unidentified knots, e.g. seen only in flight, were assigned to species based onratios determined from surveys at roosts where identification to species level was possible.*

DISCUSSION

Comparison within the survey period 2019-20

There are many constraints on meaningful comparisons of results for migratory shorebirds on the Flinders Coast within the survey period (4 survey events) in 2019-20. Two of the survey events (Jan 2019, Aug- Sep 2019) were in months/seasons that were not replicated. Even though there were two survey eventsin March and/or April, circumstances were markedly different: in 2019, birds undoubtedly were scarce due to a recent cyclone and major flood in the Flinders River (fresh water killing much of the saltwater invertebrate food: M. Burford pers. com.) and in 2020 only three brief surveys were possible due to the COVID-19 pandemic.

Keeping these caveats in mind, nevertheless it is noteworthy in comparing the similar survey efforts in January 2019 and August-September 2019 (Annex 5), that:

- Though numbers of Great Knot and Black-tailed Godwit were high in both instances, they weremuch higher in January.
- Red knot was scarce in January but relatively abundant in August-September; Curlew Sandpiper exhibited a similar result but at smaller scale.
- Numbers of Eastern Curlew in January were almost twice the number in August-September.

These outcomes may in part reflect seasonal migration. Leg-flag re-sightings in the Flyway and BirdLife Australia databases indicate passage of Red Knot and Curlew Sandpiper through the Gulf of Carpentariafrom or to south-eastern Australia and/or New Zealand, in August-September and March-April—though they are present in small numbers in the Gulf in other months (Driscoll, 2001; QWSG data; Flyway leg- flag database). Black-tailed Godwit is known to partly disperse to non-tidal habitats in the northern wet season, December to April (Driscoll 2001). Higher numbers of Great Knot and Eastern Curlew in Januarymay reflect that some of these birds arrive late from the northern hemisphere and although some curlewsmay pass through the area from eastern Australia during northward migration, this may not be a major factor in their pattern of occurrence in the Gulf.

Comparison of historical and 2019-2020 results

By Species

The maximum number counted of each species in any survey event from the period 1998 to 2015 (Annex2 of CLCAC 2019) is compared with the same data for 2019-20 in Annex 6, below. A result determined as being an ‘increase’ or ‘decrease’ in numbers is based on 30% [6] of the historical maximum and the sixspecies with no count above 30 are ignored.

[4] Calculated as for Jan. 2019 event. Likely to be less realistic due to some migration occurring.

[5] Calculated as for Jan. 2019 event. Likely to be less realistic due to some migration occurring.

[6] The choice of percentage decrease/increase is somewhat arbitrary for the present purpose, and the data are notsufficiently robust to apply a low % figure (e.g. a 10% change), but 30% has been applied as it is the criterion for species listed as Vulnerable (in terms of reduction in Flyway population size) under the EPBCAct 1999, derived from the IUCN Red List criteria. https://www.environment.gov.au/system/files/pages/d72dfd1a-f0d8-

4699-8d43-5d95bbb02428/files/tssc- guidelines-assessing-species-2020.pdf accessed 15 May 2020.

Eastern curlew and Terek sandpipers

Great knots (at front) and black-tailed godwits

Black-tailed godwit and great knot

Asian dowitcher (at left) and black-tailed godwits

Photos: Some of the migratory shorebirds photographed on the Flinders-Bynoe coast during the project

2019-2020.

Comparisons show that the maximum number of birds recorded between the historical survey data and 2019-20 data was similar for six species. These included the three most abundant species in the Gulf region: Great Knot, Black-tailed Godwit and Red Knot. One species, the Terek Sandpiper, showed an increase in numbers. A decrease was evident for 11 species, nearly half of all species recorded in Zone E. Four of the 7 threatened species—including two of the Critically Endangered species, Eastern Curlewand Curlew Sandpiper—showed a similar maximum count whereas three (Bar-tailed Godwit, Greater Sand Plover and Lesser Sand Plover) showed a decrease. Four species were not recorded at all during2019-20. These are species more commonly associated with non-tidal habitats such as grassland (e.g. Little Curlew) or seem to have decreased in the Flyway (e.g. Sanderling).

