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The effect of wet season river flows on flood plume distribution across northern Australia; contribution to coastal productivity, and future extent under climate change

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ABSTRACT

Northern Australia is home to some of the world's most expansive and ecologically significant river systems, including the Flinders, Gilbert, and Daly Rivers. These river catchments, which drain into the Gulf of Carpentaria and the Timor Sea, are vital to both the health of the region's estuaries, coastal ecosystems and its commercial fisheries. This study investigates the relationship between wet season river flows, flood plume extent, and primary productivity in adjacent coastal seas, with a focus on understanding potential impacts from climate change and water extraction on these dynamics. Hydrological data from 2003 to 2023 was analysed for the Flinders, Gilbert, and Daly Rivers to determine peak flow events and their corresponding flood plume sizes using MODIS satellite imagery. The study found that flood plumes were highly variable across the 20-year period, with significant events recorded in 2019 and 2023 and strong relationships between 7-day river flows and plume extents for all rivers. Chlorophyll-a concentration, as a proxy for primary productivity, was significantly associated with plume sizes in the southern Gulf of Carpentaria and Anson Bay, specifically for tertiary plumes from the Flinders, Gilbert, and Daly Rivers. Future climate projections indicate potential reductions in rainfall by 2070–2099, which could lead to decreases in flood plume extent and associated primary productivity. This research highlights the critical connection between river flows, coastal flood plumes, and marine productivity in northern Australia. The findings underscore the importance of maintaining environmental water flows to sustain coastal ecosystems and fisheries, particularly in the context of increasing water allocation pressures and the potential impacts of climate change on regional rainfall patterns.

1. Introduction

Northern Australia is notable for its expansive river catchments and estuaries, which represent vital hydrological and habitat components of the regions terrestrial and marine ecosystems. The wet season, extending approximately from November to April, constitutes a pivotal period during which copious rainfall inundates the landscape, profoundly impacting floodplains, and inland ecosystems. Many coastal processes, microflora and habitat-forming plants, and animal species, rely on this freshwater influx that reduces the hyper-salinity of the late dry season, and brings nutrients that drive the coastal and offshore productivity vital for fisheries species and migrating birds (Burford and Faggotter, 2021; Lowe et al., 2022). The catchment floodwaters empty into the ocean via an estuarine interface and then extend seaward as large plumes of sediment and nutrient laden brackish water (Burford et al., 2012), sometimes for 100's of kilometres. Wet season rainfall, however, is highly variable across northern Australia, with approximately one in five years considered as low-flow year. During these 'dry' summers, the reduction in fresh water entering the ocean can impact commercial fisheries and higher trophic species through reduced food availability, hyper salinity, and other processes, e.g. changes to triggers such as flooding that are key emigration cues (Broadley et al., 2020).

In recent years, there has been increased interest in northern Australian river catchments as a resource for further water development to support activities such as irrigated agriculture and critical minerals mining (CSIRO, 2013; DNRME, 2018). This has highlighted the need for increased understanding of how water extraction might impact not only freshwater/floodplain ecosystems, but offshore productivity and the

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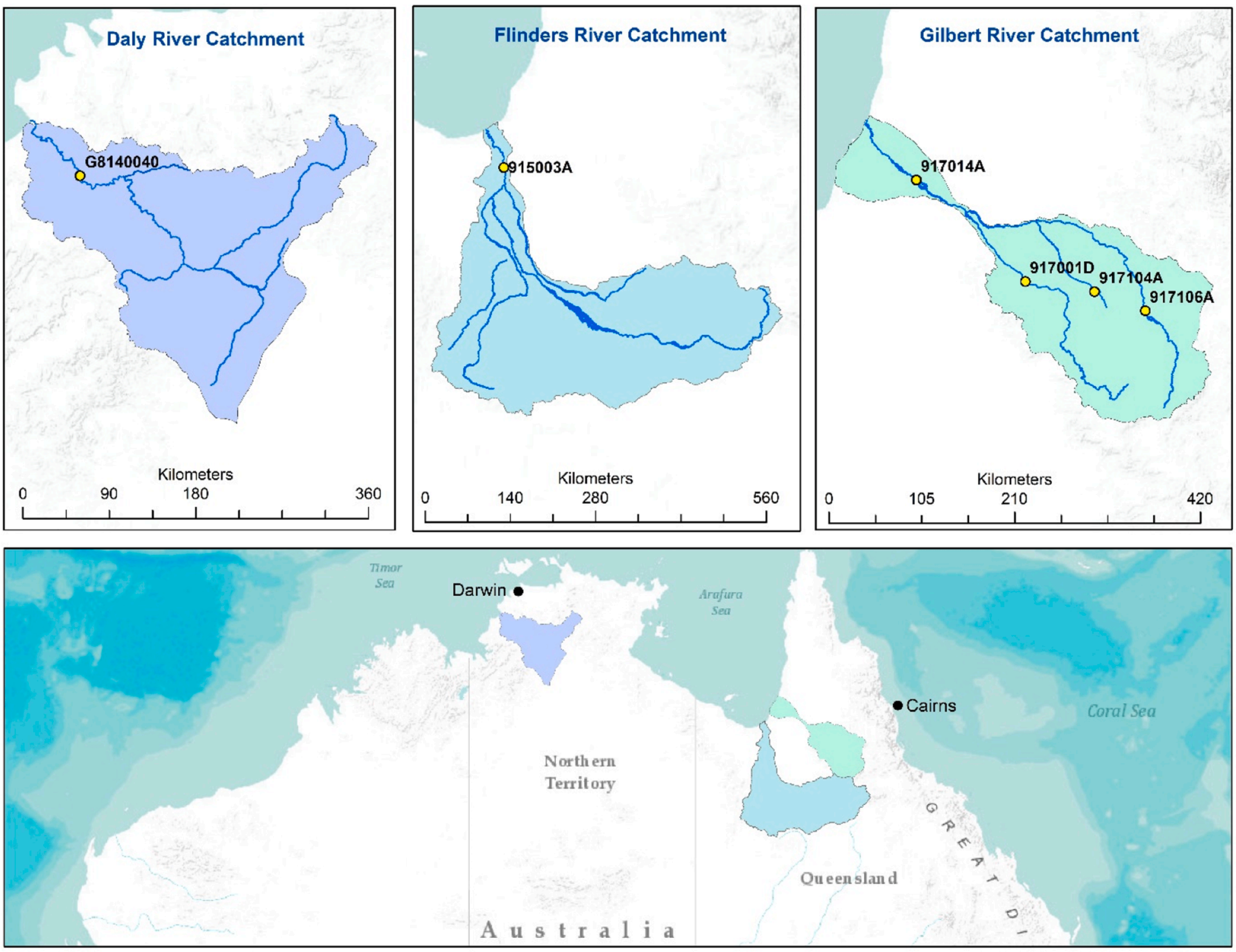
ecology of coastal ecosystems. Previous studies have shown that higher wet season flows are associated with increased catches of fish and crustaceans, including prawns (Broadley et al., 2020; Robins et al., 2005). The Northern Australia Prawn Fishery, for example, accounted for 21 % of Australia's fishery income in 2021, making it the country's largest fishery. Potential reductions in prawn catch due to future water extraction during low flow years has been estimated to be over 50 % (498–646 tonnes less catch; Broadley et al., 2020). Given that climate change adds further uncertainty regarding future rainfall levels in the region (Ridder et al., 2021), it is crucial to understand the relationship between wet season river flows, the extent of coastal flood plumes, and the resulting variations in coastal productivity, to assess the ecological resilience of northern Australia under changing flow regimes.

Our research aims to explore how wet season rainfall events in the Flinders, Gilbert and Daly River catchments drive flood plume extents and primary productivity in the adjacent coastal waters and to assess how a reduction in historically un-regulated freshwater flood-flows caused by climate change and/or water re-allocation could reduce plume extent and ensuing coastal productivity across northern Australia.



Station name	Station Number	Commence date	Latitude	Longitude	Distance from sea	Catchment area
Daly River-Mount Nancar	G8140040	19/11/1952	-13.7662	130.7113	80 km	53,000 km^2
Flinders River at Walkers Bend	915003A	12/12/1969	-18.1617	140.8582	103 km	106,300 km^2
Gilbert River at Bourke Development Rd	917014A	11/02/2015	-17.1683	141.7675	102 km	39,100 km^2
Etheridge River at Roseglen	917104A	14/01/1967	-18.3064	143.579	350 km	867 km^2
Gilbert River at Rockfields	917001D	14/01/1967	-18.2025	142.876	267 km	10,990 km^2
Einasleigh River at Einasleigh	917106A	15/02/1968	-18.5002	144.0959	420 km	8,244 km^2

Fig. 1. Map of study area showing the Daly, Flinders and Gilbert catchments, their major tributaries, and the hydrological stations used in the flow analysis of this study. Note that the only downstream hydro station for the Gilbert River was offline before 2015. The upstream tributary stations 917001D, 917104 A and 917106 A were accessed to produce a visual plot of long term annual flows but were not used in the flow/ plume regression models as they do not capture the catchments entire flow regime.

2. Methods

2.1. Study region

Three notable river systems in northern Australia - the Flinders, Gilbert, and Daly – were selected for this study, each exhibiting catchments of substantial dimensions and ecological importance (Fig. 1). The Flinders and Gilbert Rivers are located in northern Queensland, and both discharge into the Gulf of Carpentaria within 200 km of each other. Despite this proximity, the catchments exhibit different environments, water quality, and anthropogenic pressures.

The Daly River catchment is located in the Northern Territory and discharges in Anson Bay in the Timor Sea. The volume of water discharged into the seas is the second highest of any river in Australia (CSIRO, 2009). Major streams within the catchment include the Katherine and Douglas Rivers, with perennial flow supported by significant groundwater input, a finite resource increasingly utilised for new agricultural and mining developments (Currell et al., 2024; Lamontagne et al., 2021). The streams and rivers in the Flinders, Gilbert and Daly River catchments are classified as Class 10 rivers i.e. predictable summer highly intermittent flows (Kennard et al., 2010), and during the dry season the rivers can be reduced to a series of drying waterholes.

2.2. Hydrological data

Hydrological flow data from the Flinders and Gilbert River catchments between 2003 and 2023 was retrieved from the Queensland Government Water Monitoring Information Portal (https://water-monitoring.information.qld.gov.au/). For the Daly River, hydrological data was extracted from the Bureau of Meteorology Water Data Online portal (http://www.bom.gov.au/waterdata/).

Downstream hydrological stations were selected for flow analysis (Fig. 1). For the Flinders River, this was station 915003 A (Flinders River at Walkers Bend), ~70 km upstream from the river mouth. This station has been continually gauging data since 1969. For the Gilbert River, data from station 917014 A (Gilbert River at Bourke Development Road) approximately 100 km from the Gulf was used. Unfortunately, this station only re-started gauging data in February 2015 after a 25-year hiatus and this limited the Gilbert analysis to a shorter period of analysis. For the Daly River, the station was G8140003 (Daly River- Mt Nancar), ~70 km upstream from where the river enters Anson Bay in the Timor Sea.

Flow hydrographs were created for each river, and peak flow events for each year 2003–2023 were identified. For the Gilbert River, flow levels for the years 2003–2015 (when downstream station 9170014 A was not operational) were obtained from three upstream tributaries (Einasleigh, Etheridge and Gilbert Rivers, station numbers 917106 A, 917104 A and 917001D respectively), and the flow levels were summed. Calendar years (as opposed to fiscal years that are often used to encapsulate wet season rainfall) were used, as very little flow occurred before January each wet season, and the analysis was related to peak flow events of 7-day durations, not annual rainfall levels.

2.3. Flood plume analysis

A search was conducted for satellite imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) true colour, corrected radiance products, covering the period immediately following peak flow events. The MODIS satellite images from the south-eastern Gulf of Carpentaria region that encompassed the Flinders and Gilbert River outflows (Coordinate limits −18.580, 137.250, −14.361, 142.031) and from Anson Bay region that encompassed the Daly River outflow (Coordinate limits −12.673, 129.446, −14.009, 130.534) were downloaded in GeoTIFF format from the NASA Worldview Snapshots Portal (https://wvs.earthdata.nasa.gov/). The products were loaded onto ArcMap (ArcGIS Desktop 10.8) for spatial plume size analysis.

Flood plume categories were defined as in Devlin and Schaffelke (2009), that were based on the plume concentration of water quality parameters that can be distinguished through ocean colour remote sensing, as follows:

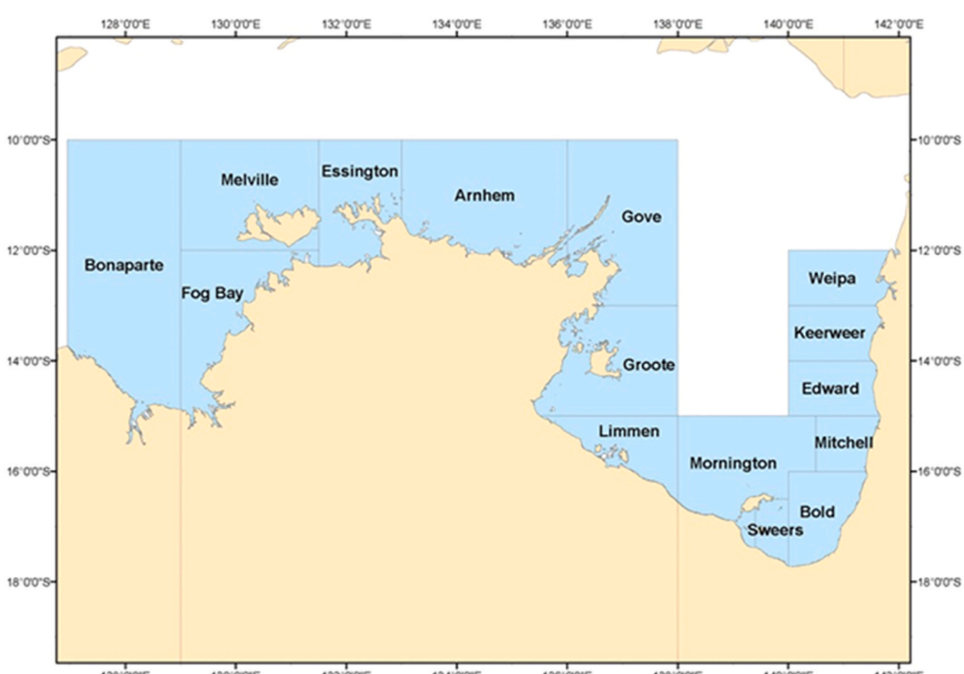


Fig. 2. Statistical areas of the Northern Prawn Fishery. The Gilbert and Flinders Rivers discharge into the Bold region, while the Daly River discharges into the Fog Bay region.

