Resilient Landscapes

National Environmental Science Program

Synthesising ecological research for water planning

Models for the Gulf of Carpentaria

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Acknowledgement of Country

We acknowledge the Traditional Owners of Country throughout Australia and their continuing connection to and stewardship of land, sea and community. We pay our respects to them and their cultures and to their Ancestors, Elders and future leaders. Our Indigenous research partnerships are a valued and respected component of National Environmental Science Program research.

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Summary

The Gulf of Carpentaria's wet–dry tropical rivers support ecological assets whose condition is tightly governed by seasonal flow regimes. In Queensland, water is managed through the implementation of Water Plans. A water plan is a framework for sustainable management of water. The water plan and its instruments that implement the plan define water availability, priorities of water use, management strategies, performance indicators and monitoring and reporting requirements that apply over its life. The development and implementation of water plans is informed by a   assessment process aimed at evaluating the risks to the flow-related aspects of ecological assets. This approach relies on defining flow-related dependencies as ecohydrological rules and thresholds of concern, which define the environmental flow needs of those assets. This report brings together new and existing research on primary production, migratory shorebirds, and fish assemblages to inform such thresholds for Queensland's water planning process. We determined critical aspects of the hydrology which sustain the flow-dependent ecological values of these catchments and identify potential risk thresholds which express how far these hydrological conditions can be altered due to flow management without affecting the sustainability of these systems (i.e. thresholds of concern). The findings highlight that hydrological connectivity, both within and between rivers, floodplains, estuaries and coastal flats, is fundamental to sustaining productivity, biodiversity and species of conservation significance across the region.

Primary production across floodplains, salt flats and intertidal mudflats is a critical component of estuarine and freshwater ecological food webs and as such, is critical for ecological assets, such as higher order biodiversity and fisheries production. We found that primary production in these habitats depended strongly on the duration of inundation. Experimental incubations were used to show that benthic primary production remains low for the first 3–5 days after wetting, peaks around day 17, and then either plateaus or declines depending on site conditions. Consequently, the recommended ecohydrological rule is that the frequency and duration of floodplain inundation should last five days or more during the wet season providing an opportunity for peak primary production to occur. This led to a threshold of concern for potential reduction in primary productivity, i.e., a minimum of five days of inundation, initiate a significant increase in primary production, with peak productivity occurring at approximately 17 days. Hydrological modelling indicates that many floodplain areas remain inundated long enough to meet these requirements in natural flow years, underscoring the importance of protecting the timing and duration of wet-season flows.

Migratory shorebirds are protected under a suite of international treaties to which Australia is a signatory. The shorebirds in the Gulf of Carpentaria rely on the intertidal flats as critical feeding and staging areas within the East Asian–Australasian Flyway. Although the region currently provides abundant food resources, often exceeding estimated energetic requirements, several species show long-term declines, and macrobenthos abundance is lowest during wet-season low-salinity periods when birds' energy demands are highest. There is a strong relationship between salt flat inundation, macrobenthos productivity, and food requirements of birds, which suggests altering inundation frequency and duration will impact on bird populations. Additionally, it has been shown that intertidal mud flats are chronically nutrient-limited and that freshwater flows are the principal mechanism for nutrient inputs. Due to uncertainty in bird population estimates, food availability

estimates, and seasonal variability, it was not possible to determine a quantitative threshold of concern. Nonetheless, it is clear that any reduction of food resources, particularly post migration, is likely to have a negative impact on bird fitness and survival. As such, flow regimes must continue to support nutrient delivery, and primary productivity as the basis for secondary productivity supporting feeding habitat and benthic food resources during key migration periods, given the region's international significance for threatened and endangered species.

The fish communities of the Gulf of Carpentaria represent a significant component of the region's biodiversity and support valuable traditional harvest and commercial fishery catch. Fish assemblage analyses from the Mitchell River catchment show that hydrological connectivity shapes age structure, movement patterns and recruitment. Highly connected sites support a broader range of age classes, including older individuals, whereas disconnected or intermittently connected sites are dominated by young, small-bodied species. Provenance studies confirm that most fish undertake at least one major movement during their lifetime. These findings led to a recommended ecohydrological rule that ensures hydrological connection between the main channel and major tributaries that allows fish movement. The resulting threshold of concern is that a site should not fail to connect for more than one year in three, as prolonged disconnection would likely lead to the loss of older, larger-bodied and migratory species, including culturally and commercially important taxa such as barramundi and catfish, and a shift toward simplified assemblages dominated by small resident species.

This synthesis emphasises that ecohydrological thresholds used for assessing the ecological risks of current and future potential water-resource development in the Gulf have a sound scientific basis. While data availability varies across assets, the combined evidence demonstrates that maintaining natural patterns of flow magnitude, duration and connectivity is essential for sustaining ecosystem processes and species of conservation and cultural importance. The report highlights the need for continued monitoring, targeted research to fill key knowledge gaps, and adaptive management to ensure that water-planning decisions remain responsive to emerging science and changing environmental conditions.

1 Introduction

The Gulf of Carpentaria region has been identified as a priority area for water-resource development by state and federal governments. The Water Plan (Gulf) 2007, herein referred to as the water plan, includes an area of approximately 315,000 km^2 and incorporates eight river catchments. It supports major industry growth with increasing demands for water to support new irrigated agriculture and need to access critical minerals (such as copper, vanadium and tungsten). Each year, almost 25,000 gigalitres of water from the plan area flows into the Gulf of Carpentaria to support economic and environmentally significant fisheries and important environmental values (DLGWV 2023). The region also supports many ecological assets, such as national and internationally significant wetlands, freshwater and estuarine floodplains, waterholes, rivers and estuaries that are, amongst other things, habitats for commercial species and many threatened species (Petheram et al. 2013). A resource assessment study of the Flinders and Gilbert rivers in the southern Gulf of Carpentaria, commissioned by the Commonwealth Government, identified the need for further information on flow thresholds for river/coastal flood plume connectivity and associated ecosystem effects (Waltham et al. 2013). Since the last revision of the plan in 2007, and subsequent Minister's Performance Assessments (DSITIA 2014, DNRME 2018, DLGWV 2023), new scientific information has been collected on ecosystem water requirements, which will be used to inform an update of the water plan.

The wet-dry tropical climate of this region consists of a wet season with major, but variable, rainfall events over a few months each year, followed by an extended dry period with little or no rainfall. Wet season freshwater flows have been shown to be important in providing hydrological connectivity between various habitats of the region (rivers, floodplains, estuaries, waterholes, wetlands). This was highlighted in research findings from the region that showed mass wet season fish movement between habitats for food, refuge habitat and breeding (O'Mara et al. 2021; Stewart-Koster et al. 2021; Leahy and Robins 2021), and the importance of freshwater material contributions as drivers for estuarine and floodplain productivity (Burford et al. 2016, 2021; Ndehedehe et al. 2020a; Molinari et al 2022, Lowe et al. 2022). Floodplain and estuarine benthic primary production are known to be critical foundational processes in the region that supports other higher order assets, e.g. fish diversity and coastal fisheries (Burford et al. 2020). The presence and abundance of migratory shorebirds in the region is directly related to Australia's obligations under the Ramsar convention, with the Gulf coastal region a critical foraging location on the south-east Asian flyway (Burford et al. 2021). The Gulf region supports highly diverse fish assemblages, including several threatened species (Stewart-Koster et al. 2023), which have important traditional cultural values, recreation and commercial fish value and broader ecological importance (Petheram et al. 2013). The relative importance of flow for driving connectivity and productivity means water-resource development in one area has the potential to impact other habitats (O'Mara et al. 2021). This new knowledge that has been developed in recent years from the wider region under the National Environmental Science Program may provide important data to support environmental assessments of current and future potential water resource development scenarios.

This report collates existing information on ecosystem responses to flow regimes, focusing on the south-eastern Gulf of Carpentaria region but also drawing on information from studies of rivers in the western Cape York where relevant. Key ecological assets, including flow-dependent species and processes, were identified via consultations with the Water Planning Ecology team from Queensland Department of the Environment, Tourism, Science and Innovation (DETSI). These assets include floodplain and estuarine primary production, shorebird abundances, and fish assemblages. Data was synthesised to derive ecohydrological rules and thresholds of concern to inform the ecohydrological risk assessment process used by DETSI to support water plan outcomes (McGregor et al. 2018).

2 General methodology

2.1 Study region

The Gulf of Carpentaria region is located in the wet-dry tropics of northern Australian, where the climate is characterised by high temperatures (mean annual minimum temperature = 20°C, mean annual maximum temperature = 31°C) and distinctly monsoonal rainfall (Petheram et al. 2013). This rainfall pattern results in alternating patterns of a summer wet season with extended periods of overbank flooding (Dec–Mar) and a winter dry season where no freshwater enters estuaries downstream (Apr–Nov) (Petheram et al. 2013). Rivers are classified as having unpredictable summer flow which is highly intermittent (Kennard et al. 2010), with extensive floodplains that are only inundated during the wet season, as well as wetland and waterhole habitats. Estuaries are characterised as having simple meandering river channels and small tidal creeks, with a narrow line of mangroves behind which are extensive salt flats that are only inundated at the highest astronomical tides or, similar to floodplains, through riverine inundation during the wet season (Burford et al. 2020; Petheram et al. 2013).

The water plan includes the catchment areas of the Flinders River, Gilbert River, Leichhardt River, Morning Inlet, Nicholson River, Norman River, Straaten River and Settlement Creek (Figure 1). Due to the significant connectivity between habitats in this water plan area, we have taken a whole-of-system approach in synthesising information and flow-ecology relationships to operationalize them into numerical models to inform future water plan reviews.

We have focused this synthesis on ecological assets and processes with suitable available data and models from the rivers within the water plan area and the wider western Gulf of Carpentaria, where these data could reasonably be considered relevant to the study region. Report sections for each ecological asset and process is broken up into two sub-sections: Technical Methodology, and Results and Discussion.

Figure 1. The Gulf water plan area. Source: https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/water-plan-areas/gulf

3 Ecological assets and processes

3.1 Primary production

3.1.1 Technical methodology

The interplay of intra-annual and inter-annual variation in flow duration and magnitude is a natural feature of the flow regime providing suitable conditions and access to resources for a range of species throughout the year, as well as critical nutrients that fuel food resources through algal primary production (e.g., Plaganyi et al. 2023; Broadley et al. 2022; Burford and Faggotter 2021; Ndehedehe et al. 2021; Broadley et al. 2020; Venarsky et al. 2020; Lowe et al. 2022; Burford et al 2020; Duggan et al. 2019). As such, primary production across multiple habitats in the region, i.e., floodplains, salt flats, and intertidal flats, along the wet-dry tropical rivers of the Gulf of Carpentaria region, is a vital ecological process that underpins the sustainability of aquatic ecosystems across the plan area. We synthesized recent research and data from the region as well as other applicable regions to complement available information, including a study of a dryland river system of inland Queensland (referred to as the Border Rivers, conducted by Griffith University and DETSI researchers: Woods et al. 2012). Studies from the Border Rivers region of Queensland were also used to infer potential primary productivity rates on floodplains following inundation, while studies from the Gulf region focused on floodplains, salt flats and intertidal mud flats. New information was also collected on floodplain primary productivity rates to supplement existing data.

Floodplain primary production

The previous studies outlined above provide extensive knowledge of primary productivity on salt flats and intertidal flats but our understanding of primary productivity on inundated floodplains throughout the Gulf catchments remains limited. This constrained the ability to include these important habitats for risk modelling. Therefore, as part of new research in this study, soil samples from the floodplains of the Flinders River, Gulf of Carpentaria (Figure 2) were collected to determine the daily rates of primary productivity, after wetting.

As there is limited information on floodplain productivity across Australia more broadly, and by way of comparison, we have also included information from a previous study using soil samples from the Balonne River and Weir River (The Border Rivers) in the southern Queensland, northern New South Wales region. The rainfall patterns and flow regimes for the Border Rivers are similar to the Gulf of Carpentaria in that both regions are floodplain-river systems with distinct wet (highly intermittent scale of flooding) and extended dry seasons (little to no flow) (Kennard et al. 2010).

Lower floodplain sites of the Flinders River are located closer to the river mouth (labelled as FL sites and collected on one sampling trip) and geographically separate to floodplain sites and were located further upstream in the Flinders River catchment (labelled as ED sites and collected on separate trips), although both are inundated only during periods of overbank flooding. Dry surface soils (to a depth of 2–3 cm) were taken using a shovel and placed in sealed plastic containers. Samples were transported back to Brisbane in cool conditions. Soils were then wetted with distilled water, and within an hour, multiple perspex core samples (4.5 cm dia.) were taken from all sites. The cores were capped at the bottom with rubber bungs and contained 2–3 cm of wetted soil. They were then filled with deionised water and incubated for several days. The cores were subjected to natural light and a natural day/night cycle. To control the water temperature, samples were placed in controlled temperature water baths at 30°C. To compensate for evaporation, cores were periodically filled with more freshwater. Over the several days of the experiment, the oxygen flux of each core was measured periodically by capping the cores with a perspex cap early in the day, then taking five or more readings each morning using Presens® oxygen-sensitive optode patches glued inside each core; measurements were taken with a fibre-optic oxygen sensor (FIBOX). Readings were only done on days with full or close to full sunlight. Using this rate of oxygen increase during the mornings, a rate of primary production could be calculated for multiple days over a 22-day period for the Flinders River floodplain samples, and a 10-day period for the Border Rivers samples.