By roost site

Many of the historical data for Zone E (the Flinders Coast), especially before the most recent decade, were not separated to individual roost sites and so comparison for sites is not possible for all years. There are also unknown differences in how surveys were conducted, which would have greater impact on comparison at the roost site level than where data have been aggregated across the whole zone. Furthermore, data for many species are not well suited to detailed analysis, notably the counts of knots because in some cases counts for the two species (which roost together in dense flocks) were assignedby extrapolating from samples of the most visible birds. Nevertheless, meaningful comparisons seem reasonable to make for the abundant and readily identified Black-tailed Godwit.

At Marks Beach West End, the maximum historical count for Black-tailed Godwit was 618 birds in March2013 whereas the maximum count during 2019-20 was 295 in January 2019. At Godwit Beach (West andEast ends combined), which apparently was not surveyed by QWSG, the maximum historical count for black-tailed godwit was 810 birds in March 2014 whereas the maximum count during 2019-20 was 269 in August-September 2019. In these cases, the apparent declines were 52% to 67%, which reflects general declines in the Flyway across most species. However, this must be viewed with caution becausethere is some evidence that shorebirds use different roosts in different seasons and on different tides andthis may contribute to apparent changes (overall and/or by species) at any one roost. For example, in late August and early September 2019, many of the dozen roosts on the Flinders Coast had no shorebirdsor very few, whereas 86% of all shorebirds were at The Oaks East End roost. This may have been a situation of migratory birds newly arrived from Asia aggregating in large numbers at fewer sites (i.e. ‘safety in numbers’) while recovering from their exhausting journey. Later, the birds would disperse along the coast, as is evident in the January 2019 data showing the largest proportion of the shorebird total at anyone roost (including The Oaks) being 30%. Some small roosts additional to those well known to QWSG were found and documented during the project.

CONCLUSIONS

The project was successful in providing context for the research by Griffith University on estuarine ecosystems around the mouth of the Flinders River. A minimum of three survey events over the two-yearproject was requested and four survey events were achieved,

albeit the fourth reduced due to COVID-19. These included the three main seasons of the migration calendar: southward migration (August- September 2019), the non-breeding period when the shorebirds are present, but movements are minimal(January 2019), and northward migration (March-April 2019 & April 2020).

Although the difficulties in surveying this coast, inconsistencies in tide heights and other factors limit thecapacity to conduct robust analyses of the CLCAC project data, several general conclusions nevertheless can be drawn:

Total numbers and the use of roosts

- The importance of the Flinders Coast in terms of number of shorebirds remains high. During 2019-20, the Flinders Coast held a large number of shorebirds (twice, over 10,000 species wererecorded) and once exceeded the highest historical total for this zone.

- Use of shorebird data from only one or two surveys at a site (such as the Flinders mouth) must be interpreted with caution. This was illustrated by differences in total number, in numbers at certain roost sites, and in abundance of some species, which may be attributed to the migration cycle, to variations in tide height, to short-term climatic events (e.g. cyclones) and other factors.

- Short-term events can radically impact use of the Flinders Coast by migratory shorebirds. The major flood event in the Flinders River in February 2019 could be expected to cause a drop in shorebird numbers on the nearby coast because the massive influx of fresh water predictably would kill food items for shorebirds in the intertidal flats. This certainly occurred, with total migratory shorebirds soon after in March-April 2019 reaching only 18% of the total from a few months earlier (historical totals for this date have exceeded 10,000 on at least six occasions: seeAnnex 1 in CLCAC 2019).

- Shorebird use of the coast may resume soon after short-term impacts. Whilst the impacts of theflood and the cyclone on this coast in early 2019 and impacts elsewhere in the Flyway from Mayto July cannot be fully understood, the reappearance of over 10,000 migratory shorebirds in August-September 2019 suggests that the impacts may have been short-term. This is predictable because influx of nutrients from a major river flood tends to boost productivity in the intertidal zone within several months or less than a year (M. Burford, Griffith University, pers. com.). Although shorebirds were overwhelmingly concentrated at one roost in August-September 2019,this may have been a typical, short-term recovery strategy of newly arrived, exhausted migratorybirds rather than ongoing avoidance of the coast nearest to the Flinders River mouth (presumablythat was the area most impacted by the February flood).

