Resilient Landscapes

National Environmental Science Program


# Synthesis of scientific information relevant to flow-ecology for the wet-dry tropics of northern Australia

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**Cover photographs**

Main photos: Barramundie Creek in Kakadu National Park (left) and Mitchell River estuary in north Queensland (right). Photos: Kaitlyn O'Mara. Inset photos: freshwater fern *Marsilea* sp. (nardoo) (left) and eastern curlew (right). Photos: Robyn Loomes and NESP Resilient Landscapes Hub.

This report is available for download from the Resilient Landscapes Hub website at **nesplandscapes.edu.au**.

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November 2023

# 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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# Acknowledgements

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# 2. Executive summary

This study collated and synthesised existing information on freshwater species and ecosystems across the wet-dry tropics of northern Australia to document existing information and identify knowledge gaps. As part of our collation, we examined the direct and indirect nature in which studies learn about flow alteration and used this in a qualitative way to draw inference about the level of certainty with which predictions can be made about the impacts of water resource-development. A key output of the study is a searchable database available online **here** that allows practitioners to rapidly find scientific knowledge for river systems, habitats or biotic groups of interest. Other important outputs are summary tables, available in the Appendix, that collate research for different biotic groups, flow components and habitats. These tables provide an overview of knowledge and a simple description of the likely impacts to biota from water resource development. Our outputs are the most comprehensive repository of flow-ecology knowledge to date for the wet-dry tropics of northern Australia, but our database is not exhaustive and reflects our search terms and approach to literature acquisition.

A total of 281 studies were discovered that were located in the wet-dry tropics of northern Australia and had a link to flow. The most studied river was the Daly River in the NT, followed by the Fitzroy River in WA, with considerable attention also on the southern Gulf of Carpentaria Rivers, i.e., Flinders, Norman and Mitchell, and the Magela and Alligator Rivers in NT. The most studied biotic group was fish.

In recent years studies have sought to learn about the impacts of water extraction by (1) measuring flow metrics (e.g. discharge, stage height) and describing flow-ecology relationships in flow-intact systems and (2) using predictive models, e.g. hindcasting or forecasting, to reveal the likely impacts of flow alteration. These studies can reveal the flow components that should be protected by water policy and the likely impact of a range of water-take scenarios. They can also indicate if increasing water take will cause a commensurate decline in biota (i.e. linear relationship) or if thresholds exist, which is very useful to the development of water rules. However, despite these advancements, it is important to recognise that, for the wet-dry tropics, most of our insights into flow-ecology remain indirect, i.e. discharge-ecology relationships aren't available. All that is available is a directional understanding of the potential impact of water extraction, e.g. a reduction in flow will lead to a reduction in recruitment. This makes it very difficult to predict the impact of different levels of water extraction with any certainty and increases risk for water planners.

Finally, although uncertainty remains about the specific impacts of water extraction in the wet-dry tropics, a wealth of knowledge indicates that water extraction is likely to negatively impact a myriad of biota and ecological processes. Thus, we are very confident saying there will be impacts but are less well placed to be prescriptive about what those impacts will be for any given development. Indeed, the impact to any given biota will depend on factors linked to water take, such as the magnitude and timing of water take and which flow component (e.g. flood harvesting, groundwater) is targeted, as well as other factors, such as where development occurs along the river continuum, whether barriers to connectivity (i.e. dams, weirs) exist, and the severity of additional development stressors, such as pesticides, increased or decreased nutrients or sediment.

Our synthesis highlighted knowledge imbalances, which have implications for risk assessment and knowledge transfer. Further research is needed to inform when, where and for which biota knowledge can be transferred with confidence and where it cannot. In the interim, pragmatic decisions could be made using a conceptual understanding of the factors that shape transferability, i.e. flow regime, species life history and habitat preference. However, where transferability is uncertain and risks are high, we recommend implementing precautionary policy and undertaking targeted research to fill knowledge gaps.

# 3. Introduction

There have been many reviews of the biodiversity and threats facing the wet-dry tropics of northern Australia (e.g. Finlayson et al. 1999; Brodie and Mitchell 2005; Finlayson 2005; Hamilton and Gehrke 2005; Bayliss et al. 2011; Pusey and Kath 2016; Humphrey et al. 2018), including those on flow-ecology and water-resource development (Leigh and Sheldon 2008; Bayliss et al. 2011; Close et al. 2012; Molinari et al. 2022). However, reviews pertinent to flow-ecology tend to have a narrow scope. Some focus on certain catchments (e.g. Kakadu [Humphrey et al. 2018], Ord [Doupé and Pettit 2002], Daly [Erskine et al. 2003 and King et al. 2021]) and others on certain flow components (i.e. low flows [King et al. 2015], wet/dry [Warfe et al. 2011]), biotic groups (e.g. estuarine fish [Robins et al. 2005]; prawns [Kenyon et al. 2020]), ecological processes (e.g. connectivity [Pettit et al. 2017], food web [Douglas et al. 2005], primary productivity [Molinari et al. 2022]) or abiotic factors (e.g. sediment and nutrients [Alongi et al. 2013]). These focused reviews enable a topic to be explored in detail but make it difficult to ascertain the broad state of knowledge about flow-biota in northern Australia. As a result, decision-makers wanting to identify risks with common threads must collate disparate information, which is an arduous task. A less detailed but more holistic approach is needed – one that examines the entire region, multiple flow components and habitats, as well as multiple biotic groups and ecological processes.

It is timely to undertake a rigorous synthesise of hydro-ecology, from here on termed ‘flow-ecology’ relationships for 2 reasons. Firstly, water-resource development in northern Australia is ramping up. In the Gulf of Carpentaria, Queensland, there are many proposals for water development, and the Qld Government will soon revise the current Gulf water-allocation plans (DNRME 2017, 2018a, b). In the Northern Territory, draft surface-water policy, regarding take from wet-season flows, has been released for consultation (NT Water Plan 2022; Surface Water Take Policy 2022). In Western Australia, water planning for the Fitzroy River is underway. Synthesising the state of scientific knowledge and highlighting the potential ecological consequences associated with water extraction will assist water planners and decision-makers to identify risks and develop policy accordingly. A synthesis can also highlight knowledge gaps that require targeted research and a precautionary policy approach. The second reason a synthesis is timely is that university-led research programs that have run over the last 2 decades have recently wound down. Considerable evidence has emerged from these, especially over the last few years and recently been synthesised by Kennard et al. (2022). However, while the Kennard et al. (2022) report brings diverse knowledge together in terms of hydrologic components and discusses transferability, their synthesis does not attempt a qualitative or quantitative appraisal of the knowledge available. This study takes the next step by documenting information pertinent to our ability to draw inference/make predictions and to our confidence transferring this knowledge. For instance, the direct/indirect nature of flow-ecology knowledge and the number/spatial spread of river systems where the knowledge was acquired. This study also casts the net much wider in terms of the biotic groups it includes and its search for scientific evidence.

The primary aim of this study was to collate and synthesise existing information on freshwater species and ecosystems across the wet-dry tropics of northern Australia to document existing knowledge and identify knowledge gaps. A secondary aim was to identify knowledge gaps and document risks associated with water-resource development. As part of our collation, we examined the direct and indirect nature in which studies learn about flow alteration and used this to draw inference about the level of certainty with which predictions can be made about the impacts of water resource-development. We performed a time-bound comprehensive search of the published literature using a set of deliberately chosen search terms. Unpublished information was generally beyond the scope of our study, but was included at times; however, due to the myriad reports that exist, and the ad hoc nature in which this information was found our coverage of the grey literature is limited. We synthesise our findings in 3 ways, by (i) presenting general patterns about when, where and how we have learnt about flow-ecology relationships, (ii) synthesising flow-ecology knowledge for key biotic groups and ecological processes and (iii) linking anticipated changes to 5 flow components (within-bank, overbank, recessional flows, low flows, antecedent flows) so that managers can readily identify the species and habitats most at risk from water extraction. Regarding risk, it was not the intent of this study to comprehensively evaluate risks or perform risk assessments, rather we simply present the general risks raised by the literature. Those seeking comprehensive risk assessments are encouraged to seek out and read government water plans such as (DSITIA 2013, 2014; DES 2021) as well as other outputs from the ‘Water planning in north Queensland’ project of which this report is a component.

The main output of this study is a searchable database available online through the University of Western Australia’s **research repository** (as per the hyperlink or search for ‘flow ecology’ inside the repository). The database (an excel spreadsheet) allows practitioners to rapidly find scientific knowledge for specific river systems, habitats or biotic groups of interest. Other key outputs are the tables presented in the Appendix, which summarise research for different biotic groups, flow components and habitats. These tables provide an overview of knowledge and the likely impacts to biota from water resource development, thus provide a streamlined tool for decision makers including water planners, those undertaking impact assessments, Indigenous peoples and groups, special interest groups (e.g. Fisheries, environmental groups) as well as scientists.

# 4. Methods

## 4.1 Study area and habitat types

Our study area was the wet-dry tropics of northern Australia. This region stretches from Cairns in the east to Broome in the west (Figure 4-1) and includes catchments that experience a wet-dry climate shaped by the tropical monsoon. Within this area, we sought studies on flow, freshwater habitats or habitats influenced by freshwater, i.e. riparian and floodplain habitats, and estuarine systems (note that coastal waters were typically excluded). Groundwater habitats, such as aquifers, although clearly influenced by river flow, were considered beyond the scope of the study.

Within the freshwater habitats of interest we sought studies that focussed on freshwater or estuarine biota as well as ecological processes that are biotic in nature and strongly influenced by flow, such as connectivity, primary productivity. Physical responses to flow, such as water quality, morphology, sedimentation etc. were not central to our study aims or to our searching, but where information was discovered on these attributes it was included.


Figure 4-1. The wet-dry tropics of northern Australia, showing some well-studied river systems. Markers show key towns in the region.

## 4.2 Literature search

We searched published literature using SCOPUS in November 2022 by searching research titles, abstracts and keywords for terms linked to flow or climate (‘flow*’ OR ‘discharge’ OR ‘water’ OR ‘hydro*’ OR ‘flood’ OR ‘connect*’ OR ‘fragment*’ OR ‘refuge’ OR ‘climate’), habitat (‘fresh*’ OR ‘aquatic’ OR ‘river*’ OR ‘floodplain’ OR ‘wetland*’ OR ‘stream*’ OR ‘creek*’ OR ‘estuar*’ OR ‘lagoon’ OR ‘billabong’ OR ‘waterhole’ OR ‘riparian’), biota food web or primary production (‘fish*’ OR ‘*bird’ OR ‘nutrient’ OR ‘food web’ OR ‘foodweb’ OR ‘food-web’ OR ‘energ*’ or ‘macroinvert*’ OR ‘*plankton’ OR ‘prawn*’ OR ‘crab’ OR ‘crayfish’ OR ‘crocodile’ OR ‘turtle’ OR ‘metabolism’ OR ‘primary producti*’). To narrow the search, we included terms related to climate (‘tropic*’ AND NOT ‘subtropic* or ‘sub-tropic’). We also limited outputs to the subject area (‘agricultural and biological science’, ‘environmental sciences’, ‘earth and planetary sciences’) to the affiliation country (‘Australia’), and to (‘English’). We bound our search to 1980 onwards as, even though studies exist before 1980, there were relatively few and they were difficult to obtain. Our query string is available in the Appendix.

A total of 917 papers were identified by the SCOPUS search. These were individually checked for relevance, and studies with no link to flow, hydrology or rainfall were discarded, e.g. those on taxonomy, biogeography or genetic characterisation. Studies with only a weak link to flow were retained if inference about flow or hydrology could be drawn from their description of seasonal or spatial patterns or habitat (e.g. they described that a species used the floodplain). Studies were also checked for their locality and omitted if the research was conducted wholly outside the study area; studies that included at least one river within the study area were included. While our search was designed to focus on aquatic and semi-aquatic biota, studies were included on terrestrial biota if the research described a link to a riverine environment. This allowed us to highlight the influence of river flow on the terrestrial environment; however, this knowledge is piecemeal and should not be considered to be a comprehensive appraisal of the state of knowledge for terrestrial species.

We also sought ‘grey’ literature that was relevant to flow-ecology in the wet-dry tropics. Searching for these studies was ad hoc and involved finding reports associated with prior research programs undertaken in the area. Some reports were found as they were referenced by published journal papers. Reports included impact assessments and knowledge summaries, for instance the Northern Australia Water Resource Assessment (NAWRA). In some instances, if a report or thesis existed but its findings had been also published in a journal, then the report or thesis was omitted. The Tropical Rivers Inventory and Assessment Project (TRIAP) compendium of ecological information (Finlayson and Lukacs 2008) was generally not included, as it was largely species distribution data with little detail on flow-ecology. However, we made exceptions if the TRIAP chapters included relevant data not published elsewhere, e.g. Bayliss et al. (2008) and Humphrey et al. (2008). Similarly, the Northern Australia Water Futures Assessment and the Targeted review of the water resource (Gulf) plan were largely omitted as much of the scientific evidence they rely on is already included, and because these studies focused on assessing risks associated with ecohydrological scenarios rather than describing flow-ecology evidence; however, in some instances pertinent information from these reports were included (e.g. Close et al. 2012 sections 3.3.3 to 3.3.5). Our collation of grey literature was not exhaustive, as myriad reports exist and many could not be obtained, especially those produced before 2000 including many produced by state and territory agencies. We acknowledge that the absence of these reports is a limitation of our search approach and places a bias towards outputs of small study duration (e.g. 2-3 yrs) that tend to dominate the published literature. Lastly, reports that could not be obtained were not included in the study as their flow-ecology information could not be verified.

## 4.3 Data collation

Studies considered relevant were summarised and collated in Excel. Each study had 12 attributes recorded, including (1) publication year, (2) authors, (3) title, (4) abstract, (5) publication type, (6) study river, (7) study type, (8) focal biotic group or ecosystems process, (9) habitat, (10) flow inference, (11) flow alteration and (12) flow component. Attributes 1–4 and 6 are self-explanatory. A description of the other attributes and their categories are provided in Table 4-1. Biotic groups are not shown in the table but included fish, riparian vegetation, macroinvertebrates, meiofauna/zooplankton, macrophytes, prawns, cherabin (freshwater prawn), crabs, riparian birds, waterbirds, reptiles (including turtles, crocodiles and others) and mammals (NB frogs were largely omitted). We also included primary production and food-web studies as their own groups, even though these are not ‘biota’ per se. This was done because considerable information existed about energy generation (i.e. primary production) and energy transfer (i.e. food web) that would not otherwise be captured. Many studies examined multiple biotic groups and multiple rivers and sought inference about flow in multiple ways. For these instances, all approaches were recorded, which meant that our data summary often generated numbers in excess of the total number of publications. The flow component(s) identified for each study often described the conditions under which the study was conducted but also often extended beyond that to capture the flows pertinent to the flow-ecology knowledge. For instance, if a study described the association between wetland water depth and macrophyte production during the dry season, the knowledge would be included in overbank flows and low flows/groundwater, as both may influence wetland water depth. Similarly, within-bank and overbank flows were typically listed for estuarine studies, as both of these deliver water to estuarine habitats. All studies and their attributes are available in a spreadsheet accessible through the University of Western Australia’s **research repository** (as per the hyperlink or search for ‘flow ecology’ inside the repository).

Table 4-1. The attributes used to categorise the literature, including a description of each category.

| Attribute | Category | Description |
|---|---|---|
| Habitat | River channel | Environments in the channel of a river or stream where the water is flowing directionally to the sea. This includes the main stem of a river and tributary streams. |
| | Wetland/floodplain | Environments outside of the main channel that are predominantly aquatic. This includes wetlands in distributary channels, deflation basins and the floodplain proper (including ephemeral wetlands). We chose to group wetlands and the floodplain proper because many studies did not provide enough information to differentiate between the 2, and because characterisation can be subjective, and boundaries disappear during large wet seasons. Floodplain grasses were categorised here. |

| Attribute | Category | Description |
|---|---|---|
| | Riparian | Vegetated locations adjacent to a waterway or on the floodplain. Most studies clearly identified if they were working on riparian vegetation making this a simple characterisation. |
| | Impoundment | An artificial lake created by a dam, e.g. Lake Argyle. |
| | Estuarine | Estuary referred to the lower reaches of a river that are tidally influenced. Estuary was also used to encompass tidal creeks and sand/mud flats that were influenced by freshwater flows during the wet season. |
| | Hyporheic | The porous region of sediment beneath the stream bed or alongside it, where shallow groundwater and surface water mix. |
| Study type | Field-based | The study primarily collected data in the field and analysed this data to learn. |
| | Desktop | The study was undertaken primarily in the office. Data may be collected using remote sensing. Examples of this type of study included Bayesian Belief Networks or modelling studies that used field data collected previously. The NAWRA asset analysis report (Pollino et al. 2018a) was typically included here, as it included its own desktop analysis in addition to drawing on previous ecological knowledge. |
| | Laboratory | The study, or part of the study, was undertaken in a laboratory or glasshouse. |
| | Review | The study reviewed or synthesised available literature to summarise knowledge. Some new field data may be presented, but predominantly the data mentioned comes from prior studies. The NAWRA asset description report (Pollino et al. 2018b), which uses conceptual models underpinned by research by others, was included here. |
| Publication type | Journal article | The study is published in a peer-reviewed journal. |
| | Report | The study is a published or unpublished report. |
| | Other | The study is a PhD thesis, book, book chapter, conference proceeding. |
| Flow inference | Direct | The study directly assessed the influence of flow by including a flow metric (e.g. discharge, velocity, duration of inundation, days above a stage height, flow timing) as a predictor variable in a statistical model (linear regression, ANOVA, GLM, etc.) to investigate variation in the biotic group or ecosystem process of interest OR that included a flow metric in a multivariate-pattern-finding approach (e.g. BIOENV, PERMANOVA). Estuarine or floodplain studies that used rainfall as a metric are also considered ‘direct’ if rainfall was highly correlated with flow. Although not strictly direct, we include Bayesian Belief Networks in this category if they included parent nodes that pertain to flow, as they are using a probabilistic approach to create a strong inference between flow changes and the biota of interest. Note, water-table height was not considered a flow metric as it often has a complex relationship to river discharge. |

| Attribute | Category | Description |
|---|---|---|
| | Inferred through time | A discharge metric was not included in analyses; instead, inference about flow was gained by describing changes in the factor of interest (e.g. biota/process) through time (e.g. between wet and dry seasons, between wet and dry years, before and after a flow pulse, across days or months). Studies may examine the relationship between habitat metrics influenced by flow (e.g. depth, salinity, temperature) and the biotic response of interest. The study may also have learnt through space (see below). |
| | Inferred through space | A discharge metric was not included in analyses; instead, inference about flow was gained by describing changes in the factor of interest (e.g. biota/process) through space (e.g. examining rivers with different flow regimes, sites within a river that have different hydroperiods or hydrological connection [e.g. main channel vs wetland sites], sites at different distances away from the river). Many studies go beyond spatial patterns and seek relationships between habitat metrics and the biotic response of interest (e.g. depth, salinity, distance, habitat). The study may also have learnt through time (see above). |
| | Other | Studies that did not fit neatly into one of the categories above. This included studies that sought to describe an aspect of biology and flow was not of interest. This included some reproductive and dietary studies. |
| Flow alteration | No (natural variation) | The study didn't directly assess the impact of flow alteration. Rather it used natural variation in flow, or habitats affected by flow, to learn about a flow-biota relationship and perhaps speculated about the impact of flow alteration in the discussion. Studies conducted in flow-impacted systems (e.g. Ord River) that didn't involve experimental designs to test for impact are also classified here. Similarly, studies in the Fitzroy that didn't directly assess the impact of the weir at Camballin are classified here, as are studies on the Daly River. River systems where groundwater abstraction occurs but impacts are largely diffuse and difficult to assess (e.g. Daly River) are also classified here. |
| | Direct assessment | The study examined reference and flow-altered sites to investigate the impact of flow alteration. Alternately the study examined flow alteration within a flow-regulated system by comparing conditions at different time periods. |
| | Modelled assessment | The study did not examine the impact of flow alteration directly; rather, it used a mathematical or statistical model to predict the consequences. This included studies had a flow metric as a predictor variable and ran scenarios for different flows to reveal the impact of water take or climate change. Some studies used hydrodynamic models to indicate how altered flow would alter habitat and thus the biotic response. Studies that used Bayesian Belief Networks to predict the impact of water take or climate change were also included. |
| Flow component | Within-bank | Flow in the main channel that does not overbank. The water source is predominantly surface water runoff. These flows can feed down distributary creeks and inundate wetland habitats. |

| Attribute | Category | Description |
|---|---|---|
| | Overbank | Flood flows large enough to overtop the riverbank and inundate the floodplain proper. These flows send considerable water down distributary creeks. The water source is predominantly surface water runoff. |
| | Recessional | Flows late in the wet season. These are typically within-bank. Groundwater often makes a larger contribution to these flows as a result of recharge that has occurred during the wet season. |
| | Low flow/ groundwater | Flow that is groundwater. This includes baseflow in the main channel and the surface expression of groundwater in the floodplain, i.e. springs and certain wetlands. |
| | Antecedent | Flow that has occurred prior to sampling. This can include flow weeks, months or years before. |

## 4.4 Knowledge appraisal and synthesis

Once studies were collated in Excel, information was summarised in 3 ways.