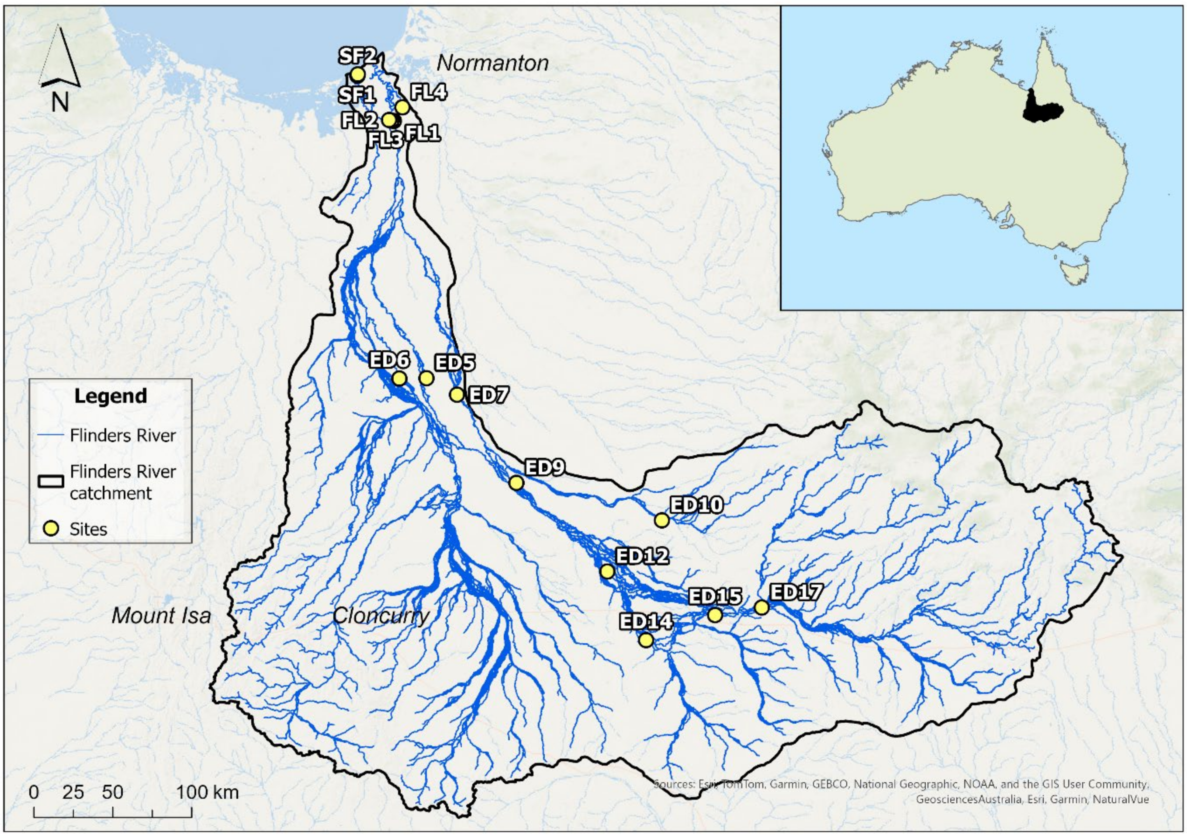


Figure 2. Sampling sites for soils on the floodplains and salt flats across the Flinders catchment. Sites located on salt flats have the prefix SF, those on the lower floodplain have the prefix FL, while sites on floodplain locations further upstream have the prefix ED.

Details of all the parameters measured, sampling methods, analysis methods and more detailed site descriptions of the locations shown in Figure 3 can be found in lower Balonne and Border Rivers study by Woods et al. (2012), noting that some of the data presented here was not published in that report.

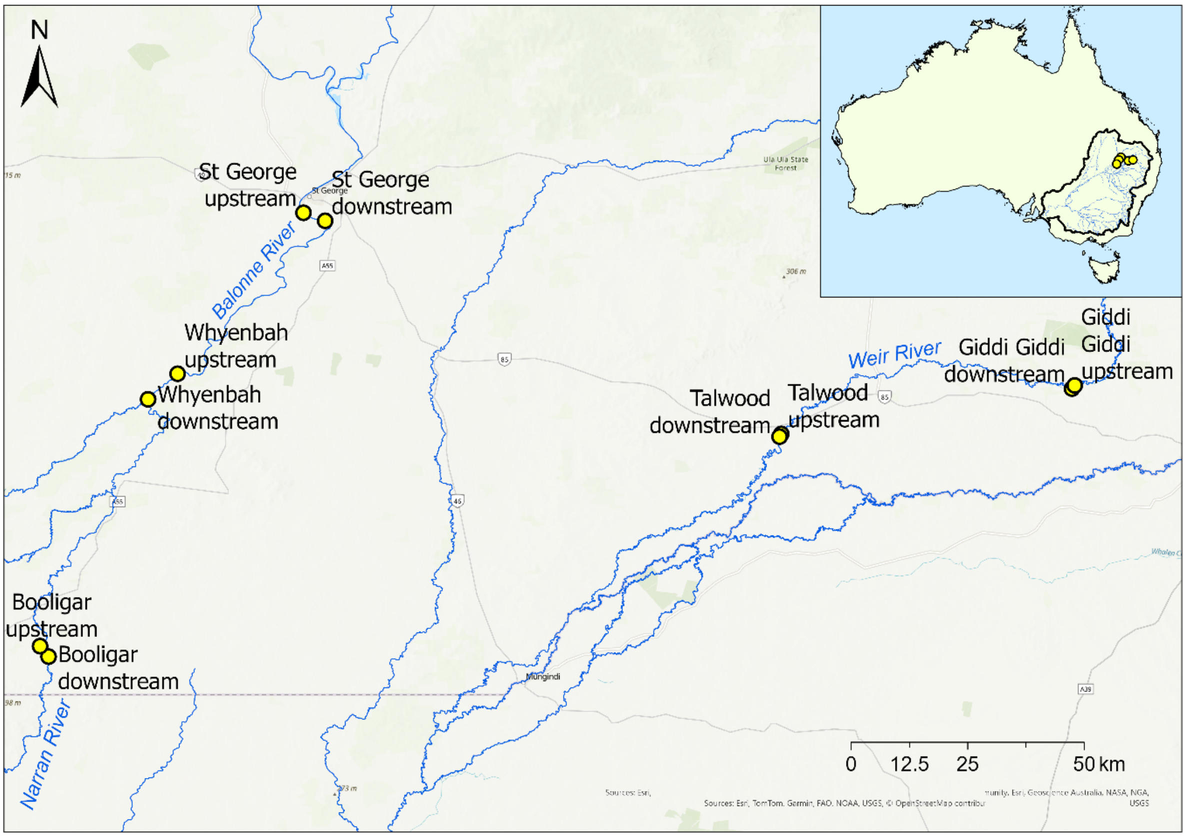


Figure 3. Sampling sites for soils in the lower Balonne and Border Rivers study by Woods et al. (2012).

Estuarine salt flat primary production

Sometimes called coastal supratidal mudflats, salt flats are shallow, relatively flat coastal environments infrequently inundated by the highest astronomical tides (Burford et al. 2016). They are also flooded for extended periods of time during the wet season due to overbank flooding. These systems represent a very large area in the southern Gulf region (Burford et al. 2020; Burford et al. 2016). The study sites included the salt flats adjacent to the Norman River, the results for which are reported in Burford et al., 2016) and sampling done in this study for the Flinders Rivers estuary (SF sites) (Figure 2).

Surface soil samples were taken during the dry season, and the same protocol was followed as described in 3.1.2. Primary production was measured over 11 days for the Norman River salt flat samples, and 22 days for the Flinders River salt flat samples. Details of all the parameters measured, sampling methods, analysis methods and more detailed site descriptions can be found in Burford et al. (2016).

Intertidal mudflat primary production

A study was also conducted on intertidal mudflats to determine primary productivity rates within the Norman River Estuary during the dry season of November 2009 and during a flood event of February 2010 (Duggan et al. 2014). Using the same experimental approach as above was used; this provides a comparison of primary production before and during flooding. The Norman River is adjacent to the Flinders River, and its estuarine reaches have many similar characteristics. The study was also compared with a study of primary productivity on intertidal mudflats on the Flinders and Gilbert

Rivers (Burford and Faggotter 2021). Details of all the parameters measured, sampling methods, analysis methods and more detailed site descriptions can be found in Duggan et al. (2014).

Using the data from these studies, we identified the duration of inundation required to stimulate the primary production required to support aquatic ecosystems. We identified the timing at which primary production began to maintain or decline to determine a threshold of concern for floodplain inundation.

3.1.2 Results and Discussion

Benthic primary production rates after inundation (measured as oxygen fluxes) remained low until day five for all floodplain and salt flat samples collected from sites in the Flinders catchment (Figure 4A-E). Prior to day five, primary production was low or heterotrophic. For all treatments, primary production peaked at 17 days and either began to decrease or was maintained over the length of the incubation period. However, primary production remained high at the conclusion of the experiment, i.e., day 22 (Figure 4D). The peak on day 17 was likely to be limited by resource availability. As the algal biomass increased on the floodplain it is likely that self-shading occurred. Therefore, light may be a limiting factor during turbid conditions at the outset of floodplain inundation, or at the climax of productivity, through self-shading. This was evident from the extensive green mat that developed over the experiment. This pattern was observed in samples from all sites of the Flinders River (Figure 4A,B,D).

Within the Border Rivers floodplains, the Balonne River (Whyenbah) and Weir River (Gidi Gidi) sites had higher rates of primary production than the other sites (Figure 4C), possibly due to nutrient runoff from nearby cotton farms at these locations (pers. comm. Glenn McGregor). For this reason, these two sites are considered not representative of the response to inundation in the broader system and were not included in defining thresholds of concern.

Based on this combined data (Figure 4), we estimate that the period of inundation needed for primary productivity commences around 3 to 5 days. Maximum productivity is achieved typically around 17 days after inundation. At some sites, productivity plateaus but at other sites it decreases after this time. Due to the nature of the experiments in enclosed containers, it was not appropriate to run the experiments for longer than 3 weeks. In situ experiments would be more useful for determining longer term primary productivity rates.

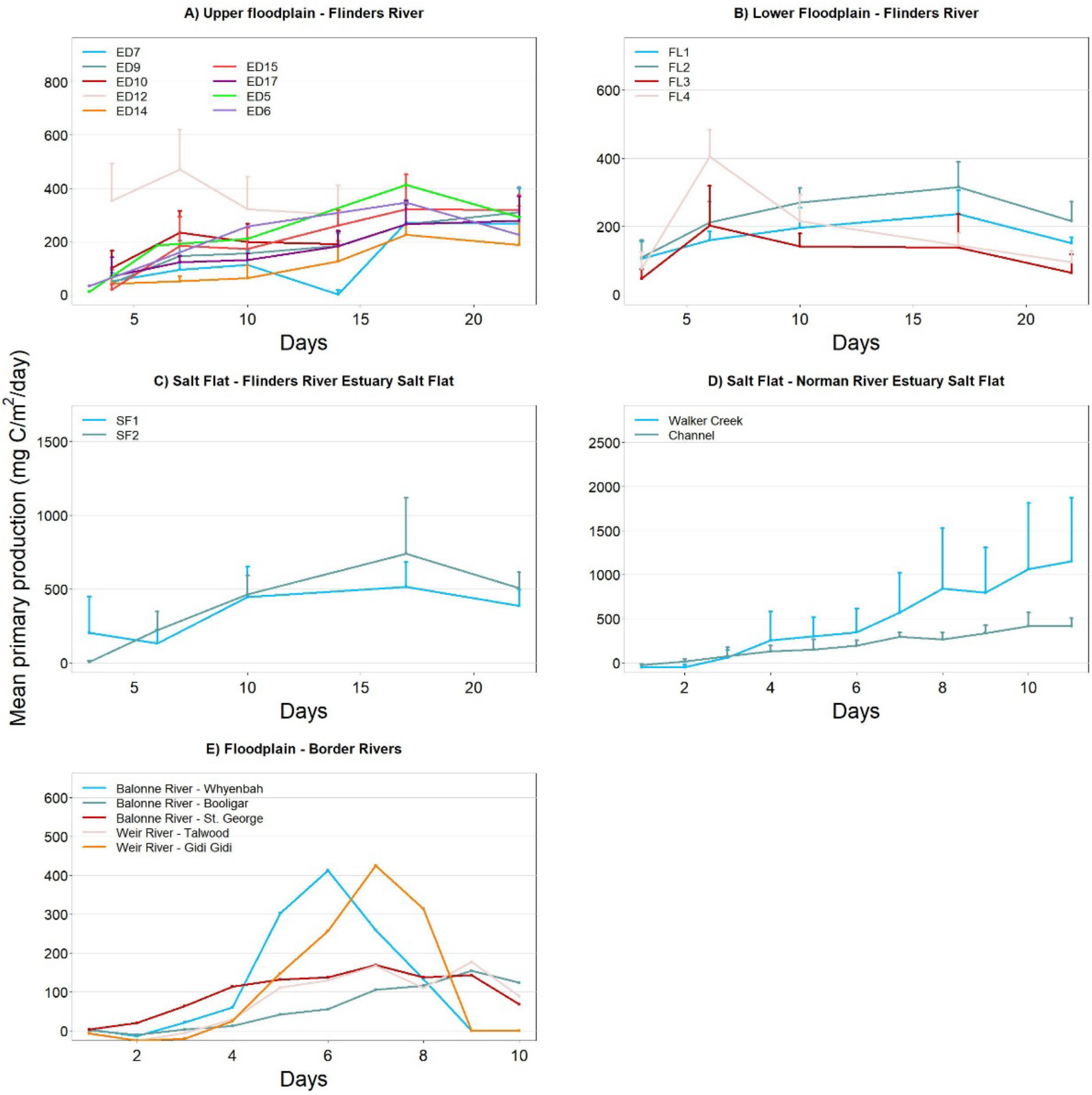


Figure 4. Mean primary production (mg C/m2/day) at 100% light on A) upstream floodplains of the Flinders River B) downstream floodplains of the Flinders River C) upstream floodplains of the Border Rivers and D) Salt flats adjacent to Flinders River Estuary B) Salt flats adjacent to Walker Creek and the main river Channel of the Norman River Estuary (June 2010) (Burford et al. 2016). Error bars are the standard deviation of the sample. Only positive error bars are shown to simplify the graphs. Note the different scales on each figure reflecting the duration of the different studies and the rates of primary production.