- Use of particular roost sites is a mix of regular and erratic. Use of many roosts during the projectwas broadly similar (at least to order of magnitude of numbers) to historical usage, where known. However, apparently for the first documented time, several thousand shorebirds (mainly knots) were documented roosting in the mouth of the Flinders River. Previous work by QWSG and CLCAC had not revealed this roost, on the west bank of the river, although perhaps it was overlooked being 500 m upstream whereas the focus of searching tends to be in the first 100-200 m width of shore. However, no aggregation of this size was found there on subsequent 2019-20 surveys and the small space of the roosting site and inundation on bigger tides suggests thatit may not be a regularly used roost, or at least only a staging roost on moderately large high tides. Furthermore, from survey experience in the region, dense flocks of thousands of knots mayoccur erratically at some roosts or sections of coast, causing large fluctuations in survey results.

Shorebird species

- The historically dominant, most abundant species on the Flinders Coast (Black-tailed Godwit and both knots) remained unchanged and proportionately their numbers were similar to those in the past. This may be a little biased because these larger birds may be more readily detected but their abundance should give a sounder basis for comparison over time than for less abundant species.

- The relative abundance of species was broadly similar in 2019-20 to historically.

- Flyway-wide declines in numbers of many shorebird species were reflected in many of the results from the Flinders Coast project, for example, Bar-tailed Godwit declined by an order of magnitude. But declines were less pronounced for some species, including some that are listed as Critically Endangered (e.g. Curlew Sandpiper and Eastern Curlew). Further reading on declines: Hansen *et al.* (2016).

- Caveats on results for certain species, especially the small shorebirds. An apparent decline of two orders of magnitude in numbers of Greater Sand Plover and a significant decline in Red- necked Stint should be viewed with caution. These small shorebirds often roost separately from the main mob of knots and godwits and can be missed entirely. Also, they may be among the sand plovers or other small shorebirds (sometimes numbering hundreds), which on some occasions could not be identified to species due to distance or poor views of birds in flight.

- International importance for three species remains unchanged. Historically, Great Knot, Black- tailed Godwit and Red Knot each met the 1% threshold for international importance on the Flinders Coast (Annex 2, CLCAC, 2019) and this has not changed. During 2019-20, each species met the 1% threshold on either one or two survey events (Annex 5).

REFERENCES

CLCAC, C.L.C.A.C., 2019. Links between Gulf Rivers and food for migratory shorebirds - Survey 1 Progress Report (Progress Report), CLCAC-GU Flinders Shorebird Project. CLCAC, Normanton,QLD.

Driscoll, P., 2001. Gulf of Carpentaria wader surveys 1998-9 (Report by Queensland Wader Study Groupof Birds Queensland Environmental Protection Agency).

Hansen, B., Fuller, R.A., Watkins, D., Rogers, D., Clemens, R.S., Newman, M., Woehler, E., 2016. Revision of the East Asian – Australasian Flyway Population Estimates for 37 listed Migratory Shorebird Species (Unpublished report for the Department of the Environment). BirdLife Australia, Melbourne.

Annex 1. Survey data for shorebirds & terns, January 2019

Maximum counts from each roost from ground or aerial surveys 15-18 January 2019

Observations by Roger Jaensch and the Normanton (CLCAC) Land & Sea Rangers.

roost site	Norman Mouth inside West	The Oaks East End	Bynoe Mouth inside East	Bynoe Mouth inside West	Godwit Beach East End	Godwit Beach West End	Marks Beach East End	Marks Beach West End	Flinders Mouth salt flats inside East	Flinders Mouth West Bank or Flat to West	Flats & front between Flinders & Jim's	Jim's Beach	total of maximum counts across Zone E
date	17-Jan-19	17-Jan-19	16-Jan-19	16-Jan-19	16-Jan-19	16-Jan-19	15-Jan-19	15 or 18-Jan-19	18-Jan-19	18-Jan-19	17-Jan-19	17-Jan-19	
waterbird species													
Asian Dowitcher										1			**1**
Australian Pied Oystercatcher		2			2	4		2					**10**
Bar-tailed Godwit		16	4		5	1		128		45			**199**
Beach Stone-curlew													
Black-fronted Dotterel													
Black-tailed Godwit	400	980	650	30	250	25		295	65	895	50	1350	**4990**
Black-winged Stilt		13			9			5					**27**
Broad-billed Sandpiper													
Common Greenshank		3		3	5	2	1	2	8	1	15		**40**
Common Sandpiper													
Curlew Sandpiper		6			6	4		3				2	**21**
Eastern Curlew		101		2	25	29	5	21		2	2	8	**195**
Great Knot		1150			950			566		X		220	**2886**
Greater Sand Plover		X						5					**5**
Grey Plover		21			2	4		1					**28**
Grey-tailed Tattler		3									2		**5**
Lesser Sand Plover								1				11	**12**
Little Curlew													
Marsh Sandpiper		4			3	5		5					**17**
Masked Lapwing										2			**2**
Oriental Plover													
Pacific Golden Plover					3							13	**16**
Red Knot		15			22			24				10	**71**
Red-capped Plover								2					**2**
Red-necked Avocet													
Red-necked Stint		X				1		80					**81**
Ruddy Turnstone					2	3							**5**
Sanderling													
Sharp-tailed Sandpiper		1			12	5	9	10				11	**48**
Sooty Oystercatcher													
Terek Sandpiper						40		4			40		**84**
Whimbrel		60			19	15	4	39		45	1	14	**197**
unidentified knots			350	3		500			380	3560	60		**4853**
unidentified sand plover		300											**300**
unidentified small shorebirds	50	500	100	25			300		30		7	25	**1037**
total number counted:	**450**	**3175**	**1104**	**63**	**1315**	**638**	**319**	**1193**	**483**	**4551**	**177**	**1664**	**15132**
Silver Gull													**X**
Caspian Tern		20						3				37	**60**
Common Gull-billed Tern (affinis)		36						8		X		6	**50**
Whiskered Tern		36						X					**X**
Crested Tern		3										55	**58**
											200	1	**201**