**1. Simple characterisation.** To reveal when, where and how we have learnt about flow-ecology in the wet-dry tropics, we summarised information from using bar charts. Reviews and non-reviews were included in this assessment.

**2. Semi-quantitative synthesis.** We synthesised knowledge about flow-biota for 29 key biota and/or ecological processes, which were chosen by the authors and included those recognised to be important or valued by people that had received enough attention for a summary to be possible. The biota/processes spanned 4 landscape components: estuarine, riverine, riparian and terrestrial, and included food web/energetics. For each, flow-related knowledge was summarised according to show:

- the number of studies
- the spatial coverage of the studies (i.e. the catchment where the study was undertaken)
- the manner in which studies gained their inference about flow (i.e. direct, inferred through space, inferred through time)
- the manner in which the studies learned about the impact of flow alteration (i.e. none, direct assessment, modelled assessment)
- the likely mechanisms through which flow exerted its influence.

Reviews were excluded from the summary, and, if the same findings had been published multiple times (i.e. in a report and a journal article), only one source was included to prevented double counting. However, if a synthesis included formerly unpublished data or a new analysis of data, then this information was included. Where a study gained flow inference in multiple ways (e.g. through space and through time), the study was checked regarding the knowledge being summarised and the most relevant one was chosen. The information extracted from this synthesis was used to qualitatively appraise the strength of evidence for flow-ecology relationships. Evidence was considered stronger when flow was measured directly, and the effect of flow alteration was directly assessed or modelling. Evidence was considered weaker when flow was indirectly assessed (i.e. through space or time), and when studies examined natural variation in flow and did not seek to quantify an impact. Assessing the strength and consistency of relationships, as per causal criterion analyses (see Webb et al. 2011; Webb et al. 2012a; Webb et al. 2012b), was outside the scope of our study.

**3. Linking ecological knowledge to flow components.** To reveal the possible impacts of water-resource development, primarily water extraction, on biota and processes, we summarised ecological information in a table. Knowledge about flow, either explicit or implicit, was examined from the point of view of water loss, and statements rephrased to indicate the expected change in response to reduced flow (e.g. decrease, increase, little change, uncertain). No information was provided on the magnitude of the change. To increase relevance to water planners, knowledge was grouped for the 5 flow components mentioned in Table 4-1 and schematically represented in Figure 4-2. The summary table was split into ‘habitat alteration’ and ‘biotic impact’ in recognition that changes to flow typically impact biota via habitat. However, the distinction between habitat and biota was not strict, with knowledge on riparian vegetation categorised as ‘biota’, but macrophytes and algae categorised as ‘habitat’. Within the habitat alteration section of each flow component, information was grouped according to habitat type (e.g. main channel, wetlands/floodplain, riparian, estuarine). Within the biotic impact section information was grouped for biota (e.g. fish, macroinvertebrates, riparian vegetation birds/reptiles and estuarine biota) and the food web. Certain habitat elements, such as hydrology, water quality and physical form, were not central to our literature search, but where information was discovered on these attributes it was included; thus, this knowledge is under-represented and should not be considered as complete. However, we believe it is representative of broad patterns.

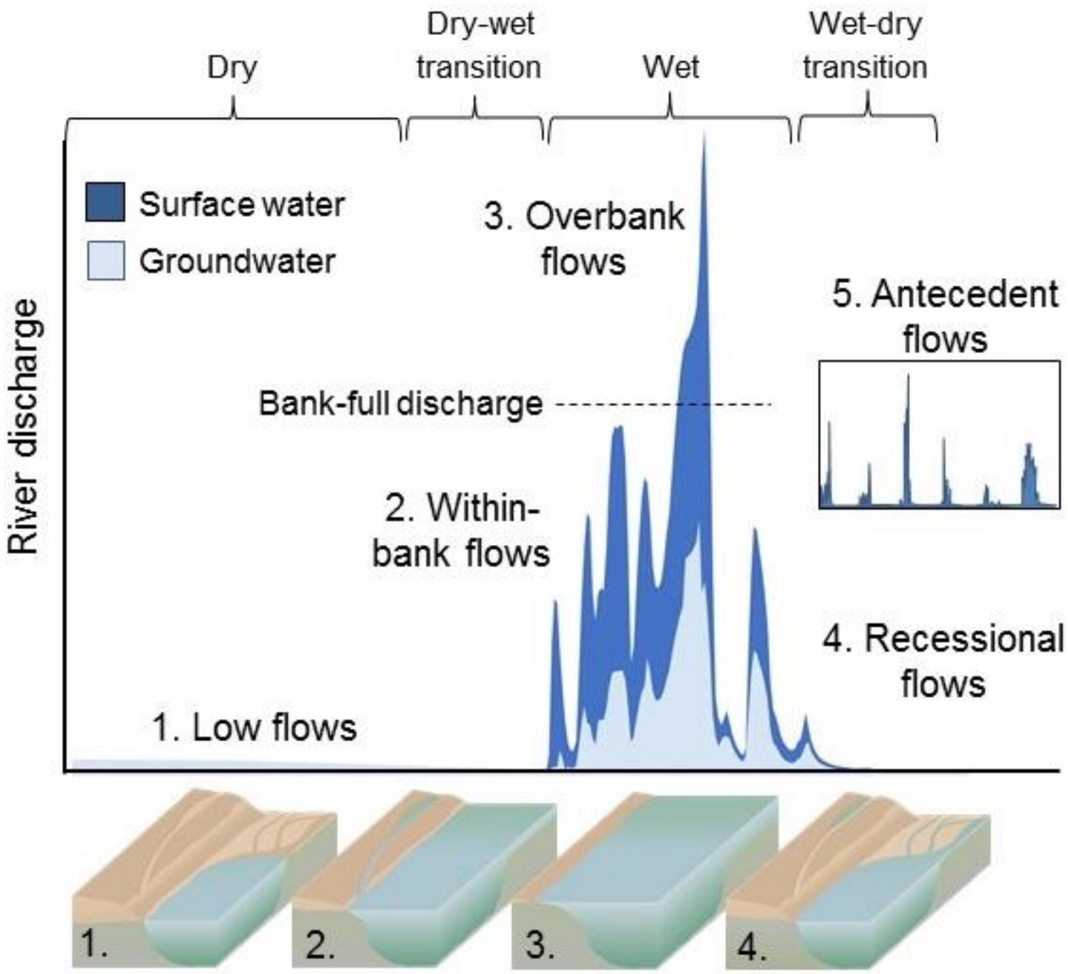


Figure 4-2. A stylised hydrograph showing the 5 flow components and aquatic habitats associated with 4 of them.Taken from Douglas et al. 2019. The flow regime depicted is ‘wet season highly unpredictable, i.e. class 10, as per Kennard et al. 2010. The hydrograph would have greater low-flow for rivers with greater groundwater inputs, e.g. the Daly River.

# 5. Results

## 5.1 Simple characterisation of studies

We identified a total of 281 studies that were located in the wet-dry tropics of northern Australia and had a link to flow. Some papers mentioned flow as part of their aims. Others did not but drew inference on flow as they described ecological patterns through time or space where flow was clearly influential. Some studies had a weak link to flow but were included if they revealed either a habitat or aspect of a species' biology where flow was influential. For instance, studies on the habitat and diet of goannas (e.g. Shine 1986a; Shine 1986b) were included, because the riparian habitat utilised by goannas is affected by flow and because the diet of some species included fish. The majority of the studies were journal articles (75%, n = 191) with the remainder reports, books, theses or conference proceedings (Figure 5-1). It is important to recognise that the number of reports is likely underestimated due to difficulties searching for and locating these documents. A total of 30 reviews were identified.

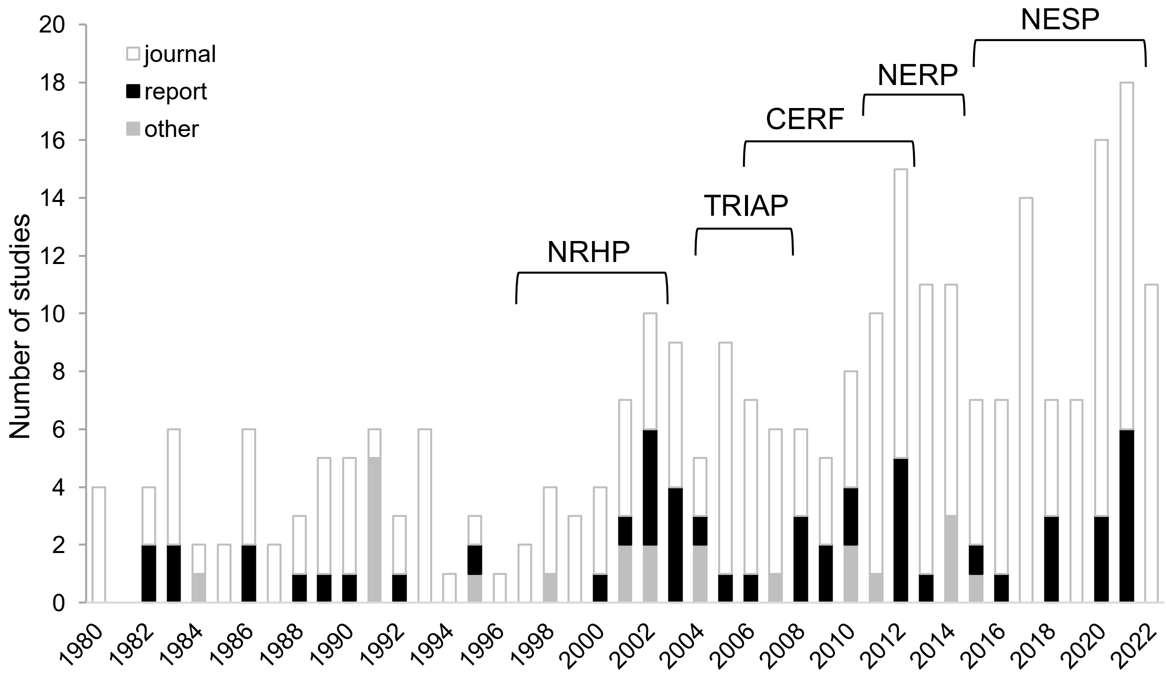


Figure 5-1. The number of studies relevant to flow-biota in the wet-dry tropics of northern Australia, showing the timing of key research programs, including the: National River Health Program (NRHP), Tropical River Inventory and Assessment Program, Commonwealth Environmental Research Facility (CERF), National Environmental Research Programme (NERP) and the National Environmental Science Program (NESP). Patterns in journal articles are reliable, but report numbers are underestimated. Includes reviews.

### 5.1.1 Changes through time and space: when and where have we learnt?

Scientific outputs on flow-ecology in the wet-dry tropics of northern Australia have changed considerably through time. In the 1980s and 1990s, research was focused on Magela Creek, which is part of the Alligator Rivers Region (NT) and includes Kakadu (Figure 5-2). This research sought to characterise natural riverine ecosystems and their biota to assess the impacts of the Ranger and Jabiluka uranium mines and assess the impact of mining at Coronation Hill. The majority of this research was undertaken by the Australian Government's Office of the Supervising Scientist, and much of it was not captured by our search criteria. Other notable studies included those on prawns and fish in the Gulf of Carpentaria (Stapels 1980; Staples 1980; Vance et al. 1985; Staples and Vance 1986; Blaber et al. 1989, 1995) and descriptive studies on freshwater turtles (Grigg et al. 1986; Georges and Kennett 1989; Georges and Rose 1993; Kennett et al. 1993; Kennett and Tory 1996; Kennett 1999) and crocodiles (Magnusson 1982; Webb et al. 1982, 1983a, b; Webb 1991). From approximately 2000 onwards, the number of scientific publications shows a gentle but noticeable increase (Figure 5-1). This increase can be attributed to increased federal investment in freshwater and marine research in the region, in line with a push by the federal government to open the region up to irrigated agriculture. Key research programs include the National River Health Program, Tropical Rivers Inventory and Assessment Project, Commonwealth Environmental Research Facility program, the National Environmental Research Programme, the National Environmental Science Program, and Fisheries Research and Development programs (Figure 5-1).

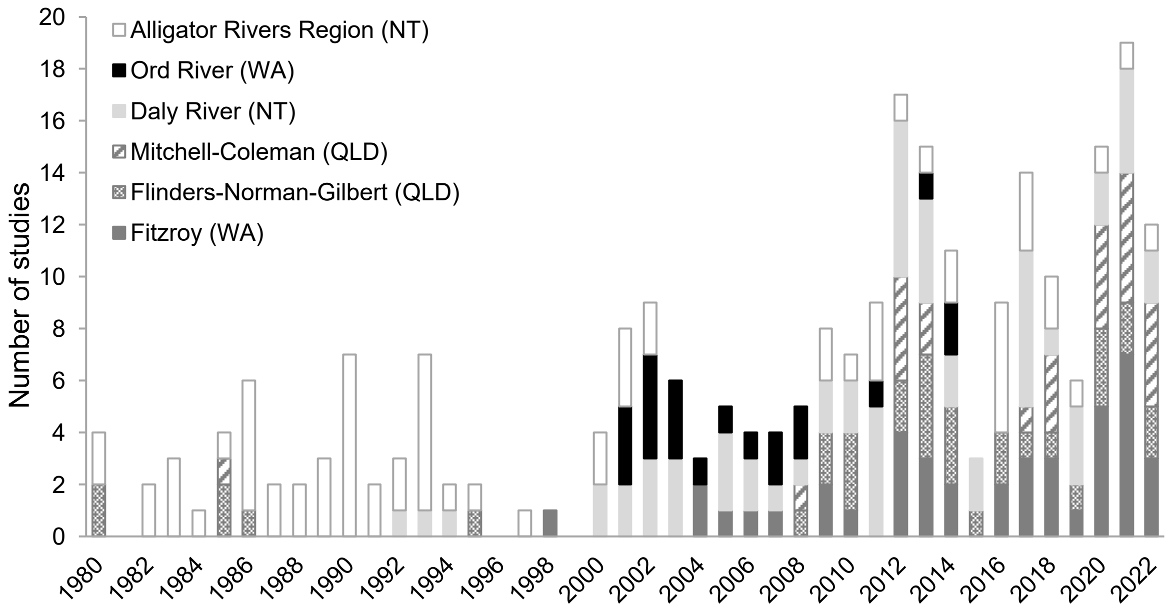


Figure 5-2. Temporal patterns in number of studies for 6 key river catchments in the wet-dry tropics of northern Australia. Note, the y-axis on this figure is greater than Figure 5-1 due to double-counting of studies conducted in multiple catchments. Reviews included. Note, many studies from the Alligator Rivers region that focussed on mining impacts are not represented because they were not identified by our search criteria.

Of the papers that met our search criteria, the spatial focus shifted after 2000, with research increasingly emerging from locations beyond the Alligator Rivers Region (Figure 5-2). For instance, in the early 2000s, studies were undertaken on the Ord River (WA), one of the few flow-regulated systems in the region. This research sought to document changes associated with river regulation (Wolanski et al. 2001; Parslow et al. 2003; Cluett 2005; Robson et al. 2008; Burford et al. 2011) and to quantify risks associated with a reduction in dry-season environmental water releases from the dam (Doupé and Pettit 2002; Storey 2002b; Parslow et al. 2003; Storey 2003; Trayler et al. 2003). From 2000 onwards, publications consistently appeared on the Daly River (NT). This perennial river, situated close to Darwin, became a focus of attention due to its high ecological values and because groundwater was being extracted for irrigated agriculture (Figure 5-3). Research on the Daly examined turtles, crocodiles, fish (Pusey et al. 2018; Keller et al. 2019; King et al. 2020; Pusey et al. 2020a; Crook et al. 2021b), cherabin (Novak et al. 2015; Novak et al. 2017a; Novak et al. 2017b), waterbirds (Bayliss et al. 2007; Bayliss et al. 2008), riparian birds (Woinarski et al. 2000), macroinvertebrates (Dostine 2000), instream primary production (Townsend and Padovan 2005; Webster et al. 2005), the aquatic food web and aquatic-terrestrial food web linkages (Jardine et al. 2012a), sediment (Wasson et al. 2010), nutrients (Webster et al. 2005; Townsend et al. 2012a), metabolism (Townsend et al. 2011), riparian vegetation (Lamontagne et al. 2005; O'Grady et al. 2006b; O'Grady et al. 2006a) and its instream breakdown (Pettit et al. 2012a). This research sought to describe the ecological values of the river to assist the conservation of threatened species, such as the pig-nosed turtle (Doody et al. 2001; Doody and Georges 2002; Doody 2002; Doody et al. 2003). It also sought to determine the environmental water requirements of the system (Rea et al. 2002; Erskine et al. 2003; Bayliss et al. 2008; Chan et al. 2012; King et al. 2021), as groundwater was being extracted from this highly valued river to support irrigated agriculture. More research papers were found studying the Daly River in the wet-dry tropics of northern Australia compared to any other river in the region (Figure 5-3), and research continues to this day (although we note that Magela Ck is also highly studied with many reports in the grey literature). Research on the Fitzroy River (WA) appeared slightly later, c.a. 2004, with the majority of emerging over the last decade (Figure 5-2). Research on this river has examined the impact of a weir at Camballin (Morgan 2005), and sought to describe ecological relationships for a range of (1) biota, including sawfish and other fish species (Whitty et al. 2014; Gleiss et al. 2017; Whitty et al. 2017; Lear et al. 2019; Lear et al. 2021; Morgan et al. 2021), as well as cherabin (Beesley et al. 2023), freshwater crocodiles and riparian birds (Skroblin & Legge 2012), (2) biogeochemical processes, i.e. nutrients, primary production and the food web (Thorburn et al. 2014; Beesley et al. 2020; Burrows et al. 2020), and (3) habitats, such as riparian vegetation (Canham et al. 2021a; Canham et al. 2021b; Freestone et al. 2022; Canham et al. 2023). Other heavily studied rivers include the Gulf of Carpentaria rivers in Queensland, e.g. Flinders and Mitchell rivers. Outputs for these systems commenced in earnest in 2008 and, like the Fitzroy and Daly, examined fish (Venarsky et al. 2020; O'Mara et al. 2021), macroinvertebrates (Leigh & Sheldon 2009), freshwater crabs (Waltham 2016), metabolism and primary production (Hunt et al. 2012; Ndehedehe et al. 2020; Burford & Faggotter 2021; Molinari et al. 2022) and the food web (Jardine et al. 2012b). Riparian vegetation in these 2 rivers remains relatively understudied, but there has been considerable research on the estuaries, in line with the commercial importance of Gulf of Carpentaria fisheries (Kenyon et al. 2016; Broadley et al. 2020; Lowe et al. 2022; Turschwell et al. 2022). Note, only a selection of references have been included intext for the sake of readability, those seeking all references are directed towards the online spreadsheet, which is available through the University of Western Australia's **research repository**.