The extent of floodplain inundation in the Flinders River catchment was calculated by Ndehedehe et al. (2020b) for a range of flooding events. This included a maximum of 7,094.9km^2 in February 2019, receding to 808.6 km^2 8 days after the peak, and 140.3 km^2 13 days after the peak. During the 2009 flood of the Flinders River catchment, floodplain inundation was a maximum of 2,522 km^2, receding to 265.7 km^2 16 days after the peak, and 140.3 km^2 32 days after the peak (Ndehedehe et al. 2020b). Floodplain inundation has also been estimated in the Michell River for three different sized flood events, showing peak inundation of 950 km^2 in a dry year, 1,815 km^2 in an average year, and 2,620 km^2 in a wet year (Molinari et al. 2022). The analysis of Molinari et al. (2022) was derived from Karim et al. (2018) where floodplain inundation was defined as surface water depths > 10 cm and included modelled output for floods of 40 days. The patterns of inundation in these modelled outputs show that large areas of floodplains in the region can remain inundated for more than the minimum 5 days estimated as the point where primary production initiated, extending beyond the 17 days estimated as the point when primary production peaks.

A previous study by Burford et al. (2016) on the Norman River salt flats, and the experiment conducted in this study on the Flinders River salt flats, found that salt flat primary production was higher than floodplain primary production, as measured in this study. Burford et al (2016) found salt flats during periods of inundation could be significant contributors to overall primary production in coastal areas, estimating up to 377 t C annual productivity on the Norman River salt flats. They also contributed significant nutrient loads to the estuary. Burford et al (2016) also found high variability in primary production from year to year, largely driven by the magnitude and duration of inundation each wet season. The study focussed on overbank flooding, but local rainfall can also be important. Salt flats are also inundated by the highest astronomical tides but the duration of wetting during these events is likely to be insufficient to stimulate primary productivity. A previous study also measured a high abundance of glass shrimp species on the inundated floodplains, suggesting that floodplains are a significant contributor to the estuarine food web (R. Kenyon, pers. Comm.)

In related research, the intertidal mudflat primary production was studied in the Norman, Flinders, Gilbert and Mitchell River estuaries (Appendix A). Studies by Duggan et al. (2014) and Burford and Faggotter (2021) showed that primary productivity decreased during freshwater flooding but substantially increased post-flooding. Studies have also showed that Gulf estuaries are chronically nutrient-limited and that nutrient inputs from freshwater flows were critical in stimulating primary production throughout estuaries (Burford et al., 2012: Burford and Faggotter, 2021). Burford et al. (2020) also quantified the area of intertidal mudflat demonstrating that is a significant area in all these river systems and therefore an important component of the food chain for marine and other species.

Macrobenthos assemblages in the Flinders, Gilbert and Mitchell Rivers were also found to have a strong response to the reduced salinity at the onset of seasonal freshwater flow, with abundance lowest when salinity was low, and recruiting back into the system once the tidal influence was re-established (Venarsky et al. 2022; Lowe et al. 2022). Duggan et al. (2014) found similar patterns of short-term negative effects of floods on meiofauna and benthic algae (due to reduced salinity), but in the longer term (months), the stimulation of benthic algal growth increased meiofaunal abundances. Duggan et al. 2014 also found the larger the flood, the bigger the positive longer-term response. However, Lowe et al. (2022) stated the lack of detailed sampling in the wet season and early dry season, as well as over consecutive seasons presents limitations in determining when macrobenthos was most and least abundant. Despite the lack of conclusive data around macrobenthos in the longer term, the longer-term increases in abundance from meiofauna and benthic algae highlight the potential for a similar pattern for macrobenthos that would support the large numbers of migratory shorebirds.

3.1.3 Synthesis of ecohydrological findings

These patterns of primary production following floodplain and salt flat inundation demonstrate their importance particularly in terms of spatial extent and minimum duration, to stimulate primary production and nutrient release. This production initiates aquatic food webs and contributes bioavailable nutrients that support wider aquatic ecosystems within and across years. Collectively these findings lead to the following recommended ecohydrological rule:

> That flow magnitude and duration at a gauge that generates floodplain or salt flat inundation with a duration of five days or more during the wet season (with months specified according to the natural flow regime) providing an opportunity for peak primary production to occur. This requires gauge specific inundation flow thresholds.

Defining a threshold of concern for this ecohydrological rule is complicated by the many different roles that primary production plays in supporting aquatic ecosystems within and between years. While inundation for a minimum of five days will ensure peak rates of primary production area reached, longer durations within a wet season would be required for higher order consumers in the aquatic food web (i.e. macroinvertebrates, fish, and turtles) to access these basal food resources and return to dry season habitats. Given the wide array other ecological assets that this would support and the lack of ecohydrological knowledge about them, individual thresholds of concern will need to be developed by comparing pre-development flows in each river system with what would be lost under different flow use scenarios.

Implementing the ecohydrological rule

The synthesis of floodplain productivity experiments above demonstrates the duration of inundation required to stimulate primary productivity in various floodplain habitats, however, they do not identify a minimum spatial extent of inundation that would support other ecological and cultural assets. It is well established that coastal commercial fisheries in the southern gulf region are more productive when access to the floodplain is facilitated for extended periods (Stewart-Koster et al. 2021; Leahy and Robins 2021). As such, implementing the findings synthesised above also requires the establishment of river flow thresholds which can be used to predict the duration and extent of floodplain inundation (and subsequently primary production) (e.g. Ndehedehe et al. 2020a).

Relationships between river discharge and floodplain inundation and aquatic primary production have been quantified using satellite-derived inundation metrics (e.g., MNDWI, AWEI), vegetation indices (e.g. EVI, OSAVI, NDVI) and gauged river discharge data (Ndehedehe et al. 2020a; 2020b, 2021). These findings can be directly applied in assessing the impacts of different water resource development scenarios and adapted to estimate minimum annual flow thresholds needed to achieve ecologically meaningful floodplain inundation. Where available, floodplain hydrodynamic models could directly simulate the inundation extent generated under different discharge scenarios (e.g. Karim et al. 2018), similar to the approach used in the Targeted review of Water Resource (Gulf) Plan 2007 (DSITIA 2014). In the absence of such models, empirical discharge–inundation relationships could be developed (sensu Ndehedehe et al. 2021).

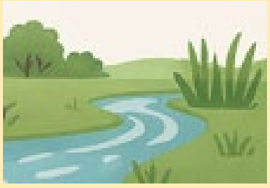
Determining the threshold of concern for the extent and duration of inundation requires an assessment of the ecological dependence on floodplain primary productivity and the roles it plays in supporting the wider ecosystem. A critical aspect of floodplain inundation is the connectivity between the major floodplain river channels and floodplain habitats, e.g. wetlands and salt flats. For instance, floodplain inundation for extended periods ensures fish species can access high quality food, leading to increased growth rates (Leahy and Robins 2021). Analyses of the connectivity of the Mitchell River floodplain under different scenarios of water resource development have shown substantial reductions in connectivity, and subsequently the amount of primary production that is available to instream food webs (Molinari et al. 2022).

Implementing these approaches would follow four general steps:

1. Identify flow thresholds of concern for inundation extents tied to ecological outcomes (e.g. different levels of inundation and primary production).
    a. A preliminary example could be the median inundation on record, as a threshold of concern for key nutrient delivery that supports floodplain and coastal ecosystems.
    b. The connectivity analyses of Molinari et al. (2022) can be applied to quantify the impact of different scenarios of water resource development on the connectivity of the floodplain and the subsequent availability of floodplain nutrients and energy to instream and coastal food webs.
2. Fit catchment-specific discharge-inundation models
    a. Use gauged river flows and satellite-derived inundation and primary production estimates, accounting for lags between measured flows and inundation.
3. Estimate the seasonal flow needed to meet the threshold of concern to determine the ecohydrological rule required
    a. Ensure uncertainty is quantified via calculation of uncertainty envelopes (e.g. confidence intervals)

While these approaches provide an empirical basis to develop ecohydrological thresholds of concern and subsequent ecohydrological rules, there are naturally limitations to the data and model outcomes. The use of remotely sensed data for wet season assessments in in tropical regions has the trade-off time series length vs time series quality. Optical data sources such as Landsat provide over 30 years of data, however, they are unable to penetrate the heavy cloud cover that persists over the southern Gulf during periods of floodplain inundation (Ndehedehe et al. 2020a). Radar satellites that can overcome the impact of cloud cover, such as Sentinel, have a much shorter time series having been launched in 2014. Additionally, whether using floodplain inundation models (e.g. Karim et al. 2018) or empirical approaches to estimate the relationship between river flow and inundation (e.g. Ndehedehe et al. 2021), there is considerable uncertainty in the relationships. These limitations do not imply the approaches should not be used, just that appropriate steps should be taken to quantify the uncertainty in the relationships and interpreted with care.

Primary Production on Floodplains, Salt Flats and Intertidal Flats



Relationship to flow: Inundation of floodplains and salt flats depends on river discharge and is critical to ensure primary production can begin, thereby fueling ecological food webs that support these ecosystems. Nutrients from flooding is critical to stimulate primary production on intertidal flats.

Potential threshold: For floodplains and salt flats, a minimum 5 days of inundation is needed, with peak primary production at day 17.

Potential threshold: For duration and extent of floodplain inundation, the median level of annual inundation on record (along with associated river discharge for that year), to ensure the duration of inundation facilitates primary production and connectivity across the floodplain.

Uncertainty: Primary productivity does increase from days 3 – 5 and while it seems to peak around day 17, the style of experiments undertaken are not suitable for longer term measurements.

The ecohydrology, including threshold of concern and ecohydrological rules for floodplain primary is presented in Appendix E.

3.2 Migratory shorebird composition and abundance

3.2.1 Technical methodology

Intertidal substrata, including sand flats and mudflats, are crucial for foraging migratory shorebirds, which feed by extracting invertebrate prey such as polychaetes and bivalves, from soft sediment. Primary producers are an important underpinning of the invertebrate resource needs of shorebirds (Lowe et al. 2022, Burford et al. 2020). Previous studies in the Gulf estuaries have shown that 1. Primary producers are nutrient limited, and 2. Nutrient loads from freshwater flows are critical to fuelling primary production (Burford and Faggotter, 2021). Therefore, species relying on primary production in and near estuaries are vulnerable to changes in flow regimes. This includes migratory shorebirds. Migratory shorebirds in the East Asian-Australasian (EAA) Flyway complete migrations from their Arctic breeding areas to their non-breeding areas in Asia and Australasia each year. The southern Gulf is a key Australian site for migratory shorebirds using the intertidal sand and mudflats for feeding on meiofauna and macrobenthos during the summer months, and during staging as they move across the flyway to sites further south in the spring, and to the north in the autumn (Burford et al. 2020).

Of the 237 global shorebird populations with trend data, 52% are in decline (Nebel et al. 2008). The Gulf of Carpentaria supports a number of the endangered and critically endangered species, including the Great and Red Knots (*Calidris tenuirostris* and *C. canutus* respectively), and the Eastern Curlew (*Numenius madagascariensis*) (CLCAC final report in Burford et al., 2021). It is also an area of international significance as it has >1% of the world's population of some species, e.g. Black-tailed Godwit *(Limosa limosa).* A range of processes are thought to contribute to population declines of shorebird along the EEA Flyway, including habitat loss and degradation (Murray et al. 2018; Zhang et al. 2018; Nebel et al. 2008). This flyway supports the highest diversity of shorebirds in the world (Zhang et al. 2018) and the Gulf of Carpentaria is an important stop-over habitat within the flyway (Milton and Driscoll 2007). Many shorebird species utilize just one or two fuelling stops along the flyway prior to their northward migration to their Arctic breeding grounds (Driscoll 1997, 2001).

During previous NESP research, a migratory shorebird survey was conducted by the Queensland Wader Study Group (QWSG; a non-government organization) in collaboration with the Carpentaria Land Council Aboriginal Corporation (CLCAC) in the river mouths and nearshore zones of the Mitchell, Flinders and Gilbert Rivers (Burford et al. 2020). Low tide counts were conducted in March 2019, which aimed to give full coverage of bird feeding sites near the estuary mouths and up into the estuaries. We can assume a high level of site fidelity for individual birds as a previous study of the same or similar migratory shorebirds in Moreton Bay, where birds had satellite trackers, showed that birds typically kept to the same feeding and roosting areas unless there was significant disturbance (Bush et al. 2022). This means that estimates of bird numbers within sites are relatively conservative. Details of all the study sites and survey methods can be found in Burford et al. (2020). Here we examine the data collected by Burford et al. (2020) in the context of previous surveys and assessments, to inform quantitative estimates of feeding requirements and carrying capacity of foraging habitats of shorebirds in the plan area.