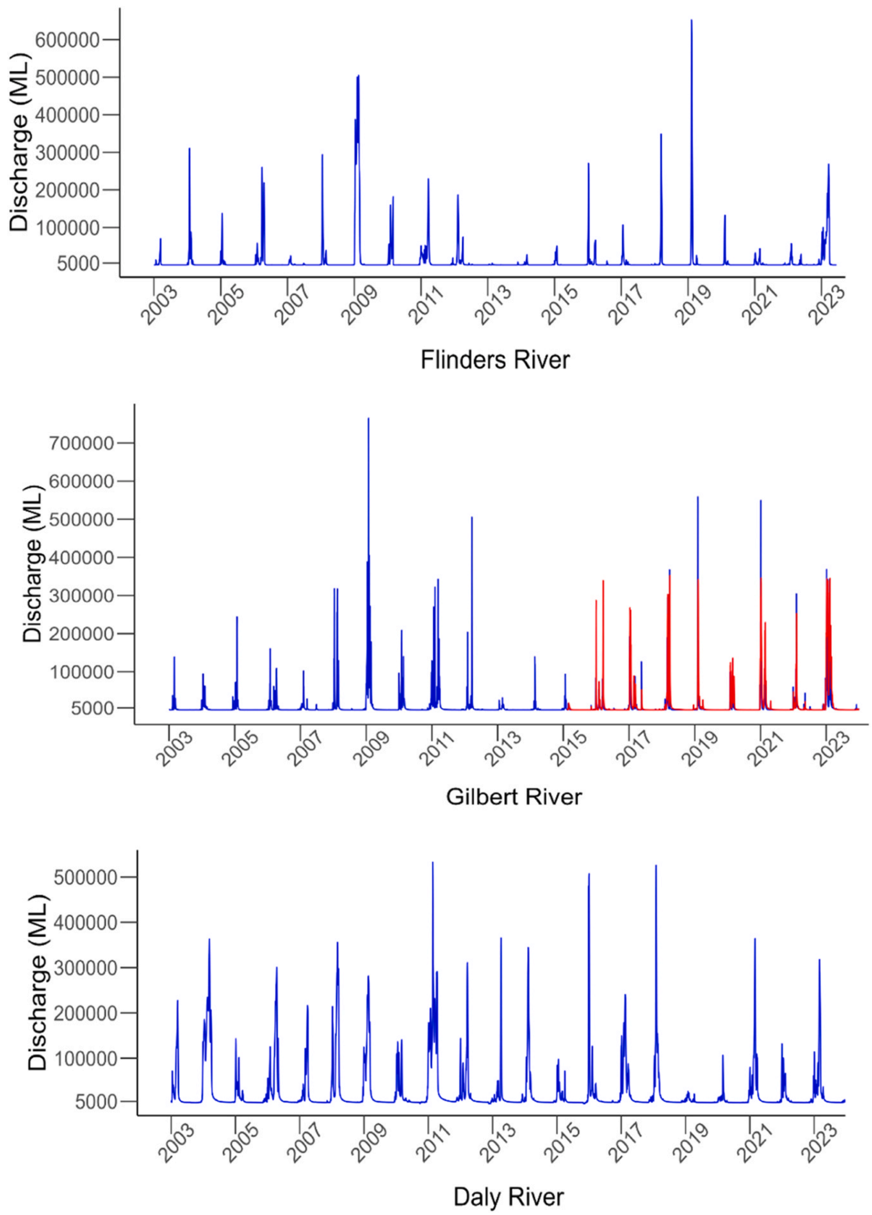


Fig. 3. Daily flow (megalitres) at the Flinders River, Gilbert River, and Daly River from 2003 to 2023, from hydrological stations 915003 A, 917014 A, and G8140040 respectively. Note that for the Gilbert River, three upstream stations, that are located on the major tributaries of the Gilbert Catchment (917104 A, 917106 A, and 917001D; see Fig. 1 for location of these stations) are shown in blue (sum of the three stations), while downstream data that is only available from 2015, is shown in red. Note also that Daly River data was missing during the 2019 wet season floods.

(i) Primary water types were defined as having a high total suspended matter (TSM) load, minimal chlorophyll (Chl-*a*) and high coloured dissolved and organic matter (CDOM).

(ii) Secondary water types were defined as a region where CDOM is still high however, the TSM has been reduced and increased light and nutrient availability has prompted phytoplankton growth. Thus, the secondary plume exhibits high Chl-*a*, high CDOM and low TSM.

(iii) Tertiary water types are the region of the plume that exhibits no elevated TSM and reduced amounts of Chl-*a* and CDOM when compared with that of the secondary plume. Tertiary plumes can be described as being the transition between a secondary plume and ambient conditions.

Primary, secondary, and tertiary plumes were drawn using the ArcMap polygon tool, and the spatial extent in square kilometres for each plume type was calculated. This hand digitising method has been shown to provide better accuracy when determining plume boundaries over shallow benthic features compared to semi-automated processes that can struggle to distinguish seafloor from turbid water (Evans et al., 2012).

To determine the relationship between flow and plume size, linear

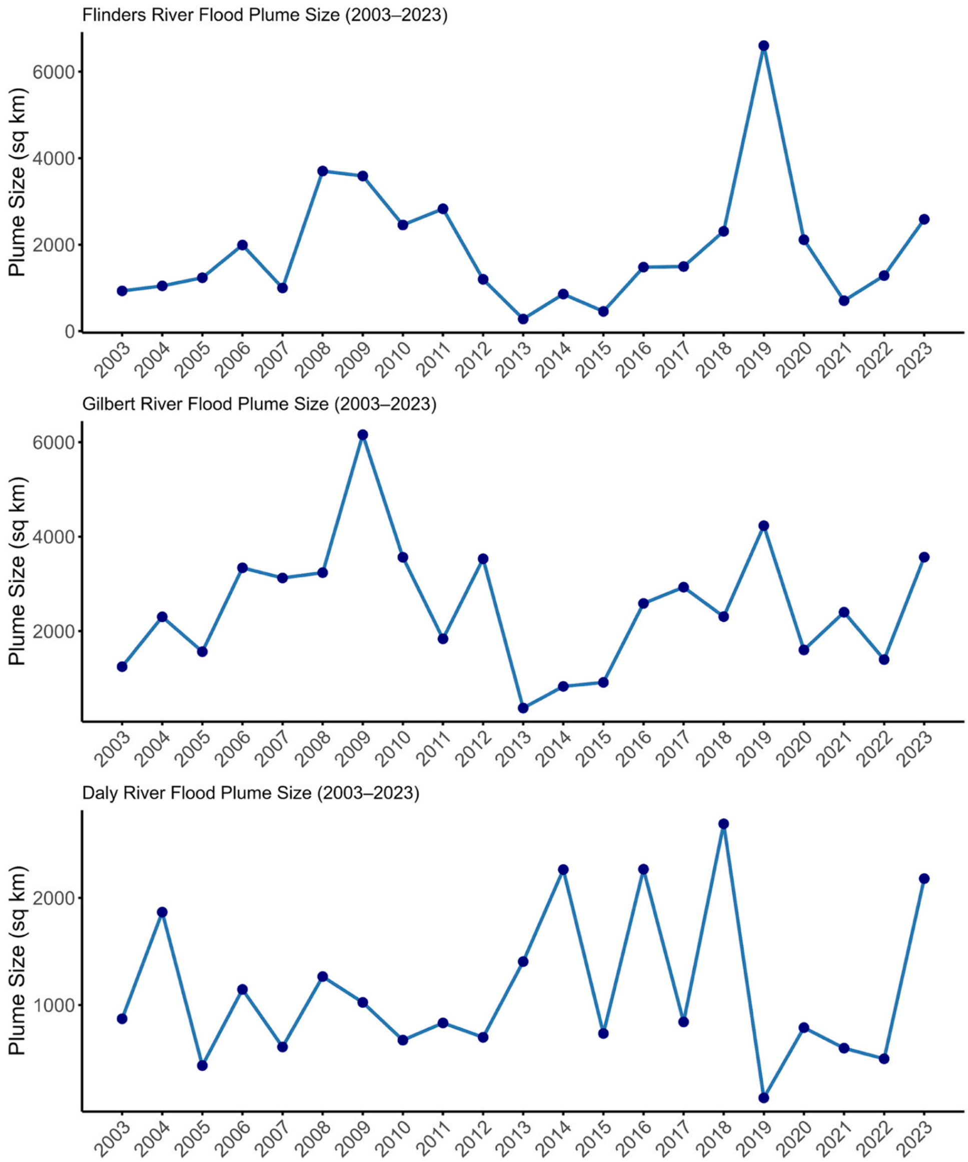


Fig. 4. Plume size after peak 7-day flow events for the Flinders, Gilbert and Daly Rivers from 2003 – 2023.

regression analyses were conducted between plume extent (sum of primary, secondary, and tertiary plumes) and 7-day hydrological flows. The analysis utilised complete hydrological data from 2003 to 2023 for the Flinders River and Daly River. For the Gilbert River, hydrological data from 2016 to 2023 only, was utilised.

Wind data were not included in this analysis, as the primary objective was to assess the influence of freshwater river discharge on flood plume dynamics and downstream ecological responses. During peak wet season events, riverine forcing is typically the dominant driver of coastal stratification and plume extent in tropical northern Australia, often overwhelming the effects of short-term wind variability. Focusing exclusively on river flow allowed for clearer attribution of observed patterns in plume behaviour and associated biological processes.

2.4. Chlorophyll-a

Chlorophyll-a fluorescence has been used for decades to study photosynthesis at both the organismal and subcellular levels (Porcar-Castell et al., 2014), providing key insights into photosynthetic efficiency. Relationships between water column integrated primary production and the vertical profile of chlorophyll *a* concentration have been previously established (Demidov et al., 2016). Building on this understanding, satellite ocean colour data has been crucial for estimating oceanic primary productivity on large spatiotemporal scales, using chlorophyll-a as a proxy for phytoplankton biomass and photosynthetic activity (Huot et al., 2007; Strutton et al., 2012; Westberry et al., 2023; Xu et al., 2016). Quantitatively relating variations in ocean colour observed from satellites to changes in phytoplankton and chlorophyll-a concentrations remains a challenge, which has been

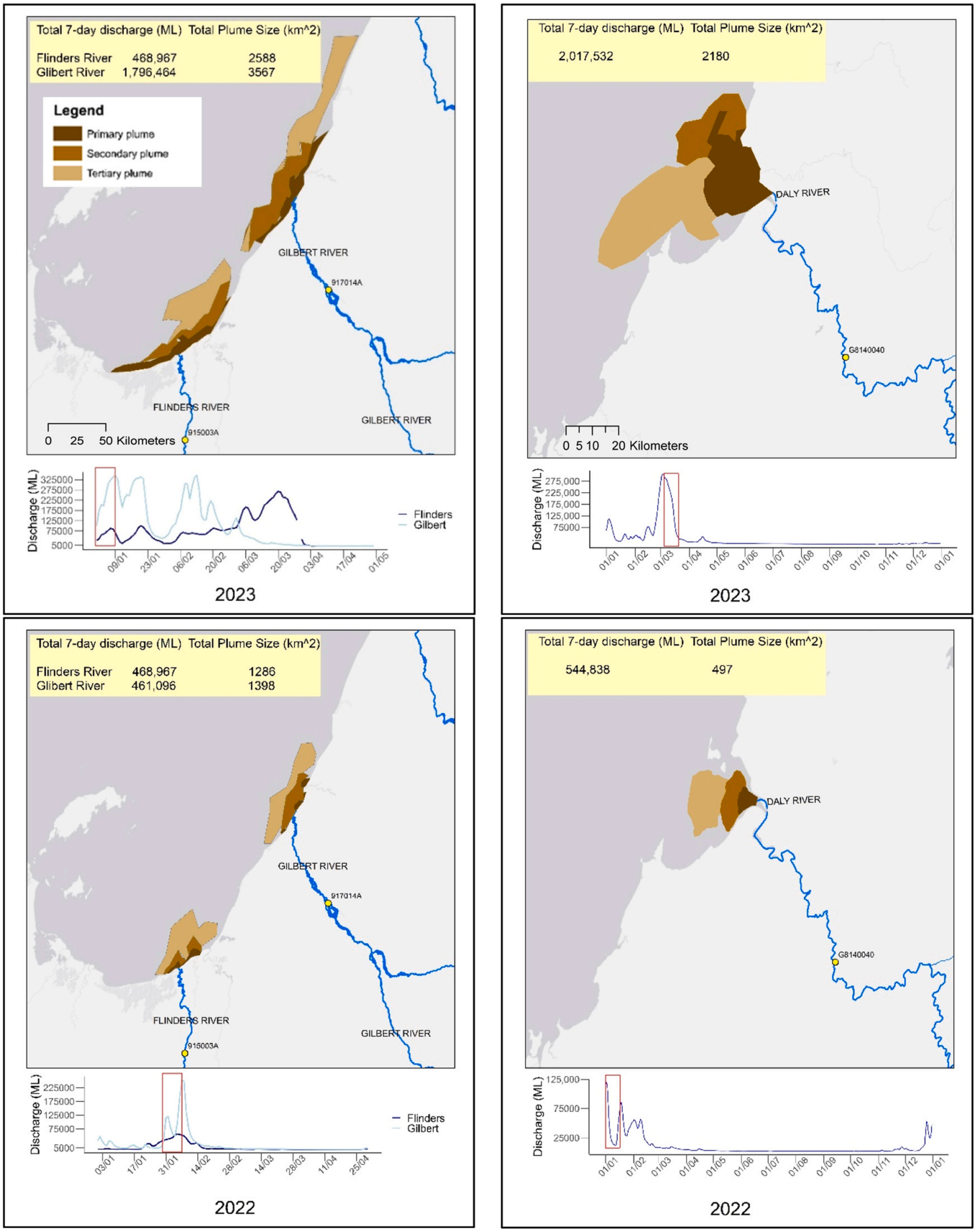


Fig. 5. Flood plumes from the Flinders, Gilbert and Daly rivers following 7-day peak flow events, during each wet season from 2003 – 2023. Hydrographs at bottom of each map show the 7-day period (red box) immediately prior to each plume event.

addressed through various ocean colour algorithms (Gholizadeh et al., 2016; Hu et al., 2019). In essence, remotely sensed chlorophyll data provides a valuable, albeit simplified, proxy for Net Primary Productivity (NPP), enabling researchers to study large-scale patterns and trends in ecosystem productivity.