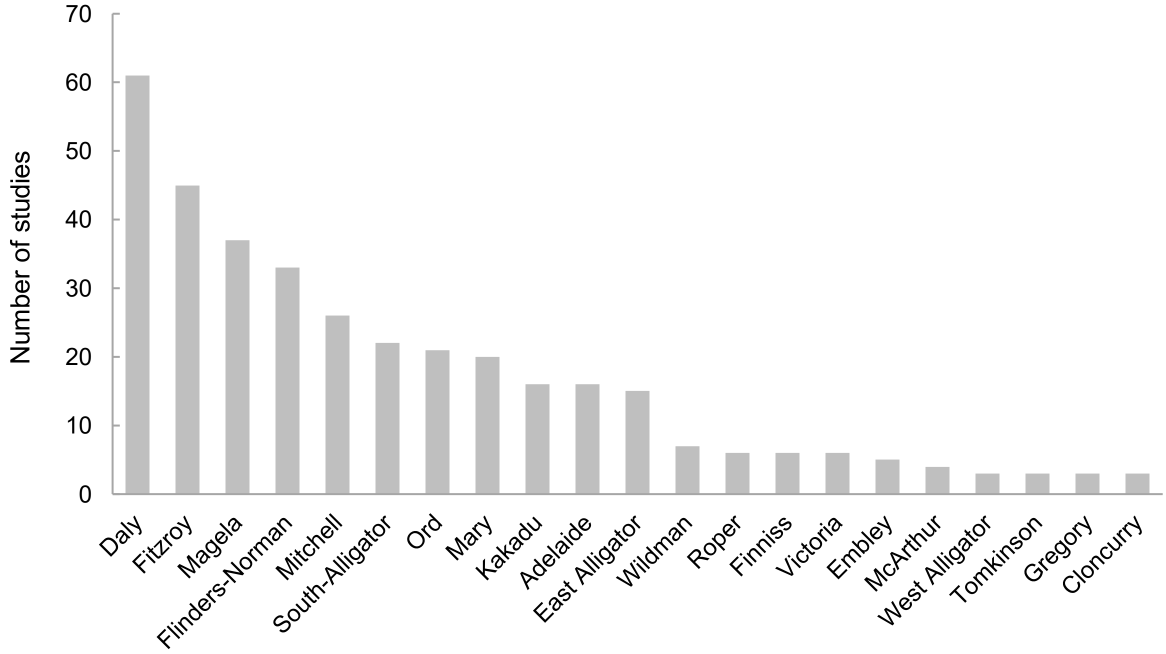


Figure 5-3. Research effort by river system in the wet-dry tropics of northern Australia. Systems with fewer than 3 studies are not shown.

### 5.1.2 What have we studied?

When reviews are excluded, our database revealed that the biotic group most comprehensively researched in the wet-dry tropics is fish. Between 1980 and 2022, there have been 95 studies on fish, which represents 28% of the total (Figure 5-4). Most studies examined the assemblages that could be caught in nets, but some focused on species of cultural, economic or management importance, such as barramundi, sawfish and sooty grunter. Research has described habitat associations (Blaber et al. 1989; Bishop et al. 2001; Pettit et al. 2013; Whitty et al. 2017; Keller et al. 2019), temporal patterns (Davis 1988; Bishop et al. 1990; Pusey et al. 2018), movement (Bishop et al. 1995; Crook et al. 2021a; Morgan et al. 2021), spawning (Bishop et al. 2001; King et al. 2020; Tyler et al. 2021), growth (Bishop et al. 2001; Roberts et al. 2019; Leahy and Robins 2021), recruitment (Bishop et al. 2001; Lear et al. 2019; Morrongiello et al. 2020), diet (Bishop et al. 2001; Davis et al. 2010; Thorburn et al. 2014) and energetics, i.e. the food web (Jardine et al. 2012a; Jardine et al. 2012b; Villamarín et al. 2016). Only a selection of references have been included in this paragraph for the sake of readability, see the online database in the **research repository** for the full body of evidence.

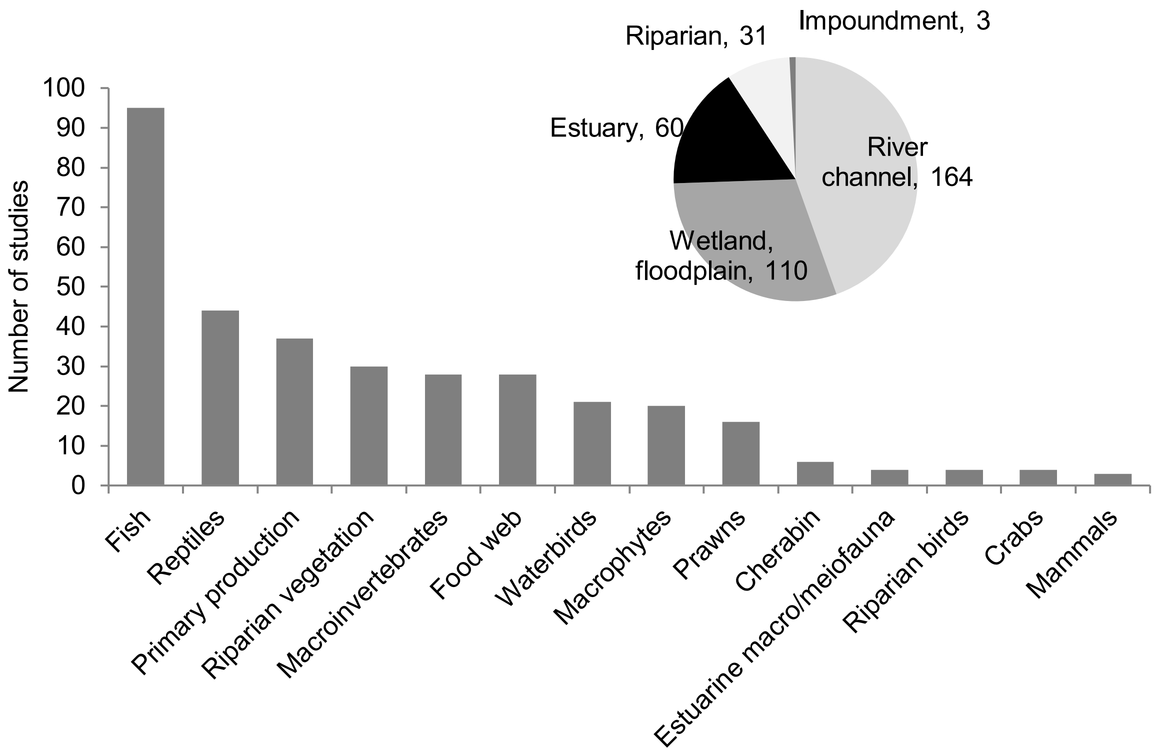


Figure 5-4. The number of studies examining different biotic groups and habitats (see inset pie chart). Note that many studies examined multiple biota and habitats, hence the sum of all biotic groups and habitats exceeds the total number of studies. Includes reviews.

Biota or ecological processes that have received a moderate amount of attention, with over 35 studies, include reptiles and primary production (Figure 5-4). Research on reptiles included goannas and snakes but predominantly focused on turtles (n = 19) and crocodiles (n = 15). Studies on turtles and crocodiles typically described distribution (Georges and Kennett 1989; Fukuda 2007), reproduction (Webb et al. 1983b; Doody et al. 2001; Doody 2002; Doody et al. 2003), diet (Webb et al. 1982; Kennett and Tory 1996; Hanson et al. 2015) and movement (Webb et al. 1983a; Dostine et al. 2021), with research on crocodiles also examining growth and abundance (Webb et al. 1983a; Fukuda and Saalfeld 2014). A considerable amount of the research on reptiles occurred in the 1980s and 1990s. In contrast, research on primary production was relatively recent, with most studies occurring after 2005. A suite of studies examined how freshwater flow to the estuary delivers nutrients that stimulate primary production (Burford et al. 2011; Burford et al. 2012; Burford et al. 2016; Burford and Faggotter 2021). In freshwater riverine environs, research also examined the role of nutrients or flow/season on primary production with studies examining phytoplankton (chlorophyll *a*) (Townsend 2006; Burford et al. 2011; Townsend and Douglas 2017), macrophytes (Rea et al. 2002), macroalgae (Townsend and Padovan 2009) or benthic algal biofilms (Garcia et al. 2015; Burford et al. 2016; Adame et al. 2017; Burrows et al. 2020), with some studies examining all forms (Webster et al. 2005; Hunt et al. 2012). A sub-set of these studies examined metabolism as well (e.g. Hunt et al. 2012; Garcia et al. 2015; Townsend et al. 2018; Burford and Faggotter 2021). For the full list of studies pertinent to each biotic group see the online database available in the **research repository**.

Riparian vegetation, macroinvertebrates and the food web are the next best studied, with 25–35 studies. Research on riparian vegetation typically described spatial patterns (Finlayson et al. 1989; Pettit et al. 2001; Petty and Douglas 2010; Warfe et al. 2013b; Freestone et al. 2022) or groundwater use (Lamontagne et al. 2005; O'Grady et al. 2006; Canham et al. 2021b), but studies also existed on seed dispersal and germination (Pettit and Froend 2001), bank erosion (Erskine 2002; Cluett 2005), in-stream wood dynamics (Pettit et al. 2013), litter fall (Finlayson et al. 1993) and in-stream breakdown (Pettit et al. 2012). Early riparian studies focused on Magela Creek and the Ord River, with effort increasing through time, particularly after 2000. Macroinvertebrate research focused heavily on Magela Creek in the 1980s, few studies were undertaken in the 1990s, but increased again after 2000. Studies typically examined the entire assemblage and described seasonal and spatial (i.e. habitat) associations (Marchant 1982; Outridge 1988; Dostine 2000), including relationships with flow (Dostine and Humphrey 2012; Leigh 2013; Warfe et al. 2013b; Venarsky et al. 2022). One early study that focussed on mussels examined the link between wet season discharge and depth and recruitment (Humphrey and Simpson 1985). Many macroinvertebrate studies sought to describe the food web and energy transfer (Leigh et al. 2010; Jardine et al. 2012a; Leigh et al. 2013; O'Mara et al. 2022), which explains the similar number of studies for these 2 groups. Food-web research is predominantly post-2000 and focused either on species diets (Wassenberg and Hill 1993; Davis et al. 2010) or the sources of energy (e.g. algal biofilm or riparian leaves) sustaining higher order biomass, i.e. macroinvertebrates and fish (Hunt et al. 2012; Fellman et al. 2013; Jardine et al. 2013; Beesley et al. 2020; Pusey et al. 2020b). However, studies also investigated the transfer of energy through space and time, including from wet-season floodplain/estuarine habitats to dry-season main-channel environs (Jardine et al. 2012a; Jardine et al. 2012b), and between the riparian zone and the main channel (Lynch et al. 2002; Leigh et al. 2013). For the full list of studies pertinent to each biotic group see the online database, available in the **research repository**.

Biota that received less attention, with 15–25 studies, included waterbirds, macrophytes and prawns (Figure 5-4). Research on waterbirds was relatively evenly spaced through time and focused strongly on the magpie goose *Anseranas semipalmata*, with 12 of the 21 studies examining this species. Waterbird studies predominantly characterised distribution (Morton et al. 1990a; Morton et al. 1990b; Chatto 2006) and abundance through time (Tulloch and McKean 1983; Bayliss and Ligtermoet 2018); however, there were also studies on movement (Traill et al. 2010; Traill and Brook 2011; Corriveau et al. 2020), diet (Recher and Holmes 1982) and breeding behaviour (Whitehead & Saalfeld 2000). Studies on macrophytes examined important species, such as *Eleocharis dulcis*, which provides important foraging and breeding habitat for magpie geese, or *Valisneria nana*, which is an important food item for freshwater turtles (Rea et al. 2002; Traill and Brook 2011); however, many studies examined the entire assemblage as part of studies quantifying aquatic/wetland productivity (Finlayson et al. 1989; Ward et al. 2016; Ndehedehe et al. 2020b; Molinari et al. 2021). Studies on prawns focused on the banana prawn *Penaeus merguiensis* and described abundance through space and time, often to learn about the impacts of river flow (Vance et al. 1985; Vance et al. 1998; Kenyon et al. 2004; Broadley et al. 2020) and the drivers of larval and juvenile immigration and emigration and growth (Stapels 1980; Staples 1980; Burford et al. 2010). We found 3 studies examining their food source (Wassenberg and Hill 1993; Loneragan et al. 1997; Vance et al. 1998). For the full list of studies pertinent to each biotic group see the online database, available in the **research repository**.

Biota that received little attention, with less than 10 studies, included cherabin, riparian birds, crabs, zooplankton, estuarine macro/meiofauna and mammals (Figure 5-4). Studies on cherabin *Macrobrachium spinipes* described habitat associations and their amphidromous life history and came from the Daly and Fitzroy rivers (Novak et al. 2015; Novak et al. 2017a; Novak et al. 2017b; Novak et al. 2017c; Beesley et al. 2023). Cherabin were also often included in surveys of the fish assemblage or food web; however, here we restrict our summary to research that targets this species. Studies on estuarine macro/meiofauna examined the influence of freshwater flow on assemblage structure and abundance/biomass (Burford et al. 2010; Duggan et al. 2014; Lowe et al. 2022; Venarsky et al. 2022). Aside from one review, we found only 3 relevant studies on riparian birds. One study examined habitat associations for the purple-crowned fairy wren *Malurus coronatus coronatus* and another the yellow chat (Alligator Rivers) *Epithianura crocea tunneyi* (Skroblin and Legge 2012; Leppitt et al. 2022). Only one study examined the entire riparian bird assemblage (Woinarski et al. 2000). Studies on crabs were limited to one study of the freshwater crab *Austrothelphusa transversa,* which described its life history (Waltham 2016), and another on its ecology in drying waterholes (Waltham et al. 2013). Studies on mud crabs were limited to desktop assessments (Pollino et al. 2018a). There were only 3 studies on zooplankton – 2 were estuarine (McKinnon and Klumpp 1998; Duggan et al. 2008) and one was freshwater, i.e. Magela Creek (Tait et al. 1984). Zooplankton studies described assemblage structure and changes through time. There were similarly few (n = 3) studies on mammals, and they mainly related to the influence of wet-season rain on the population dynamics of the dusky rat *Rattus colletti* (Madsen and Shine 2000; Madsen et al. 2006). It is important to recognise that our search terms were designed to find biota with a link to freshwater and flow, hence the low number of relevant studies for riparian birds and mammals reflects the indirect way that flow influences these species rather than a lack of research for these biotic groups.

Research effort has not been distributed evenly among habitat types. The river channel, which here refers to tributaries and the main channel of a river, has received the majority of attention, with just under half of all studies examining this habitat (Figure 5-4 inset). Wetlands and floodplains were the next best studied, followed by the estuary. The riparian zone was the least studied of the natural habitats, and only 3 relevant studies conducted in artificial habitats, i.e. dams (impoundments).

### 5.1.3 How have we learnt about flow?

Reviews and conceptual models aside, in the wet-dry tropics of northern Australia, our database revealed that information pertinent to flow-ecology has predominantly arisen from field-based research (n = 213, 85%), but other ways of learning include laboratory studies and desktop investigations that use remote sensing to acquire data or use expert opinion to populate Bayesian Belief Networks. Remote sensing was used first in 2003 and has grown in use as the quality of spectral imagery and computing power increases. Remote sensing has been used to map habitats and primary production including floodplain vegetation and algal production in floodplain and estuarine environments (Harvey and Hill 2003; Blondeau-Patissier et al. 2014; Ward et al. 2014; Ndehedehe et al. 2020a; Molinari et al. 2021; Ndehedehe et al. 2021; Molinari et al. 2022). It has also been used to map and describe hydrology (i.e. floodplain inundation, persistence and connectivity) and to identify aquatic refuges (Close et al. 2012; Hermoso et al. 2013; McJannet et al. 2014; Burford et al. 2016; Pollino et al. 2018a; Beesley et al. 2023). In instances where the biota of interest can't be characterised using optical imagery, studies couple remotely sensed hydrological maps with field measurements of biota to facilitate landscape-level predictions, see Burford et al. (2016) and Beesley et al. (2023). Bayesian Belief Networks, which are mathematical models that can be populated by data or expert opinion, have been used on 5 occasions to reveal the potential ecological implications of water-resource development (Bayliss et al. 2008; Leigh et al. 2010; Chan et al. 2012; Leigh et al. 2012; Duggan et al. 2019). Laboratory studies have also been used on 6 occasions, mainly to learn about factors affecting the survival and sex of turtle, crocodile and snake eggs (Magnusson 1982; Webb et al. 1983b; Kennett et al. 1993; Brown and Shine 2004). However, they have also been used to examine the riparian and macroinvertebrate seed bank (Paltridge et al. 1997; Pettit and Froend 2001). For the full list of studies that have used different methods see the online database in the **research repository**.

One-fifth of studies (n = 61, 24%) directly assessed a flow-ecology relationship. That is, they measured a flow metric (e.g. discharge, velocity, duration of inundation) and statistically evaluated its relationship with a biota or process of interest. Virtually all of these studies relied on natural variation to generate contrast in the data, with only a couple directly examining a flow impacted system (Figure 5-5). Researchers quantified flow-biota relationships using linear models or pattern finding statistics (e.g. multivariate methods), and half of these studies (n = 27) used a model to predict how biota would respond to flow scenarios. Modelling the impact of flow alteration is a powerful way to learn and our database suggests it was first used in the wet-dry tropics in 2002 by Georges et al. (2002) and Rea et al. (2002) but has been employed consistently since then (Figure 5-5). An example of this approach comes from Canham et al. (2021a) who modelled the occurrence of riparian woody vegetation in the Fitzroy River and ran scenarios that revealed how species distributions would change with reductions in the duration of floodplain inundation. The flow metric – duration of inundation – was obtained from a hydrodynamic model created for the system by CSIRO. Another example is Broadley et al. (2020), who modelled the catch of banana prawns in the Gulf of Carpentaria and ran scenarios to quantify the change in the catch with a reduction in flow from the Mitchell, Gilbert and Flinders rivers. Studies that use flow metrics and predict the outcome from different water take scenarios are particularly useful to water planners, as they make the potential outcomes of water take explicit.