Results and Discussion

The study was conducted in March to capture shorebirds migrating north through the flyway to arctic regions. The Gulf of Carpentaria is considered a key staging site for birds from southern Australia who spend some time increasing their body mass prior to flying onwards (Milton and Driscoll 2006). The Gulf is also considered important for the southward migration in spring, but shorebird data was not available that coincided with the measures of macrobenthic density.

A number of species identified were endangered or vulnerable or near threatened (Figure 5). The Black-tailed Godwit (near threatened) was the most abundant species across all sites in March (Burford et al. 2021) (Figure 5). This is consistent with Milton and Driscoll's (2006) findings, as well as data collected by the Queensland Wader Study Group and the CLCAC Rangers from 1998–2020 (Burford et al. 2020). Thus, these studies identify the Gulf of Carpentaria as the region in Australia where the Black-tailed Godwit is most abundant. The population in Queensland makes up 34% of the international EAAF population (Milton and Driscoll, 2007). Rogers et al. (2023) applied the IUCN red list assessment criteria to migratory shorebird counts (2020) and examined population trends from 28 years of shorebird monitoring data, classifying the Black-tailed Godwit (and the Curlew Sandpiper, *Calidris ferruginea*) as endangered.

Other abundant shorebird species in the Burford et al. (2021) study included the Red-necked Stint (*Calidris ruficollis*) (near threatened), and the Great Knot (Endangered) (Figure 5). Other common species considered endangered were the Eastern Curlew and the Lesser Sandplover (*Anarhynchus mongolus*, now renamed the Siberian Sandplover) (IUCN 2025).

Burford et al. (2021) compared the maximum number of each bird species from this survey (2019-2020) with historic surveys 1998–2015, and found similar species (Black-tailed Godwit, Great Knot) being consistently the most abundant. There was a decline in local abundances of many species compared with historical data (Murray et al. 2018; Zhang et al. 2018; Nebel et al. 2008). This is purported to be due to the human pressures on populations documented throughout Asia. This included substantial declines in Bar-tailed Godwit, Red-necked Stint and Greater Sand Plover numbers compared to historical 1998–2015 counts (Burford et al. 2021). There are some caveats to consider when comparing surveys: these include possible underestimation of smaller species due to difficulties identifying species from a distance, as well as short-term events (cyclones, floods, variations in tide height) that can temporarily impact the use of habitat by birds (Burford et al. 2021). Understanding and maintaining a healthy ecosystem with the abundance of preferred food sources being important for migratory shorebird conservation, as is understanding the relationship between food and freshwater flow (Zhang et al. 2018).

Overall the estuaries in the Gulf of Carpentaria, including the Flinders, Gilbert and Mitchell River estuaries are important sites for these internationally significant species. They use the Gulf as a staging site in spring and autumn, with some resident species over the austral summer. The exact proportion of species at these different times is unknown. Given these pressures internationally along the flyway, it is important that there are no additional human pressures placed on this species with Australia. This is also consistent with Australia's international obligations via agreements such as the Ramsar convention. Therefore, a reduction in food availability, as a result of reduced freshwater flow and associated nutrients, constitutes a risk to the fitness of these species.

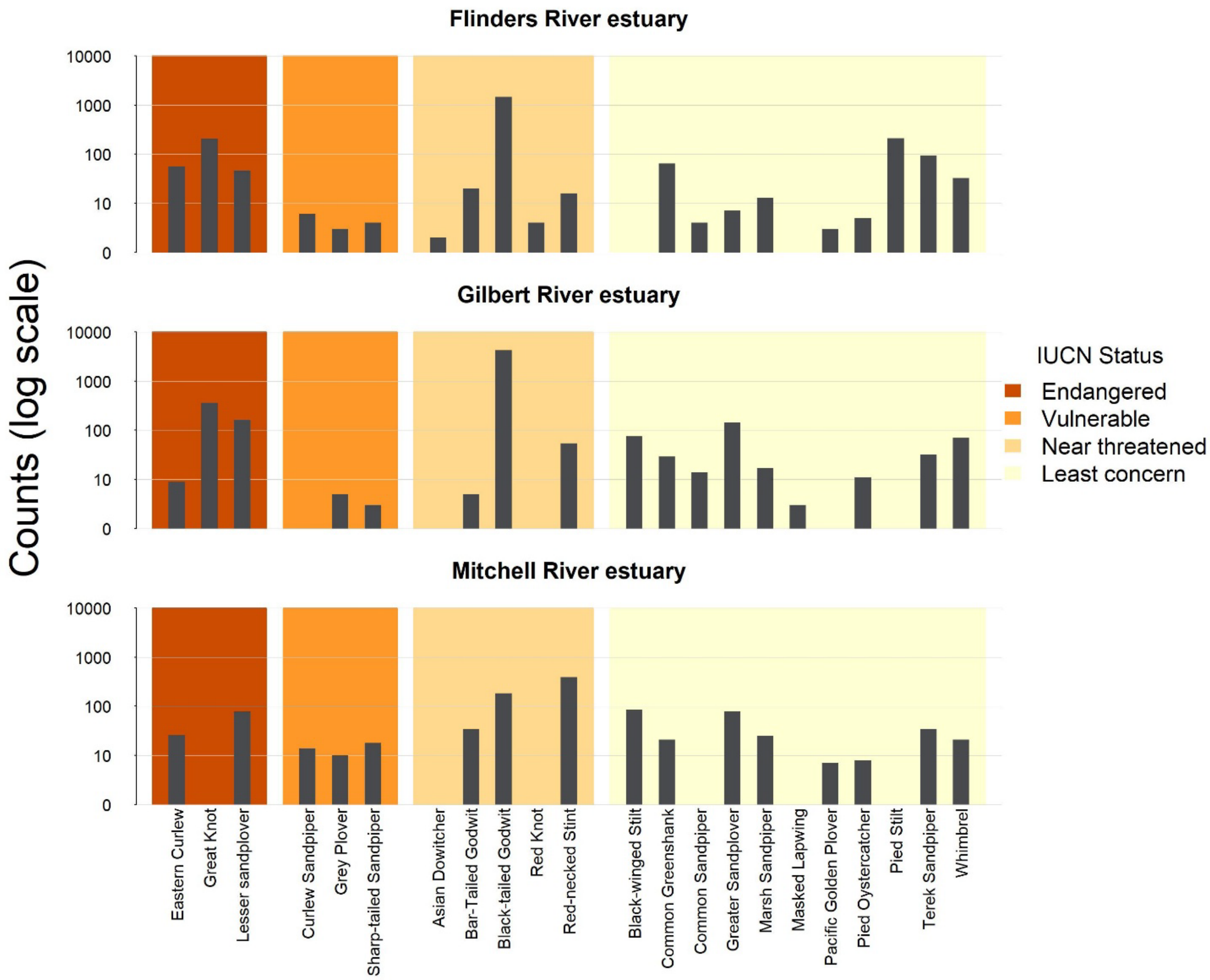


Figure 5. Bird count (abundance) of each species at each site (estuarine and nearshore combined) based on the Burford et al., (2020) study, grouped into International Union for the Conservation of Nature (IUCN) red list conservation status of endangered, vulnerable, near threatened and least concern.

Food requirements of migratory shorebirds

3.3.1 Technical Methodology

In order to determine the carrying capacity of the sand flats and mudflats for the feeding requirements of the shorebirds, the following data was used:1. bird abundances from surveys (see above), 2. areal extent of feeding habitats near river mouths, 3. data on the energetic needs of the different shorebird species, and 4. with data on the macrobenthos food availability.

Data on the bird abundances (Figure 4) was divided by data on the areal extent of usable feeding habitats within and adjacent to each estuary (Burford et al., 2020) in order to determine the areal density of birds. To determine the energetic needs of the shorebirds, a Daily Ration Model calculating digestible energy requirements (outlined below) was used. A Daily Ration Model is determined using the Basal Metabolic Rate (BMR), which is calculated based on body mass) to estimate daily digestible energy requirements for different feeding periods. This is a simplistic approach to estimating carrying capacity of an area based on the total amount of available food and the energy requirements of an average individual animal (Choi et al. 2017). Due to its simplicity, several assumptions exist, including that all individuals in a population are similarly sized with similar foraging skills (Choi et al. 2017).

The BMR was estimated using the allometric relationship between BMR (in watts) and body mass established by Kersten et al. (1998) for non-breeding migratory shorebirds in tropical climates:

$$BMR(W) = 4.02 \times M \times 0.724$$

Where M is average body mass in kilograms.

It is reasonable to apply this relationship in the Gulf Rivers because when body mass was accounted for, breeding origin had no significant effect on BMR for all species, and there was no significant difference in BMR between species (Kersten et al. 1998). Additionally, Kersten et al. (1998) used the same species or similar of migratory shorebirds found in the Gulf of Carpentaria to establish the allometric relationship between BMR and body mass.

Birds were assumed to expend no energy on thermoregulation (thermal neutral conditions) as described by Kersten et al. 1998 for migratory shorebirds in tropical environments. Therefore, during periods of regular feeding, shorebird daily Digestible Energy Requirements (DER) were twice their BMR (Piersma 2002; Choi et al. 2017). During periods of greater feeding prior to migration (fuel deposition), we assumed DER were 4.5 times higher than BMR (Piersma 2002; Choi et al. 2017). We assumed the fuel deposition period coincided with March sampling, which is just prior to their migration to the northern hemisphere.

Average body mass of shorebirds for the Gulf of Carpentaria was not available, so we used the average body mass of the same species caught elsewhere in tropical Queensland at similar times of the year (Choi et al., 2017).

The mean daily energy requirements of shorebirds at all sites were much higher in March compared to December, corresponding to the higher energy demands of their pre-migration fattening period March to May (Table 1). Estimates of daily energy requirements for each species are listed in Appendix B.

Table 1. Mean daily energy requirements (kJ/m2) of shorebirds in the estuarine and nearshore of the three catchments in the (high feeding period prior to migration). This was based on collected shorebird density data, considering the proportion of different species, and daily energy requirements per animal.

Sampling Date	Mitchell	Gilbert	Flinders
March 2019	0.0012	0.0037	0.0048

We combined the results of the daily ration model with estimates of available food to estimate the carrying capacity of Gulf Rivers.

3.3.2 Food available for migratory shorebirds - Macrobenthos

Shorebirds feed on a variety of benthic animals. To determine the availability of macrobenthos on and in intertidal mudflats and nearshore sandflats, sampling was conducted in and around the estuaries of the Mitchell, Gilbert and Flinders Rivers (Venarsky et al. 2022; Lowe et al. 2022). Standard sampling and sorting methods were used to identify individuals to the lowest practical taxonomic level (usually family). Details of all the parameters measured, sampling methods, analysis methods and more detailed site descriptions can be found in Venarsky et al. (2022) and Lowe et al. (2022).

Food availability for migratory shorebirds was calculated from these benthic samples. Typically, ash-free dry mass (AFDM) was used in calculating food availability as it more accurately measures the digestible component of a prey item. This is particularly the case for molluscs which lay down new shell layers each year, increasing the weight of the non-digestible shell (Coughlan et al. 2021). Nonetheless, dry weight (DW), rather than AFDW is currently available from Venarsky et al. (2022) and Lowe et al. (2022) so this was used to estimate gross energy content (kJ) of 22 kJ/g for bivalves and 21.48 kJ/g for all other taxa). This was then converted to digestible energy content by assuming an assimilation efficiency of 0.8 as stated in Choi et al. (2017).

3.3.3 Results and Discussion

Studies in Gulf estuaries have shown that freshwater flows temporarily reduce macrobenthos densities, due to the low salinity, but post-flooding, the nutrients transported to estuaries and the nearshore are critical to stimulating primary producers, which are the food supply for macrobenthos. As a result, macrobenthos densities rapidly increase post-flooding (Burford and Faggotter, 2021, Lowe et al. 2022). The highest abundance of birds in the Gulf is before and after the wet season, as they migrate north (Burford et al., 2021). Therefore, this coincides with periods when macrobenthos densities are highest.

The energetic carrying capacity for migratory shorebirds (the ratio of digestible energy available to digestible energy required) was greater than one in all sites, where sampling of macrobenthos and migratory shorebird surveys coincided (Table 2). This suggests that during periods where food is needed for fattening prior to migration (March) there was a higher carrying capacity than current usage, not considering prey specialization. Based on these calculations, it was estimated that there is more food available than needed by migratory shorebirds at the time of the surveys, however the food needs of other species consuming macrobenthos (e.g. prawns, crabs, fish) are not considered. More data is needed on shorebirds and other species in estuaries to gain a more holistic estimate of food availability, but this study makes a first attempt at this comparison.

Table 2. The total estimated digestible energy required by migratory shorebirds over three months, and the digestible energy content available in the estuarine mud flat and nearshore sand flat (combined) of the Gilbert River (March 2019) and the Mitchell River (March 2019 and November 2019).