MODIS-aqua Level 2 ocean colour satellite products from the same satellite pass as the GeoTIFF products used to identify plumes, were downloaded from NASA (https://oceancolor.gsfc.nasa.gov) and the

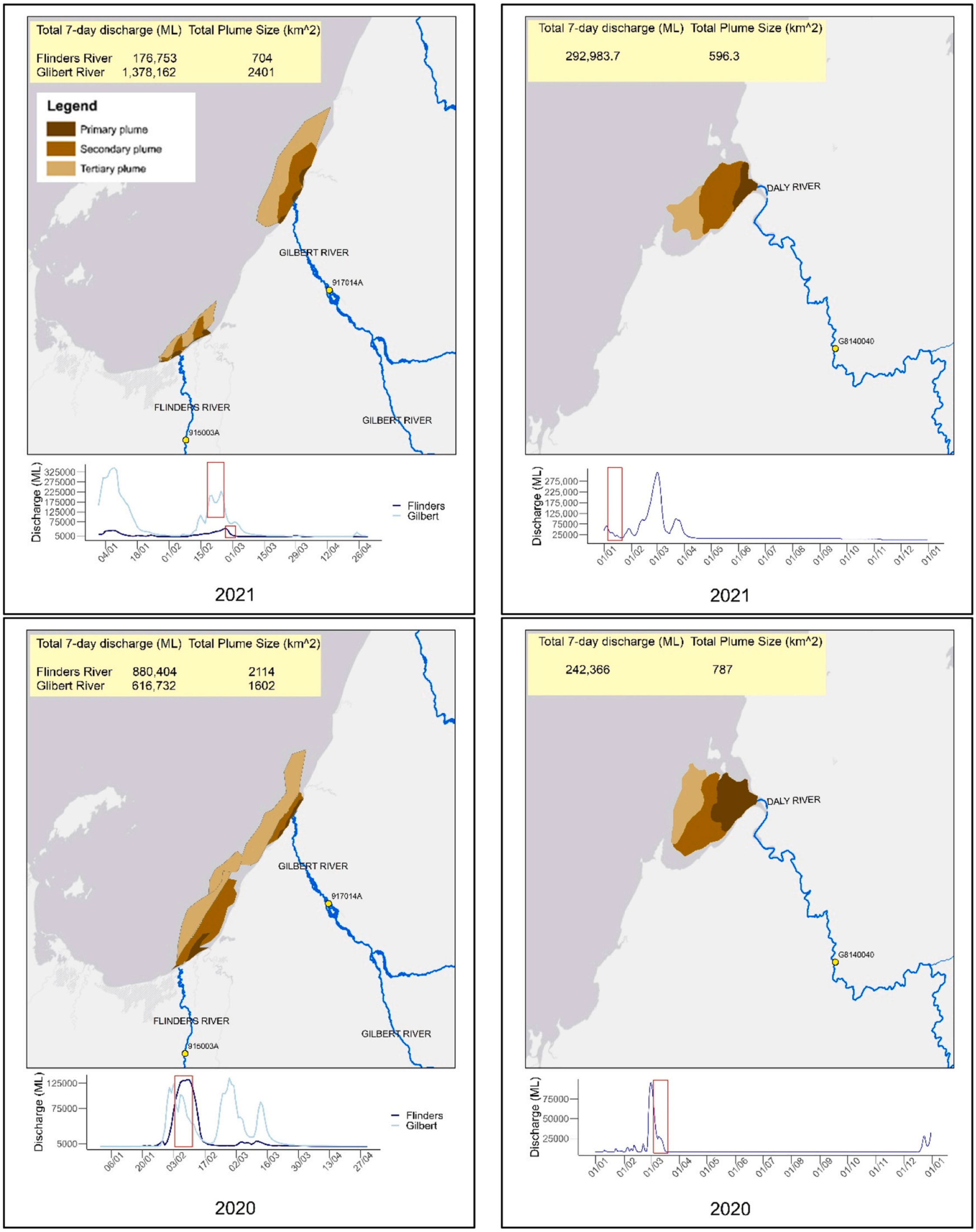
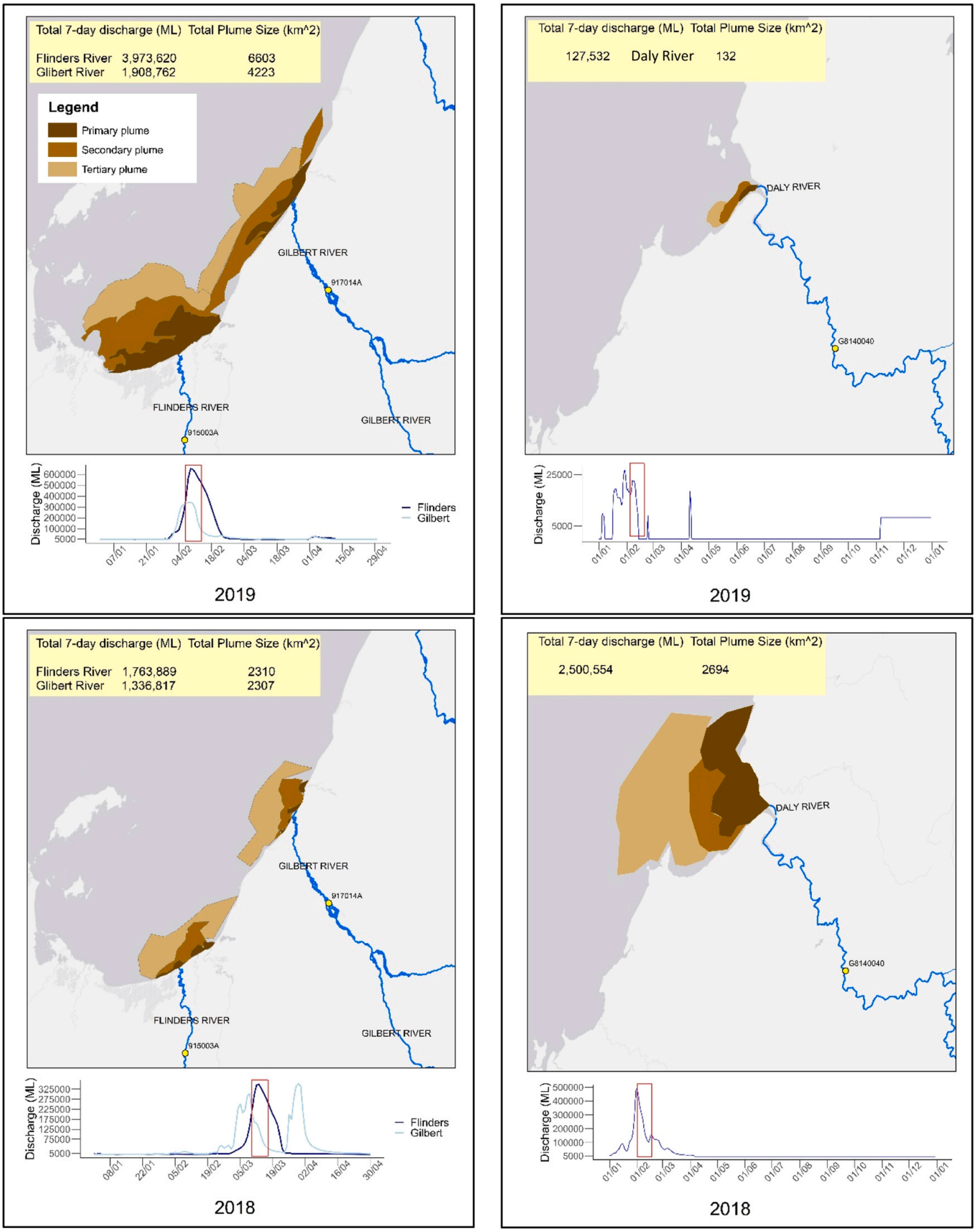


Fig. 5. (*continued*).

chlorophyll-a (chlor_a) bands opened in software package SeaDAS version 8.3.0 (NASA). The 'chlor_a' band, as described in Hu et al. (2019), returns the near-surface concentration of chlorophyll-a in mg m^{-3} ($\mu g\ L^{-1}$). An arbitrary but consistent region was chosen to compare across each year and each satellite product was subsetted to the same spatial extent which was a) the south-east section of the Gulf of Carpentaria defined by the oceanic region south of latitude 15.5°S and bounded by the mainland, and b) the region of Anson Bay in the Timor Sea defined by the latitudes 13.0°S to −13.55°S, and longitudes 129.7°E to 130.3°E. The statistical analysis tool was run to quantify mean chlor_a following each flow event within these regions. Because chlorophyll-a commonly increases as secondary/ tertiary plumes expand seaward,



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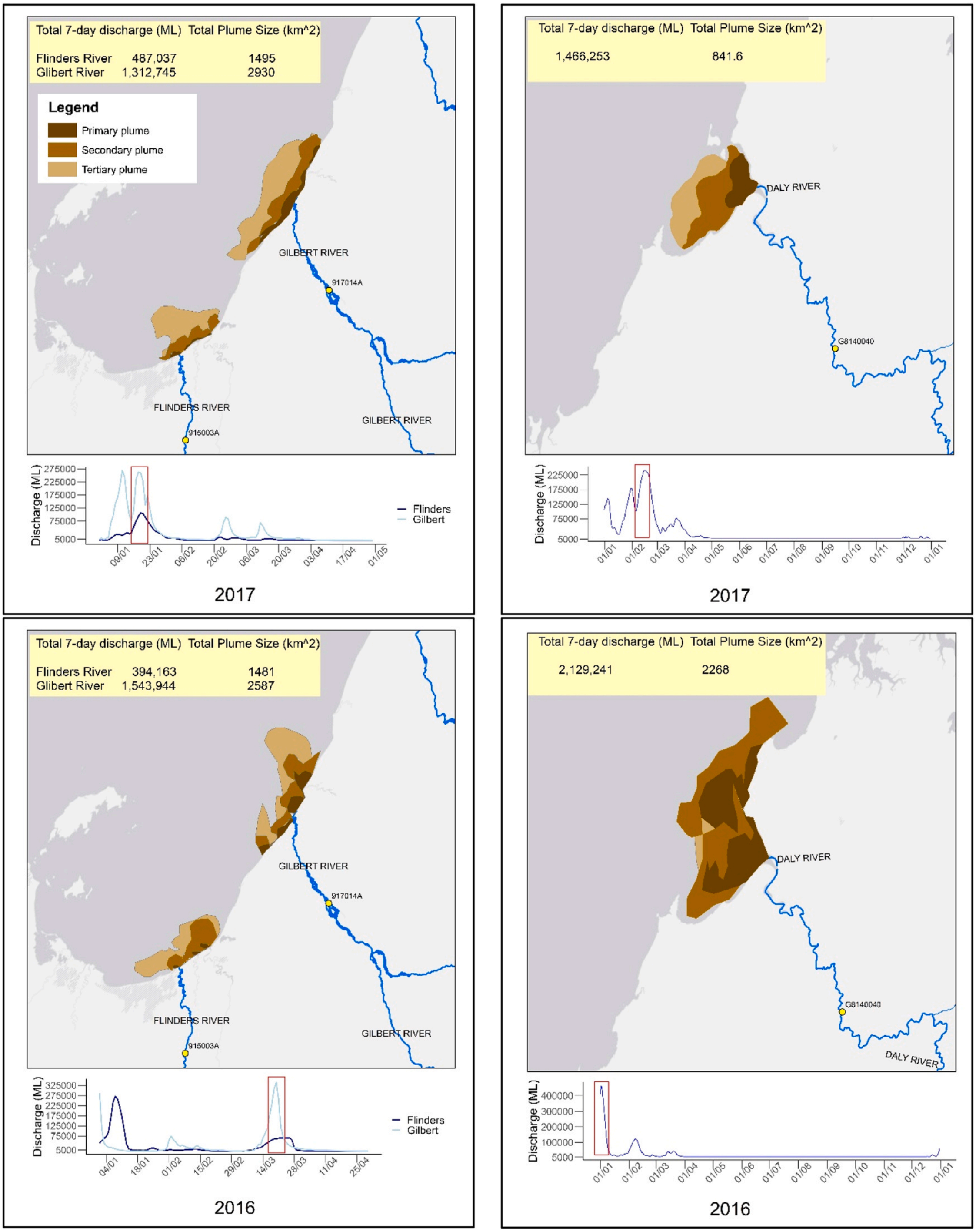
multiple products encompassing lags of 3–5 days (where cloud-free satellite imagery was available) were used to assess quantifiable changes in the chlor_a spatial extent in the week following peak flow events. Regression analyses were conducted between 7-day flow during peak flood events and total plume size, and 7-day flow and tertiary plume size.