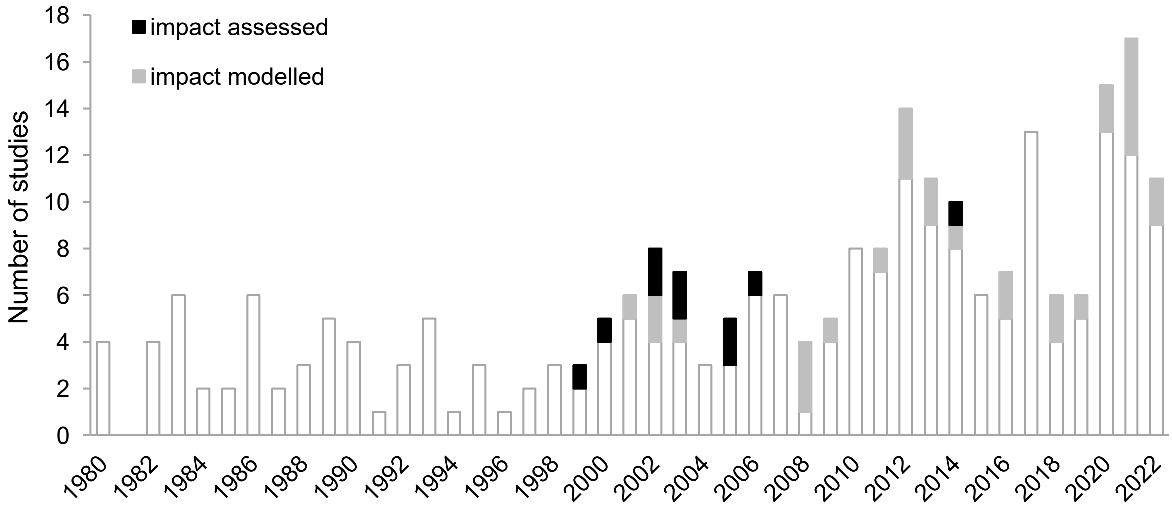

Figure 5-5. The number of studies that directly examined the relationship between flow and a biotic group through time.Studies that assessed the impact of flow alteration either directly (impact assessed) or via modelling (impact modelled) are shown compared to those that did not (impact not assessed). Reviews not included.The majority of studies learnt about flow indirectly (n = 177, 71%). More than half learnt by describing ecological patterns through time, i.e. among weeks, months, seasons or years. Examples are Paltridge et al. (1997) who examined macroinvertebrate recolonisation of a dry river stretch after flow recommenced, Webster et al. (2005), who examined primary production in the Daly River as flows declined over the dry season, and Duggan et al. (2014), who examined chlorophyll *a* and meiofaunal abundance on estuarine mudflats over 2 years with different wet-season flows. The other studies learnt by describing patterns through space i.e. among rivers or river reaches with different flow regimes, among habitats, or with distance away from the main channel. Examples include Jardine et al. (2012a), who studied the coupling between consumers (fish, macroinvertebrates) and their diets in 3 river systems with different flow regimes, Lynch et al. (2002), who studied the abundance and biomass of aquatic and terrestrial insects with distance from lowland streams in Kakadu, and Canham et al. (2021b), who studied groundwater uptake by riparian trees near and far from the river. Many studies employed both techniques. It is important to recognise that while learning about flow was the priority for many studies, for some it was never an aim; it was merely the ecological context in which they were conducted. Like the studies that examined flow directly, the indirect studies typically used natural environmental variation to provide an insight into flow rather than directly assessing flow alteration.

Less than 5% (n = 10) of all studies learnt about flow alteration by directly assessing an impact. The majority of studies that did so came from the Ord River, with some learning through space by comparing flow-regulated reaches downstream of dams with unregulated tributaries nearby (Wolanski et al. 2001; Trayler et al. 2003). This aforementioned research examined riparian vegetation, macroinvertebrates and fish, primary production, food webs and siltation. The other studies on the Ord River learnt about flow through time by comparing biota before and during a 3-day period of water drawdown that mimicked increased agricultural water take during the dry season (Storey 2002b, a, 2003). This research examined instream habitats, macroinvertebrates and fish. These studies used pattern-finding statistics (i.e. multivariate methods) rather than predictive models, which limited their ability to predict impacts beyond the conditions examined. Other studies that examined the impact of water-resource development included those on impoundments and barriers. Examples include Townsend (1999), who examined seasonal patterns in oxygenation in 2 reservoirs in the Northern Territory, Gill et al. (2006), who examined the fish assemblage of Lake Kununurra, and Morgan (2005) and Whitty et al. (2014), who examined the impact of the Camballin barrage, a 3-m high weir on the Fitzroy River, on fish, including sawfish.

The final way that we have learnt about flow and flow alteration in the wet-dry tropics of northern Australia was by synthesising knowledge and by using desktop approaches to qualitatively (i.e. conceptual models) or quantitively assess impacts. We identified 30 reviews. Many summarised ecological understanding (e.g. Douglas et al. 2005; Finlayson 2005; Hamilton and Gehrke 2005; Robins et al. 2005; Finlayson et al. 2006; Pettit et al. 2011; Warfe et al. 2011; Pettit et al. 2017) and/or management issues, including the threats associated with water-resource development (Finlayson et al. 1999; Doupé and Pettit 2002; Leigh and Sheldon 2008; Robson et al. 2008; King et al. 2015; Pollino et al. 2018a; Kenyon et al. 2020). NAWRA used a 2-step process, where they firstly created conceptual models to characterise flow-ecology relationships and potential impacts of water-resource development (Pollino et al. 2018b) then used hydrometrics, preference curves, spatial inundation modelling/mapping or statistical models to quantitatively reveal the potential impacts of water extraction (Pollino et al. 2018a).

## 5.2 Semi-quantitative synthesis

Our synthesis of flow-biota relationships for 29 key biotic groups or ecological processes highlighted the considerable breadth of knowledge for Australia's wet-dry tropics. Knowledge spanned different macrohabitats, a range of biotic groups and ecological processes, and was pertinent to multiple flow components (Appendix Table A1). The synthesis highlighted flow-ecology relationships for each flow component which are summarised below.

- Flows to the estuary transport nutrients that stimulate primary production and the growth/recruitment of diadromous species (e.g. barramundi, sawfish, cherabin) and prawns. They also influence the movement of diadromous and coastal fish, and structure estuarine fish and macro/meiofaunal assemblages.
- Flows onto the floodplain sustain floodplain and wetland habitats that support high primary and secondary production (e.g. macrophytes, grasses, fish, aquatic invertebrates) which are important food for terrestrial animals (i.e. waterbirds, reptiles, mammals). They also promote the movement of fish, crocodiles, turtles and waterbirds across the landscape, which facilitates the transfer energy from the floodplain to the main channel. Flow onto the floodplain also shapes the distribution of trees and promotes the dispersal and germination of vegetation.
- Within-bank flows mobilise nutrients and sediment and create scouring flows which regulate in-stream primary production (e.g. algae, macrophytes). They also promote fish and turtle movement and can be important for the breeding and recruitment of saltwater crocodiles and some fish and turtle species. Within-bank flows facilitate the downstream drift of macroinvertebrates and disperse the seeds of riparian vegetation. They can also reach switching points that profoundly alter macroinvertebrate community composition. Depending on antecedent conditions, flows early in the wet season can sometimes create impact water quality, however, follow up flows usually remedy this. that can lead to fish kills but follow up flows ameliorate them.
- Low flows/groundwater support riparian trees. These trees provide food (i.e. leaves, fruit, terrestrial insects) for aquatic macroinvertebrates and fish and, reciprocally, the aquatic animals provide food for riparian birds and invertebrates (e.g. spiders). Riparian vegetation is an important habitat for some threatened riparian birds. Low flows are also important for the breeding and recruitment of freshwater crocodiles and some fish and turtles. These flows also structure fish and macroinvertebrate assemblages and regulate in-stream primary production (e.g. algae, macrophytes). Low flows also facilitate the movement of sawfish and turtles along the length of the river for foraging and nesting, respectively. Thermal springs created by groundwater upwelling in the main channel are important to the breeding of pig-nosed turtles.
- Recessional flows support the upstream migration of juvenile cherabin. They also assist fish to migrate from the floodplain and intermittent creeks back to permanent

refuges and support fish 'homing behaviour'. Recessional flows can also influence the breeding success of reptiles on the floodplain. Macroinvertebrate composition among sites can be greatest once recessional flows have stabilised (Humphrey et al. 2000).

- Antecedent flows shape the abundance of longer-lived species such as waterbirds, crocodiles, turtles, barramundi and sooty grunters. The influence of previous flows can be appreciated over a short timescale, e.g. as the dry season progresses, fish become less reliant on energy from the floodplain and increasingly reliant on energy produced locally in the main channel. They can also be appreciated over a long timescale, e.g. how flow regimes structure fish and macroinvertebrate assemblages.

Biotic groups varied in the extent to which they had been studied and the spatial coverage of the research (Figure 5-6). Generally, the more studies undertaken on a biotic group, the more catchments were included (r = 0.19); however, there were several groups that bucked this trend. For instance, in-stream primary production received a large amount of attention with 15 studies but had a narrow spatial scope, with research undertaken in only 5 catchments. In contrast, riparian birds received relatively little attention with only 3 studies, but the broad-scale nature of the research translated into large spatial coverage, i.e. 17 catchments.

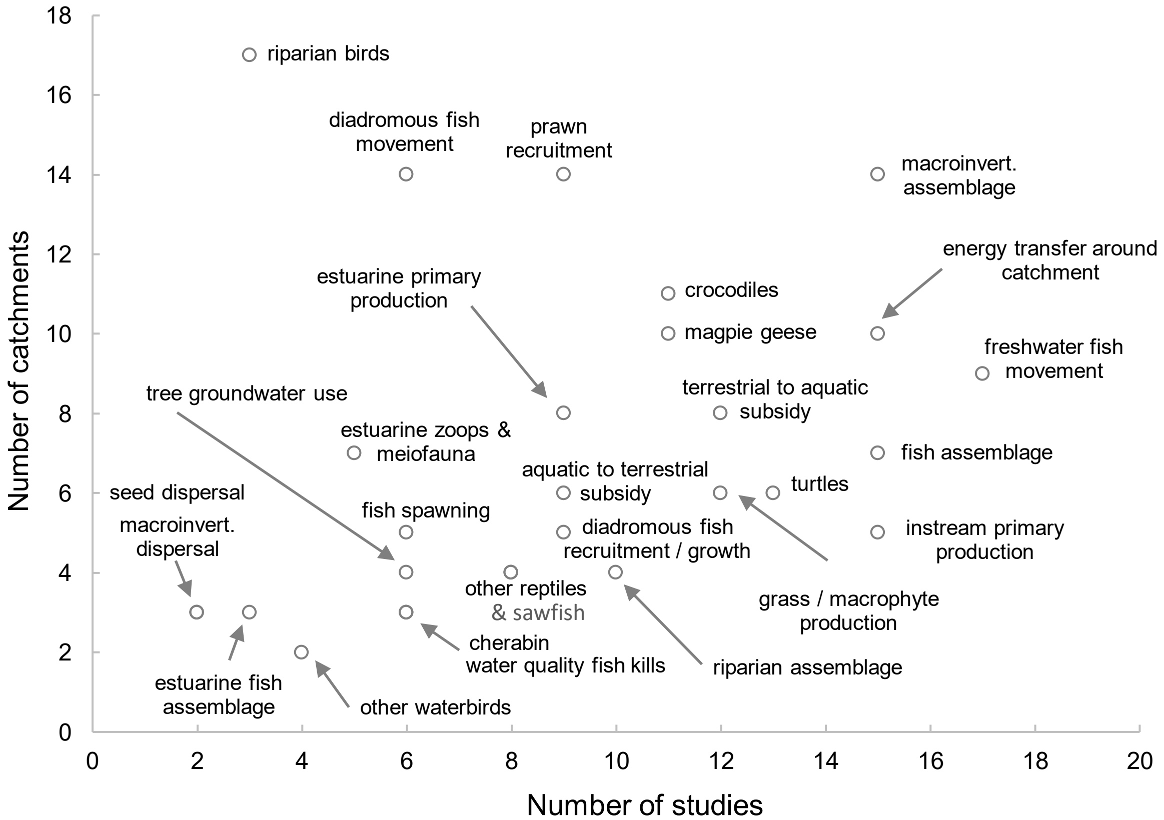


Figure 5-6. The number and spatial coverage of flow-biota knowledge for the 29 biota/processes.

The vast majority of biota or processes examined had relatively weak causal inference about flow alteration, i.e. there were relatively few studies that measured flow directly and even fewer that examined the impact of flow alteration, either directly or via modelling (Figure 5-7).

The strength of inference varied considerably among biotic groups. Relatively speaking, inference was strongest for freshwater fish movement and fish assemblage structure, followed by in-stream primary production and prawn recruitment (Figure 5-7). Inference was moderate for the macroinvertebrate assemblage, riparian assemblage and diadromous fish recruitment/growth, and low for estuarine primary productivity, magpie geese, sawfish, turtles and cherabin. There were a great many biotic groups with extremely weak causal inference about flow alteration with either no studies that directly measured flow, no studies that examined flow alteration, or both (Figure 5-7).

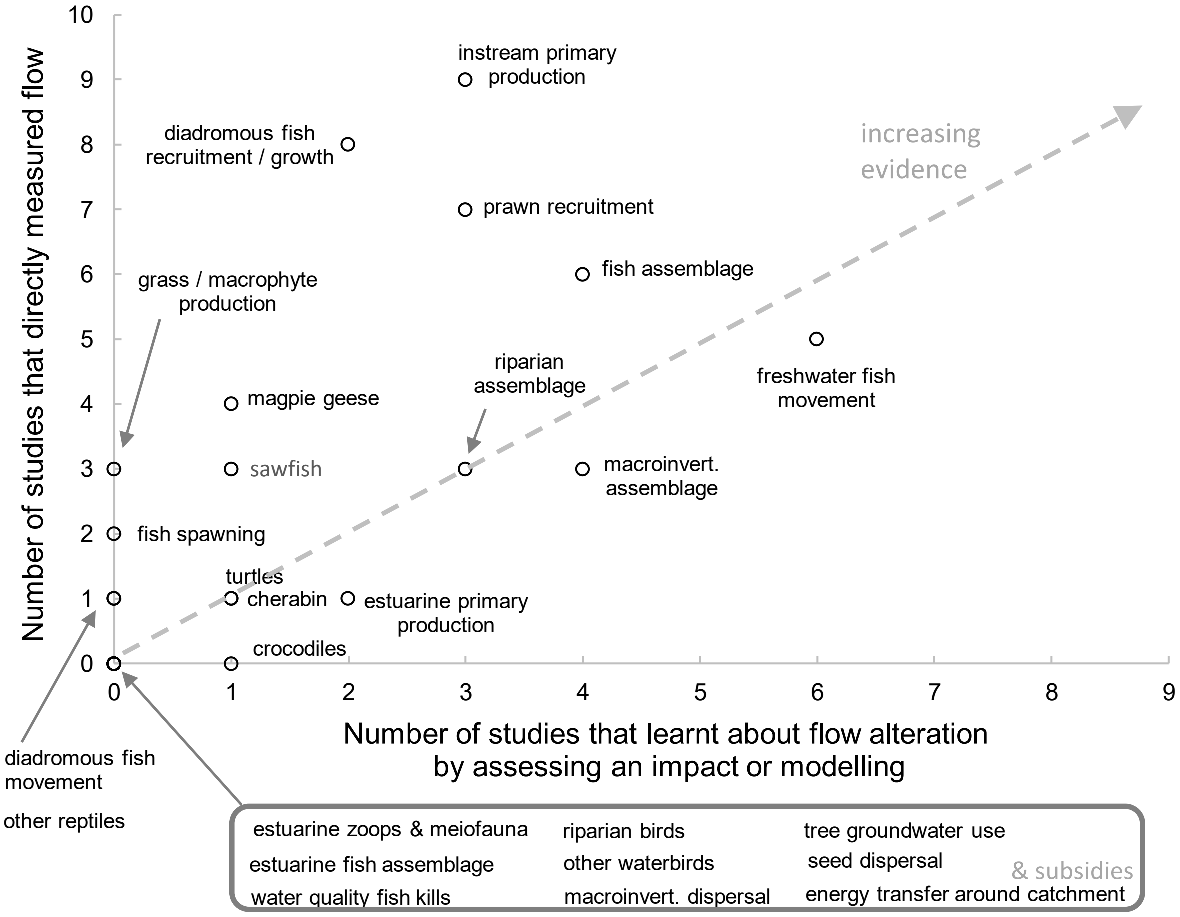


Figure 5-7. Evidence summary of flow-biota knowledge for 29 biota/processes. The dashed line indicates the increasing quality of evidence. Evidence was considered stronger when flow was measured directly, and flow alteration was evaluated by assessing an impact or by modelling. Evidence was considered weaker when flow was not measured directly and when studies did not assess a flow impact directly or by modelling.

Although causal inference about flow alteration varied markedly among biotic groups, the importance of flow to all groups meant that water-resource development was predicted to impact all groups (Appendix Table A1). For most biotic groups or processes, our knowledge synthesis suggested a directional change, i.e. a decrease or increase which was typically adverse; however, for some groups, the direction of change was unclear. For instance, in-stream primary production may increase or decrease in response to water extraction, depending on the extent to which macrophytes versus algae drive primary production

(Appendix Table A1 Item 14). Similarly, water taken from overbank flows may increase or decrease nesting and recruitment success of saltwater crocodiles, depending on whether the drop in water level reduces whether nests will drown or not. For some biotic groups, flow alteration was expected to generate different responses at different time scales. For instance, a reduction in flow to the estuary were predicted to reduce disturbance to meiofauna over the short term but cause declines over the medium term to long term (Appendix Table A1 Item 6).

The level of detail provided by studies regarding the likely impacts of flow alteration varied among groups in line with the level of knowledge and the way in which studies were conducted. For instance, a decline in flow to the estuary was simply predicted to reduce estuarine primary production (Appendix Table A1 Item 1), while a decline in flow was predicted to impact prawn recruitment/abundance in the Gulf of Carpentaria primarily during years with low wet season flow (Appendix Table A1 Item 2). The increased detail for prawns was available because a study used mathematical models to predict the impact of different water take scenarios (Duggan et al. 2019).

## 5.3 Linking ecological knowledge to flow components

Appendix Table A1 provides a rapid way for water managers to identify the potential impacts of water extraction from different flow components on different habitats and biotic groups. It also revealed where most information lay and where knowledge gaps existed. The majority of information pertained to within-bank, overbank and low flows, with relatively little information about recessional and antecedent flows. Currently, recessional flows tend to be recognised as important for the upstream migration of juvenile cherabin (Novak et al. 2017a), the movement of fish from intermittent to permanent habitats (Bishop et al. 1995; Crook et al. 2020), the timing of nesting of northern snake-necked turtles (Kennett 1999), the stability of macroinvertebrate assembalges (Humphrey et al. 2000), and the breeding success of pythons and filesnakes on floodplains (Shine and Brown 2008). More is known about antecedent flows, although most knowledge is focused on aquatic fauna. For instance, antecedent flows were recognised as influencing the recruitment and abundance of fish, particularly longer-lived species such as sooty grunter and barramundi (Stewart-Koster et al. 2011; Turschwell et al. 2019; Leahy and Robins 2021), shaping fish (Warfe et al. 2013a; Pusey et al. 2018; Pusey et al. 2020a) and macroinvertebrate assemblages (Leigh and Sheldon 2009; Leigh et al. 2013), and the reliance of main-channel fish on floodplain energy (Venarsky et al. 2020). There was little information about antecedent flows and riparian vegetation, even though large-scale floods likely exert considerable influence on tree recruitment and mortality. However, it was recognised that antecedent flow shapes populations of magpie geese, saltwater crocodile, turtles, pythons and filesnakes due to influences on juvenile survival/recruitment (Bayliss 1989; Doody et al. 2003; Shine and Brown 2008; Fukuda and Saalfeld 2014). Knowledge gaps were also evident for certain biota and certain biota-habitat combinations. For instance, we found no relevant studies on seagrass and only one that briefly examined mangroves (Duggan 2012), even though these habitats are important for many estuarine and coastal species, and likely rely on nutrients delivered by freshwater flows (Hayes et al. 2019). Similarly, there were no relevant studies on mud crabs, although research elsewhere in Australia reports a positive relationship between flow and catch (Loneragan and Bunn 1999). Only one study each existed for freshwater crabs (Waltham 2016) and hyporheic fauna (Paltridge et al. 1997), which highlights the lack of knowledge for these biotic groups. There were few diet or food-web studies in the estuary (see Wassenberg and Hill 1993; Loneragan et al. 1997; and Duggan 2012 as exceptions), as well as few studies on the estuarine fish assemblage (see Table A1, item 5), and none that examined their spawning. Few studies also existed for riparian birds and the dispersal and germination of riparian plants (Table A1, Item 15). Similarly, we found only one study on macroinvertebrate dispersal and recolonisation (Paltridge et al. 1997), and studies on macroinvertebrate assemblage structure were predominantly conducted in the main channel. There were also relatively few studies on stream metabolism. Lastly, there were very few studies on mammals, the exception being the dusky rat which is a floodplain specialist (Madsen and Shine 1999), and no studies on stygofauna were uncovered by our search. However, it is important to acknowledge that our literature search was not designed to identify terrestrial or subterranean species, thus we expect them to be under-represented in our dataset. Finally, although describing physical relationships with flow was beyond the scope of our study, it was apparent that few studies exist on the relationship between flow and groundwater recharge.