Date (January 2019)	High tide prediction at Karumba
Tuesday 15	Low: 1.74 m at 08:30 High: 3.46 m at 22:18
Wednesday 16	Low: 1.65 m at 08:10 High: 3.36 m at 21:32
Thursday 17	Low: 1.52 m at 07:55 High: 3.56 m at 18:27
Friday 18	Low: 1.34 m at 07:49 High: 3.91 m at 18:18

Annex 2. Survey data for shorebirds & terns, March – April 2019

Maximum counts from each roost from ground or aerial surveys 29-30 March & 1-2 Apr

Observations by Roger Jaensch and the Normanton (CLCAC) Land & Sea Rangers.

roost site	Norman Mouth inside West	The Oaks East End	Bynoe Mouth inside East	Godwit Beach East End	Godwit Beach West End	Marks Beach West End	Flinders River west bank	Jim's Beach	total of maximum counts across ZoneE
date	01-Apr-19	29-Mar-19 & 1-Apr-19	01-Apr-19	30-Mar-19 & 1-Apr-19	30-Mar-19 & 1-Apr-19	29-Mar-19	29-Mar-19 & 2-Apr-19	02-Apr-19	
waterbird species									
Asian Dowitcher						6			**6**
Australian Pied Oystercatche	1	2		2	3			1	**9**
Bar-tailed Godwit		7		15	8	5		7	**42**
Beach Stone-curlew									
Black-fronted Dotterel									
Black-tailed Godwit	114	695		49	220	260		9	**1347**
Black-winged Stilt	35	X		39	12	16		68	**170**
Broad-billed Sandpiper									
Common Greenshank		8		1	2				**11**
Common Sandpiper									
Curlew Sandpiper	4			7	4	2			**17**
Eastern Curlew		14		10	4	21		17	**66**
Great Knot		55		7	3	40			**105**
Greater Sand Plover	3			1	1				**5**
Grey Plover	2	20		6	12	2		1	**43**
Grey-tailed Tattler	1								**1**
Lesser Sand Plover	31				17	1			**49**
Little Curlew									
Marsh Sandpiper	24	8		20	18	18			**88**
Masked Lapwing									
Oriental Plover									
Pacific Golden Plover									
Red Knot		18		3	2	1			**24**
Red-capped Plover		6		1	18	2			**27**
Red-necked Avocet									
Red-necked Stint	38				7				**45**
Ruddy Turnstone				4	2				**6**
Sanderling									
Sharp-tailed Sandpiper		14			23	12			**49**
Sooty Oystercatcher									
Terek Sandpiper	8			1	3			17	**29**
Whimbrel		X		46	15	53		3	**117**
unidentified knots									
unidentified sand plover		77		1	3			89	**170**
unidentified large shorebirds		63	120				45		**228**
unidentified medium shorebir	ds							16	**16**
unidentified small shorebirds		2						47	**49**