2.5. Prawn fishery and river discharge

The northern prawn fishery (NPF) is divided into 15 statistical regions where catch is recorded separately (Fig. 2). To establish the relationships between the river catchment discharge and prawn catch, linear models were produced between annual river discharge and



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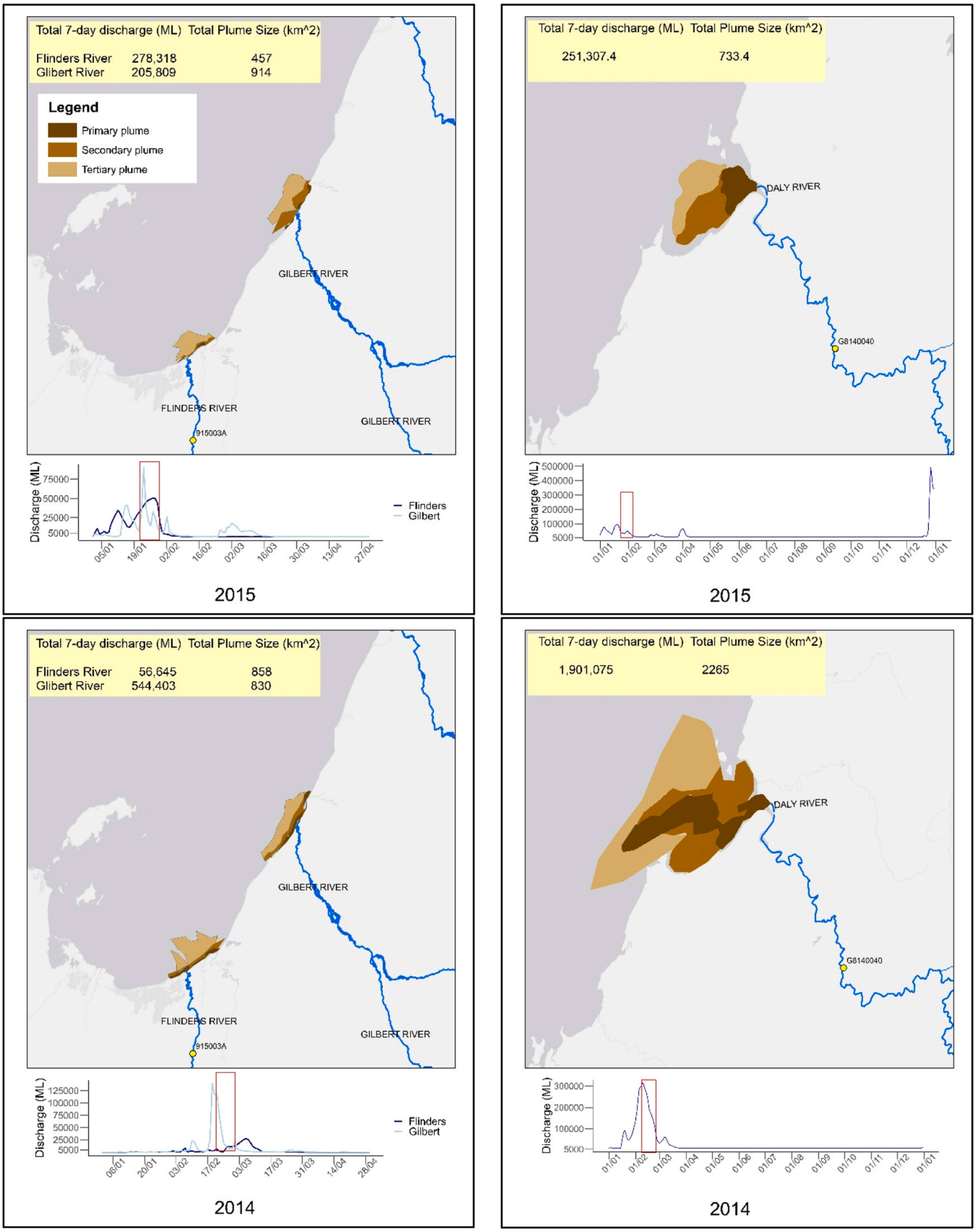
annual prawn catch in the fishing regions of Bold (south-east Gulf of Carpentaria) and Fog Bay (adjacent Daly River). Prawn catch data was retrieved from the Northern Prawn Fisheries Data Summary (https://www.afma.gov.au/fisheries/northern-prawn-fishery/data-summaries-northern-prawn-fishery). There are caveats that should be acknowledged with the prawn catch data, in that catch can be related to effort, which is not always consistent, but dependent on many factors including fuel and other costs, and economic take limits. Additionally, prawn catch data relies on logbooks that are filled at sea by fishers, and may also be of inconsistent accuracy.



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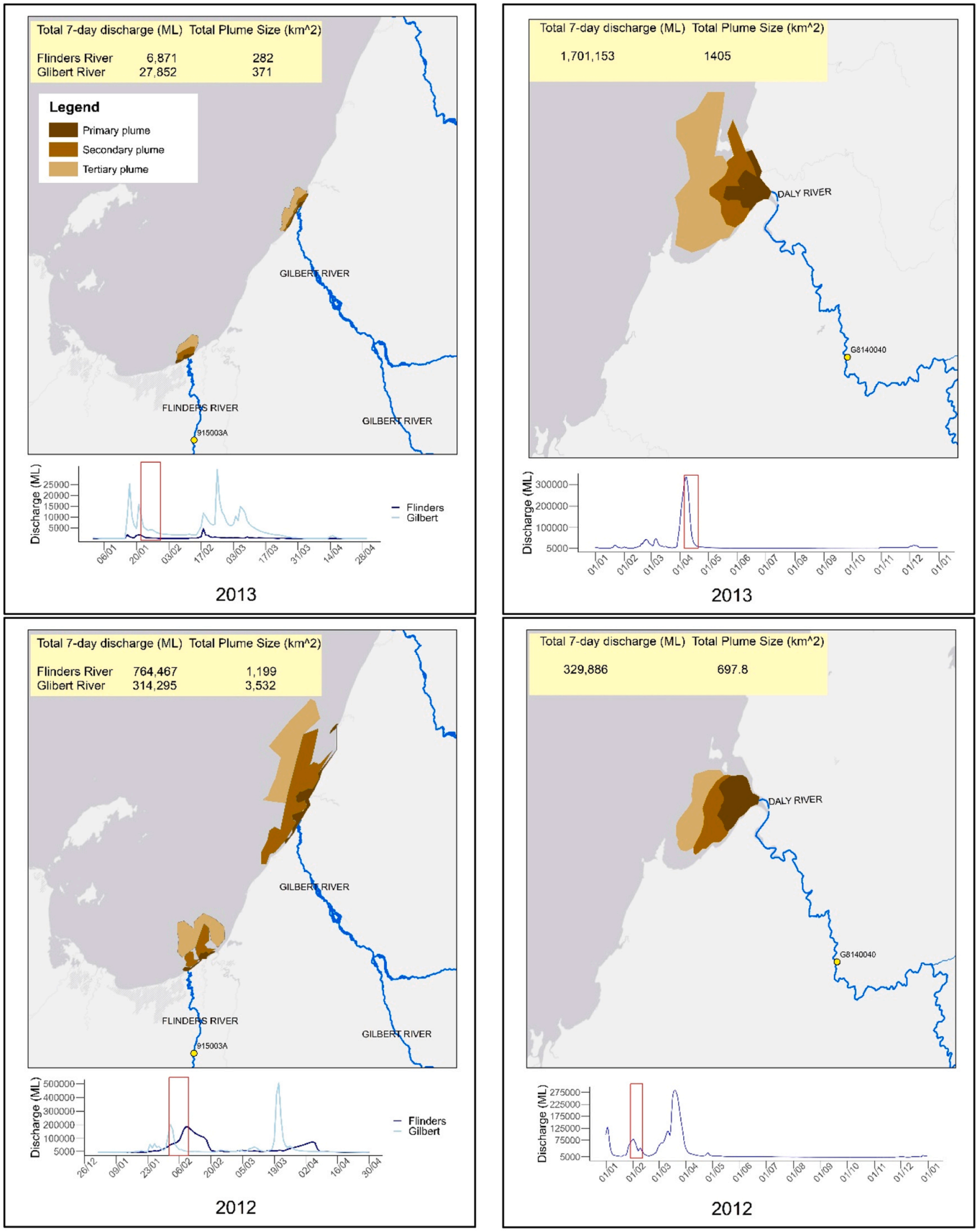
2.6. Climate change and rainfall

Future climate predictions were retrieved from the Climate Change Web Portal (Earth Systems Research Laboratory, 2014), developed by the National Oceanic and Atmospheric Administration's (NOAA) to collate and regionally downscale (to approximately 1° spatial resolution) the climate model outputs from the Coupled Model Intercomparison Project phase 6 (CMIP6; Eyring et al., 2016). The portal calculates the anomaly as the difference in the mean precipitation between the future climate (we used 2070–2099) and the model baseline reference period of 1985–2014, under the different Shared Socio-economic Pathways (SSP's). Six climate models were chosen for use in the analysis as they have shown the best performance against historical climate for northern Australia (Ridder et al., 2021). The models used were CESM2-WACCM (NSF-DOE-NCAR, USA), FGOALS-G3 (Chinese Academy of Sciences), INM-CM5–0 (INM, Russia), ACCESS-CM2 (CSIRO-BOM, Australia), MRI-ESM2–0 (MPI-M, Germany) and NorESM2-MM (NCC, Norway). The scenario SSP5–8.5 was used as it projects the most global warming of all Shared Socio-economic Pathways, representing the continuation of a fossil fuel intensive world. In research applications, SSP5–8.5 is often used as the climate signal is strongest under this emissions scenario, making the signal most easily identifiable from the background noise of natural climate variability. Projected future rainfall anomalies, both seasonal and annual, were extracted for each climate



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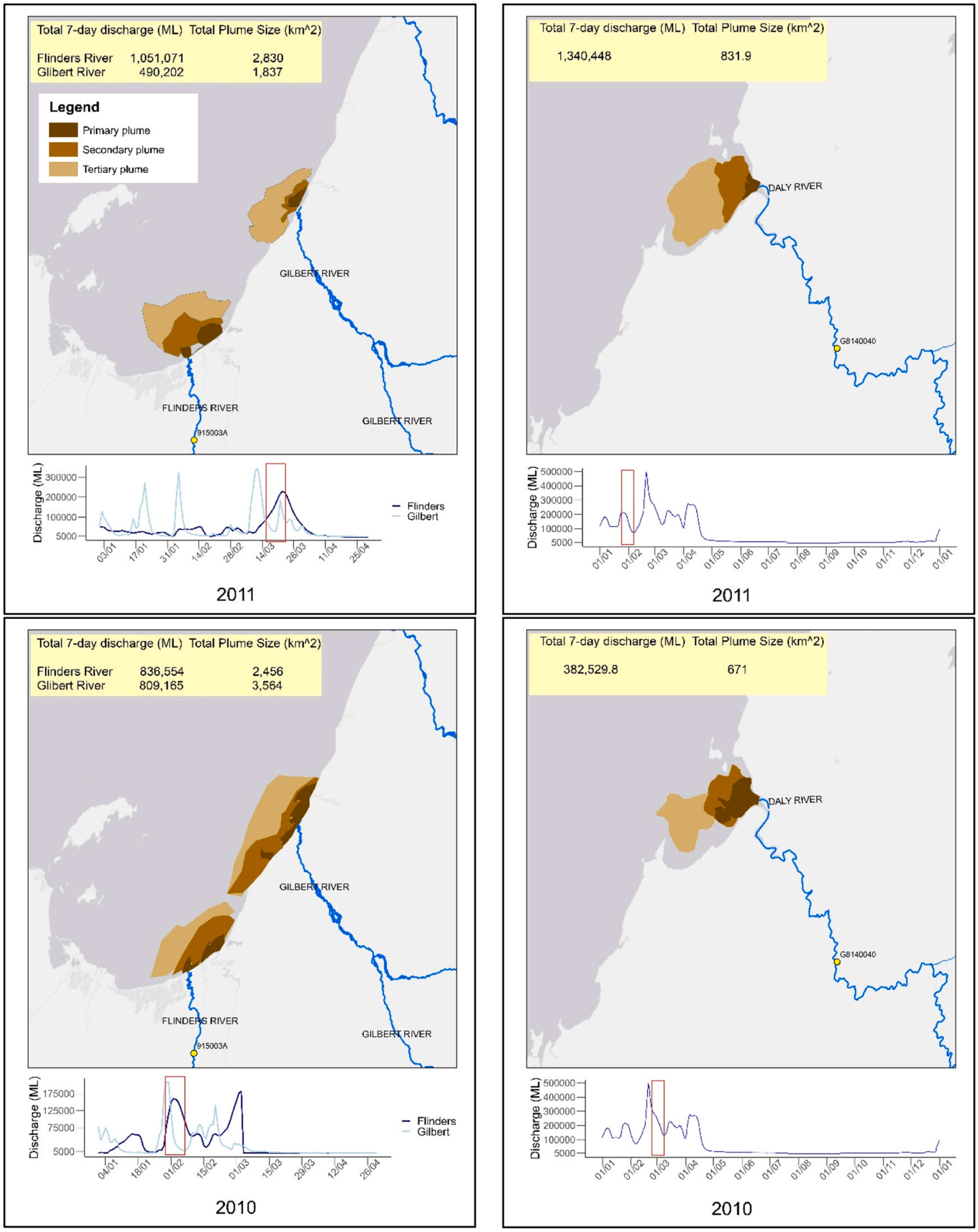
model and the percentage increase or decrease in rainfall against baseline values (1995–2014) was calculated for each region (Gilbert, Flinders, and Daly catchments).

The projected percentage reduction in rainfall was applied to the 7-day flow – plume size regression models, with the assumption that the percentage reduction in rainfall would be the same as the percentage reduction in hydrological flow, and the projected changes in flood plume extent in square km calculated.

3. Results

3.1. Annual flows

The Flinders River hydrological flow was highly variable (Fig. 3) across the study period 2003–2023, with the highest sustained flows in 2009 (total annual flow of 19,503,455 ML), followed by 2019 (7563,696 ML) and 2011 (5029,243 ML). The most significant flood event took place in 2019 where daily flow peaked at 652,117 ML. In contrast, very low flows were experienced in 2013 (total annual flow of 58,949 ML), with low flows also in 2014 (327,320 ML) and 2007 (397,489 ML).