# 6. Discussion

Our synthesis of flow-biota knowledge for the wet-dry tropics of northern Australia has highlighted the depth and breadth of information available and revealed numerous flow-biota relationships. However, it has also revealed imbalances in knowledge among biotic groups, river systems and habitats. How studies draw inference about flow and flow alteration has become more sophisticated through time; however, many studies continue to learn about flow indirectly. The flow-intact status of most rivers in northern Australia means that little direct evidence exists about the impact of water-resource development, with scientists gaining insights largely via statistical modelling. However, the vast array of research on different biotic groups and how they respond to river flow provides a substantial knowledge base for decision-making and policy development.

Our knowledge synthesis highlights numerous flow-biota relationships for the wet-dry tropics of northern Australia. For instance:

- the importance of flows to the estuary for stimulating primary production and the recruitment of diadromous species (e.g. barramundi, sawfish) and prawns.
- the importance of flows onto the floodplain for stimulating primary and secondary production, promoting fish and crocodile movement, and shaping the abundance of waterbirds and other floodplain species
- the importance of within-bank flows for fish and turtle movement, spawning and recruitment, as well as the downstream dispersal of macroinvertebrates and riparian seeds
- the importance of low flows/groundwater to the instream movement of sawfish and turtles, riparian trees, instream primary production, as well as the structure of fish and macroinvertebrate assemblages
- the importance of recessional flows for the upstream migration of cherabin, the movement of fish back off the floodplain and in support of 'homing behaviour'.
- the importance of antecedent flows to recruitment of longer-lived species such as barramundi and waterbirds.

Many of these relationships have already been identified by previous reviews (Georges and Rose 1993; Finlayson 2005; Robins et al. 2005; Shine and Brown 2008; Warfe et al. 2011; Pettit et al. 2017; Pollino et al. 2018b) but some have received relatively little attention to date. Our study is the first in the region to collate flow-biota information across a broad range of biotic groups and to perform a semi-quantitative assessment of their ability to draw inference on flow and flow alteration.

Importantly, our synthesis has highlighted knowledge imbalances, which have implications for risk assessment and knowledge transfer. Risks associated with water-resource development can be assessed more readily and with more confidence for well-studied biota, river systems and habitats, but remain more uncertain for biota, rivers and habitats where information is scant. In some instances, information can be transferred from other species, other river systems or other regions. However, 'borrowing' information must be done carefully and critically, as it may not be appropriate and result in suboptimal decision-making and reduced conservation outcomes. Further research is needed to inform when, where and for which biota knowledge can be transferred with confidence and where it cannot. In the interim, pragmatic decisions can be made using a conceptual understanding of the factors that shape transferability, i.e. flow regime, species life history and habitat preference. However, where transferability is uncertain and risks are high, we recommend implementing precautionary policy and undertaking targeted research to fill knowledge gaps.

It is important to reinforce that because a biotic group, habitat or river system is under-studied does not mean it is ecologically unimportant or at less risk from water-resource development. Indeed, many small and inconspicuous taxa, such as insects and molluscs, play pivotal roles in the aquatic and riparian food web and deliver important ecological functions. For instance, mussels are important for water filtration (Vaughn 2018; McCasker and Humphries 2021) and chironomids play a key role in sediment bioturbation which promotes nutrient transformation (Adámek and Maršálek 2013). Mussels and some chironomid species are known to be highly sensitive to pollutants and changes in flow (Viarengo and Canesi 1991; Gresens et al. 2007), but few studies in Australia’s wet-dry tropics, beyond those interested in mine site impacts (e.g. Bollhofer et al. 2011), have used these taxa as indicator species in the wet-dry tropics of northern Australia. Similarly, although the riparian zone has been investigated less than the river channel and wetlands/floodplains, that does not mean it is unimportant. Indeed, riparian soils and vegetation likely play important roles in nutrient dynamics, bank stability, energy inputs, instream temperature and habitat for wet-dry tropical streams (Pusey and Arthington 2003; Pettit et al. 2016). They also provide habitat for terrestrial plants and animals and are particularly important corridors for animal passage in dry areas of the wet-dry tropics (Woinarski et al. 2000).

Our ability to predict the impacts of water extraction on biota has improved through time. In the early 2000s, the simplest way to assess the likely impacts of water-resource development in the wet-dry tropics was to examine long-term changes in the Ord River, a large river dammed to generate hydropower and support irrigated agriculture. However, examining a single system that has undergone marked transformation can make it difficult to disentangle the effects of damming, surface water extraction, groundwater take and land use change. It also provides no way to examine the impact of differing amounts of water take. More recent studies have sought to learn about the impacts of water extraction by (1) measuring flow metrics (e.g. discharge, stage height) and describing flow-biota relationships in flow-intact systems and (2) using predictive models, e.g. hindcasting or forecasting, to reveal the likely impacts of flow alteration. These studies can reveal the flow components that should be protected by water policy and the likely impact of a range of water-take scenarios. They can also indicate if increasing water take will cause a commensurate decline in biota (i.e. linear relationship) or if thresholds exist, which is very useful to the development of water rules. However, despite these advancements, it is important to recognise that, for the wet-dry tropics, most of our insights into flow-biota are indirect, i.e. discharge-biota relationships aren’t available. All that is available is a directional understanding of the potential impact of water extraction, e.g. a reduction in flow will lead to a reduction in recruitment. This makes it extremely difficult to predict the impact of different levels of water extraction with any certainty and increases risk for water planners.

Finally, although uncertainty remains about the specific impacts of water extraction in the wet-dry tropics, a wealth of knowledge indicates that water extraction is likely to negatively impact a myriad of biota and ecological processes. Thus, we are extremely confident saying there will be impacts but are less well placed to be prescriptive about what those impacts will be for any given development. Indeed, the impact to any given biota will depend on factors linked to water take, such as the magnitude and timing of water take and which flow component (e.g. flood harvesting, groundwater) is targeted, as well as other factors, such as where development occurs along the river continuum, whether barriers to connectivity (i.e. dams, weirs) exist, and the severity of additional development stressors, such as pesticides, increased or decreased nutrients or sediment. Attributes of the environment will also play a role; for instance, a river's flow regime, its geologic and biotic setting, and the size of the groundwater reservoir. A greater understanding of how these factors shape riverine vulnerability to development will improve our ability to conserve these biodiverse systems valued greatly by Indigenous and non-Indigenous peoples.

## 6.1 Recommendations

This synthesis of research has identified the different levels of uncertainty about likely outcomes of water resource development for a range of ecological processes and species of northern Australia. This leads to four clear recommendations for research and management to improve the knowledge base for river management.

1. Improving the transferability of knowledge is critical to the management of remote regions that are difficult to access, such as many of the catchments of northern Australia. To improve the management outcomes in such areas, we need to develop specific research agenda. It would be ideal to implement specific comparative, field based, research programs to help identify knowledge that can be transferred. Such a program would involve matching sampling designs in different, representative river types to facilitate directly comparable data collection for similar species and ecological processes. The definition of different river types for such comparative research should involve classifications based on biophysical characterisation of at scales that are known to influence ecological processes (e.g. hydrological, geomorphic and biological information). Reproducible findings across different species, ecological processes and river systems would provide a clear identification of transferability.
2. It is clear from our findings that broadening the range of study species and ecological processes would be beneficial to the improved management of northern Australian ecosystems. We have identified comparatively under-studied species and processes as well as those that have had greater research focus. In addition to broadening this research focus, broadening the research approach, where possible, would assist in improving outcomes. This could include a greater focus on experimental ecology, including making use of natural experiments such as research into the ecological impacts of specific events such as the mangrove dieback in the Gulf of Carpentaria in 2015-2016.
3. Research effort to document the grey literature in substantial detail. There is a lot of research conducted by state government agencies and other researchers that was not covered by this synthesis, as it is not published in the scientific literature. Despite not going through formal peer review at a journal, there is a lot of high quality data,

some from comparatively long term monitoring, that could be used to guide management decisions in northern Australia. A research effort to develop a database of this knowledge, in a similar manner to this study, would help ensure this research is readily available to water planners and managers to inform decision making around water resource development.

4. Finally, it is important to recognise that the uncertainties identified in this synthesis are frequently around confidence in the nature and magnitude of impacts on specific ecological processes, species or understudied catchments. There is high certainty that hydrological changes from water resource development in general will impact aquatic ecosystems, the nature of such impacts is less certain.  As such, until the knowledge base is increased to increase this certainty in relatively unstudied catchments and for understudied species and processes, managers should continue to follow a precautionary approach to decision making.

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# Appendix

Scopus query string

(TITLE-ABS-KEY("fresh*" OR "aquatic" OR "river*" OR "floodplain" OR "wetland*" OR "stream*" OR "creek*" OR "estuar*" OR "lagoon" OR "billabong" OR "waterhole" OR "riparian") AND TITLE-ABS-KEY("flow*" OR "discharge" OR "water" OR "hydro*" OR "flood" OR "connect*" OR "fragment*" OR "refuge" OR "climate") AND TITLE-ABS-KEY("fish*" OR "*bird" OR "nutrient" OR "food web" OR "foodweb" OR "food-web" OR "energ*" or "macroinvert*" OR "*plankton" OR "prawn*" OR "crab" OR "crayfish" OR "crocodile" OR "turtle" OR "metabolism" OR "primary producti*")) AND TITLE-ABS-KEY("tropic*") AND NOT TITLE-ABS-KEY("subtrop*" OR sub-trop*) AND ( LIMIT-TO ( AFFILCOUNTRY,"Australia" ) ) AND ( LIMIT-TO ( SUBJAREA,"ENVI" ) OR LIMIT-TO ( SUBJAREA,"AGRI" ) OR LIMIT-TO ( SUBJAREA,"EART" ) ) AND ( LIMIT-TO ( LANGUAGE,"English" ) )

Table A1. Evidence synthesis detailing flow-biota knowledge for 29 key biota and/or processes in the wet-dry tropics of northern Australia and the likely impact of water resource development. Reviews were not included and where possible only one study is included if the same result has been reported multiple times, i.e. report and manuscript.