Estuary site	**Sampling Date**	**Digestible energy required (kJ per m²)**	**Digestible energy content available (kJ per m²)**	**Energetic carrying capacity (per m²)**
Gilbert River	March 2019	0.33	359.35	1,089
Mitchell River	March 2019	0.11	15.12	137
Flinders River	March 2019	0.43	83.86	195

There are some limitations to the conclusions that can be drawn from these initial estimates since dry weight (not ash free dry weight) was recorded for macrobenthos, thus overestimating the digestible energy content of macrobenthos.

3.3.4 Synthesis of ecohydrological findings

The uncertainty associated with the estimates of shorebird density, food availability, and shorebird food requirements prevent the derivation of specific thresholds of concern. Nonetheless, shorebird feeding is an ecosystem value supported by coastal productivity and annual high flows and during the wet season provides the nutrients necessary to support high levels of coastal productivity. Therefore, reduced flooding and wet seasons flows, leading to reduced nutrient delivery, would threaten shore bird food requirements. As this reflects the inter-annual wet-dry pattern of hydrology, this would likely be more of an annual to interannual pressure on shorebird populations given the long-term benefits to bird food from flooding.

Migratory Shore Birds

Relationship to flow: There is a relationship between flow and feeding habitat/food at key points of bird migration, underpinned by primary production.

Potential threshold: Cannot identify a specific threshold. However, flow does affect feeding habitat, there is abundant food (more than in other similar areas) and bird species are of international significance.

Uncertainty: There is inherent uncertainty in bird counts and carrying capacity estimates, however, the importance of the region to these species is very clear.

Fish assemblage structure and connectivity

3.4.1 Technical Methodology

In the Gulf of Carpentaria, freshwater flow regimes can influence fish species composition and abundance by mediating habitat availability, connectivity and food availability, with some fish species also requiring flow for reproductive migration (Broadley et al. 2022, Leahy and Robins 2021, O'Mara et al. 2021, Stewart-Koster et al. 2021, Broadley et al. 2020). The Mitchell River flows into the Gulf of Carpentaria, with its major tributaries including the Walsh, Lynd, Alice, and Palmer Rivers (O'Mara et al. 2021). The main channel of the Mitchell River experiences perennial flow most years, while the Palmer and Walsh tributaries frequently experience no flow conditions during the dry season from May to October (O'Mara et al. 2021). The Mitchell River catchment has a high diversity of fish (46 recorded species), many of which move between habitats within the catchment, as well as mostly unmodified flow and few barriers to fish movement (O'Mara et al. 2021; Jardine et al. 2017; Marshall 2016). The Mitchell River flows to the Gulf of Carpentaria and is subject to the same climate and rainfall conditions as the rivers located in the Gulf Water Plan, however, it generally has more sustained flow and more floodplain wetlands.

Here we synthesised data collected in previous NESP research between 2017 and 2018 on the age structure of fish assemblages in the Mitchell River Catchment, including the relationships between age structure and hydrological connectivity (Stewart-Koster et al. 2021). Fish collection sites from this previous research were distributed throughout the Mitchell River catchment, encompassing a range of habitat types and hydrological characteristics—including river channels, floodplain creeks, and wetlands—that become hydrologically connected during the wet season. (O'Mara et al. 2021). Sampling was restricted to the late wet/early dry (June to July) period due to accessibility limitations at other times. Boat or backpack electrofishing was used to collect fish, targeting whole fish communities and habitat types. Weight and standard length were recorded for each fish collected, and a subset was aged via otoliths. For further details on fish sampling and sampling sites, see O'Mara et al. (2021) and Stewart-Koster et al. (2021).

Sagittal otoliths were dissected in the field, cleaned, and stored in paper envelopes to dry. The otolith sections were aged by counting annual opaque increments using digital microscopy. Annual growth increments were identified as alternating opaque and translucent bands, with each pair representing one year of growth. Ages were assigned by counting the number of opaque zones along the axis from the primordium to the proximal edge adjacent to the sulcus (for samples in which a sulcus was clearly visible). Each otolith was aged without prior knowledge of fish size or capture date to minimize bias.

Age-length relationships

Von Bertalanffy growth models (VBGMs) were used to quantify the relationship between age and fish length for the subset of fish where age was measured (n=754). These relationships for each fish species were then applied to fish length data for all fish collected and analysed in O'Mara et al. (2021) to estimate the age of all individuals sampled. The VBGM was used to predict mean length at age (Lt) (Wright et al. 2020; Ogle and Isermann 2017; von Bertalanffy 1938):

$$L_t = L_{inf}\left(1 - e - K(t - t_0)\right)$$

Where L_t is the expected length at age t, L_{inf} is the maximum length an individual could obtain, K is the Brody growth coefficient, t is age, and t_0 is the theoretical age when the average length is zero.

See Appendix C for VBGM coefficients of each fish species.

An inverse VBGM (Mackay and Moreau 1990) was then used to predict age at length:

$$t_L = -1/K \times \ln\left(1 - L/L_{inf}\right) + t_0$$

Where t_L is expected age at length, and all other parameters are the same as the VBGM, above (Figure 7A).

For species where no age-length relationship could be developed due to small sample size, measured age was used from those fish in the aged subset in subsequent fish assemblage analyses. For larger fish, such as older individuals of the various catfish species, the VMGMs consistently under-predicted their age (Figure 7B). This was apparent when comparing modelled and measured ages for these individuals. To overcome this systematic bias, a revised estimated age was applied for these older fish, where measured age was used instead of age calculated by inverse VBGMs and for individuals without a measured age, the measured age of a fish of similar size (both weight and length) of the same species was used.

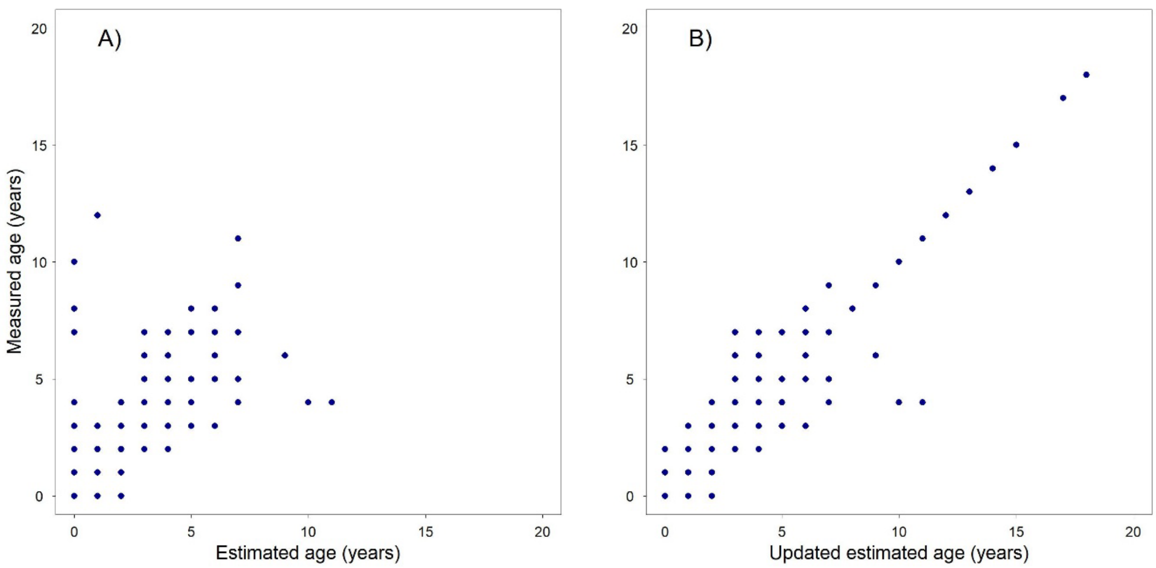


Figure 6. A) Estimated fish age in years, calculated by inverse VBGMs, against measured fish age showing goodness of fit for fish captured in the Mitchell River in June and July 2017 and 2018. B) Updated fish ages, where estimated ages for large fish that were systematically under-estimated by the VBGMs were replaced with measured ages.

3.4.3 Connectivity

O'Mara et al. (2021) created a site connectivity index (connectivity of a site to the rest of the river network) for the Mitchell River catchment over a 15-year period, calculated as pairwise proportions of days that flow was above the passable depth at each of the gauges the fish needed to pass to reach the second gauge in the pair. A value of one was assigned for days where all gauges in the connection pathway between a pair of sites were above the 10 cm flow depth (visible pass flow). A value of zero was assigned for days where one or more gauges in the connection pathway had flow below the 10 cm flow depth. A connectivity index for 1 year and 4 years prior to fish sampling was calculated in this study by adapting the methodology from O'Mara et al. 2021. A cost function was added to account for fish swimming in an upstream direction compared to downstream (Watson et al. 2019). These 1 year and 4-year increments provided an estimate of conditions during the most recent wet season before sampling and the wet seasons over the average lifespan of many species in the catchment. This study used gauge flow data from the Queensland Government Water Monitoring Information Portal, whereas O'Mara et al. 2021 used modelled flow data.

We used the estimated ages of all fish caught across the catchment to quantify the age structure of the assemblages at each site, calculating mean age, kurtosis and skewness of the age distribution across the catchment in relation to connectivity.

3.4.4 Results and discussion

Across the entire assemblages of the Mitchell River, age frequency histograms show most fish were less than four years old, with few fish older than six years old (Figure 8). Additionally, more fish were caught in tributary sites than channel sites for fish four years and younger, while the numbers of fish older than four were mixed between channel and tributary sites (Figure 8). The three sites with the highest connectivity index for both one year and four years prior to sampling were all main channel sites in the Mitchell River, whereas the three sites with the lowest connectivity index one year and four years prior to sampling were all tributary sites (Table 3).

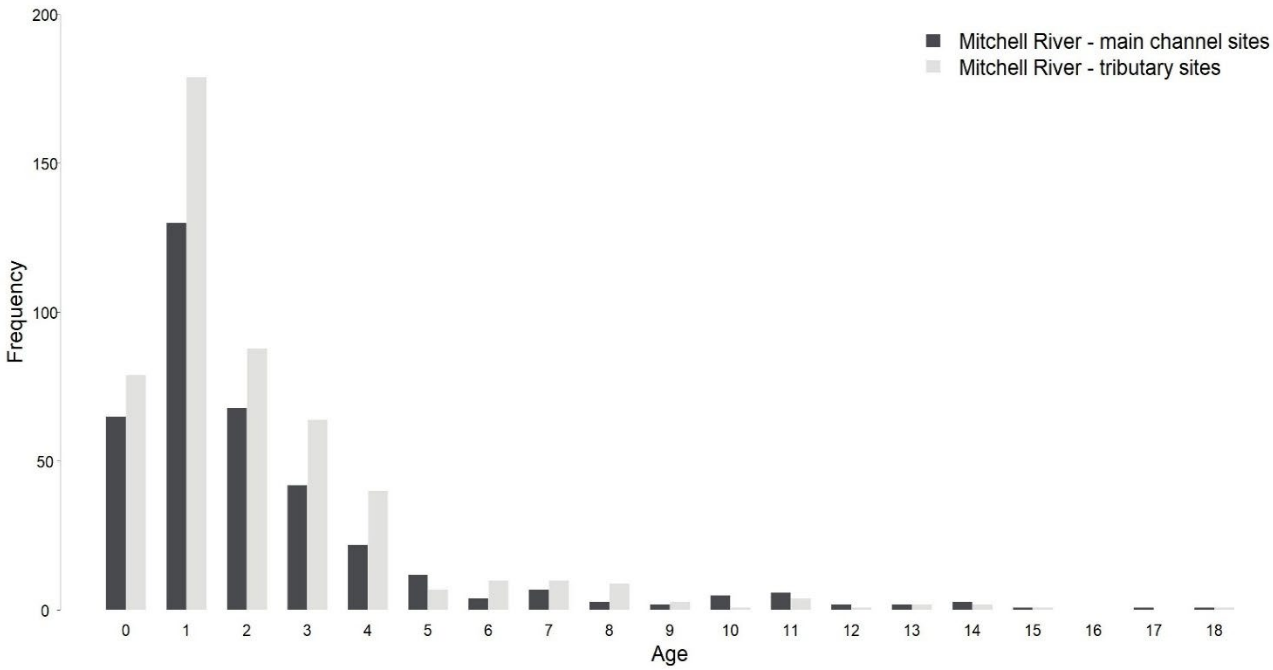


Figure 7. Age frequency histogram of fish captured in the Mitchell River channel and tributary sites in June and July 2017 and 2018. Tributary sites refer to sites in the Palmer, Walsh and Alice Rivers. Age is in years.

Table 3. Mean age (estimated from inverse VBGMs), standard deviation and connectivity index for each site.