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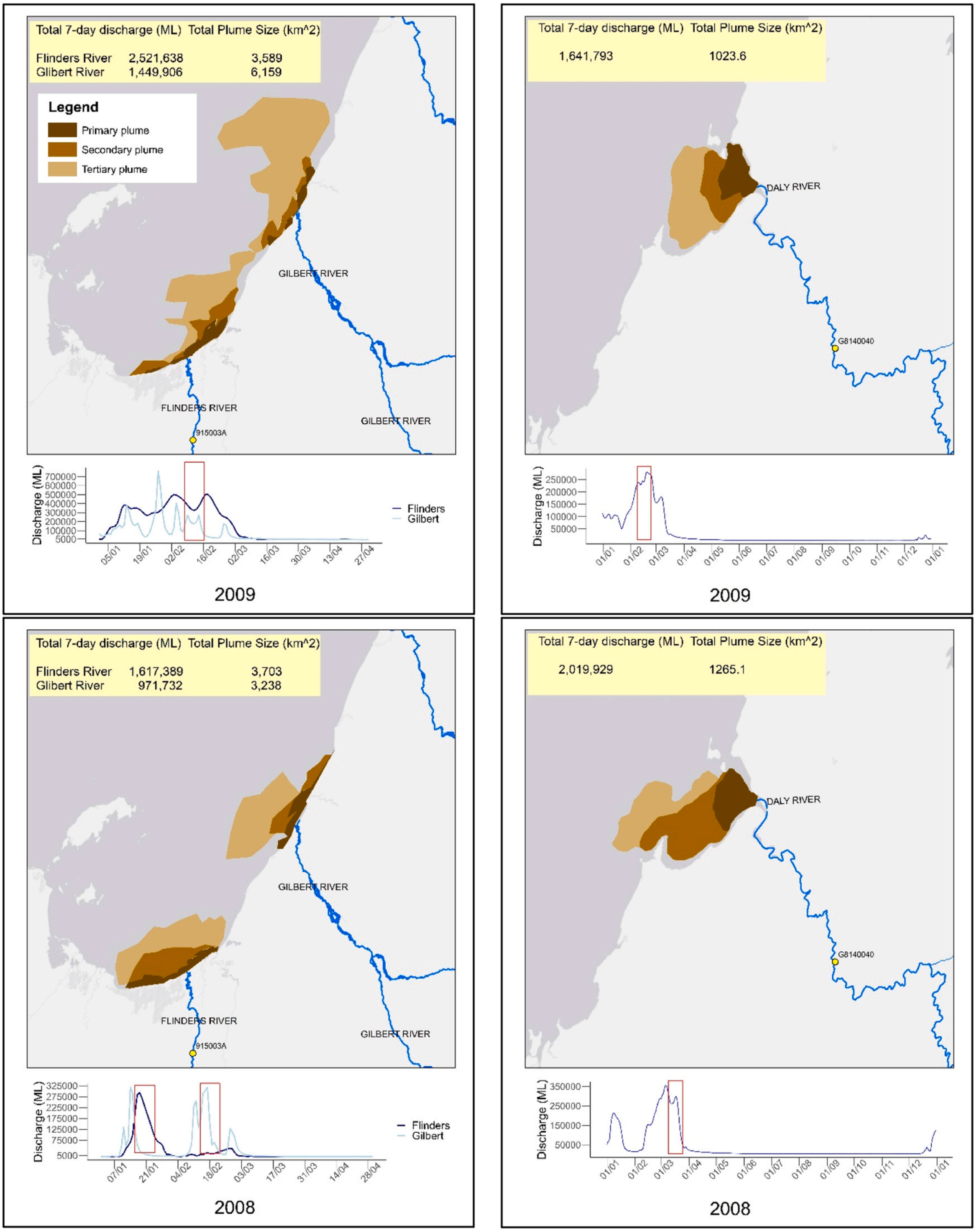
In contrast to the Flinders River, the Gilbert River (Fig. 3) had more sustained flows but smaller peak flood events. The highest annual flows were in 2023 (total annual flow of 12,320,221 ML), 2009 (9345,647 ML *upstream data only) and 2021 (7152,598 ML), and the lowest flow was in 2022 (2656,258 ML). Peak downstream flood events were similar across most years between 2016 and 2023 where they did not exceed 353,000 ML/day.

The Daly River (Fig. 3) exhibited the largest flow volumes of the three catchments, with 2011 having an annual flow of 23,820,198 ML, followed by 2004 with 19,762,590 ML and 2008 15,520,934 ML. The year 2019 saw record flooding in the catchment, with hydrological stations becoming disabled for most of the wet season and flows were unable to be recorded accurately. The flood plume analysis for 2019 was therefore not carried out during a peak flood event but during a smaller flow period prior to the flooding. Low flow years include 2022 (3826,776 ML) and 2020 (2564,811 ML).

3.2. Flood plume mapping

Over the 20-year study period, flood plumes in the Gilbert, Flinders and Daly Rivers were highly variable (Fig. 4; Fig. 5). The largest plume event from the Flinders River occurred in 2019 (plume size 6603 km^2), coinciding with the largest peak flood event ever recorded in the river, while the next largest plumes were found in 2008 and 2009 (3703 km^2



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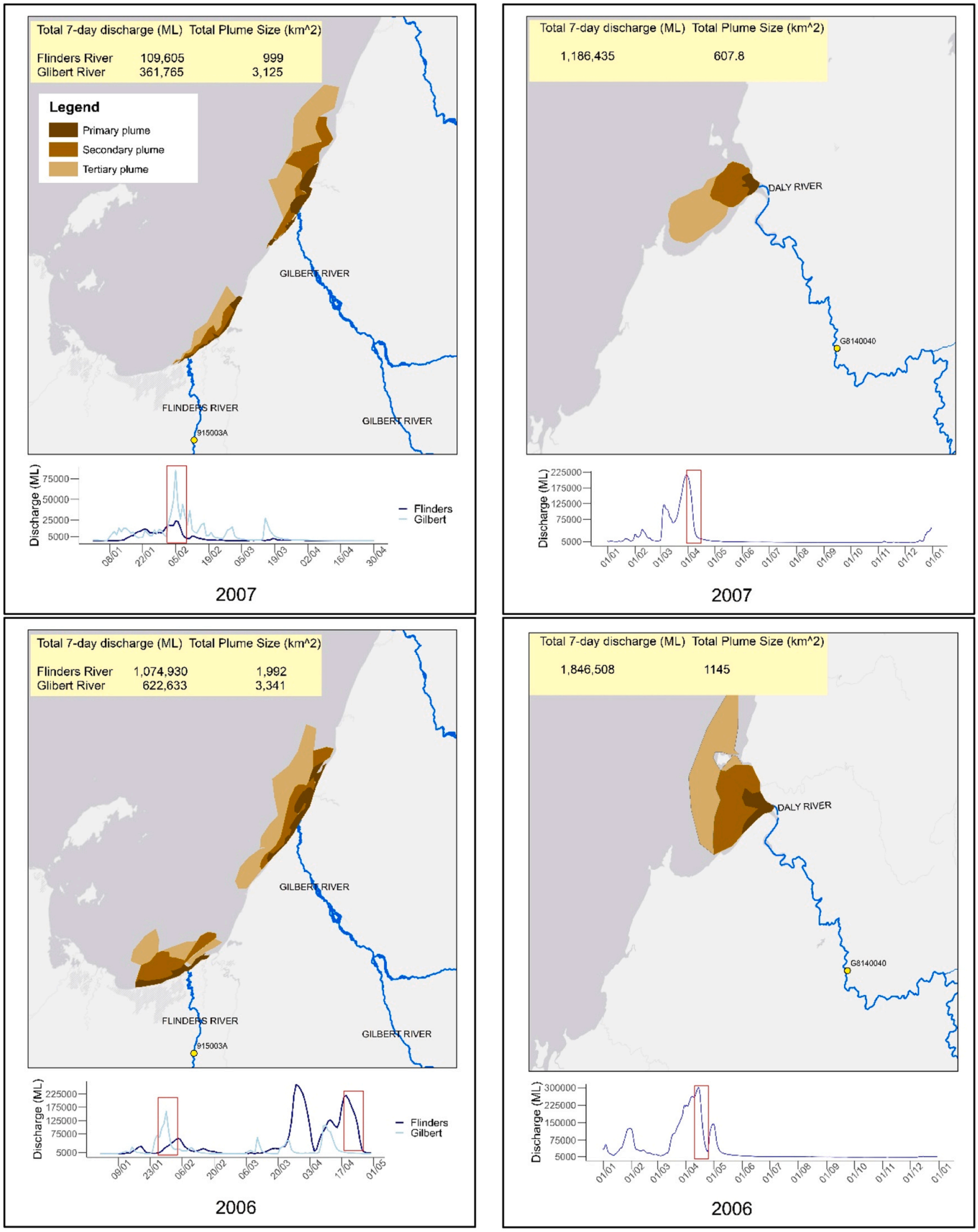
and 3589 km^2 respectively). The Gilbert River had its largest plumes of the study period in 2009 (6159 km^2) followed by 2012 and 2019 (4927 km^2 and 4233 km^2 respectively), with all years from 2006 – 2010 also having large plumes (>3000 km^2). The Daly River had its largest plume events of this study in 2014 (2265 km^2), 2016 (2268 km^2), and 2023 (2180 km^2), due to an extended flow event over several weeks that lead to a larger-than-normal tertiary plume. Note that 2019 was potentially a larger event for the Daly however flooding caused the loss of hydrological data for most of the wet season and there were few opportunities for cloud-free remotely sensed imagery.



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3.3. Linear regression analysis

The relationships between flood plume extent and hydrological flows were significant for all three rivers in this study, with the Flinders and Gilbert Rivers exhibiting stronger relationships than the Daly River.

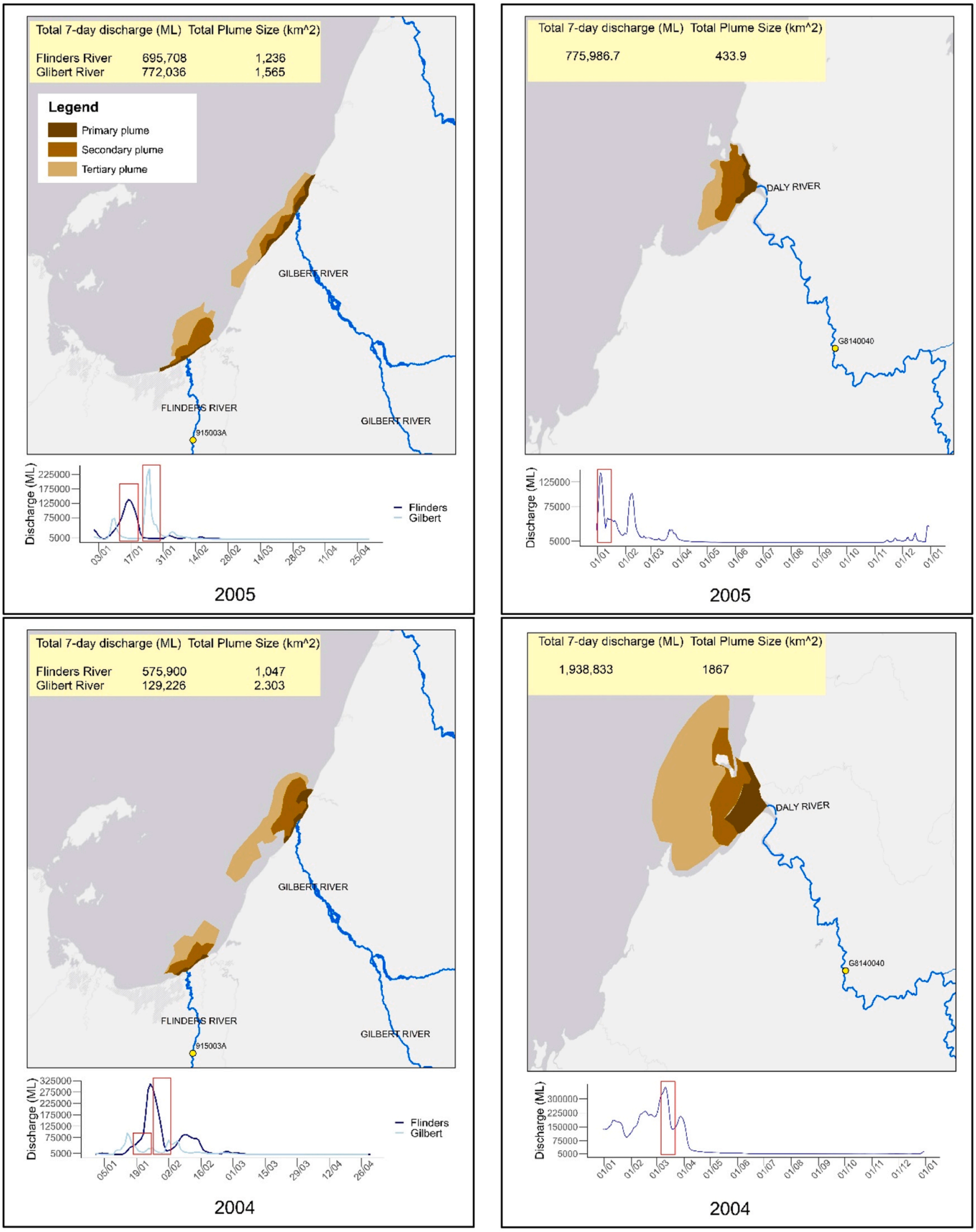
Scatterplots illustrating the relationships between river flow (7-day total) and plume size (sum of primary, secondary, tertiary) are presented in Fig. 6. The regression coefficients, standard errors, and significance levels are summarized in Supp. Tables 6–8. Linear regression analyses examining the relationship between river flow and plume size for the Flinders, Gilbert and Daly Rivers were as follows.