March & April 2019	Low tide (m)	Low tide time	High tide (m)	High tide time
Friday 29	1.35	3:19 am	3.82	1:46 pm
Saturday 30	1.23	4:14 am	3.83	2:30 pm
Sunday 31	1.17	5:12 am	3.75	3:17 pm
Monday 1	1.18	6:09 am	3.63	4:06 pm
Tuesday 2	1.25	6:59 am	3.48	4:53 pm

total number counted:	261	989	120	213	377	439	45	275	2719
Silver Gull									
Caspian Tern		5		1	1				**7**
Australian Gull-billed Tern		10		25	15	8			**58**
Common Gull-billed Tern (aff	inis)	18		9	11	6			**44**
Whiskered Tern		X		1	2	2			**5**
Crested Tern		8							**8**
Lesser Crested Tern		310							**310**
Little Tern		145		4	150				**299**

Annex 3. Survey data for shorebirds & terns, August-September 2019

See Annex 4 for tide data

Maximum counts from each roost from ground survey or aerial reconnaissance, 30-31 August & 2-3 September 2019

Observations by Roger Jaensch and the Normanton (CLCAC) Land & Sea Rangers; assisted by Griffith University.

roost site	Norman Mouth inside West	The Oaks East End	Bynoe Mouth inside East	Bynoe Mouth inside West	Godwit Beach East End	Godwit Beach West End	Bays between Godwit & Marks	Marks Beach East End	Marks Beach West End	Flinders Mouth salt flats inside East	Flinders Mouth West Bank or Flat to West	Flats & front between Flinders & Jim's	Jim's Beach	total of maximum counts across Zone E
date	31/08/2019 & 3/9/19	30/8, 31/8 & 2/9/19	31/08/2019 & 3/9/19	31/08/2019 & 3/9/19	31/08/2019 & 3/9/19	30-Aug-19	31/08/2019 & 3/9/19	31/08/2019 & 3/9/19	31/08/2019 & 3/9/19	31/08/2019 & 3/9/19	31/08/2019 & 3/9/19	31/08/2019 & 3/9/19	30-Aug-19	
waterbird species														
Asian Dowitcher		1												**1**
Australian Pied Oystercatcher		3	nil	nil	nil	6		nil	2	nil		nil	2	**13**
Bar-tailed Godwit		3	birds	birds	birds	4		birds		birds		birds		**7**
Beach Stone-curlew														**0**
Black-fronted Dotterel														**0**
Black-tailed Godwit		1927				80							740	**2747**
Black-winged Stilt		50				90					40		123	**303**
Broad-billed Sandpiper		2												**2**
Common Greenshank		31				8								**39**
Common Sandpiper														**0**
Curlew Sandpiper		390				2								**392**
Eastern Curlew		86				14								**100**
Great Knot		4900											40	**4940**
Greater Sand Plover		23				1								**24**
Grey Plover		11												**11**
Grey-tailed Tattler														**0**
Lesser Sand Plover		43				12								**55**
Little Curlew														**0**
Marsh Sandpiper						4								**4**
Masked Lapwing														**0**
Oriental Plover														**0**
Pacific Golden Plover														**0**
Red Knot		2700											160	**2860**
Red-capped Plover		93				15								**108**
Red-necked Avocet														**0**
Red-necked Stint		175				35								**210**
Ruddy Turnstone														**0**
Sanderling														**0**
Sharp-tailed Sandpiper		39				6							1	**46**
Sooty Oystercatcher														**0**
Terek Sandpiper		1												**1**
Whimbrel		50												**50**
unidentified knots/medium	70												20	**90**
unidentified sand plover		15											3	**18**
unidentified small shorebirds		240											270	**510**
unidentified All shorebirds							60							**60**
total number counted:	**70**	**10783**	**0**	**0**	**0**	**277**	**60**	**0**	**2**	**0**	**40**	**0**	**1359**	**12591**

Silver Gull		8											40	**48**
Caspian Tern		30											29	**59**
Crested Tern		20											75	**95**
Lesser Crested Tern		68											3	**71**
Australian Gull-billed Tern		65											8	**73**
Common Gull-billed Tern (affinis)		7											3	**10**
Whiskered Tern		9				1							18	**28**
Little Tern		195											2	**197**
unidentified terns		184											360	**544**