	Category	Mean age	Standard deviation	Connectivity index 1 year prior to sampling	Connectivity index 4 years prior to sampling
12 Mile Lagoon (9190073)	Disconnected lagoon	1.674	2.684	0.000	0.000
Walsh River D/S junction with Bulluburrah Creek (9193028)	Tributary	2.167	2.768	0.167	0.173
Palmer River at Maytown (919205a)	Tributary	1.467	1.290	0.231	0.238
Mitchell River U/S of Hurricane Station (9190015)	Channel	2.302	3.111	0.247	0.137
Palmer River D/S of Fern Hill Bend (9192008)	Tributary	2.020	2.025	0.325	0.336
Walsh R at Picnic hole (9193022)	Tributary	2.533	2.677	0.327	0.330
Walsh River D/S (9193014)	Tributary	2.014	2.148	0.491	0.481
Mitchell R @ Gordon Arthur Crossing (9190011)	Channel	1.395	2.259	0.647	0.605
Palmer River D/S of GS (919203A)	Tributary	3.096	3.351	0.736	0.708
Walsh River at Trimbles Crossing (919309a)	Tributary	1.633	1.098	0.839	0.800
Mitchell River at Hughes Crossing (9190035)	Channel	3.083	3.792	1.043	0.993
Mitchell River at Gamboola (9190010)	Channel	2.319	2.503	1.056	1.001
Mitchell River at Koolatah Crossing (9190043)	Channel	1.935	1.937	1.521	1.449

No significant relationship was found between connectivity index at a site and the average age of the fish assemblage (Figure 9A and B). However, there was a relationship between connectivity and kurtosis of the age structure distribution of the fish assemblages, as well as connectivity and skewness of the age structure distribution, with increasing as connectivity increased for both one year and four years prior to sampling (Figure 9C-F). Kurtosis and skewness both describe the shape of a distribution, identifying the length of the tails of the distribution. A site where the age structure distribution has higher values of kurtosis and skewness is likely to have a greater spread of fish ages relative to its average, meaning it will have a larger number of older individuals, and these assemblages generally occurred in sites with higher connectivity. Examples of this can be seen in Figure 10, where several sites were selected to demonstrate how the spread of fish ages differs between sites with low and high connectivity.

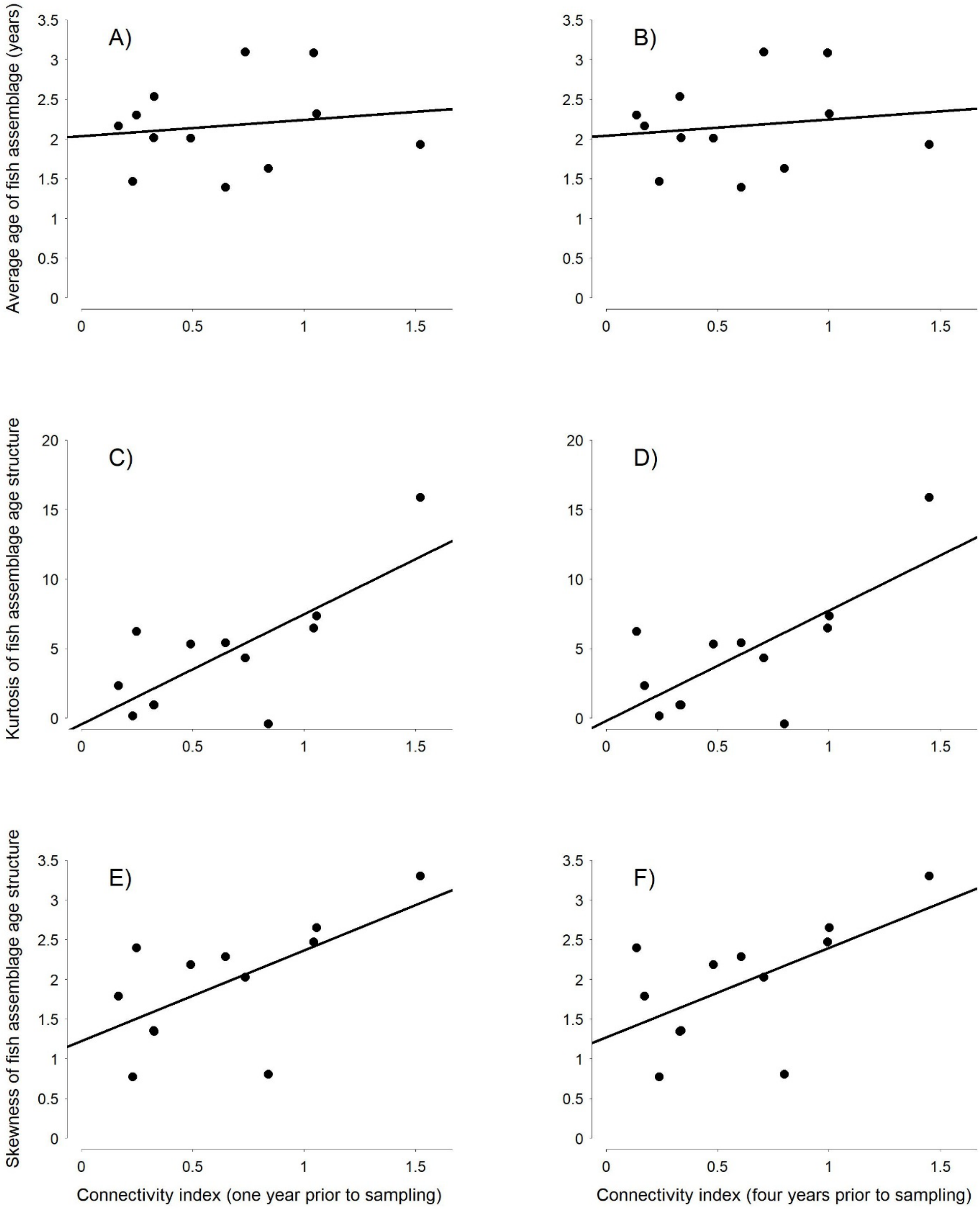


Figure 8. The connectivity index, modified from O'Mara et al. 2021, calculated for 1 year and 4 years prior to fish sampling (June and July 2017) against plotted against kurtosis of estimated age, skewness of estimated age, and mean estimated age.

Although there are location specific differences, the sites in Figure 10 are examples of no, low, moderate and high connectivity. Lower connectivity sites (12 Mile Lagoon with no connectivity, and Palmer River at Maytown with low connectivity of 0.2) are dominated by fish that are two years old and younger, with relatively few older fish. Both mid-level and high connectivity sites (Walsh River D/S 9193014 connectivity 0.5, Mitchell River at Hughes Crossing connectivity 1) have a broader range of fish ages and more older fish than the no or low connectivity sites, although are still dominated by younger fish.

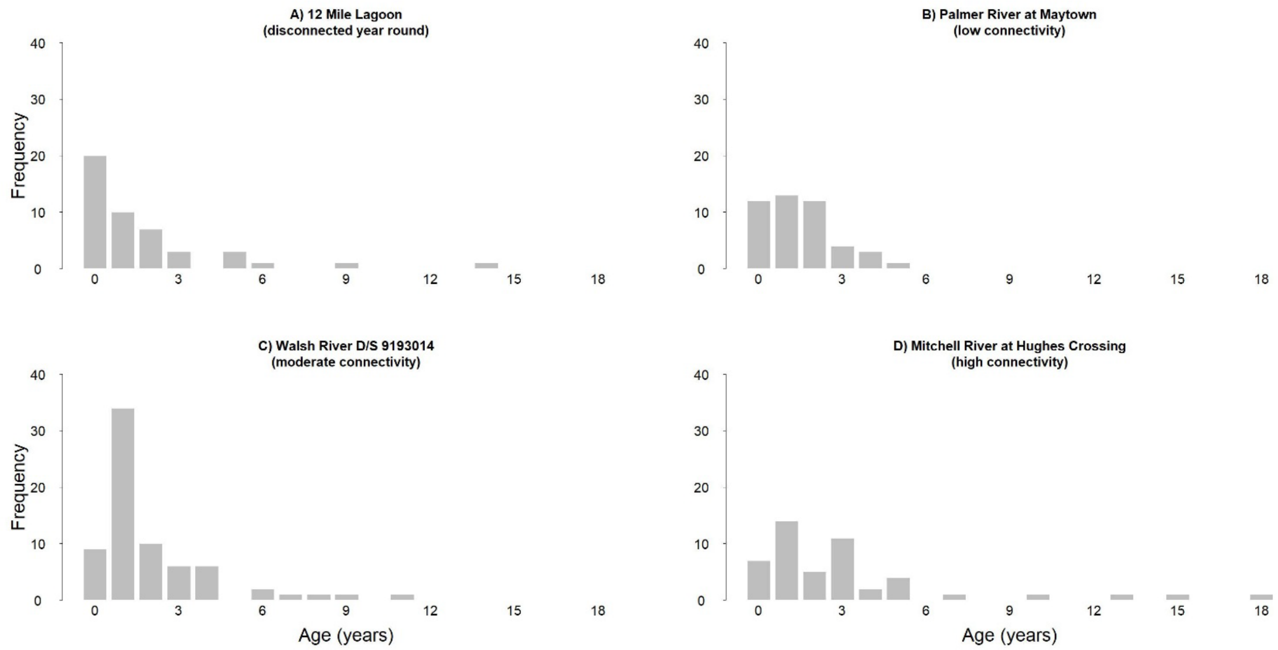


Figure 9. Age frequency histograms of fish collected from Mitchell River sites - example sites of A) a disconnected (no connectivity), B) low connectivity (0.2), C) mid-level connectivity (0.5) and D) high connectivity (1).

Connectivity within the main river channels and to surrounding habitats in tributaries and floodplains is important for fish species to be able to move for reproductive migrations, recruitment, access to food resources and migration to nursery habitats (O'Mara et. al. 2021; Stewart-Koster et al. 2021). The results from these analyses build on those of O'Mara et. al. (2021) who found that as connectivity decreased, the percentage of migrants at the same site also decreased (Figure 11). With a population age structure made up of many young and few old fish in the Mitchell River, fewer migrants to a site with decreased connectivity could result in older fish dying off if connectivity, and therefore migration, were to be reduced. This is consistent with what is seen in 12 Mile Lagoon. At this site, most fish are two years or younger with only two fish older than six years old, a northern saratoga (*Scleropages jardinii*) aged nine and a salmon catfish (*Neoarius graeffei*) aged 14 (Appendix D). The younger fish are mainly comprised of smaller bodied fish species, such as Rainbow fish, Glass fish, Fly-specked hardy head and Mouth almighty (Appendix D).

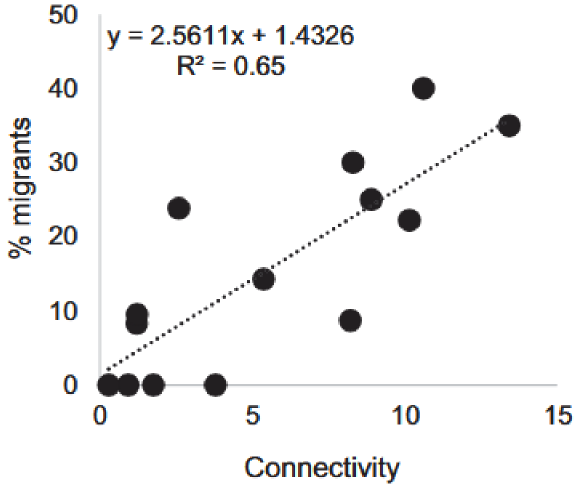


Figure 10. Relationship between river channel site connectivity and percentage of migrants at the same site (from O'Mara et al. 2021).

A provenance study of these same individuals, based on otolith microchemistry found that most fish made at least one large-scale movement in their lifetime, to access different parts of the catchment (Stewart-Koster et al. 2021). Across the catchment, most fish captured were found to be born in a different location to their capture site (Stewart-Koster et al. 2021), with the Mitchell River main channel found to be an important source location for fish caught in all sub-catchments (Figure 12). Having perennial flow most years, the Mitchell River main channel has been shown to have a strong relationship between connectivity and fish recruitment, as well as being an important site where fish are born (O'Mara et al. 2021; Stewart-Koster et al. 2021), supporting the finding that main channel sites were the sites with highest connectivity in both the 1 year and 4 year periods we examined (Table 3).

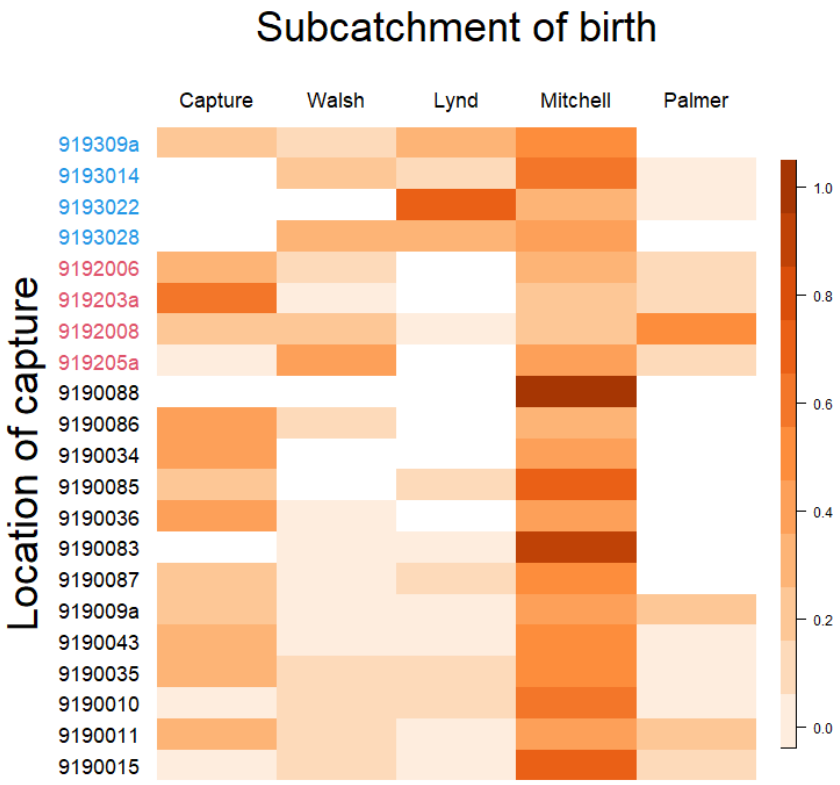


Figure 11. Heat map of predicted sub-catchment of birth of fish sampled across the Mitchell River catchment. Rows indicate site of fish capture and columns are major sub-catchments. The darkest colour in each row indicates the sub-catchment where the highest proportion of fish were predicted to have been born. Site codes in black are on the Mitchell River main channel, sites in red are on the Palmer River and sites in blue are on the Walsh River. From Stewart-Koster et al. (2021).