3.3.1. Flinders River

The regression model explained a substantial proportion of the variance in plume size, with an R-squared value of 0.8613. The F-statistic was significant ($F(1, 19) = 117.9$, $p < 0.001$), indicating that the regression model as a whole was statistically significant. The model was specified as Flinders plume size (sq km) = 678.0 + 0.0014 * 7-day flow (ML)

3.3.2. Gilbert River

The regression model explained a substantial proportion of the variance in plume size, with an R-squared value of 0.848. The F-statistic was significant ($F(1, 6) = 33.48$, $p < 0.01$), indicating that the



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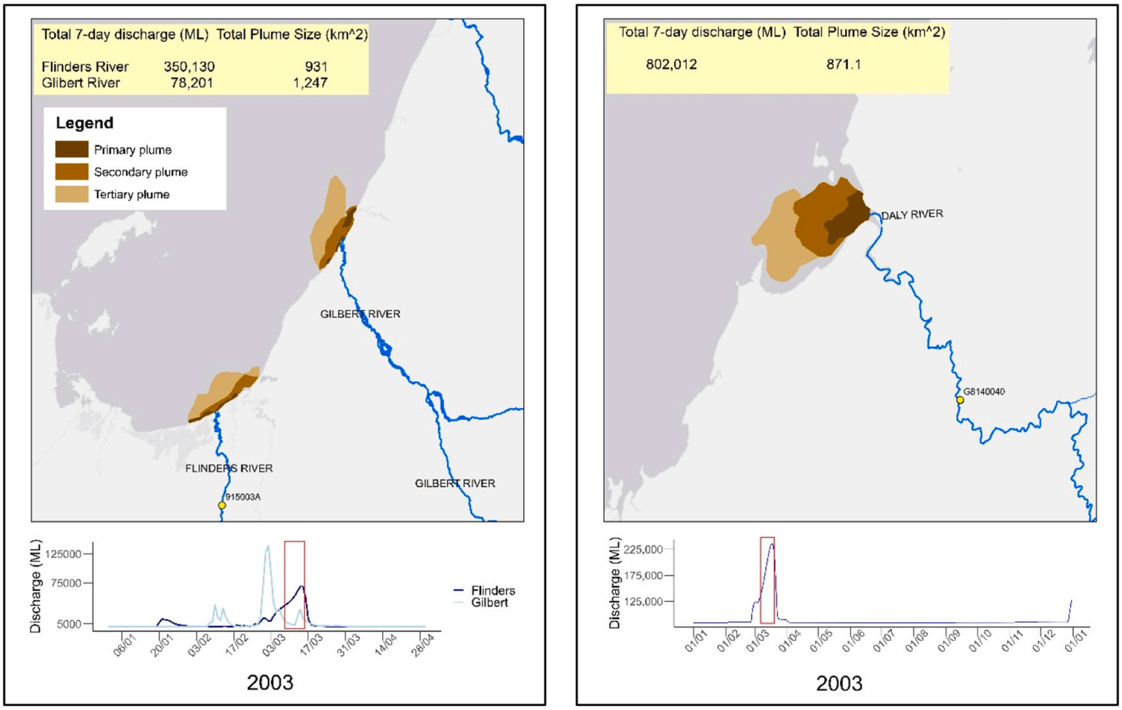
regression model as a whole was statistically significant. The model was specified as Gilbert plume size (sq km)= 436.4 + 0.0017 * 7-day flow (ML)

3.3.3. Daly River

The regression model explained a smaller proportion of the variance in plume size compared to the Gilbert and Flinders models with an R-squared value of 0.706. The F-statistic was however still highly significant ($F(1,19) = 45.5$, $p < 0.001$). The model was specified as Daly plume size (sq km) = 193.8 + 0.000776 * 7-day flow (ML).

3.4. Chlorophyll-a

Chlorophyll-*a* presence in the southern Gulf of Carpentaria was significantly associated with flood plume size from the Flinders and Gilbert Rivers (Fig. 7; model summary results in Appendix). The strongest relationships were found between tertiary plume size and Chlorophyll-*a* (lag), with r-squared values of 0.383 and 0.718 respectively. The relationship between total plume size (combined primary, secondary and tertiary plume) was less strong, but still significant, for the Flinders and Gilbert Rivers, with r-squared values of 0.548 and 0.379 respectively. In contrast, the Daly River only had a significant relationship between tertiary plume size and lagged chlorophyll-a (Fig. 7). There was



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no significant relationship between non-lagged chlorophyll-a and the total plume size at the direct 7-day flood event for any river, indicating that it took days for the Chl-a to develop after each flood event.

3.5. Prawn fishery and river discharge

There was a significant relationship ($p < 0.05$, $R = 0.286$) between annual Flinders River discharge and annual banana prawn catch (Fig. 8). There was also a significant relationship ($p < 0.05$, $R = 0.255$) between annual Daly River discharge and annual banana prawn catch (Fig. 8). There was no significant effect of the Gilbert River annual flow on any prawn fishery. Endeavour and tiger prawn catch was not associated with river discharge at the Flinders or Daly Rivers.

3.6. Climate change and rainfall

Projected rainfall anomalies from an ensemble of six CMIP6 global climate models, under climate forcing scenario SSP5–8.5 are presented in Table 1.

Predicted future precipitation anomalies from the ensemble (average of all six models) showed reduced rainfall for all river catchments, with annual reductions by 2070–2099 (from a baseline of 1985–2014 average rainfall) of 13.8 % for the Gilbert River, 10.4 % for the Flinders and 5.1 % for the Daly. There was large variation between the six individual climate models, with predictions ranging from a 26 % decrease (Flinders catchment under CESM2-WACCM modelling) to a 13.6 % increase (Daly catchment under MRI-ESM2-MM) in annual rainfall. Seasonal anomalies also varied between models, with the ensemble predicting highest reductions during the wet season months of January- March and October-December. The Gilbert and Flinders catchment also show fairly large reductions in April to June and July to September rainfall, with the Daly showing smaller reductions over the dry season.

When the projected percentage decreases in rainfall were applied to the linear models describing flow contribution to flood plume size, reductions in the extent of flood plumes were in the range of 26 km^2 – 579 km^2 for the Flinders River, 108 km^2 – 448 km^2 for the Gilbert River and 5 km^2 to 100 km^2 for the Daly River, when based on the historic flows used in this study.

4. Discussion

4.1. Tropical estuarine systems and coastal productivity

Northern Australia's major rivers discharge into extensive estuarine systems that serve as ecologically rich transition zones between riverine and marine environments. These tropical estuaries support dense macroflora such as mangroves and seagrasses, as well as abundant microflora that underpin much of the primary productivity in coastal ecosystems (Burford et al., 2012; Burford et al., 2016). These habitats are crucial nursery areas for commercially important species, including banana prawns (*Penaeus merguiensis*), which depend on mangrove and mudbank environments during their juvenile stages (Vance et al., 1990). High river flows and associated flood plumes deliver nutrients such as nitrogen and phosphorus to coastal waters, stimulating phytoplankton and microflora growth and enhancing the food web that supports juvenile and sub-adult prawns (Brodie et al., 2010). These nutrient pulses promote increased primary productivity, which cascades through the food web, contributing to observed increases in commercial catch rates during high-flow years. This linkage demonstrates how freshwater inflow can directly enhance estuarine and nearshore ecosystem services, particularly for species of commercial value.

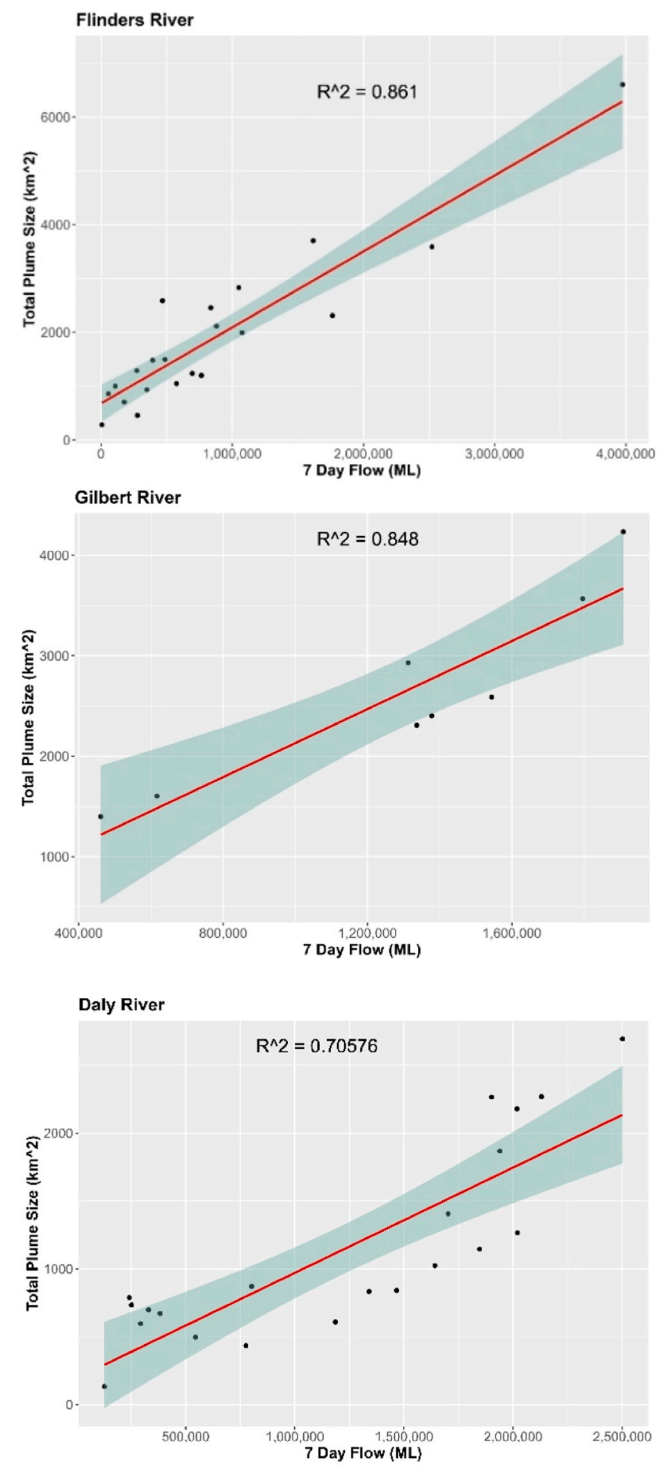

Fig. 6. Relationship between total plume size and 7-day flow from the Flinders, Gilbert and Daly catchments. The plots show a linear regression model with a 95 % confidence interval (green shaded area) around the regression line (red). The model explains a proportion of the variance in plume size as indicated by the R^2 value on each plot. The confidence interval reflects the uncertainty in the estimated relationship, with a narrower interval suggesting higher confidence in the model's prediction.

4.2. Banana prawn ecology and hydrological cues

The life cycle of banana prawns is tightly coupled with the wet-dry hydrological cycle. Adults spawn offshore, larvae develop in marine waters, and post-larvae migrate into estuaries where they reside for 3–5 months. Emigration of sub-adults is cued by freshwater flood events (Broadley et al., 2020; Vance et al., 1996). Enhanced productivity within flood plumes likely promotes faster growth and survival of prawns during the critical offshore transition (Fig. 9). The interplay between flow timing, nutrient availability, and habitat use underscores the biological importance of wet season flows.

4.3. Plume variability and coastal retention

Flood plumes from all three catchments (Flinders, Gilbert, and Daly) were highly variable over the 20-year analysis period, reflecting inter-annual differences in catchment rainfall. The Flinders and Gilbert Rivers often produced plumes that spread alongshore and extended offshore, shaped by prevailing wind and current conditions. In contrast, the Daly River's plume remained largely confined to Anson Bay due to its more enclosed geomorphology, although wind still influenced its tertiary plume extent.

The southern Gulf of Carpentaria (~50,000 km2) offers a longer residence time for nutrient-laden waters compared to the smaller, more open Anson Bay (~2500 km2). This disparity likely affects the duration and intensity of primary productivity responses to flooding. These observations align with earlier work by Wolanski (1993a), (1993b), who found that the morphology of coastal embayments significantly influences plume retention and productivity. Further analysis using shorter temporal windows or high-resolution wind datasets could clarify these relationships.

4.4. Chlorophyll-a as a proxy for plume influence

This study has quantified the spatial extent of flood plumes in three catchments across northern Australia; however, it did not quantify Total Suspended Sediments (TSS), i.e., the total discharge (in weight) of sediment, or the mg/L in each pixel of the satellite image. The most accurate method for quantifying TSS over large spatial scales is taking water samples and conducting in-situ radiometry to ground-truth satellite reflectance data. However, sampling in the Gulf of Carpentaria and Anson Bay during the wet season and peak flow events is prohibited by the remoteness and flooded access of these regions.

While applying third-party algorithms for quantifying TSS from satellite data is feasible (e.g., Cartwright et al., 2021), the primary plume often saturates the satellite sensor, and in this case cloud/stray light masking removed critical data from high-flow regions. An example of this is shown in Fig. 8, where the chlorophyll reflectance band displays no data (white space) in the concentrated primary plume region of the flood event.

While this limitation affects TSS quantification, it does not hinder chlorophyll-a (Chl-a) estimation. Chl-a is less associated with the primary plume and instead emerges as the primary plume evolves into secondary and tertiary plumes. Chl-a concentrations increase in the weeks following flood events, coinciding with the expansion of the tertiary plume and nutrient uptake by phytoplankton (Fig. 10). While the mean values in Fig. 10 represent a spatial average (ranging from $<$1 mg/m3 to $>$20 mg/m3), they still illustrate the broader trend of plume-driven productivity.

4.5. Regional fishery comparisons: bold vs. fog bay

The Bold fishery, where the Flinders and Gilbert Rivers enter the Gulf, consistently outperformed other NPF regions, producing 65–200 % more banana prawns than any other zone (Fig. 11). This productivity may result from nutrient-laden waters being partially 'trapped' in the shallow head of the Gulf, enhancing primary productivity and prawn survival. Similar dynamics occur in Western Australia's Exmouth Gulf and Shark Bay, which also support large prawn (Kangas et al., 2015, Kangas et al., 2015a). In contrast, the Fog Bay region, fed by the Daly River, is less productive despite being larger. Its more complex coastline,