Annex 4. Survey data for shorebirds & terns, April 2020

Results from review of photos by consultant

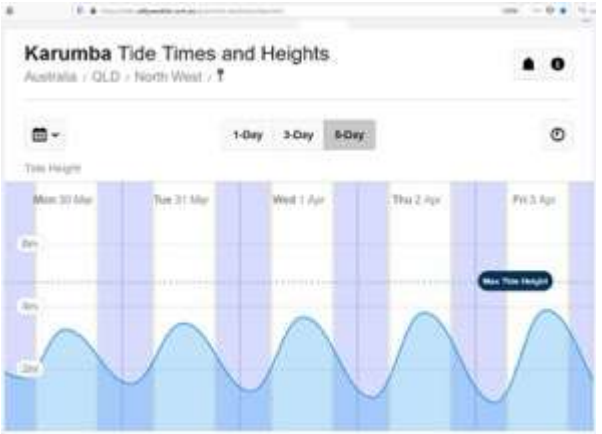
Shorebird survey on Flinders Coast, April 2020

Roger Jaensch roger.jaensch.bne@gmail.com Threatened species are in red font.

species	Phillip's Beach 2-Apr-20	Godwit Beach East 3-Apr-20	Godwit Beach West 3-Apr-20	totals
Bar-tailed Godwit		5		**5**
Black-tailed Godwit	32	16	51	**99**
Common Greenshank		1	5	**6**
Eastern Curlew			18	**18**
Great Knot	600	X	X	**600**
Grey Plover		1		**1**
Marsh Sandpiper			14	**14**
Red Knot	30	X		**30**
Red-necked Stint		1	9	**10**
Terek Sandpiper			2	**2**
unidentified knots (medium shorebirds)		154	130	**284**
unidentified sand plovers	39	8		**47**
Whimbrel	14			**14**
SUB-TOTALS	**715**	**186**	**229**	**1130**
Black-winged Stilt		33	60	**93**
Pied Oystercacther	2	4	2	**8**
Silver Gull	1			
Caspian Tern			2	
Lesser Crested Tern	1			
Common Gull-billed Tern			1	
unidentified Gull-billed Terns		13		
Little Tern	180		125	

date Aug.-Sep. 2019	High tide prediction at Karumba
Friday 30	High: 3.65 m at 07:14 Low: 0.28 m at 21:04
Saturday 31	High: 3.61 m at 08:17 Low: 0.39 m at 21:48
Sunday 1	High: 3.46 m at 09:14 Low: 0.65 m at 22:27
Monday 2	High: 3.19 m at 10:04 Low: 1.04 m at 23:02
Tuesday 3	High: 2.82 m at 10:45

date Mar.-Apr. 2019	High tide prediction at Karumba
Tuesday 31	High: 3.5 m at 12:28 Low: 1.5 m at 01:53
Wednesday 1	High: 3.7 m at 12:52 Low: 1.3 m at 02:15
Thursday 2	High: 3.8 m at 13:31 Low: 1.1 m at 03:00
Friday 3	High: 3.9 m at 14:23 Low: 0.9 m at 04:03



Annex 5. Summary of shorebird counts for Zone E in 2019 and 2020 from the four survey events

Species in red are listed as threatened under the *EPBC Act 1999*. Names shaded blue are migratory species. Count data in red exceed the 1% threshold for international importance (Hansen *et al.* 2016).

vent dates	owitcher	an ter-catcher	dGodwit	one-curlew	ntedDotterel	ledGodwit	ngedStilt	lledSandpiper	n Greenshank	nSandpiper	andpiper	Curlew	ot
1% threshold:	140		3250			1600		300	1100	1900	900	350	4250
n-19	1	10	199			**4990**	27		40		21	195	**7496**
o 2-Apr 19	6	9	42			1347	170		11		17	66	105
o 3-Sep 19	1	13	7			**2747**	303	2	39		392	100	**4940**
ril 2020		8	5			99	93		6			18	600
maximum value:	**6**	**13**	**199**	**0**	**0**	**4990**	**303**	**2**	**40**	**0**	**392**	**195**	**7496**

vent dates	SandPlover	ver	edTattler	andPlover	rlew	andpiper	apwing	Plover	oldenPlover	t	pedPlover	kedAvocet	kedStint
1% threshold:	2000	800	700	1800	1100	1300		2300	1200	1100			4750
n-19	5	28	5	12		17	2		16	314	2		81
o 2-Apr 19	5	43	1	49		88				24	27		45
o 3-Sep 19	24	11		55		4				**2860**	108		210
ril 2020		1				14				30			10
maximum value:	**24**	**43**	**5**	**55**	**0**	**88**	**2**	**0**	**16**	**2860**	**108**	**0**	**210**