3.4.5 Synthesis of ecohydrological findings

The movement of fish in all parts of the catchment plays a critical role in maintaining the instream biodiversity of the Mitchell River. Collectively, these ecological patterns of connectivity and fish movement, and connectivity and age structure, suggest that changes to the flow regime that subsequently impact connectivity will affect this biodiversity. Given the typical age structure of the instream fish populations being dominated by fish that are four years and under, with highly connected locations both providing recruits to the rest of the system and supporting older fish, altered hydrological conditions that reduce connectivity for extended periods (e.g. three years or more), would likely result in diminished fish assemblages and populations that are dominated by younger, smaller bodied fish species recruited locally, with migratory and older, larger bodied fish species at risk of local extirpation. These larger bodied fish include critical fishery species, such as catfish and barramundi. This is due to the catchment wide population and assemblage turn over that occurs within 4 years, providing a maximum time frame for recruitment and dispersal processes to maintain ecosystem structure. As such, we would expect a loss of assemblage structure in a site that failed to connect for more than 1 in each 3 years.

Collectively, these findings lead to the following recommended ecohydrological rule, and thresholds of concern:

Ecohydrological rule: Ensure hydrological connection that allows fish movement between the main channel and major tributaries.

Thresholds of concern:

1) One wet season without connection between the main channel and major tributaries for a sufficient duration to allow for fish migration (low risk)
2) One to two consecutive wet seasons without connection between the main channel and major tributaries for a sufficient duration to allow for fish migration (medium risk)
3) Three or more consecutive wet seasons without connection between the main channel and major tributaries for a sufficient duration to allow for fish migration (high risk)

Implementing the ecohydrological rule

The importance of hydrological connectivity to fish movement and the age structure of fish assemblages shows the importance of catchment scale perspective in implementing the ecohydrological rules for fish assemblages. Several steps are required to implement the ecohydrological rule in each catchment:

1. Define the 'main channel' within the catchment or sub-catchment
    a. In the Mitchell River catchment, this would be the Mitchell River itself based on the fish provenance results in Figure 12, as well as hydrological analyses that show it is the only perennial flowing river within the catchment.
2. Calculate the distance between each flow gauge and its nearest main channel
3. Estimate the minimum duration of connection required to facilitate fish movement between the main channel and the sub-catchment represented by each flow gauge
    a. A fish movement estimate of 20 km/day (Tim Marsden, pers comm.)
    b. Estimate the flow required to maintain sufficient depth between the flow gauge and the main channel with the assumption being at least 20cm above the flow gauge to be sufficient.
    c. Calculate the duration above the flow required for fish to move to each flow gauge from the main channel, based on the rules determined in 3a and 3b,

From these steps, it is then possible to determine the annual frequency each river gauge has met the requirements over the duration of the historical flow record, which would help refine the ecohydrological rules. It is also possible to analyse the frequency with which the ecohydrological rules would be met in each sub-catchment under different water resource development scenarios.

Defining whether an entire catchment has met the ecohydrological rule for a given year (or a given 3-year sequence for the high-risk ToC) would then depend on the extent to which each of its sub-catchments have met it. A heuristic estimate for a catchment-scale assessment could be that at least half of the sub-catchments meet the high-risk ToC for a given three-year sequence. This could then be accumulated over the period of record under different water resource scenarios to estimate the long-term impact on fish assemblages under the scenario.

Fish Assemblage

Relationship to flow: Flow impacts connectivity between habitats/sites and subsequently fish movement patterns and assemblage structure.

Potential threshold: loss of assemblage structure in a site that failed to connect for more than 1 in each 3 years, and that year-to-year connectivity may be required.

Uncertainty: The Mitchell River, which is the source of this research has a more consistent flow interannually and a more extended flow each year than other rivers in the Gulf Water Plan Area. Therefore, the period of connectivity and the availability of wetlands is greater compared to the Gilbert and Flinders. Nonetheless, the broadly consistent wet-dry tropical hydrology is likely to lead to similar migratory patterns

The ecohydrology, including threshold of concern and ecohydrological rules for fish assemblage structure is presented in Appendix F.

4 Conclusion

Collectively the findings in this synthesis were used to determine ecohydrological dependencies and thresholds of concern for key ecological assets for implementation in assessing current and future water resource development in the Gulf of Carpentaria. These provide a scientific basis for management strategies that aim to sustain these assets. While they have been derived from across the region, they are broadly applicable to the Southern Gulf, given the similar hydrological and ecological patterns observed in the systems.

The Queensland water planning risk assessment process is based around identifying ecohydrological requirements and thresholds of concern for flow alteration of ecological assets within specified water plan areas (McGregor et al. 2018). These are derived from best available flow-ecology research; however, such research may not have been conducted within the water plan area itself. In such cases, synthesis of flow-ecology relationships from nearby, or similar, ecosystems can provide the basis for the thresholds. While this ensures ecological knowledge is not ignored for important ecological assets, there will be some degree of uncertainty associated with such synthesis. In this report we have derived ecohydrological requirements and thresholds of concern for key ecological assets in the Gulf Water Plan area based on research conducted within the water plan area itself, in the neighbouring Mitchell River catchment and from ecosystems across wider Queensland.

Transferring knowledge from nearby systems is a common practice in environmental risk assessment as necessary research is not always available in locations under management. In such cases it is critical to manage the uncertainty that this can introduce. This can come from at least two sources including uncertainty in the relationships of the underlying research and uncertainty from the differences between the system under management and that where the research had been conducted. The first of these can be addressed by thorough integration and quantification of the uncertainty in the models. An example of that from this report is the inclusion of confidence intervals around all regression relationships and analyses of one and four years of connectivity with metrics of fish age structure. The second source of uncertainty can be addressed qualitatively by focusing on species (or congeners) that co-occur in the focal catchments and/or using knowledge from hydrologically similar systems. An additional step to address the second source of uncertainty is to define the confidence around the evidence supporting the risk assessment, which is a critical step in the process (McGregor et al. 2018). With these steps in place, the knowledge synthesised in this report provides a robust basis for determining environmental flow guidelines based on key thresholds of concern across the ecosystems.

Appendix A: Collation of Gulf of Carpentaria Primary Production measurements

Summary of mean primary production across multiple Gulf of Carpentaria estuaries and multiple sampling times for intertidal mudflat microphytobenthos, including available primary production estimates of water column phytoplankton for completeness (though phytoplankton was not included in the derivation of the ecohydrological rules). Source: Burford and Faggotter (2021); Molinari et al. (2021); Duggan et al. (2014).

Primary production	Wet season mg C/m²/day	Dry season mg C/m²/day	Source
Supratidal (Salt flat)			
Norman river estuary - Channel site day 1-4	47.58		Burford et al (2016)
Norman river estuary - Channel site day 5+	295.78		Burford et al (2016)
Norman river estuary - Walker Ck site day 1-4	50.84		Burford et al (2016)
Norman river estuary - Walker Ck site day 5+	723.5		Burford et al (2016)
Flinders river estuary - Site 1	335.96		This study
Flinders river estuary - Site 2	386.55		This study
Estuarine Intertidal Mudflat (Microphytobenthos)			
Norman river estuary - Nov 2009 & Feb 2010	0	432	Duggan et al (2014)
Mitchell river estuary - Nov 2016		244.95	Burford and Faggotter (2021)
Mitchell river estuary - Nov 2017		67.26	Burford and Faggotter (2021)
Mitchell river estuary - Mar 2019 - late wet	253.59		Burford and Faggotter (2021)
Mitchell river estuary - Dec 2019		217.2	Burford and Faggotter (2021)
Gilbert river estuary - Nov 2016		324.84	Burford and Faggotter (2021)
Gilbert river estuary - Nov 2017		178.53	Burford and Faggotter (2021)
Gilbert river estuary - Mar 2019 - late wet	417		Burford and Faggotter (2021)
Gilbert River estuary - Dec 2019		208.26	Burford and Faggotter (2021)
Flinders River estuary - Nov 2016		178.53	Burford and Faggotter (2021)
Flinders River estuary - Nov 2017		151.53	Burford and Faggotter (2021)

Primary production	Wet season mg C/m²/day	Dry season mg C/m²/day	Source
Flinders River estuary - May 2018 - early dry		144.33	Burford and Faggotter (2021)
Flinders River estuary - Mar 2019 - late wet	269.22		Burford and Faggotter (2021)
Flinders River estuary - Dec 2019		357.63	Burford and Faggotter (2021)
Estuarine Phytoplankton			
Norman River estuary - Nov 2009	112	328	Burford et al (2012)
Gilbert River estuary - Dec 2019		124.72	Burford and Faggotter (2021)
Flinders River estuary - Dec 2019		241.76	Burford and Faggotter (2021)
Mitchel River estuary - Dec 2019		337.6	Burford and Faggotter (2021)
Algae on Macrophytes			
Mitchell River - emergent	121.3		Molinari et al (2021)
Mitchell River - floating	88.5		Molinari et al (2021)
Mitchell River - submerged	335.7		Molinari et al (2021)
Waterhole			
Cloncurry River - in channel water hole		750	Faggotter et al (2013)
Cloncurry River - off channel water hole		3,496	Faggotter et al (2013)
Floodplain			
Mitchell River - open water floodplain	112.9		Molinari et al (2021)
Border Rivers – Weir River Talwood	166.60		Unpublished from Woods et al. 2012
Border Rivers – Balonne River Booligar	154.10		Unpublished from Woods et al. 2012
Border Rivers – Balonne River St. George	169.39		Unpublished from Woods et al. 2012
Flinders River – lower floodplain – site FL1	236.66		This study
Flinders River – lower floodplain – site FL2	315.20		This study
Flinders River – lower floodplain – site FL3	138.50		This study
Flinders River – lower floodplain – site FL4	144.00		This study
Flinders River - upper floodplain - site ED5	412.07		This study
Flinders River - upper floodplain - site ED6	345.57		This study
Flinders River - upper floodplain - site ED7	271.32		This study

Primary production	Wet season mg C/m²/day	Dry season mg C/m²/day	Source
Flinders River - upper floodplain - site ED9	310.41		This study
Flinders River - upper floodplain - site ED10	232.45		This study
Flinders River - upper floodplain - site ED12	470.37		This study
Flinders River - upper floodplain - site ED14	225.37		This study
Flinders River - upper floodplain - site ED15	318.42		This study
Flinders River - upper floodplain - site ED17	277.94		This study

Appendix B: Migratory shorebird daily energy requirements

Total Bird Daily Energy Requirements (DER) for each migratory shorebird species at each survey location and date

Common name	Species name	Total Bird Daily Energy Requirements (DER) kJ per day				
		Flinders River	Gilbert River		Mitchell River	
		Dec 2019	Mar 2019	Dec 2019	Mar 2019	Dec 2019
Asian Dowitcher	*Limnodromus semipalmatus*	0.00000150	-	-	-	-
Bar-Tailed Godwit	*Limosa lapponica*	0.00004381	0.0000035	0.0000592	0.0000093	0.0001585
Black-tailed Godwit	*Limosa limos*	0.00291400	0.0031967	0.0005120	0.0085608	0.0013712
Black-winged Stilt	*Himantopus himantopus*	-	0.0000436	0.0000072	0.0001167	0.0000194
Common Greenshank	*Tringa nebularia*	0.00010065	0.0000168	0.0000013	0.0000449	0.0000036
Common Sandpiper	*Actitis hypoleucos*	0.00000186	0.0000030	0.0000003	0.0000081	0.0000008
Curlew Sandpiper	*Calidris ferruginea*	0.00000365	-	0.0000001	-	0.0000003
Eastern Curlew	*Numenius madagascariensis*	0.00025665	0.0000140	0.0000311	0.0000375	0.0000833
Great Knot	*Calidris tenuirostris*	0.00029052	0.0001929	0.0000654	0.0005165	0.0001752
Greater Sandplover	*Charadrius leschenaultii*	0.00000449	0.0000398	0.0000372	0.0001067	0.0000995
Grey Plover	*Pluvialis squatarola*	0.00000414	0.0000031	-	0.0000083	-
Lesser sandplover	*Charadrius mongolus*	0.00003686	0.0000498	0.0000007	0.0001332	0.0000018
Marsh Sandpiper	*Tringa stagnatilis*	0.00001004	0.0000050	0.0000001	0.0000134	0.0000004
Masked Lapwing	*Vanellus miles*	-	0.0000016	-	0.0000044	-
Pacific Golden Plover	*Pluvialis fulva*	0.00000252	-	-	-	-
Pied Oystercatcher	*Haematopus longirostris*	0.00000620	0.0000058	0.0000028	0.0000156	0.0000076
Pied Stilt	*Himantopus leucocephalus*	0.00097321	-	-	-	-
Red Knot	*Calidris canutus*	0.00000380	-	-	-	-
Red-necked Stint	*Calidris ruficollis*	0.00000646	0.0000086	0.0000545	0.0000229	0.0001459
Sharp-tailed Sandpiper	*Calidris acuminata*	0.00000238	0.0000006	-	0.0000016	-
Terek Sandpiper	*Xenus cinereus*	0.00007933	0.0000100	0.0000006	0.0000268	0.0000015
Whimbrel	*Numenius phaeopus*	0.00008707	0.0000704	0.0000131	0.0001885	0.0000352