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
|---|---|---|---|---|---|---|---|
| 1. Estuarine primary production | Overbank and within-bank flows<br>Estuary | n=9<br>(McKinnon & Klumpp 1998; Burford et al. 2010; Burford et al. 2011; Burford et al. 2012; Blondeau-Patissier et al. 2014; Duggan et al. 2014; Burford et al. 2016; Burford & Faggotter 2021; Lowe et al. 2022) | • Direct (n=1) (Burford et al. 2016)<br>• Inferred through time (n=8) (McKinnon & Klumpp 1998; Burford et al. 2010; Burford et al. 2011; Burford et al. 2012; Blondeau-Patissier et al. 2014; Burford & Faggotter 2021; Lowe et al. 2022)<br>• Inferred through space (n=0) | • None: n=7 (McKinnon & Klumpp 1998; Burford et al. 2010; Burford et al. 2012; Blondeau-Patissier et al. 2014; Burford & Faggotter 2021; Lowe et al. 2022)<br>• Direct assessment: n=1 (Burford et al. 2011)<br>• Modelled: n=1 (Burford et al. 2016) | 8 catchments, focus on Gulf of Carpentaria<br>• Qld: Flinders, Gilbert, Mitchell, Norman, Pascoe, Claudie,<br>• NT: Van Diemen's Gulf<br>• WA: Ord | Freshwater flow to the estuary during the wet season deliver nutrients (McKinnon & Klumpp 1998; Burford et al. 2011; see Burford et al. 2012 as an exception; Burford et al. 2016; Burford & Faggotter 2021) that increase primary production i.e. phytoplankton, benthic algae on mud flats, epiphyton on seagrass, over the short to medium term (Burford et al. 2011; see Burford et al. 2012 for exception; Blondeau-Patissier et al. 2014; Duggan et al. 2014; Burford et al. 2016). Over very short time scales, flow disturbance can reduce benthic primary production (Duggan et al. 2014; Lowe et al. 2022). Flows also inundate mudflats and sand flats in the coastal zone which release nutrients and stimulate primary production (Burford et al. 2010). | Reduced primary production which will impact higher order animals that feed in these habitats such as fish and migratory shorebirds. Reduction in estuarine algal blooms in nutrient enriched catchments. |
| 2. Prawn recruitment/ abundance | Overbank, within-bank, low flows<br>Estuary | n=9<br>(Vance et al. 1985; Staples & Vance 1986; Vance et al. 1998; Kenyon et al. 2004; Burford et al. 2010; Duggan et | • Direct (n=7) (Vance et al. 1985; Staples & Vance 1986; Vance et al. 1998; Duggan et al. 2019; Broadley et al. 2020; Kenyon et al. 2020; Turschwell et al. 2022) | • None: n=6 (Vance et al. 1985; Staples & Vance 1986; Vance et al. 1998; Burford et al. 2010; Kenyon et al. 2020; Turschwell et al. 2022)<br>• Direct assessment: n=1 (Kenyon et al. 2004) | 14 catchments, focus on Gulf of Carpentaria<br>• Qld: Mitchell, Gilbert, Flinders, Norman, Embley, Mission<br>• NT: Roper, Leichhardt, McArthur | Low freshwater discharge during the late dry season creates favourable salinity in estuarine river reaches and flood tides assist post-larval prawns to immigrate into this habitat (Stapels 1980; Kenyon et al. 2004). Flow during the wet season reduce salinity in the lower reaches of the river and cause a decline in their food meiofauna (item 6). This plus salinity stress promotes the movement of juvenile prawns to offshore areas (Vance et al. 1985; Staples & Vance 1986; Vance et al. 1998; Burford et al. 2010) where they are caught by commercial fishers. Increased migration of prawns and | Reduced prawn abundance. It is expected that impacts of water extraction on the prawn fishery will be lowest during years with high or very high flow but marked during years of low flow. Marine species that consume prawns are likely to be also affected. River regulation and irrigation runoff that increases dry season flows, i.e. Ord, |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
|---|---|---|---|---|---|---|---|
| | | al. 2019; Broadley et al. 2020; Kenyon et al. 2020; Turschwell et al. 2022) | • Inferred through time (n=1) (Burford et al. 2010)<br>• Inferred through space (n=1) (Kenyon et al. 2004)<br>Note, Rainfall often used as correlate of flow in these studies. | • Modelled: n=2 (Duggan et al. 2019; Broadley et al. 2020) | • WA: Joseph Bonaparte Gulf; King George River, Berkeley River, Ord River, Keep River, Victoria River<br>Note, not all rivers on the Gulf listed | higher primary production in the estuary (see item 1) lead to increased recruitment and catch of prawns in the coastal waters (Vance et al. 1985; Staples & Vance 1986; Vance et al. 1998; Duggan et al. 2019; Kenyon et al. 2020; Turschwell et al. 2022). Migrating prawns also tend to be larger in size (Staples & Vance 1986). River regulation that increases dry season low flows will reduce salinity in estuarine river reaches and interfere with post larval recruitment and reduce prawn catch/abundance (Kenyon et al. 2004; Duggan et al. 2019).<br>Note (Stapels 1980) not included as it includes relevant ecological knowledge, but not relevant to flow-biota relationship. | reduce salinity in lower reaches of the river and are likely to reduce prawn recruitment. |
| 3. Growth, recruitment and abundance of diadromous fish | Overbank and within-bank flows<br>Estuary, River channel | n=9 (Bayliss et al. 2007; Stewart-Koster et al. 2011; Lear et al. 2019; Roberts et al. 2019; Turschwell et al. 2019; Lear et al. 2020; Morrongiello et al. 2020; Leahy & Robins 2021; Crook et al. 2022) | • Direct (n=8) (Bayliss et al. 2007; Stewart-Koster et al. 2011; Lear et al. 2019; Turschwell et al. 2019; Lear et al. 2020; Morrongiello et al. 2020; Leahy al. 2020; Leahy & Robins 2021; Crook et al. 2022)<br>• Inferred through time (n=0)<br>• Inferred through space (n=1) (Roberts et al. 2019) | • None: n=7 (Bayliss et al. 2007; Stewart-Koster et al. 2011; Lear et al. 2019; Roberts et al. 2019; Turschwell et al. 2019; Lear et al. 2020; Morrongiello et al. 2020)<br>• Direct assessment: n=0<br>• Modelled: n=2 (Leahy & Robins 2021; Crook et al. 2022) | 8 catchments<br>• NT: Daly, Mary, Roper, McArthur<br>• WA: Fitzroy<br>• Qld: Mitchell Flinders and Gilbert<br>Note, studies elsewhere in Qld that report positive relationship between barramundi recruitment, growth rates and river discharge | Freshwater flow into the estuary during the wet season increase food production (see item 1) which increases the growth rates (Roberts et al. 2019; Morrongiello et al. 2020; Leahy & Robins 2021), reduces predation, and recruitment/abundance of barramundi (Bayliss et al. 2007; Bayliss et al. 2008; Stewart-Koster et al. 2011; Turschwell et al. 2019; Crook et al. 2022). Protracted flood flows are important for sawfish recruitment (Lear et al. 2019) presumably because they assist pups to move into freshwater via the floodplain where they face lower predation pressure than the main channel or the estuary (Lear et al. 2019). The magnitude of wet season flow has little impact on the recruitment of the bull shark (*Carcharhinus leucas*) (Lear et al. 2020).<br>Note, (Bayliss et al. 2008) included in knowledge summary but omitted from evidence studies as the same dataset is used. | Reduced recruitment of diadromous species that are important commercial, recreational species such as Barramundi. Reduced recruitment for the critically endangered EBPC listed sawfish *Pristis pristis*. |
| 4. Movement of diadromous | Overbank, within-bank | n=6<br>(Davis 1985; Davis 1988; | • Direct (n=1) (Morgan et al. 2021) | • None: n=6 (Davis 1985; Davis 1988; Blaber et al. | 14 catchments | Freshwater flows and tides stimulate or assist fish to move around estuarine habitats. Some marine and diadromous species (e.g. juvenile | Altered use of tidal creeks, swamps, and the lower reaches of the river by |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
|---|---|---|---|---|---|---|---|
| and coastal marine fish | flows and low flows<br>Estuary, Tidal Creeks, River channel | Blaber et al. 1989; Walther et al. 2011; Lyon et al. 2017; Morgan et al. 2021) | • Inferred through time (n=5) (Davis 1985; Davis 1988; Blaber et al. 1989; Walther et al. 2011; Lyon et al. 2017)<br>• Inferred through space (n=0) | 1989; Walther et al. 2011; Lyon et al. 2017; Morgan et al. 2021)<br>• Direct assessment: n=0<br>• Modelled: n=0 | • NT: Buffalo Ck, Victoria, Daly, Alligator, South Alligator, West Alligator, Wildman, Mary<br>• WA: Fitzroy<br>• Qld: Wenlock, Gilbert, Smithburne, Norman, Embley | barramundi) use high river flows and high tides to access tidal creeks and swamps (Davis 1985; Davis 1988). Freshwater flows also stimulate juvenile barramundi to move into freshwater (Davis 1985; Walther et al. 2011) where growth is maximised (Roberts et al. 2019). Species that use rivers as nurseries, e.g. the speartooth shark *Glyphis glyphis*, the bullshark *Carcharhinus leucas*, and sawfish *Pristis pristis*, also have their movement cued by flow/salinity – i.e. moving upstream during low flow/high salinity periods and downstream during high flows/low salinity (Blaber et al. 1989; Thorburn et al. 2007; Lyon et al. 2017; Morgan et al. 2021). Flows low enough to expose sandbars can prevent the instream movement of sawfish in the estuarine reaches, as can instream barriers [410].<br>Note (Thorburn et al. 2007) included in knowledge summary but omitted from evidence studies as the same dataset was published later in (Morgan et al. 2021). | estuarine and diadromous fish. Responses will be species specific, but some species and life stages will move further into the estuarine reaches of the river as salinity increases, others will move less. |
| 5. Estuarine fish assemblage (excluding diadromous species) | Overbank, within-bank<br>Estuary | n=3<br>(Davis 1988; Blaber et al. 1989; Pusey et al. 2016) | • Direct (n=0)<br>• Inferred through time (n=3) [14, 239, 429]<br>• Inferred through space (n=0) | • None: n=3 (Davis 1988; Blaber et al. 1989; Pusey et al. 2016)<br>• Direct assessment: n=0<br>• Modelled: n=0 | 3 catchments, focus on NT<br>• NT: Buffalo Ck, Embley, South Alligator<br>• Qld: none<br>• WA: none | The estuary supports diverse habitats and more species than the adjacent nearshore zone (Davis 1988; Blaber et al. 1989). It is also a nursery for many species (Davis 1988; Blaber et al. 1989; Pusey et al. 2016). The fish assemblage is shaped by seasonal patterns in flow (Davis 1988; Pusey et al. 2016), likely due to changes in salinity, food production and the spawning behaviour of fish (Pusey et al. 2016). | Altered fish assemblage, including reduced diversity and productivity. |
| 6. Estuarine zooplankton and macro/ meiofauna | Overbank, within-bank, Low flow<br>Estuary | n=5<br>(Duggan et al. 2008; Burford et al. 2010; Duggan et al. 2014; | • Direct (n=0)<br>• Inferred through time (n=5) (Duggan et al. 2008; Burford et al. 2010; Duggan et al. | • None: n=5 (Duggan et al. 2008; Burford et al. 2010; Duggan et al. 2014; Lowe et al. 2022; Venarsky et al. 2022) | 7 catchments, focus on NT<br>• NT: Blackmore, Elizabeth, Darwin Harbour | Zooplankton and mudflat/sandflat meiofauna are important food sources for animals living in the estuary, including larval fish, prawns and endangered migratory shorebirds. Estuarine zooplankton and mudflat meiofaunal communities undergo seasonal shifts in line with the wet and dry season (Duggan et al. 2008; | Altered zooplankton and benthic mudflat invertebrate communities, but secondary production may be relatively unchanged, at least over the medium term (i.e. < 2 years). Longer term consequences |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| | | Lowe et al. 2022; Venarsky et al. 2022) | 2014; Lowe et al. 2022; Venarsky et al. 2022)<br>• Inferred through space (n =0) | • Direct assessment: n=0<br>• Modelled: n=0 | • Qld: Norman, Mitchell, Gilbert, Flinders<br>• WA: none | Burford et al. 2010; Duggan et al. 2014; Lowe et al. 2022; Venarsky et al. 2022). Abundance is typically highest in the late dry season when intertidal flats are hypersaline and benthic algae are abundant (Lowe et al. 2022). Wet season flows disturb meiofaunal and microbenthic invertebrates, via changes in salinity, sedimentation and benthic algal production, causing short-term decreases in density of individuals (Duggan et al. 2014; Lowe et al. 2022) and a medium-term increase (Burford et al. 2010). Low flows are thought to affect benthic macroinvertebrates by shaping the salinity regime (Venarsky et al. 2022). There is evidence that production of the benthic community (i.e. abundance, biomass) is resistant to changes in salinity regime due to diverse salinity preferences among species (Venarsky et al. 2022). | of altered flow are not as clear, but reduction in flow could reduce food production of macro/meiofauna which could impact prawns, fish and shorebirds. It could also reduce the ability of prawns and fish access the intertidal flats via changes to salinity and physicochemical tolerances. |
| 7. Water quality and fish kills | Within-bank. Early wet season flows<br>River channel, Wetlands | n=6<br>(Bishop 1980; Brown et al. 1983; Hart et al. 1987a; Townsend et al. 1992; Townsend 1994; Townsend & Edwards 2003)<br><br>Note (Bishop & Forbes 1991) not included as it is a review. | • Direct (n=0)<br>• Inferred through time (n=6) (Bishop 1980; Brown et al. 1983; Hart et al. 1987a; Townsend et al. 1992; Townsend 1994; Townsend & Edwards 2003)<br>• Inferred through space (n=0) | • None: n=6 (Bishop 1980; Brown et al. 1983; Hart et al. 1987a; Townsend et al. 1992; Townsend 1994; Townsend & Edwards 2003)<br>• Direct assessment: n=0<br>• Modelled: n=0 | 3 catchments, focus on Magela Ck and Kakadu<br>• NT: East Alligator, Daly, Mary<br>• Qld: none<br>• WA: none | Early wet season flows can lead to poor water quality that causes fish kills (Bishop 1980; Brown et al. 1983; Townsend et al. 1992; Townsend 1994). Poor water quality can arise because organic matter leached from leaves, that have accumulated during the dry season, increase microbial demand for oxygen and cause an oxygen crash (Bishop 1980; Townsend et al. 1992; Townsend & Edwards 2003). Acid and metals (e.g. aluminium) mobilised by the inundation of acid-sulphate soils on some floodplains can also create toxic water (Brown et al. 1983; Hart et al. 1987a; Townsend et al. 1992). Naturally occurring ichthyocides and phytocides leached from trees and shrubs may also play a role (Bishop & Forbes 1991). | If water extraction impacts the first flush or subsequent cleaning flows, it could exacerbate poor water quality and increase the risk of fish kills early in the wet season. |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| 8. Freshwater fish movement and dispersal | Within-bank, Over-bank, Recessional<br><br>River channel, Wetland, Floodplain | n=17<br><br>(Bishop et al. 1990; Bishop et al. 1995; Trayler et al. 2003; Morgan 2005; Gill et al. 2006; Heupel et al. 2011; Walther et al. 2011; Jardine et al. 2012b; Warfe et al. 2013b; Whitty et al. 2014; Crook et al. 2017; Pusey et al. 2018; Turschwell et al. 2019; Crook et al. 2020; Crook et al. 2021a; Crook et al. 2021b; O'Mara et al. 2021) | • Direct (n=5) (Morgan 2005; Whitty et al. 2014; Crook et al. 2021a; Crook et al. 2021b; O'Mara et al. 2021)<br>• Inferred through time (n=9) (Bishop et al. 1990; Bishop et al. 1995; Heupel et al. 2011; Walther et al. 2011; Jardine et al. 2012b; Crook et al. 2017; Pusey et al. 2018; Turschwell et al. 2019; Crook et al. 2020)<br>• Inferred through space (n=3) (Trayler et al. 2003; Gill et al. 2006; Warfe et al. 2013b) | • None: n=9 (Bishop et al. 1990; Bishop et al. 1995; Walther et al. 2011; Jardine et al. 2012b; Warfe et al. 2013b; Pusey et al. 2018; Turschwell et al. 2019; Crook et al. 2020; Crook et al. 2021a)<br>• Direct assessment: n=4 (Trayler et al. 2003; Morgan 2005; Gill et al. 2006; Whitty et al. 2014)<br>• Modelled: n=2 (Crook et al. 2021b; O'Mara et al. 2021) | 9 catchments. focus on NT<br>• NT: Magela, East Alligator, South Alligator, Fergusson, Daly, Victoria<br>• WA: Fitzroy, Ord River<br>• Qld: Mitchell | Within-bank flows facilitate the movement and dispersal of fish along the river system (Bishop et al. 1990; Pusey et al. 2018; Turschwell et al. 2019; Crook et al. 2021a; Crook et al. 2021b; O'Mara et al. 2021) including diadromous species (Walther et al. 2011; Crook et al. 2017; O'Mara et al. 2021). These movements allow individuals to recolonise intermittent river reaches (Pusey et al. 2018; Turschwell et al. 2019). Overbank flows facilitate the movement of fish onto the floodplain (Trayler et al. 2003; Jardine et al. 2012b; Crook et al. 2020), and flows late in the wet season (recessional flows) facilitate the movement of fish back to refuges, including from floodplain habitats back to the main channel (Bishop et al. 1995; Crook et al. 2021a). Dispersal plays more of a role structuring fish assemblages in intermittent than perennial river reaches (Warfe et al. 2013b).<br><br>Instream barriers inhibit the movement of fish (O'Mara et al. 2021) including the upstream movement of species that migrate as part of their life cycle i.e. cherabin, barramundi, tarpon and sawfish (Trayler et al. 2003; Morgan 2005; Gill et al. 2006; Whitty et al. 2014; O'Mara et al. 2021) as well as other species e.g. fork-tailed catfish and freshwater longtom (O'Mara et al. 2021). Species little affected are those that don't move much and individuals of diadromous species that are residents in freshwater i.e. resident barramundi (Heupel et al. 2011; Crook et al. 2017). | Reduced distribution of migratory species within a catchment. Reduced recolonisation of sites by fish after local extirpation resulting in slower population recovery after disturbance. Reduced body condition and health of individuals due to reduced ability to access high quality habitats. |
| 9. Fish spawning and recruitment | Within-bank, Overbank, Low flows | n=6<br><br>(Bishop et al. 2001; Stewart-Koster et al. 2011; King | • Direct (n=3) (Stewart-Koster et al. 2011; Lear et al. 2020; King et al. 2021)<br>• Inferred through time (n=3) | • None: n=5 (Bishop et al. 2001; Stewart-Koster et al. 2011; King et al. 2020; Lear et al. | 5 catchments, focus on NT<br>• NT: Magela, East Alligator, South Alligator, Daly | Wet season flows cue the spawning of many fish species including catfish and the Terapontids (Bishop et al. 2001; King et al. 2020; Tyler et al. 2021) and promote the recruitment of species such as the freshwater longtom (*Strongylura krefftii*) and black catfish (*Neosilurus ater*) (King et al. 2021), including aseasonal spawners such | Altered spawning and recruitment of many fish species leading to reduced abundance of some species and reduced potential for |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| | River channel, Wetland | et al. 2020; Lear et al. 2020; King et al. 2021; Tyler et al. 2021)<br>Note, (Pusey et al. 2004) not included as it is a review. | (Bishop et al. 2001; King et al. 2020; Tyler et al. 2021)<br>• Inferred through space (n=0) | 2020; Tyler et al. 2021)<br>• Direct assessment: n=0<br>• Modelled: n=1 (King et al. 2021) | • Qld: none<br>• WA: Fitzroy | as *Nematalosa erebi* (Lear et al. 2020). Recruitment of many species is often highest in floodplain wetlands indicating this habitat is a nursery (Bishop et al. 2001).<br>Species that spawn during low flows (Bishop et al. 2001; King et al. 2020; Tyler et al. 2021), including hardyheads and rainbowfish will have recruitment decline with high flows (Stewart-Koster et al. 2011; Lear et al. 2020; King et al. 2021). Note, the recruitment of sooty grunter (*Hephaestus fuliginosus*), which spawns during the wet season, decreases with greater wet season flow (Stewart-Koster et al. 2011; King et al. 2021) because high flows disturb the riffle habitat and associated backwaters where it spawns (Pusey et al. 2004).<br>Note, see Item 3 for details of the recruitment of diadromous species such as barramundi and sawfish that are spawned in the estuary. | populations of these species to recover from disturbance. |