vent dates	urnstone	ng	iledSandpiper	yster-catcher	ndpiper	el	fiedsand plover	identified l shorebirds	fiedshorebirds	All shorebirds	**ryshorebirds**
1% threshold:	300	300	850		500	650					
n-19	4		48		84	197	300	1037		15131	15090
o 2-Apr 19	6		49		29	117	170	49	244	2719	2513
30-Aug to 3-Sep 19			46		1	50	18	510	150	12591	12167
2 & 3 April 2020					2	14	47		284	1231	1130
maximum value:	**6**	**0**	**49**	**0**	**84**	**197**	**300**	**1037**	**284**	**15131**	**15090**

NOTES:

- In some cases, numbers for great knot and red knot were derived by applying the ratio of these species as identified in ground counts, to the number of unidentified knots, and combining the results. Results for these two species shown in this table therefore are less robust than for other species.
- The data in the table are from ground-level surveys, with few exceptions.

Annex 6. Comparison between 2019-2020 and previous surveys.
Derived from Annex 1 of Jaensch (2019) and Annex 5 above.

Maximum number counted for migratory shorebirds recorded in Zone E
South-East Gulf of Carpentaria, Queensland, 1998 to 2020

Prepared for Carpentaria Land Council Aboriginal Corporation by R. Jaensch, May 2020
Based on data collected by the Queensland Wader Study Group and the CLCAC Rangers.

species	scientific name	max. count 1998-2015	date	max. count 2019-2020	date	difference in max. count
Asian Dowitcher	*Limnodromus semipalmata*	5	24-Mar-98	6	Apr-19	
Bar-tailed Godwit	*Limosa lapponica*	914	12-Apr-99	199	Jan-19	decrease
Black-tailed Godwit	*Limosa limosa*	5325	24-Mar-98	4990	Jan-19	similar
Broad-billed Sandpiper	*Limicola falcinellus*	190	24-Mar-98	2	Sep-19	decrease
Common Greenshank	*Tringa nebularia*	178	**30-Aug-15**	40	Jan-19	decrease
Common Sandpiper	*Actitis hypoleucos*	1	**22-Mar-13**	0		
Curlew Sandpiper	*Calidris ferruginea*	455	**30-Aug-15**	392	Sep-19	similar
(Far) Eastern Curlew	*Numenius madagascariensis*	268	**03-Apr-13**	195	Jan-19	similar
Great Knot	*Calidris tenuirostris*	7880	**03-Apr-13**	7496	Jan-19	similar
Greater Sand Plover	*Charadrius leschenaultii*	1177	**03-Apr-13**	24	Sep-19	decrease
Grey Plover	*Pluvialis squatarola*	130	**22-Mar-13**	43	Apr-19	decrease
Grey-tailed Tattler	*Tringa brevipes*	18	**30-Aug-15**	5	Jan-19	
Lesser Sand Plover	*Charadrius mongolus*	254	**22-Mar-13**	55	Sep-19	decrease
Little Curlew	*Numenius minutus*	5	**22-Mar-13**	0		
Marsh Sandpiper	*Tringa stagnatilis*	227	**30-Aug-15**	88	Apr-19	decrease
Oriental Plover	*Charadrius veredus*	3	12-Apr-99	0		
Pacific Golden Plover	*Pluvialis fulva*	22	**03-Apr-13**	16	Jan-19	
Red Knot	*Calidris canutus*	3035	**22-Mar-13**	2860	Sep-19	similar
Red-necked Stint	*Calidris ruficollis*	1506	**30-Aug-15**	210	Apr-20	decrease
Ruddy Turnstone	*Arenaria interpres*	36	25-Mar-99	6	Apr-19	decrease
Sanderling	*Calidris alba*	85	**30-Aug-15**	0		decrease
Sharp-tailed Sandpiper	*Calidris acuminata*	274	**22-Mar-13**	49	Apr-19	decrease
Terek Sandpiper	*Xenus cinereus*	41	**22-Mar-13**	84	Jan-19	increase
Whimbrel	*Numenius phaeopus*	197	**03-Apr-13**	197	Jan-19	similar

Data are from ground-level surveys of high-tide roosts, with few exceptions.

Dates in bold are from the past decade.

Difference in max. count: decrease if greater than 30% lower than historical max.; increase if greater than 30% higher.

No comparison drawn if both max. counts are less than 30 birds.