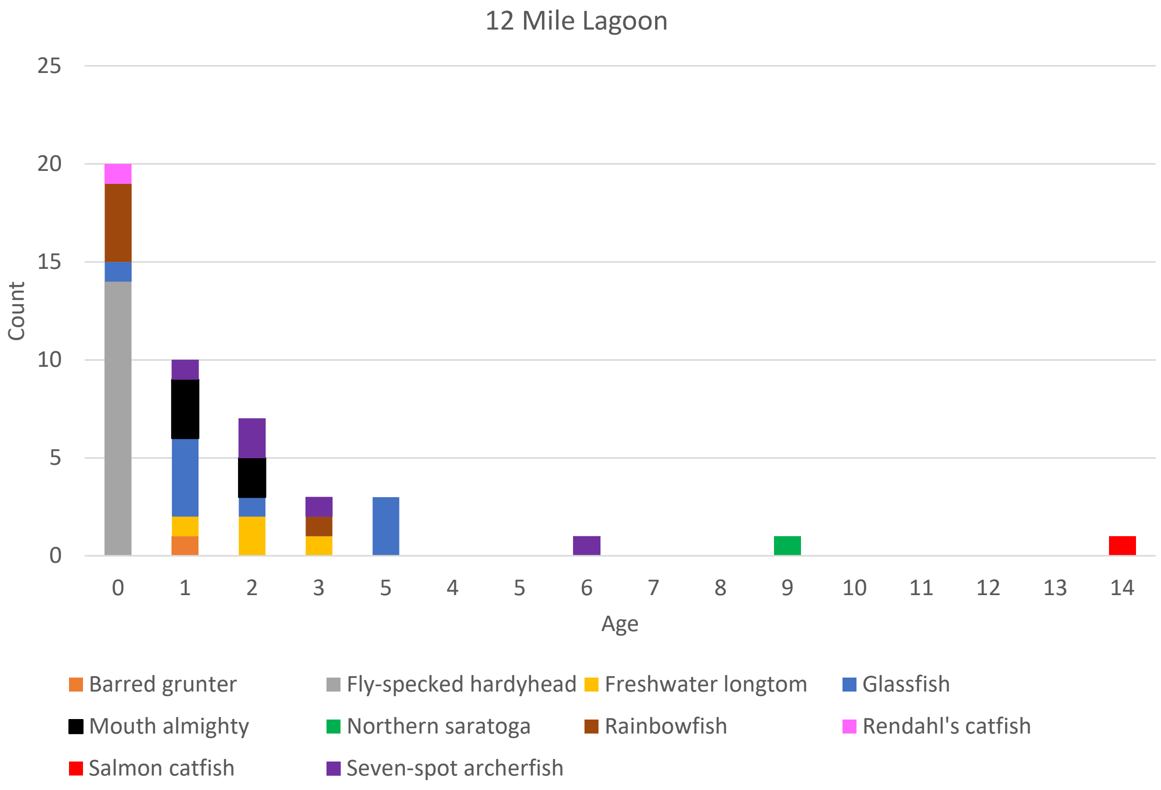
Appendix C: Von Bertalanffy Growth Models coefficients and sample size

Species	Common name	Sample size	Total Length (mm)	Age (years)	Weight (g)	Linf	K	t0
Ambassis agassizii	Glassfish	60	20 - 70	0 - 6	0.2 - 12.8	58.571	0.894	0.000
Amniataba percoides	Barred grunter	51	36 - 270	0 - 6	2 - 480	321.516	0.305	0.000
Anodontiglanis dahli	Toothless catfish	14	165 - 405	2 - 12	121 - 510	382.397	0.509	0.499
Glossamia aprion	Mouth almighty	36	20 - 148	0 - 3	1.1 - 82	128.863	1.107	0.000
Hephaestus fuliginosus	Sooty grunter	71	34 - 320	0 - 11	1.29 - 800	272.542	0.341	0.000
Lates calcarifer	Barramundi	23	23 - 263	1 - 7	228 - 675	899.866	0.279	0.000
Leiopotherapon unicolor	Spangled perch	67	40 - 170	0 - 4	2. 3- 138.7	146.501	0.727	0.000
Melanotaenia splendida	Rainbowfish	81	15 - 96	0 - 3	0.1 - 14	89.742	0.858	0.000
Nematalosa erebi	Bony bream	68	26 - 230	0 - 4	0.2 - 318	144.800	6773.027	0.000
Oxyeleotris lineolatus	Sleepy cod	88	23 - 365	0 - 8	0.5 - 900	407.235	0.252	0.000
Scortum ogilbyi	Gulf grunter	28	106 - 370	1 - 8	34.8 - 640	273.520	0.564	0.307
Strongylura krefftii	Freshwater longtom	15	195 - 585	0 - 4	7 - 680	283.463	0.693	0.000
Arrhamphus sclerolepis	Snub-nosed garfish	1	145	1	29	real age used	age range, sample size too small	
Brachirus selheimi	Freshwater sole	1	70	1	3.9	real age used	age range, sample size too small	
Brachirus sp.	Freshwater sole	1	65	2	14.8	real age used	age range, sample size too small	
Craterocephalus stercusmuscarum	Fly-specked hardyhead	19	25 - 53	0 - 1	0.2 - 3.1	real age used	age range too small	
Glossogobius sp.	Goby	31	35 - 105	0 - 2	0.3 - 19.5	real age used	age range too small	
Hephaestus carbo	Coal grunter	5	85 - 155.8	1 - 4	1.29 -158	real age used	sample size too small	
Megalops cyprinoides	Tarpon	17	123 - 350	1 - 4	208 - 560	real age used	poor VBGM fit	
Neosilurus ater	Black catfish	18	215 - 370	2 - 10	96 - 790	real age used	poor VBGM fit	
Neoarius graeffei	Salmon catfish	32	78 - 435	3 - 17	14.8 - 1970	real age used	poor VBGM fit	
Neosilurus hyrtlii	Hyrtl's tandan	18	59 - 201	0 - 3	5.2 - 46	real age used	sample size too small	

Species	Common name	Sample size	Total Length (mm)	Age (years)	Weight (g)	Linf	K	t0
Neoarius midgleyi	Shovel-nosed catfish	8	300 - 580	8 - 18	only recorded in 2 fish	real age used	sample size too small	
Oxyeleotris selheimi	Giant gudgeon	6	95 - 327	1 - 6	15 - 412	real age used	sample size too small	
Pingalla gilberti	Gilbert grunter	10	55 - 94	0 - 2	4.1 - 21.3	real age used	sample size too small	
Porochilus argenteus	Silver tandan	1	73	0	not recorded	real age used	sample size too small	
Porochilus rendahli	Rendahl's catfish	1	115	0	12.2	real age used	sample size too small	
Scleropages jardinii	Northern saratoga	1	435	9	1020	real age used	sample size too small	
Toxotes chatareus	Seven-spot archerfish	36	54 - 175	0 - 6	4.7 - 172.5	real age used	poor VBGM fit	

Appendix D: 12 Mile Lagoon age frequency histogram and species

Age frequency histogram of 12 Mile Lagoon (disconnected lagoon), including species composition.



Appendix E: Ecohydrology of primary production on floodplain and salt flats

Floodplain primary production

Asset: Primary productivity floodplains and salt flats

Assessment endpoint: Historically consistent rates of primary production across these habitats

Measurement endpoint: Frequency and duration of floodplain inundation that facilitates floodplain and salt flat primary production

Ecohydrological rule: The flow magnitude and duration at a gauge that generates floodplain inundation lasting five days or more during the wet season (with months specified according to the natural flow regime) providing an opportunity for peak primary production to occur, which can take up to 17 days. This requires gauge specific floodplain inundation flow thresholds.

There are a number of potential formulations of this for duration: 1) for fish and other fully aquatic biota to make use of the primary production the inundated floodplain needs to be connected to the river for at least 5 days, or be reconnected to the river before it dries; 2) for land biota (frogs), or flying biota (insects or birds) to make use of the primary production it needs to stay wet long enough for them to complete the aquatic phases of their life cycle; 3). Runoff from wetted areas releases nutrients which enter rivers, estuaries and the nearshore, 4) Primary producers form crusts (known as biological crusts) on the surface of soils which stabilize the soils, reducing erosion.

Inundation-connectivity relationships can be determined using remote sensing, provided there is on-ground calibration. More information on how a range of aquatic species, as well as frogs and aquatic insects use floodplains throughout their life history stages is needed via on-ground studies to develop additional evidence in support of this rule.

Threshold of concern: A ToC for this needs to relate to the requirements of the system for the opportunities for peak production described by the ecohydrological rules. This would be how many days or how much area by days or similar is needed over annual or longer time steps. This will require comparisons with pre-development flows and identifying what would be lost under flow use scenarios.

Input files:

- Extent of overbank flooding
- Duration of overbank flooding

Rule	1	2
Description	Initiation of floodplain primary production	Peak of floodplain primary production
Rule class	Wet season overbank flooding	Wet season overbank flooding
Environmental trigger	Daily discharge	Daily discharge
Duration	Ensure floodplain inundation for a minimum of 5 days to initiate primary production	Ensure floodplain inundation for a minimum of 17 days to reach peak primary production
Time series input	Daily discharge	Daily discharge
Rationale	Duration of overbank wet season flooding needed to initiate floodplain primary production	Duration of overbank wet season flooding needed to reach peak floodplain primary production

Ecohydrological rules (reflecting rules for primary production on floodplains)

<u>Operation</u>:

1. Determine flow required to initiate floodplain primary production:
    a. Is the flow in season (Wet season)
    b. Is the flow of sufficient magnitude for overbank flooding?
    c. Does water remain on the floodplain for at least 5 days?
    d. What is the spatial extent of the inundation, and does it meet at least the median extent on record?

<u>Operation</u>:

2. Check for required to reach peak floodplain primary production:
    a. Is the flow in season (Wet season)
    b. Is the flow of sufficient magnitude for overbank flooding?
    c. Does the overbank flooding last for at least 17 days?

Appendix F: Ecohydrology of fish assemblage structure

Fish assemblage structure

Asset: Fish populations of the Gulf catchments

Assessment endpoint: Fish assemblage structure and the population viability of the fish populations of the Gulf catchments

Measurement endpoint: frequency and duration of connectivity opportunities to support recruitment and dispersal of fishes

Ecohydrological rule: hydrological connection allowing opportunity for fish movement between tributary locations and main river channel during the wet season. Minimum flow magnitude required (to be determined for each gauge, ensuring >0.2 metres of flow above the gauge).

Duration of flow required: Estimate of 20 km per day represents typical fish movement rates from the region (Tim Marsden, pers comm.), which would necessitate a minimum duration for connectivity between the main channel and a tributary location (in days) to be the distance from the main channel divided by 20.

This can be developed for catchment wide connectivity as pairwise proportions of days that flow is above the passable depth at each of the gauges a fish needed to pass to reach the second gauge in the pair. A value of one would be assigned for days where flow at stream gauges were at or above the required water depth. A value of zero would be assigned for days where one or more gauges in the connection pathway had flow below the required flow depth.

Three **Thresholds of Concern** are evident: 1) (low risk) One wet season without connection between the main channel and major tributaries for a sufficient duration to allow for fish migration 2) (medium risk) One to two consecutive wet seasons without connection between the main channel and major tributaries for a sufficient duration to allow for fish migration, 3) (high risk) Three or more consecutive wet seasons without connection between the main channel and major tributaries for a sufficient duration to allow for fish migration. These are based on the failure to provide successful movement opportunities at the appropriate scale being likely to lead to a loss of biodiversity.

Risk applies to the whole system but is particularly important for tributary locations within the system given their lower connectedness. As the distance from the main channel as well as annual wet season flow will influence spatial risk, an annual 'map' of connectivity would illustrate medium and high risk sub-catchments based on the ToCs. Quantifying the inter-annual risk by "stacking" the maps and summarising by river segment (from geofabric) would be demonstrate the long-term risk for each segment over the period of record (e.g. for river segment X over 120 years it was high risk 5% of years under pre-development but 25 % of years under development scenario A).

Input files:

- Connectivity matrix
- Requires gauge flow data (instructions within template)

Rule	1
Description	Wet season connectivity event
Rule class	Connectivity event occurs each wet season. Loss of assemblage structure in a site that failed to connect for more than 1 in each 3 years.
Environmental trigger	Visible pass flow, determined by gauge
Duration	At least 1 instance each wet season with sufficient duration to facilitate migration of fish from main channels to tributaries. The duration of this will depend on the distance between tributary habitats but a rule of thumb of 20 km per day represents typical fish movement rates from the region (Tim Marsden, pers comm.). This would necessitate a minimum duration for connectivity between the main channel and a tributary location (in days) to be the distance from the main channel divided by 20.
Time series input	Gauge flow data
Rationale	Flow required to ensure suitable frequency of movement opportunity (connectivity). Need to maintain connectivity between main river channels and major tributaries, to as this support fish assemblage biodiversity across catchments via (1) migration opportunities and (2) access to diverse habitats.

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