| 10. Fish assemblage structure and abundance | Low flow, within-bank, overbank, antecedent<br>River channel, Wetland | n=15<br>(Bishop et al. 1990; Kennard 1995; Storey 2002b, 2003; Faggotter 2010; Stewart-Koster et al. 2011; Chan et al. 2012; Warfe et al. 2013b; Pusey et al. 2018; Keller et al. 2019; Turschwell et al. 2019; | • Direct (n=7) (Stewart-Koster et al. 2011; Chan et al. 2012; Keller et al. 2019; Turschwell et al. 2019; Crook et al. 2021b; King et al. 2021; Crook et al. 2022)<br>• Inferred through time (n=5) (Bishop et al. 1990; Kennard 1995; Storey 2002b; Faggotter 2010; | • None: n=9 (Bishop et al. 1990; Storey 2003; Faggotter 2010; Stewart-Koster et al. 2011; Warfe et al. 2013b; Pusey et al. 2018; Keller et al. 2019; Turschwell et al. 2019; Pusey et al. 2020a)<br>• Direct assessment: n=1 [65]<br>• Modelled: n=4 (Chan et al. 2012; Crook et al. 2021b; King et al. | 7 catchments, focus on Daly<br>• NT: Daly, Mary, McArthur, Roper<br>• Qld: Normanby<br>• WA: Ord, Fitzroy | Fish assemblages are shaped by flow across a temporal hierarchy. 1.Fish abundance is influenced by historical conditions, i.e. the flow regime, with assemblages in perennial tributaries/rivers different from those in intermittent ones (Stewart-Koster et al. 2011; Warfe et al. 2013b; Pusey et al. 2018; Turschwell et al. 2019; Pusey et al. 2020a). Intermittent tributaries support a subset of the species present in perennial reaches (Pusey et al. 2018). 2. Fish abundance is influenced by the magnitude of the current or preceding wet season (Stewart-Koster et al. 2011; Turschwell et al. 2019) with the abundance of barramundi, longtom *Strongylura krefttii,* black catfish *Neosilurus ater* and fork-tailed catfish *Neoarius* spp decreasing with declining wet season flow (Stewart-Koster et al. 2011; King et al. 2021; Crook et al. 2022). In contrast, the abundance of rainbowfish *Melanotaenia australis* increases | Altered flow will change the fish assemblage. Reduced wet season flow will reduce the abundance of many species that spawn and recruit during the wet season, including barramundi and sawfish. Water extraction that shifts a waterway from perennial to intermittent will reduce species richness.<br>Decreasing water velocity and/or depth during dry season low flows will reduce the occurrence and abundance of many species, particularly if depth falls |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| | | Pusey et al. 2020a; Crook et al. 2021b; King et al. 2021; Crook et al. 2022) | Pusey et al. 2020a)<br>• Inferred through space (n=3) (Storey 2003; Warfe et al. 2013b; Pusey et al. 2018) | 2021; Crook et al. 2022) | | with declining wet season flow (Stewart-Koster et al. 2011). Flow variation can also be influential (Stewart-Koster et al. 2011; Turschwell et al. 2019). 3. Fish abundance is influenced by recent or current flow conditions, such as velocity and depth (Bishop et al. 1990; Kennard 1995; Storey 2003; Faggotter 2010; Stewart-Koster et al. 2011; Chan et al. 2012; Warfe et al. 2013b; Keller et al. 2019; Crook et al. 2021b) which affect habitat quality and the strength of competition and predation (Kennard 1995; Turschwell et al. 2019). Reductions in low flow are likely to decrease the abundance of certain species (Crook et al. 2022) as the habitats they inhabit or spawn in disappear (Storey 2002b; Chan et al. 2012; Crook et al. 2021b). | below critical thresholds. Water extraction that reduces the amount of riffle habitat will impact sooty grunters, and extraction that reduces slow flowing backwater habitats in perennial flowing rivers will impact small bodied species. |
| 11. Cherabin life history, recruitment and abundance | Within-bank, Overbank, Recessional, Low flow<br>River channel, Wetland, Estuary | n=6<br>(Storey 2002b; Novak et al. 2015; Novak et al. 2017a; Novak et al. 2017b; Novak et al. 2017c; Beesley et al. 2023) | • Direct (n=1) (Novak et al. 2017a)<br>• Inferred through time (n=3) (Novak et al. 2015; Novak et al. 2017c; Beesley et al. 2023)<br>• Inferred through space (n=2) (Novak et al. 2017b; Beesley et al. 2023) | • None: n=5 (Novak et al. 2015; Novak et al. 2017a; Novak et al. 2017b; Novak et al. 2017c; Beesley et al. 2023)<br>• Direct assessment: n=1 (Storey 2002b)<br>• Modelled: n=0 | 3 catchments, focus on Daly<br>• NT: Daly<br>• Qld: none<br>• WA: Ord, Fitzroy | Cherabin *Macrobrachium spinipes* are amphidromous and flow connectivity between the river and estuary is critical to their life history (Novak et al. 2015; Novak et al. 2017c; Beesley et al. 2023). This includes the downstream drift of larvae on wet season flows (Novak et al. 2017c) and the upstream migration of juveniles on recessional wet season flows (Novak et al. 2017a). Aquatic habitat in the main channel is particularly important to juveniles (Beesley et al. 2023), whereas adults live in main channel and wetland/floodplain pools (Beesley et al. 2023). Decreases in wet season flow reduce main channel and floodplain habitats and decrease the size of the metapopulation (Beesley et al. 2023). Wet season flows increase body condition (Novak et al. 2015). Macrophyte beds and sandbar runs are important habitat for juveniles (Novak et al. 2017b) but cherabin leave if water levels fall (Storey 2002b)[65]. | Reductions in the magnitude of wet season flows may reduce the downstream drift of larvae to the estuarine nursey reducing recruitment. They may also reduce the availability of main channel and floodplain habitat for the species reducing landscape level abundance. Reductions in receding wet season flows may reduce recruitment and dispersal by limiting the upstream migration of juveniles. Instream barriers will limit and prevent upstream migration and impact the distribution and abundance of the species. Floodplain harvesting that diminishes wetland pools will impact the abundance of adults. Declining low flows can impact habitats and |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| | | | | | | | increase competition for resources and predation. |
| 12. Macroinvertebrate dispersal and recolonisation | Within-bank, Low flow<br>River channel | n=2<br>(Dostine et al. 1998; Warfe et al. 2013b) | • Direct (n=0)<br>• Inferred through time (n=1) (Dostine et al. 1998)<br>• Inferred through space (n=1) (Warfe et al. 2013b) | • None: n=2 (Dostine et al. 1998; Warfe et al. 2013b)<br>• Direct assessment: n=0<br>• Modelled: n=0 | 3 catchments<br>• NT: East Alligator, Daly<br>• Qld: none<br>• WA: Fitzroy | Early wet season flows facilitate the downstream drift of macroinvertebrates in intermittent streams/rivers (Dostine et al. 1998). Colonising animals come from upstream permanent pools as well as from dry sand-bed sediments (Dostine et al. 1998). Recolonisation occurs rapidly after the first flow (Dostine et al. 1998). Sites closer together have more similar communities (Warfe et al. 2013b). Egg laying from winged adults is likely to also be an important facet of recolonisation for insects, but little information is available. | Reduced macroinvertebrate drift and associated recolonisation of intermittent river reaches, leading to delayed recovery following drying disturbance. |
| 13. Macroinvertebrate assemblage structure | Within-bank, Low flow<br>River channel, Wetland | n=15<br>(Marchant 1982; Outridge 1988; Dostine 2000; Storey 2002a; Trayler et al. 2003; Storey & Lynas 2007; Humphrey et al. 2008; Leigh & Sheldon 2009; Dostine & Humphrey 2012; Leigh et al. 2012; Townsend et al. 2012a; Leigh 2013; | • Direct (n=3) (Dostine & Humphrey 2012; Townsend et al. 2012a; Leigh 2013)<br>• Inferred through time (n=4) (Marchant 1982; Outridge 1988; Waltham et al. 2013; Garcia et al. 2015)<br>• Inferred through space (n=7) (Dostine 2000; Storey 2002a; Trayler et al. 2003; Storey & Lynas 2007; Humphrey et al. 2008; Leigh & Sheldon 2009; | • None: n=11 (Marchant 1982; Outridge 1988; Dostine 2000; Storey & Lynas 2007; Humphrey et al. 2008; Leigh & Sheldon 2009; Dostine & Humphrey 2012; Townsend et al. 2012a; Leigh et al. 2013; Warfe et al. 2013b; Garcia et al. 2015)<br>• Direct assessment: n=2 (Storey 2002a; Trayler et al. 2003)<br>• Modelled: n=2 (Leigh et al. 2012; Waltham et al. 2013) | 14 catchments<br>• NT: Daly, South Alligator, East Alligator, Mary, Adelaide, Finniss, Victoria, Roper, Melville Island<br>• Qld: Gregory, Flinders, Gilbert<br>• WA: Ord, Fitzroy | Flow is a driving force of macroinvertebrate assemblages. Changes to flow will alter assemblage structure (Dostine 2000; Storey 2002a; Trayler et al. 2003; Storey & Lynas 2007; Humphrey et al. 2008; Leigh & Sheldon 2009; Waltham et al. 2013; Warfe et al. 2013b). This includes a decline in flow-dependent macroinvertebrate taxa velocity declines (Storey 2002a; Storey & Lynas 2007; Dostine & Humphrey 2012; Leigh et al. 2013), i.e. a shift from filterers and grazers to gatherers (Leigh & Sheldon 2009). Decreases in species richness as aquatic habitats contract have been found by many (Marchant 1982; Outridge 1988; Storey 2002a; Leigh et al. 2013; Waltham et al. 2013), although some report little change (Trayler et al. 2003). In floodplain habitats, reduced flow that prevents fish colonisation increases macroinvertebrate species richness and abundance (Trayler et al. 2003). | Altered macroinvertebrate assemblage structure, including a decline in flow-dependent taxa. |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| | | Waltham et al. 2013; Warfe et al. 2013b; Garcia et al. 2015) | Warfe et al. 2013b)<br>• Other (n=1) (Leigh et al. 2012)<br>Note, many studies used space and time to investigate the influence of flow on macroinverts. The dominant approach was used in the categorisation. | | | | |
| 14. Instream primary production (macrophytes, spirogyra, benthic algae, phytoplankton) | Within-bank; Low flows<br>River channel | n=16<br>(Rea et al. 2002; Storey 2002b; Townsend & Padovan 2005; Webster et al. 2005; Townsend & Padovan 2009; Robson 2010; Townsend et al. 2011; Hunt et al. 2012; Townsend et al. 2012b; Faggotter et al. 2013; Townsend & Douglas | • Direct (n=9) (Rea et al. 2002; Townsend & Padovan 2005; Townsend & Padovan 2009; Robson 2010; Hunt et al. 2012; Townsend et al. 2012a; Townsend et al. 2012b; Townsend & Douglas 2017; Burrows et al. 2020)<br>• Inferred through time (n=7) (Storey 2002b; Webster et al. 2005; Townsend et al. | • None: n=13 (Townsend & Padovan 2005; Webster et al. 2005; Robson 2010; Townsend et al. 2011; Hunt et al. 2012; Townsend et al. 2012a; Townsend et al. 2012b; Faggotter et al. 2013; Townsend & Douglas 2014; Garcia et al. 2015; Townsend & Douglas 2017; Townsend et al. 2018; Burrows et al. 2020)<br>• Direct assessment: n=1 (Storey 2002b) | 5 catchments, focus on Daly<br>• NT: Daly<br>• WA: Ord, Fitzroy Qld: Mitchell, Flinders | During the dry season, high light and stable baseflow in clearwater rivers support high primary production, e.g. macrophytes, filamentous algae (e.g. spirogyra), benthic algae and phytoplankton (Rea et al. 2002; Townsend & Padovan 2005; Webster et al. 2005; Townsend & Padovan 2009; Townsend et al. 2011; Hunt et al. 2012; Faggotter et al. 2013; Townsend & Douglas 2017; Townsend et al. 2018), see Robson (2010) as an exception]. A reduction in scouring/turbid flows typically leads to an increase primary production (Webster et al. 2005; Hunt et al. 2012; Townsend & Douglas 2014, 2017; Townsend et al. 2018; Burrows et al. 2020). However, if primary production is heavily nutrient limited, decreases in flow may have little effect (Townsend et al. 2012b; Garcia et al. 2015). Further, certain species adapted to high flows, such as the ribbon weed (*Vallisneria nana*) are adversely affected if flows decline (Rea et al. 2002).<br>In perennially flowing rivers such as the Daly, primary production is likely to diminish through time if low flows are protracted (Townsend & | Unclear, potentially negative or positive. Change likely to depend on the extent of (i) baseflow in the waterway, (ii) water extraction, (iii) whether macrophytes versus other forms of plants/algae drive primary production. For intermittently flowing rivers, reduced flow may generate water quality issues due to algal blooms. |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| | | 2014; Garcia et al. 2015; Townsend & Douglas 2017; Townsend et al. 2018; Burrows et al. 2020) | 2011; Faggotter et al. 2013; Townsend & Douglas 2014; Garcia et al. 2015; Townsend et al. 2018)<br>• Inferred through space (n=0) | • Modelled: n=2 (Rea et al. 2002; Townsend & Padovan 2009) | | Padovan 2005; Webster et al. 2005; Townsend & Padovan 2009), but see Robson (2010) as an exception] because slow flows can reduce the ability of primary producers to uptake nutrients required for growth (Robson 2010; Townsend et al. 2012a). Rapidly falling baseflow can also negatively impact primary production by exposing macrophyte beds (Rea et al. 2002; Storey 2002b).<br>In intermittently flowing rivers, primary productivity can increase as waterholes contract and nutrients elevate [200]. | |
| 15. Dispersal and germination of riparian vegetation | Within-bank, Overbank<br>River channel | n=2<br>(Pettit & Froend 2001; Warfe et al. 2013b)<br>NB (Doupé & Pettit 2002) not included as it is a review | • Direct (n=0)<br>• Inferred through time (n=0)<br>• Inferred through space (n=2) (Pettit & Froend 2001; Warfe et al. 2013b) | • None: n=2 (Pettit & Froend 2001; Warfe et al. 2013b)<br>• Direct assessment: n=0<br>• Modelled: n=0 | 3 catchments<br>• NT: Daly<br>• WA: Ord, Fitzroy<br>• Qld: none | Within-bank and overbank flows disperse plant seeds (Pettit & Froend 2001). Those that end up in safe sites, e.g. moist bare sediments at higher elevations away from scouring flows are most likely to survive and germinate (Pettit & Froend 2001). Flood debris may be an important site of seed store and germination for overstorey tree species (Pettit & Froend 2001). Riparian communities at intermittent sites close together are more similar than those that are further apart due to dispersal constraints (Warfe et al. 2013b). | Reduced germination and recruitment of riparian vegetation.<br>If WRD alters flow seasonality, e.g. releases from a dam cause unnaturally high dry season flows, these can reduce seed germination of the tree species that live along the bank e.g. *Melaleuca leucadendra* (Doupé & Pettit 2002) |
| 16. Riparian vegetation assemblage structure (woody vegetation) | Within-bank, Overbank, Low-flow<br>Riparian zone, Floodplain | n=10<br>(Pettit & Froend 2001; Pettit et al. 2001; Erskine 2002; Trayler et al. 2003; Cluett 2005; Franklin et al. 2007; Petty & | • Direct (n=3) (Pettit et al. 2001; Cluett 2005; Canham et al. 2021a)<br>• Inferred through time (n =0)<br>• Inferred through space (n =7) (Pettit & Froend 2001; Erskine 2002; Trayler et al. 2003; | • None: n=7 (Pettit & Froend 2001; Pettit et al. 2001; Erskine 2002; Franklin et al. 2007; Petty & Douglas 2010; Warfe et al. 2013b; Freestone et al. 2022)<br>• Direct assessment: n=2 (Trayler et al. | 4 catchments, focus on Ord and Fitzroy<br>• NT: Daly, East Alligator, South Alligator<br>• WA: Ord, Fitzroy<br>• Qld: none | Riparian vegetation is structured by flow in multiple ways. High flows in the main channel exert a scouring force that dislodges vegetation that is not flood-resistant (Pettit et al. 2001; Erskine 2002; Cluett 2005; Freestone et al. 2022). Overbank flood flows kill vegetation that aren't able to sustain being submerged (Doupé & Pettit 2002; Trayler et al. 2003). Overbank flows also inundate the floodplain and are important for replenishing soil moisture and recharging the water table both of which are important for the survival and recruitment of riparian plants (Canham et al. 2021a). Changes | Altered riparian vegetation assemblage structure, including encroachment of riparian vegetation into the channel, increased cover of exotic plant species, decreased shrub and grass production on the floodplain. |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| | | Douglas 2010; Warfe et al. 2013b; Canham et al. 2021a; Freestone et al. 2022)<br>NB Doupé and Pettit (2002) and Finlayson (2005) not included as they are reviews | Franklin et al. 2007; Petty & Douglas 2010; Warfe et al. 2013b; Freestone et al. 2022) | 2003; Cluett 2005)<br>• Modelled: n=1 (Canham et al. 2021a) | | in flow/inundation are associated with different riparian assemblages (Trayler et al. 2003; Cluett 2005; Franklin et al. 2007; Petty & Douglas 2010; Canham et al. 2021a; Freestone et al. 2022). | |
| 17. Riparian vegetation production (grasses, macrophytes) | Overbank<br>Floodplain, Wetland | n=12<br>(Bailey et al. 1983; Finlayson 1988; Finlayson et al. 1989; Finlayson 1991; Pettit et al. 2001; Finlayson 2005; Pettit et al. 2011; Traill & Brook 2011; Pettit et al. 2012b; Ward et al. 2014; Ward et al. 2016; Ndehedehe et al. 2020) | • Direct (n=3) (Pettit et al. 2001; Ward et al. 2014; Ndehedehe et al. 2020)<br>• Inferred through time (n=9) (Bailey et al. 1983; Finlayson 1988; Finlayson et al. 1989; Finlayson 1991, 2005; Pettit et al. 2011; Traill & Brook 2011; Pettit et al. 2012b; Ward et al. 2016)<br>• Inferred through space (n=0) | • None: n=12 (Bailey et al. 1983; Finlayson 1988; Finlayson et al. 1989; Finlayson 1991; Pettit et al. 2001; Finlayson 2005; Pettit et al. 2011; Traill & Brook 2011; Pettit et al. 2012b; Ward et al. 2014; Ward et al. 2016; Ndehedehe et al. 2020)<br>• Direct assessment: n=0<br>• Modelled: n=0 | 6 catchments, focus on Alligator Rivers Region<br>• NT: East Alligator, Mary River, South Alligator, Kakadu<br>• WA: Ord<br>• Qld: Mitchell, Flinders | Overbank flows that inundate the floodplain promote the growth and production of grasses and macrophytes on the floodplain proper and in wetlands (Bailey et al. 1983; Finlayson 1988; Finlayson et al. 1989; Finlayson 1991; Pettit et al. 2001; Finlayson 2005; Pettit et al. 2011; Traill & Brook 2011; Pettit et al. 2012b; Ward et al. 2014; Ward et al. 2016; Ndehedehe et al. 2020). | Reduced primary production, including grasses and macrophytes, across the landscape. |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| | | Note Finlayson et al. (2006) not included as it is a review. | | | | | |
| 18. Riparian vegetation groundwater use | Groundwater<br>Riparian | n= 6<br>(Cook et al. 1998; Lamontagne et al. 2005; O'Grady et al. 2006b; O'Grady et al. 2006a; Petty & Douglas 2010; Canham et al. 2021b) | • Direct (n=0)<br>• Inferred through time (n=1) (Cook et al. 1998)<br>• Inferred through space (n=5) (Lamontagne et al. 2005; O'Grady et al. 2006b; O'Grady et al. 2006a; Petty & Douglas 2010; Canham et al. 2021b)<br>Note studies O'Grady et al. (2006a), O'Grady et al. (2006b), Lamontagne et al. (2005) and Canham et al. (2021b) directly measure groundwater use but, groundwater is not considered a flow metric. | • None: n=6<br>• Direct assessment: n=0<br>• Modelled: n=0 | 4 catchments<br>• NT: Daly, South Alligator, Finniss<br>• WA: Fitzroy<br>• Qld: none | Groundwater is an important water source for riparian trees (Cook et al. 1998; Lamontagne et al. 2005; O'Grady et al. 2006b; O'Grady et al. 2006a; Petty & Douglas 2010; Canham et al. 2021b), particularly those situated low in the landscape, such as those close to the river e.g. Melaleucas and Barringtonia (Lamontagne et al. 2005; O'Grady et al. 2006b; O'Grady et al. 2006a; Canham et al. 2021b). | Increase water stress to trees situated low in the landscape close to the river, such as Melaleucas. This may lead to reduced condition and mortality during years (or consecutive years) with small wet seasons. Vegetation may become more fire prone. |
| 19. Energy transfer around the landscape | Overbank<br>River channel, Floodplain, | n=15<br>(Shine 1986b; Shine | • Direct (n=0)<br>• Inferred through time (n=8) (Shine 1986b; | • None: n=15 (Shine 1986b; Shine 1986a; Finlayson et al. | 10 catchments, focus on Alligator rivers region for waterbird | Overbank flows facilitate the movement of aquatic animals, such as fish, and semi-aquatic animals such as crocodiles and waterbirds (see item 8, 23 and 24). The movement of these | Reduced transfer of energy around the catchment. Reduced ecological stability. |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| | Wetland, Estuary | 1986a; Finlayson et al. 1993; Traill et al. 2010; Traill & Brook 2011; Hunt et al. 2012; Jardine et al. 2012a; Jardine et al. 2012b; Fellman et al. 2013; Warfe et al. 2013a; Hanson et al. 2015; Villamarín et al. 2016; Jardine et al. 2017; Corriveau et al. 2020; Venarsky et al. 2020)<br><br>NB Douglas et al. (2005), Pettit et al. (2017a) and (Williams & Newsome 1991) not included as evidence as they are reviews. | Shine 1986a; Traill et al. 2010; Traill & Brook 2011; Hunt et al. 2012; Villamarín et al. 2016; Corriveau et al. 2020; Venarsky et al. 2020)<br>• Inferred through space (n=5) (Finlayson et al. 1993; Jardine et al. 2012a; Jardine et al. 2012b; Fellman et al. 2013; Warfe et al. 2013a)<br>• Other (n=2) (Hanson et al. 2015; Jardine et al. 2017)<br><br>Note, many food web studies used space and time to reveal energy sources. The dominant approach is used in the categorisation. | 1993; Traill et al. 2010; Traill & Brook 2011; Hunt et al. 2012; Jardine et al. 2012a; Jardine et al. 2012b; Fellman et al. 2013; Warfe et al. 2013a; Hanson et al. 2015; Villamarín et al. 2016; Jardine et al. 2017; Corriveau et al. 2020; Venarsky et al. 2020)<br>• Direct assessment: n=0<br>• Modelled: n=0 | movement, focus on Fitzroy, Daly and Mitchell for fish energy transfer studies.<br>• NT: Mary River, South Alligator, East Alligator, Wildman, Kakadu, Daly, Darwin Region<br>• WA: Fitzroy River<br>• Qld: Mitchell, Wenlock | animals, particularly large-bodied species, such as predatory fish, crocodiles and waterbirds, facilitate the movement of energy around the river system, including between floodplain, estuarine and riverine habitats (Finlayson et al. 1993; Traill et al. 2010; Traill & Brook 2011; Hunt et al. 2012; Jardine et al. 2012a; Jardine et al. 2012b; Warfe et al. 2013a; Hanson et al. 2015; Villamarín et al. 2016; Jardine et al. 2017; Pettit et al. 2017a; Corriveau et al. 2020; Venarsky et al. 2020) but see (Fellman et al. 2013) as an exception]. Terrestrial animals also facilitate energy transfer across the landscape. For instance, the dusky rat, goannas and water python feed in productive floodplains during the dry season (Shine 1986b; Shine 1986a) and move back to terrestrial landscapes during wet season flooding. The aforementioned movement allows energy generated in high productive areas, i.e. floodplains or estuaries, to move to less productive areas (Douglas et al. 2005). This transfer of energy should increase the ecological stability of the system.<br><br>Note, evidence for energy transfers is strong for large fish as it has been directly measured. Energy transfer for other species is inferred from diet and movement. | |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| 20. Energy subsidy: terrestrial to aquatic | Low flows, Overbank<br>Riparian zone | n=12<br>(Webb et al. 1982; Finlayson et al. 1993; Lynch et al. 2002; Davis et al. 2010; Leigh et al. 2010; Hunt et al. 2012; Pettit et al. 2012a; Fellman et al. 2013; Jardine et al. 2013; Thorburn et al. 2014; Beesley et al. 2020; Pusey et al. 2020b)<br>NB Pusey et al. (2004) and Pusey and Arthington (2003) are not included as evidence as it is a review. | • Direct (n=0)<br>• Inferred through time (n=5) (Hunt et al. 2012; Jardine et al. 2013; Thorburn et al. 2014; Beesley et al. 2020) 444]<br>• Inferred through space (n=5) (Finlayson et al. 1993; Lynch et al. 2002; Leigh et al. 2010; Pettit et al. 2012a; Fellman et al. 2013)<br>• Other (n=2) (Webb et al. 1982; Davis et al. 2010)<br>Note, many food web studies used space and time to reveal energy sources. The dominant approach is used in the categorisation. | • None: n=12 (Webb et al. 1982; Finlayson et al. 1993; Lynch et al. 2002; Davis et al. 2010; Leigh et al. 2010; Hunt et al. 2012; Pettit et al. 2012a; Fellman et al. 2013; Jardine et al. 2013; Thorburn et al. 2014; Beesley et al. 2020; Pusey et al. 2020b)<br>• Direct assessment: n=0<br>• Modelled: n=0 | 8 catchments<br>• NT: East Alligator, Daly, Kakadu, Mary<br>• WA: Fitzroy<br>• Qld: Flinders, Albert, Mitchell | Many main channels are fringed by dense riparian vegetation. The fruits and leaves from this vegetation are important food sources for aquatic animals. Specifically, leaf litter is an important food source for macroinvertebrates (Leigh et al. 2010; Pettit et al. 2012a; Fellman et al. 2013; Beesley et al. 2020) and some fish such as bony bream and grunters (Davis et al. 2010; Pusey et al. 2020b). Fruit is food for some fish (Pusey & Arthington 2003; Pusey et al. 2004; Thorburn et al. 2014) and certain turtles (Georges & Kennett 1989; Kennett & Tory 1996). Terrestrial insects are also an important food source to some fish, e.g. Archerfish and Rainbowfish and saratoga (Pusey & Arthington 2003; Pusey et al. 2004) and freshwater crocodiles particularly when they are small (Webb et al. 1982). Insects are most abundant in riparian vegetation and over the stream (Lynch et al. 2002). Low flows are important in sustaining riparian vegetation and overbank flows are important transporting leaves into the river (Finlayson et al. 1993), and for providing fish access into riparian areas to eat figs (Thorburn et al. 2014). | Reduced energy subsidy from the terrestrial to the aquatic environment.<br>Disrupted aquatic food web. Reduced condition and abundance of species that rely on terrestrial energy sources. Reduced ecological stability. |