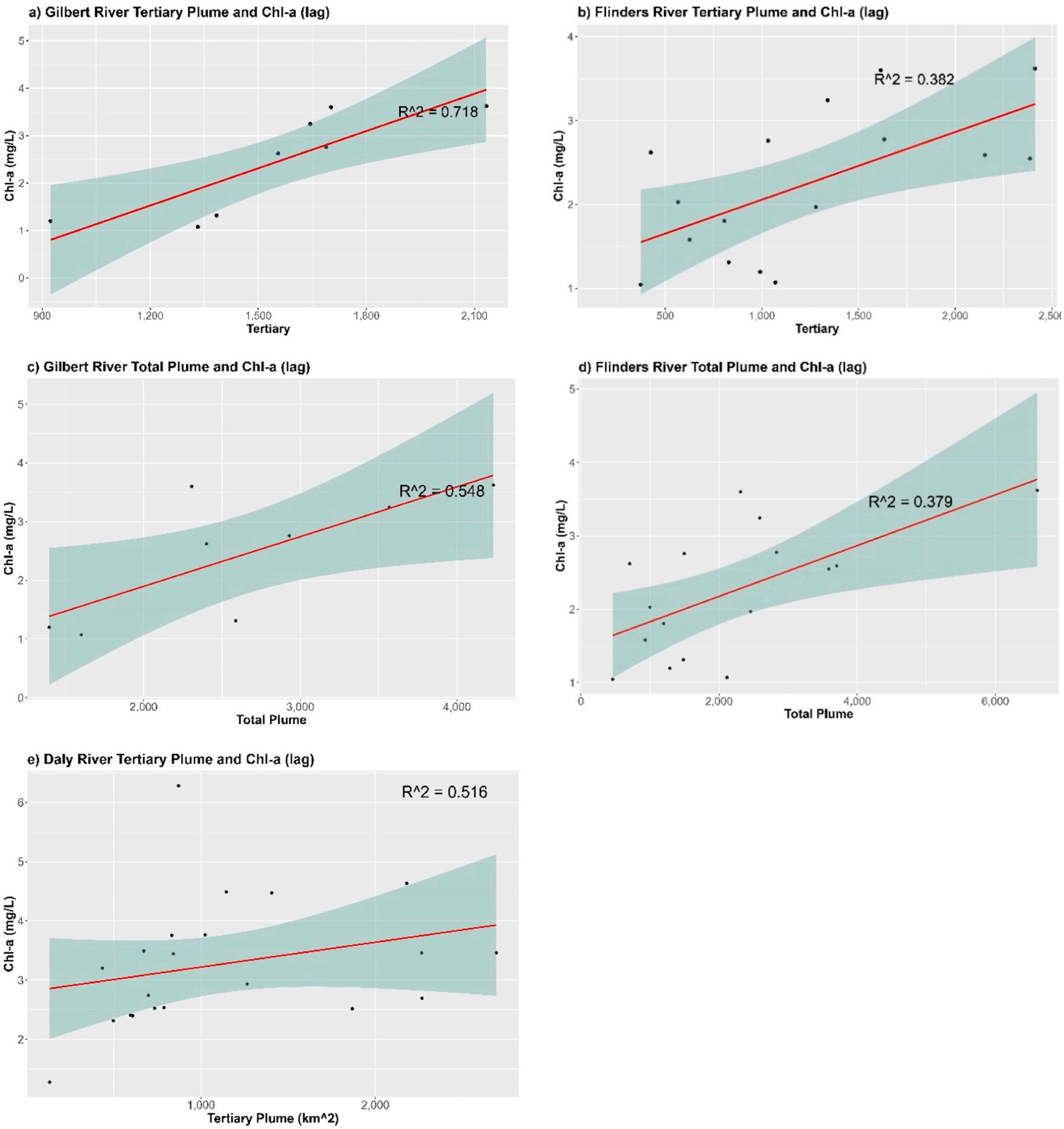

Fig. 7. Relationship between total plume size/ tertiary plume size, and chlorophyll-a concentration (Chl-a) at three river catchments across northern Australia. a) Gilbert River tertiary plume and chlorophyll-a production; b) Flinders River tertiary plume and chlorophyll-a production; c) Gilbert River total flood plume (primary, secondary and tertiary combined) and chlorophyll-a production; d) Flinders River total flood plume (primary, secondary and tertiary combined) and chlorophyll-a production; e) Daly River tertiary plume and chlorophyll-a production. The plots show a linear regression model with a 95 % confidence interval (green shaded area) around the regression line (red). The model explains a proportion of the variance in Chl-a as indicated by the R^2 value on each plot. The confidence interval reflects the uncertainty in the estimated relationship, with a narrower interval suggesting higher confidence in the model's prediction.

multiple river inputs, and mix of banana prawn species (*P. merguiensis* in the north, *P. indicus* in the south) also complicates attribution of catch success to any single river (Kenyon et al., 2004; Plagányi et al., 2021). Juvenile habitats and fishing grounds are also more dispersed, reducing the clarity of flow-catch relationships.

4.6. *Climate risks to future flow and productivity*

Climate models offer inconsistent projections of rainfall in northern Australia by 2079–2099, ranging from declines to increases. When considered as an ensemble, the models predict an overall decrease in rainfall, with the Gilbert River catchment expected to see the largest reduction (13.8 %), followed by the Flinders (10.4 %). These reductions

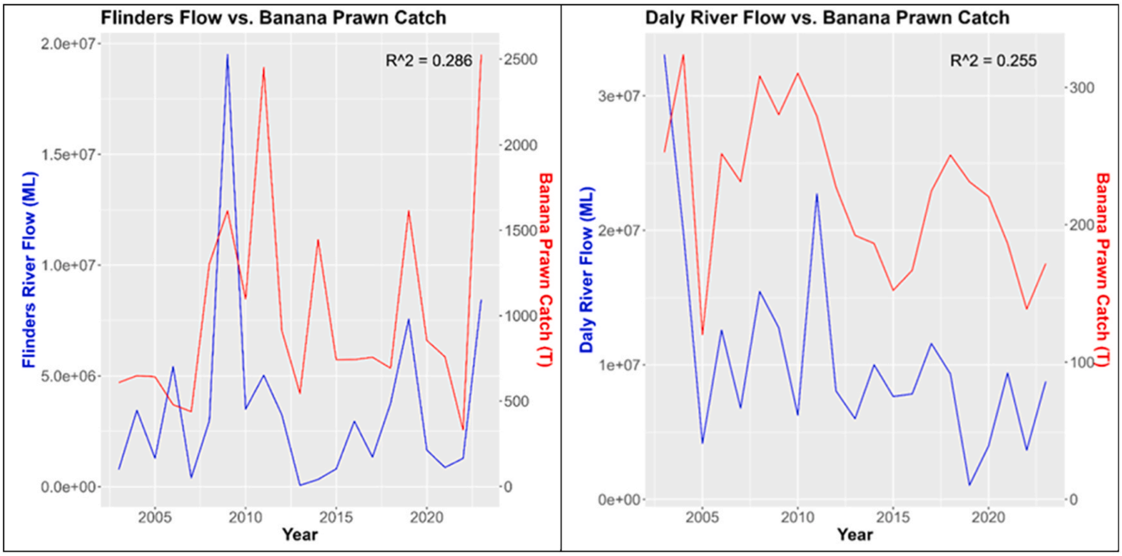

Fig. 8. a) The linear relationship between annual water discharge from the Flinders River (at Walkers Bend) and annual banana prawn catch.in the Bold (south-east Gulf of Carpentaria) fishery; and b) The linear relationship between annual water discharge from the Daly River (at Nancar station) and annual banana prawn catch. in the Fog Bay fishery. Note that this relationship would likely have been stronger if the 2019 extreme rainfall event had been captured by the hydrological station that failed due to flooding.

Table 1
Future annual (Ann) and seasonal (JFM- January, February, March; AMJ – April, May, June; JAS – July, August, September; OND – October, November, December) precipitation anomalies by 2070–2099 under climate forcing scenario SSP5-8.5.

Gilbert catchment precipitation anomalies (mm) – Mean and standard deviation (SD)											% change
SP5-8.5											
	Ann	**SD**	**JFM**	**SD**	**AMJ**	**SD**	**JAS**	**SD**	**OND**	**SD**	
CESM2-WACCM	−277	21	−210	15	−19	5	3	10	−59	3	−22.5
FGOALS-G3	−117	61	−75	36	−13	13	1	2	−37	6	−14
INM-CM5–0	62	68	93	8	−19	3	−14	2	30	22	6.9
ACCESS-CM2	−119	13	−56	13	−39	7	−20	5	−6	3	−30
MRI-ESM2–0	15	22	61	33	−32	10	−11	1	−21	8	4.7
NorESM2-MM	−239	25	−43	11	−9	4	−23	7	−145	18	−22.6
Ensemble	**−112**	**35**	**−38**	**19**	**−22**	**7**	**−11**	**5**	**−40**	**10**	**−13.8**
Flinders catchment precipitation anomalies (mm) – Mean and standard deviation (SD)											% change
SP5–8.5											
	Ann	**SD**	**JFM**	**SD**	**AMJ**	**SD**	**JAS**	**SD**	**OND**	**SD**	
CESM2-WACCM	−254	38	−178	29	−24	13	−20	8	−43	7	−26.5
FGOALS-G3	−9	21	−8	12	12	9	−6	4	−22	10	−1.5
INM-CM5–0	81	55	61	37	−31	6	−10	6	46	13	7.7
ACCESS-CM2	−95	19	−45	10	−26	9	−16	6	−5	4	−16.2
MRI-ESM2–0	35	34	71	20	−13	10	−17	3	−2	6	8.2
NorESM2-MM	−237	21	−67	28	−17	8	−39	11	−97	15	−23.6
Ensemble	**−80**	**31**	**−28**	**23**	**−16**	**9**	**−18**	**6**	**−20**	**15**	**−10.4**
Daly catchment precipitation anomalies (mm) – Mean and standard deviation (SD)											% change
SP5–8.5											
	Ann	**SD**	**JFM**	**SD**	**AMJ**	**SD**	**JAS**	**SD**	**OND**	**SD**	
CESM2-WACCM	−203	23	−99	18	−33	25	−1	1	−57	3	−15.1
FGOALS-G3	−174	69	−184	52	75	6	−1	1	−53	23	−9.9
INM-CM5–0	50	50	24	37	−31	7	−9	3	50	13	3.3
ACCESS-CM2	17	57	75	55	−51	3	−8	2	−4	6	1.6
MRI-ESM2–0	131	9	133	15	14	5	−6	1	−24	14	13.6
NorESM2-MM	−237	31	−124	11	2	7	−12	3	−95	29	−15.7
Ensemble	**−69**	**40**	**−29**	**31**	**−4**	**9**	**−6**	**2**	**−31**	**15**	**−5.1**

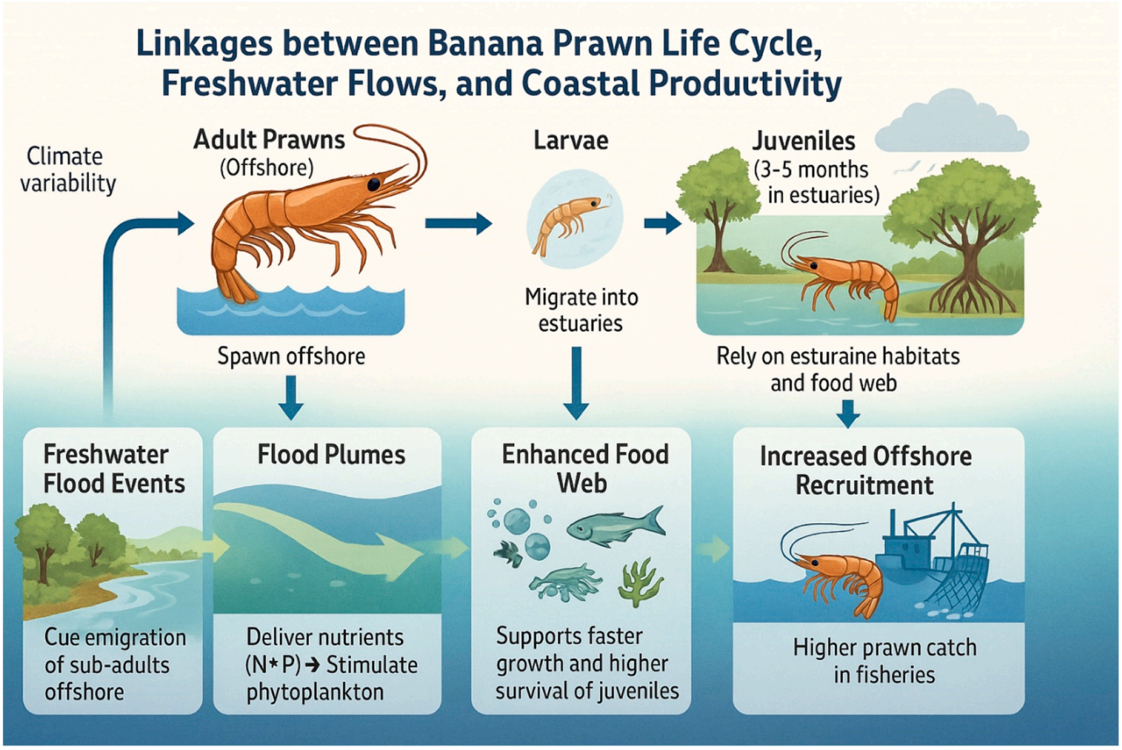

Fig. 9. Conceptual diagram illustrating the life cycle of banana prawns and their ecological linkages to freshwater flows and coastal productivity. Freshwater flood events drive nutrient-rich plumes that enhance coastal food webs, supporting juvenile prawn growth and leading to increased offshore recruitment and fishery yields.

are concentrated in the wet season months (October–March), which are critical for flood events.

Reduced rainfall could decrease flood plume extent and productivity, especially in regions like the Bold fishery. Conversely, longer dry seasons could increase erosion and turbidity, further affecting nearshore processes. The Daly River catchment shows the smallest projected rainfall reduction (5.1 %), but almost all occurs during the wet season, which is crucial for aquifer recharge and dry-season flows (Barton and Pantus, 2010; Smerdon et al., 2012).

4.7. Management implications and water allocation

These findings underscore the need for integrated water management that includes the receiving marine environment. The Northern Territory Government's current water allocation practices—lacking formal plans and granting free water licenses—have been criticized by scientists and Traditional Owners (Currell et al., 2024; O'Donnell et al., 2022). Given potential rainfall declines, especially in arid sub-catchments, future allocations should consider the downstream ecological and economic value of flood plumes.

In Queensland, the ongoing review of the Gulf Water Plan—which includes the Flinders and Gilbert catchments—presents an opportunity to incorporate downstream marine linkages into water allocation decisions. This region is experiencing growing demand for water to support irrigated agriculture and mineral extraction, and nearly 25,000 GL of water flows annually from these catchments into the Gulf of Carpentaria, sustaining valuable fisheries. As the plan moves through its technical assessment and consultation stages, it is essential that the role of flood plumes in coastal productivity is formally recognised in water planning frameworks (Queensland Government, 2024).

4.8. Knowledge gaps and future research

Several uncertainties remain. It is unclear whether the marine habitat maintains a stable level of productivity that supports prawn survival during high-flow years or whether nutrient pulses actively expand habitat carrying capacity. Key questions include:

Is the Bold catch zone underutilised in low-flow years?

Does carrying capacity expand during high-flow years to support greater prawn abundance?

There is limited understanding of sub-adult prawn survival and distribution after estuarine emigration. Factors like predation risk in turbid waters, foraging success, and dispersal patterns remain unstudied. These gaps likely apply to other fish and crustaceans exploiting plume productivity. Incorporating high-resolution wind data, field sampling, and biophysical modelling would greatly enhance future analyses.

Other important gaps relate to hydrological flows and flood plume dynamics themselves. For example, future research could investigate how plume persistence is influenced by estuarine geomorphology (which is changeable) and wind regimes, or how frequently nutrient-rich conditions persist beyond the immediate post-flood window. Improved characterisation of the biogeochemical transformations within secondary and tertiary plumes—particularly for nitrogen and carbon cycling—would help clarify how productivity is sustained over time. More detailed analysis of plume retention zones, stratification dynamics, and cross-shelf transport processes would also enhance understanding of how freshwater flow regimes underpin marine ecosystem productivity.

5. Conclusion

Wet season river flow is highly variable across northern Australia and strongly influences the spatial extent of coastal flood plumes. These plumes, particularly in the southern Gulf of Carpentaria, contribute to Australia's most productive prawn fisheries. Climate change projections suggest future declines in rainfall could reduce plume extent, with implications for coastal productivity and fishery success.

A whole-of-catchment approach that includes estuarine and marine receiving environments is essential for sustainable water allocation. Future work should explore whether nutrient-driven productivity

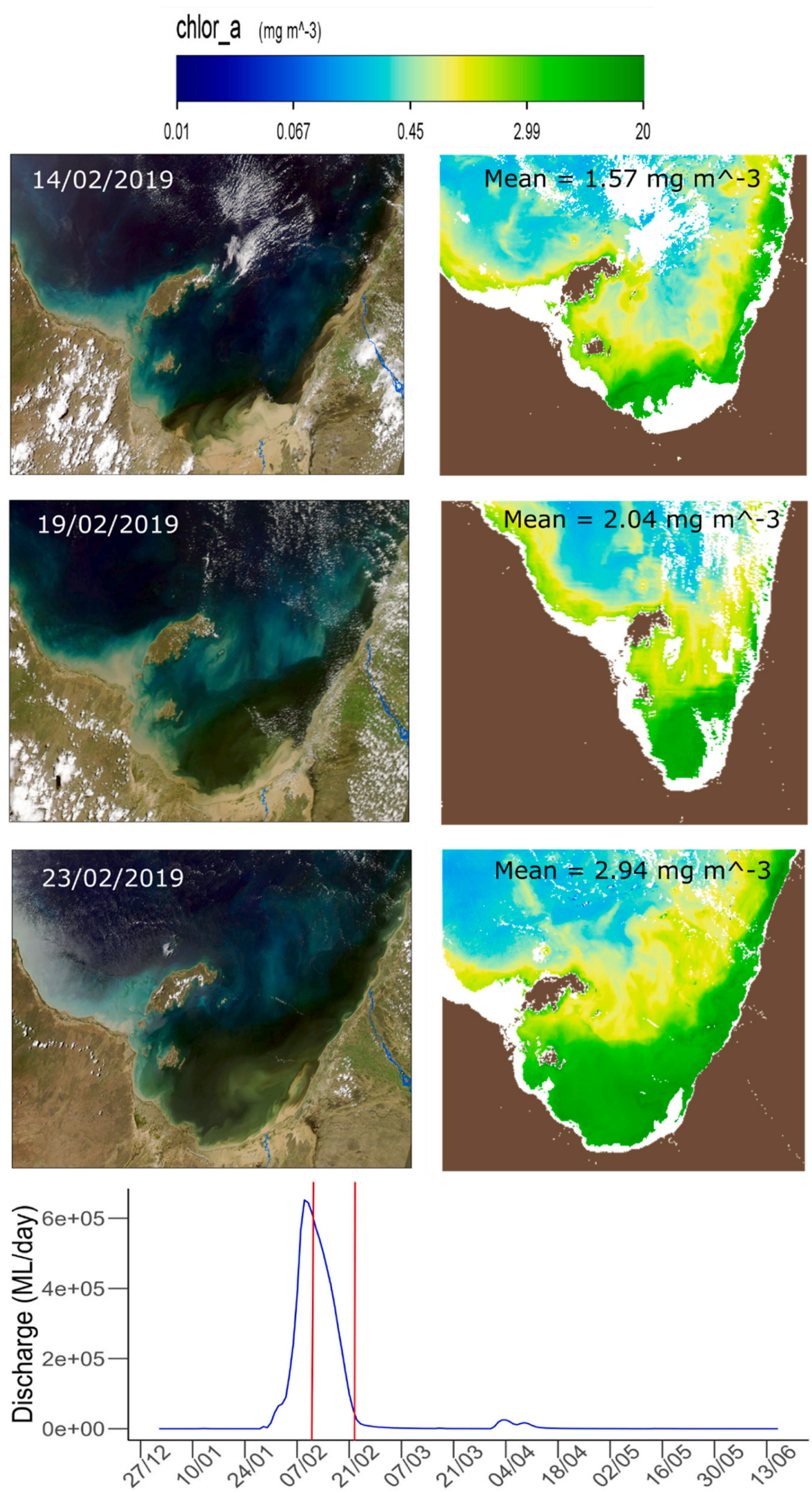

Fig. 10. True colour images (left) and chlorophyll-a reflectance band data (right) immediately following a large flood event (top), 5 days post event (middle) and 9 days post event (bottom). Bottom graph shows the flow hydrograph over the period of flood plume development depicted in the images.

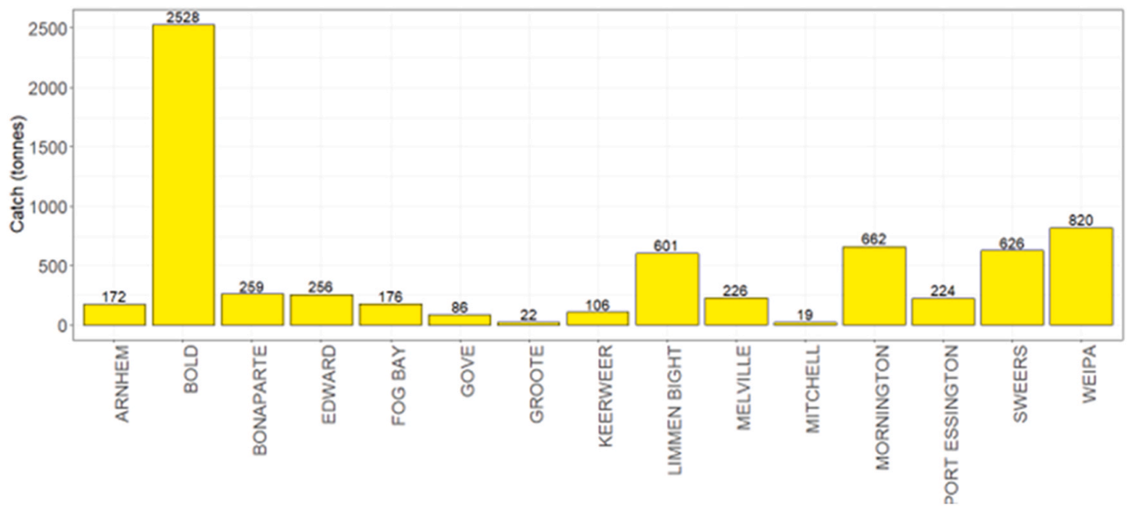

Fig. 11. Total catch of Banana Prawns for each statistical area of the Northern Prawn Fishery (NPF) in 2023. (Taken from: NPF Annual Data Summary 2023).

actively expands habitat capacity, and how species exploit these dynamic environments. Clarifying these mechanisms will strengthen the scientific basis for linking freshwater flow regimes to coastal ecosystem resilience under climate variability.

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CRediT authorship contribution statement

Paula Cartwright : Writing – original draft, Validation, Software, Project administration, Investigation, Data curation, Writing – review & editing, Visualization, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **Allyson Genson:** Data curation, Writing – review & editing. **Nathan Waltham:** Supervision, Funding acquisition, Writing – review & editing, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table A 1
Model summary of relationship between Gilbert River tertiary flood plume size and mean Chlorophyll-a in the southern Gulf of Carpentaria

Residuals:					
Min	1Q	Median	3Q	Max	
−0.79752	−0.4337	0.06151	0.43767	0.76082	
Coefficients:					
	Estimate	Std.Error	t-value	Pr(>|t|)	
(Intercept)	1.6176664	1.0584819	−1.528	0.1773	
Tertiary	0.0026185	0.0006701	3.907	0.00792	*
Residual standard error: 0.6211 on 6 degrees of freedom					
Multiple R-squared: 0.7179, Adjusted R-squared: 0.6709					
F-statistic: 15.27 on 1 and 6 DF, p-value: 0.007916					

Table A 2
Model summary of relationship between Gilbert River total flood plume size (sum of primary, secondary and tertiary plumes) and mean Chlorophyll-a in the southern Gulf of Carpentaria

Residuals:				
Min	1Q	Median	3Q	Max
−1.08097	−0.2636	−0.07319	0.15255	1.44355
Coefficients:				
	Estimate	Std.Error	t-value	Pr(>|t!)
(Intercept)	0.202639	0.8704429	0.233	0.8236
Plume_sum	0.0008469	0.0003139	2.698	0.0357

(*continued on next page*)

Table A 2 (*continued*)

Residuals:
Residual standard error: 0.786 on 6 degrees of freedom
Multiple R-squared: 0.5482, | Adjusted R-squared: 0.4729
F-statistic: 7.28 on 1 and 6 DF, p-value: 0.03567

Table A 3
Model summary of relationship between Flinders River tertiary flood plume size and mean Chlorophyll-a in the southern Gulf of Carpentaria

Residuals Min	1Q	Median	3Q	Max	
-1.0412	−0.5306	−0.1358	0.4871	1.0466	
Coefficients:					
	Estimate	Std.Error	t-value	Pr(>|t|)	
(Intercept)	**1.251388**	**0.3774881**	**3.315**	**0.00511**	**
Tertiary	**0.0008061**	**0.0002737**	**2.945**	**0.01066**	*
Residual standard error: 0.7015 on 14 degrees of freedom					
Multiple R-squared: 0.3825, Adjusted R-squared: 0.3384					
F-statistic: 8.672 on 1 and 14 DF, p-value: 0.01066					

Table A 4
Model summary of relationship between Flinders River total flood plume size (sum of primary, secondary, and tertiary plumes) and mean Chlorophyll-a in the southern Gulf of Carpentaria

Residuals:	Min	1Q	Median	3Q	Max
	−1.1432	−0.4228	−0.1606	0.4237	1.3163
Coefficients:					
	Estimate	Std.Error	t-value	Pr(>|t|)	
(intercept)	1.4850688	0.31133	4.77	0.000299	***
plume_sum	0.0003457	0.0001183	2.922	0.01114	*
Residual standard error: 0.7036 on 14 degrees of freedom					
Multiple R-squared: 0.3789, Adjusted R-squared: 0.3345					
F-statistic: 8.54 on 1 and 14 DF, p-value: 0.01114					

Table A 5
Model summary of relationship between the Daly River total flood plume size (sum of primary, secondary, and tertiary plumes) and mean Chlorophyll-a in Anson Bay

Residuals:	Min	1Q	Median	3Q	Max
	−1.0754	−0.4453	−0.3031	0.3684	3.1075
Coefficients:					
	Estimate	Std.Error	t-value	Pr(>/t|)	
(Intercept)	1.8776906	0.5068408	3.705	0.0015	**
plume_sum	0.0014845	0.0005541	2.679	0.0148	*
Residual standard error: 0.9133 on 19 degrees of freedom					
Multiple R-squared: 0.2742, Adjusted R-squared: 0.236					
F-statistic: 7.178 on 1 and 19 DF, p-value: 0.01484					

Table A 6
Model summary of relationship between the Daly River tertiary flood plume size and mean Chlorophyll-a (lagged) in Anson Bay

Residuals:	Min	1Q	Median	3Q	Max
	0.73542	−0.32437	−0.02718	0.38211	0.7486
Coefficient:					
	Estimate	Std.Error	t-value	Pr(>/t|)	
(intercept)	1.9755032	0.2692811	7.336	2.49e−05	***
Tertiary	0.0014838	0.0004548	3.263	0.00854	**
Residual standard error: 0.4932 on 10 degrees of freedom					
Multiple R-squared: 0.5156, Adjusted R-squared: 0.4672					
F-statistic: 10.64 on 1 and 10 DF, p-value: 0.008538					

Table A 7
Model summary of relationship between river flood plume extent (sum of primary, secondary, and tertiary plumes) and 7- day flow events in the Flinders River

Residuals:					
	Min	1Q	Median	3Q	Max
	−858.7	−424.4	100	246.4	1247.8
Coefficients:					
	Estimate	Std.Error	t-value	Pr(>it!)	
(Intercept)	6.78e+ 02	1.65e+ 02	4.101	0.000608	***
Flow7	1.41e−03	1.300e−04	10.86	1.37e−09	***
Residual standard error: 550.1 on 19 degrees of freedom					
Multiple R-squared: 0.8613, Adjusted R-squared: 0.854					
F-statistic: 117.9 on 1 and 19 DF, p-value: 1.371e−09					

Table A 8
Model summary of relationship between river flood plume extent (sum of primary, secondary, and tertiary plumes) and 7- day flow events in the Gilbert River

Residuals:	Min	1Q	Median	3Q	Max
	−463.8	−375.1	105	203.3	564.4
coefficients:					
	Estimate	Std.Error	t-value	Pr(>|t|)	
(intercept)	4.36e+ 02	4.04e+ 02	1.08	0.32175	
flow7	1.69e−03	2.93e−04	5.786	0.00117	**
Residual standard error: 398.5 on 6 degrees of freedom					
Multiple R-squared: 0.848, Adjusted R-squared: 0.8227					
F-statistic: 33.48 on 1 and 6 DF, p-value: 0.001166					

Table A 9
Model summary of relationship between river flood plume extent (sum of primary, secondary, and tertiary plumes) and 7- day flow events in the Daly River

Residuals:	Min	1Q	Median	3Q	Max
	−506.81	−402.29	54.83	344.52	595.74
Coefficients:					
	Estimate	Std.Error	t-value	Pr(>/t|)	
(Intercept)	1.94E+ 02	1.64e+ 02	1.183	0.252	
ML	7.76E−04	1.15e−04	6.751	1.89e−06	***
Residual standard error: 396.1 on 19 degrees of freedom					
Multiple R-squared: 0.7058, Adjusted R-squared: 0.6903					
F-statistic: 45.57 on 1 and 19 DF, p-value: 1.892e−06					

Data availability

Data will be made available on request.

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