| 21. Energy subsidy: aquatic to terrestrial | Low Flows, Groundwater, Overbank | n=9<br>(Recher & Holmes 1982; Shine 1986a; | • Direct (n=0)<br>• Inferred through time (n=3) (Madsen & Shine 2000; | • None: n=9 (Recher & Holmes 1982; Shine 1986b; Shine 1986a; Dostine & Morton | 6 Catchments, focus on Magela Ck for diet of semi-aquatic and terrestrial animals, | Low flows (groundwater) support fish and semi-aquatic insects in main channel and floodplain wetlands which are an important food source for animals living in the riparian zone, such as birds, spiders and other invertebrates (Dostine & | Reduced energy subsidy from the aquatic to the terrestrial environment.<br>Disrupted terrestrial food web. Reduced condition and |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| | River channel, Floodplain, Wetlands | Shine 1986b; Dostine & Morton 1989; Madsen & Shine 2000; Pettit et al. 2011; Traill & Brook 2011; Leigh et al. 2013; Sergo & Shrine 2015) | Pettit et al. 2011; Traill & Brook 2011)<br>• Inferred through space (n=2) (Recher & Holmes 1982; Leigh et al. 2013)<br>• Other (n=4) (Shine 1986b; Shine 1986a; Dostine & Morton 1989; Sergo & Shrine 2015) | 1989; Madsen & Shine 2000; Pettit et al. 2011; Traill & Brook 2011; Leigh et al. 2013; Sergo & Shrine 2015)<br>• Direct assessment: n=0<br>• Modelled: n=0 | study on riparian food undertaken in Qld<br>• NT: East Alligator, Mary, South Alligator, Kakadu<br>• WA: none<br>• Qld: Flinders, Gregory | Morton 1989; Leigh et al. 2013). This is particularly the case when riparian vegetation is in good condition (Leigh et al. 2013). Overbank flows sustain floodplain and wetland habitats that support high production, e.g. macrophytes, grasses, fish, aquatic invertebrates which are important food for waterbirds (Recher & Holmes 1982; Traill & Brook 2011), snakes (Madsen & Shine 2000; Pettit et al. 2011), goannas (Shine 1986b; Shine 1986a), rats (Williams & Newsome 1991) and wallabies (Williams & Newsome 1991) and animals that prey on them in-turn (Sergo & Shrine 2015). Much of the energy produced and stored in the wet season (i.e. in fish, macrophytes) transfers to terrestrial animals (i.e. waterbirds, reptiles, mammals) during the dry season (Pettit et al. 2011).<br>Note, (Williams & Newsome 1991) included as part of knowledge summary but omitted as evidence as it is a review | abundance of species that rely on aquatic energy sources. Reduced ecological stability. |
| 22. Turtles | Within-bank flows, Overbank, Low flows, Antecedent<br>River channel, Wetlands | n=13<br>(Grigg et al. 1986; Georges & Kennett 1989; Kennett et al. 1993; Kennett & Tory 1996; Kennett 1999; Doody et al. 2001; Doody & Georges 2002; Doody 2002; Georges et al. 2002; | • Direct (n=1) (Georges et al. 2002)<br>• Inferred through time (n=7) (Grigg et al. 1986; Kennett & Tory 1996; Kennett 1999; Doody et al. 2001; Doody 2002; Doody et al. 2003a; Dostine 2021)<br>• Inferred through space (n=3) (Georges & Kennett 1989; Doody & | • None: n=12 (Grigg et al. 1986; Georges & Kennett 1989; Kennett et al. 1993; Kennett & Tory 1996; Kennett 1999; Doody et al. 2001; Doody & Georges 2002; Doody 2002; Doody et al. 2003a; Doody et al. 2003b; Welsh et al. 2017; Dostine 2021)<br>• Direct assessment: n=0 | 6 catchments, focus on Daly<br>• NT: Adelaide, Douglas, Daly, Kakadu, Tomkinson, Darwin region<br>• WA: none<br>• Qld: none | Riverine flows are important to turtle biology and ecology in many ways. At the start of the wet season within-channel flows inundate the nests of the pig-nosed turtle, *Carettochelys insculpta*, which nests in sand adjacent to the water, and cue hatchling emergence (Georges & Kennett 1989; Doody et al. 2001). These same flows are important for movement of female pig-nosed turtles within the main channel potentially allowing access to more productive feeding areas (Dostine 2021). Overbank flows inundate ephemeral wetlands, which are important habitat for Cann's snake necked turtle (*Chelodina canni*) and the northern snake-necked turtle, *Chelodina rugosa* (Kennett & Tory 1996). The latter species nests underwater in wetlands at the end of the wet season and eggs remain in stasis until the wetland dries and eggs are exposed to air (Kennett et al. 1993; Kennett 1999); adults | WRD that reduces the magnitude of early within-bank flows at the start of the wet season may delay the timing of hatching of pig-nosed turtles and may reduce movement of adults along the river. Reduced overbank flows are likely to lead to population declines in species that prefer floodplain wetlands, such as the snake-necked turtles via reduced habitat availability. A reduction in wet season flows will also impact main channel species, reducing the reproductive output, movement and foraging of |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| | | Doody et al. 2003a; Doody et al. 2003b; Welsh et al. 2017; Dostine 2021) | Georges 2002; Doody et al. 2003b)<br>• Other (n=2) (Kennett et al. 1993; Welsh et al. 2017) | • Modelled: n=1 (Georges et al. 2002) | | aestivate in mud when wetlands dry out (Grigg et al. 1986). Wet season flows also facilitate the movement of the pig-nosed turtle into riparian and floodplain habitats where it can forage on riparian fruit (Doody 2002; Dostine 2021). The size of wet season flow also affects the reproductive output of the pig-nosed turtle with females laying smaller, lighter and fewer eggs if the preceding wet season, has been small, or the wet season before that (Doody et al. 2003a). Dry season flows support the instream aquatic food sources for many turtles, including the northern snapping turtle, *Elseya dentata,* which eats aquatic algae (Kennett & Tory 1996; Welsh et al. 2017), and the pig-nosed turtle which eats ribbonweed (*Valisneria*) and molluscs (Georges et al. 2002; Welsh et al. 2017; Dostine 2021). Main channel depth/flows support the movement of pig-nosed turtles along the river (Georges et al. 2002) and sand moisture dictates nesting sites for this species (Georges et al. 2002; Doody et al. 2003b). Lastly, thermal springs that upwell into riverbeds are used by breeding turtles to keep warm during the winter dry season (Doody & Georges 2002; Dostine 2021)<br>Note, the pig-nosed turtle is listed as Endangered on the IUCN Red List. | the pig-nosed turtle. Reduced dry season flows will potentially reduce the body condition and abundance of turtles if habitat contraction causes food sources e.g. aquatic algae, ribbonweed, molluscs, to diminish or if it limits access to food sources. Declines in dry season flows may also decrease the nesting success of pig-nosed turtles due to reduced soil moisture and declines in groundwater that prevent thermal spring upwelling in main channels may reduce the body condition and breeding success of this species. |
| 23. Crocodiles | Within-bank; Overbank; Low flows; Antecedent<br>River channel; Estuary; Floodplain; Wetlands | n=11<br>(Magnusson 1982; Webb et al. 1983a; Webb et al. 1983c, b; Harvey & Hill 2003; Fukuda et al. 2008; Pettit et al. 2011; Somaweera | • Direct (n=0)<br>• Inferred through time (n=4) (Magnusson 1982; Webb 1991; Fukuda et al. 2008; Adame et al. 2018)<br>• Inferred through space (n=7) (Webb et al. 1983c, b; | • None: n=13 (Magnusson 1982; Webb et al. 1983a; Webb et al. 1983c, b; Harvey & Hill 2003; Fukuda et al. 2008; Pettit et al. 2011; Somaweera & Shine 2013; Fukuda & Saalfeld 2014; | 11 catchments, focus on NT<br>• NT: Adelaide, Liverpool, Tomkinson, Mary, Daly, Wildman, South Alligator, East Alligator, Blyth<br>• WA: Fitzroy, Ord | Riverine flows are important to the biology and ecology of freshwater and saltwater crocodiles. Overbank flows promote the dispersal of the freshwater crocodile, *Crocodylus johnstoni*, across the floodplain (Webb et al. 1983a; Webb 1991). Reduced competition, increased food abundance and higher temperatures likely drive increased growth at this time (Webb et al. 1983b). Overbank flows are also important for reproduction of the saltwater crocodile, *C. porosus*, because they promote vegetation that is important nesting habitat, i.e. grasses, | If WRD impacts the extent and duration of floodplain inundation it could reduce the dispersal and growth of freshwater crocodiles and alter the nesting success/recruitment of saltwater crocodiles. Changes to flow that impact riparian vegetation will have consequences for nesting of both species. Decreases in |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| | | & Shine 2013; Fukuda & Saalfeld 2014; Adame et al. 2018; Hipsey et al. 2021)<br>Note, Webb (1991); (Semeniuk et al. 2011) and (Somaweera et al. 2019) are reviews | Harvey & Hill 2003; Fukuda et al. 2008; Pettit et al. 2011; Somaweera & Shine 2013; Hipsey et al. 2021) | Adame et al. 2018; Hipsey et al. 2021)<br>• Direct assessment: n=1<br>• Modelled: n=0 | • Qld: none | sedges, *Melaleucas* (Fukuda et al. 2008; Pettit et al. 2011; Semeniuk et al. 2011). However, if floods are too large they can drown saltwater crocodile nests (Magnusson 1982; Webb 1991; Fukuda & Saalfeld 2014). Groundwater is also important for nesting of saltwater crocodiles, as *Melaleuca* swamps in the lower reaches of the river are important nesting grounds (Webb et al. 1983c; Webb 1991; Harvey & Hill 2003). Saltwater crocodiles shift their diet with season, relying primarily on aquatic food, e.g. fish, during the wet and terrestrial food e.g. wallabies, buffaloes and pigs, during the dry (Adame et al. 2018). Low flows are important for reproduction of freshwater crocodiles, with sandy soils, close to water and shaded by riparian vegetation prime nesting sites in the main channel (Somaweera & Shine 2013; Hipsey et al. 2021). Soil moisture is also critical to egg survival (Webb et al. 1983c; Hipsey et al. 2021). Freshwater crocodiles move upstream during low flows seemingly to avoid negative interactions with saltwater crocodiles (Webb et al. 1983a). | low flows that reduce soil moisture in the main channel will impact nesting/recruitment of freshwater crocodiles. Impoundments will drown out nesting habitat of freshwater crocodiles. |
| 24. Magpie Geese | Overbank, Antecedent<br>Floodplain, Wetlands | n=11<br>(Tulloch & McKean 1983; Bayliss 1989; Bayliss & Yeomans 1990; Morton et al. 1990b; Whitehead & Saalfeld 2000; Chatto 2006; | • Direct (n=4) (Bayliss 1989; Bayliss & Yeomans 1990; Whitehead & Saalfeld 2000; Bayliss et al. 2008)<br>• Inferred through time (n=6) (Tulloch & McKean 1983; Morton et al. 1990b; Traill et al. 2010; Traill & | • None: n=11<br>• Direct assessment: n=0<br>• Modelled: n=1 (Bayliss et al. 2008) | 10 catchments, focus on Kakadu and NT<br>• NT: Kakadu, South Alligator, East Alligator, West Alligator, Darwin Region, Daly, Mary, Howard, Adelaide, Wildman + others | Overbank flood flows that inundate floodplains and wetlands are critical for the Magpie Goose, *Anseranas semipalmata,* because they promote the growth of macrophytes, particularly the sedge *Eleocharis dulcis* which is critical nesting habitat in the late wet and feeding habitat in the dry (Bayliss 1989; Bayliss & Yeomans 1990; Morton et al. 1990b; Chatto 2006; Bayliss et al. 2008; Traill & Brook 2011; Bayliss & Ligtermoet 2018). The abundance and population growth of geese track cycles in rainfall/river inundation (Bayliss & Yeomans 1990). Delays in the timing of overbank flooding during the early wet will lead to delayed nesting, reduced nest density and smaller clutch sizes (Whitehead & Saalfeld 2000). Decreases in maximum river height and | If wet season overbank flows are reduced this can reduce the abundance of magpie geese by reducing the area of wet season nesting habitat and by reducing the area of dry season feeding and refuge habitat. |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
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| | | Bayliss et al. 2008; Traill et al. 2010; Traill & Brook 2011; Bayliss & Ligtermoet 2018; Corriveau et al. 2020) | Brook 2011; Bayliss & Ligtermoet 2018; Corriveau et al. 2020)<br>• Inferred through space (n=1) (Chatto 2006)<br>Note, rainfall is a strong correlate of floodplain inundation, hence we consider such studies 'direct' | | • WA: none<br>Qld: none | the timing of peak flows have been found by some to have little effect on nest density (Whitehead & Saalfeld 2000); however, others describe a quadratic/threshold relationship with too little water causing problems and too much water drowning nests (Bayliss et al. 2008). Geese will typically wait until after peak flows to start nesting (Whitehead & Saalfeld 2000). During years with small wet seasons the dispersal of Magpie Geese across the landscape is restricted and birds concentrate in locations of permanent water and food (Bayliss & Yeomans 1990; Morton et al. 1990b; Traill et al. 2010; Traill & Brook 2011; Corriveau et al. 2020). | |
| 25. Other waterbirds (excludes Magpie geese) | Overbank; Groundwater<br>Floodplain; Wetlands | n=4<br>(Recher & Holmes 1982; Morton et al. 1990a, 1993a, b)<br>Note, (Morton & Brennan 1991) is a review | • Direct (n=0)<br>• Inferred through time (n=1) (Morton et al. 1993a)<br>• Inferred through space (n=3) (Recher & Holmes 1982; Morton et al. 1990a, 1993b) | • None: n=4 (Recher & Holmes 1982; Morton et al. 1990a, 1993a, b)<br>• Direct assessment: n=0<br>• Modelled: n=0 | 2 catchments, focus on South Alligator<br>• NT: South Alligator, East Alligator<br>• WA: none<br>• Qld: none | Overbank flood flows and groundwater that sustain permanent floodplain habitats shape the abundance of ducks, egrets, herons, ibises, spoonbills, pelicans and cormorants (Morton et al. 1990a; Morton & Brennan 1991; Morton et al. 1993b). More ephemeral habitats are preferred by black-necked storks (Morton et al. 1993a). | WRD that reduces overbank and groundwater such that the permanence of floodplain wetland habitats decreases will lead to declines in the abundance of ducks, egrets, herons, ibises and spoonbills and an increase in black-necked storks |
| 26. Sawfish | Overbank; Within-bank; Low flows; Antecedent<br>River channel; Estuary | n=8<br>(Morgan 2005; Thorburn et al. 2007; Phillips et al. 2009; Gleiss et al. 2017; Whitty et al. 2017; Lear et al. 2019; | • Direct (n=3) (Lear et al. 2019; Lear et al. 2021; Morgan et al. 2021)<br>• Inferred through time (n=3) (Thorburn et al. 2007; Phillips et al. 2009; Gleiss et al. 2017) | • None: n=7 (Thorburn et al. 2007; Phillips et al. 2009; Gleiss et al. 2017; Whitty et al. 2017; Lear et al. 2019; Lear et al. 2021; Morgan et al. 2021)<br>• Direct assessment: n=1 (Morgan 2005) | 4 catchments, focus on Fitzroy<br>• NT: none<br>• WA: Fitzroy River, Doctors' Creek, Airport Creek, Robinson River<br>• Qld: none | Sawfish use rivers as nurseries (Thorburn et al. 2007; Morgan et al. 2021) and flows are important to them in several ways. Protracted flood flows (overbank) promote recruitment of the freshwater sawfish *Pristis pristis* (Lear et al. 2019) presumably because they assist pups to move into freshwater via the floodplain where they face lower predation pressure than the main channel or the estuary (Lear et al. 2019). The magnitude of overbank and within-bank flows during the wet season also affects the | Within-stream barriers likely to limit upstream distribution.<br>WRD that reduces the magnitude of wet season flows likely to reduce the survival of sawfish during the dry (if the system dries down into isolated shrinking pools). WRD that reduces the duration of very large wet |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
|---|---|---|---|---|---|---|---|
| | | Lear et al. 2021; Morgan et al. 2021) | • Inferred through space (n=2) (Morgan 2005; Whitty et al. 2017) | • Modelled: n=0 | | body condition of freshwater sawfish at the start of the dry season which in turn influences their body condition late during the dry season when they are most stressed (Lear et al. 2021). Thus, wet season flows are likely linked to juvenile survival (Lear et al. 2021). Flows within the channel are important for dispersal of freshwater sawfish along the river (Phillips et al. 2009), with instream barriers and periods of 'no flow' limiting movement (Thorburn et al. 2007; Phillips et al. 2009). Flow also influences the movement of the dwarf sawfish, *Pristis clavata*, via its influence on salinity (Morgan et al. 2021). This species moves upstream during low flow/high salinity periods and downstream during high flows/low salinity (Morgan et al. 2021).<br>Low flows are important for the foraging of juvenile freshwater sawfish – a species that prefers to forage at night-time in shallow sandbar (glide/run) habitats (Whitty et al. 2017). Low flows can change the resting behaviour of sawfish if pools thermally stratify, with individuals resting in deep cool waters during the day (Gleiss et al. 2017). | season flows will negatively impact recruitment.<br>Extraction that causes dry season main channel pools to shrink will increase stress to sawfish. |
| 27. Riparian birds | Low flow<br>Riparian zone | n=3<br>(Woinarski et al. 2000; Skroblin & Legge 2012; Leppitt et al. 2022)<br>Note, (Morton & Brennan 1991) excluded as it is a review | • Direct (n=0)<br>• Inferred through time (n=0)<br>• Inferred through space (n=3) (Woinarski et al. 2000; Skroblin & Legge 2012; Leppitt et al. 2022) | • None: n=3 (Woinarski et al. 2000; Skroblin & Legge 2012; Leppitt et al. 2022)<br>• Direct assessment: n=0<br>• Modelled: n=0 | 17 catchments<br>• NT: Adelaide, Mary, Wildman, West Alligator, South Alligator, East Alligator, Victoria, Keep, Daly, Finniss, Roper, Goyder, McArthur<br>• WA: Fitzroy, Durack, Isdell, Drysdale<br>• Qld: none | Riparian zones are important habitat for many birds, supporting higher species richness and abundance than non-riparian savannah habitats (Morton & Brennan 1991; Woinarski et al. 2000). This is especially the case when the riparian zone has dense cover of rainforest plants and Melaleucas or when the region has low rainfall (Woinarski et al. 2000). Several threatened species live in riparian habitat including the purple-crowned fairy wren *Malurus coronatus coronatus* (Skroblin & Legge 2012), crimson finch *Neochmia phaeton* (Woinarski et al. 2000) and Alligator River's yellow chat *Epthianura crocea tunneyi* (Leppitt et al. 2022). The riparian plant *Pandanus aquaticus* is particularly | Reduced occurrence, abundance and species richness of riparian birds including several EPBC listed species. |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
|---|---|---|---|---|---|---|---|
| | | | | | | important for the purple-crowned fairy wren (Skroblin & Legge 2012). Unburnt riparian locations that have the plant *Sesbania sesban* are important for the Alligator River's yellow chat (Leppitt et al. 2022). | |
| 28. Frogs and reptiles (excluding turtles and crocodiles) | Overbank<br><br>Floodplain | n = 8<br><br>(Shine 1986b; Shine 1986a; Woinarski & Gambold 1992; Madsen & Shine 2000; Brown & Shine 2004; Madsen et al. 2006; Pettit et al. 2011; Sergo & Shrine 2015)<br><br>Note, Shine and Brown (2008) and Braithwaite et al. (1991) are reviews | • Direct (n=1) (Madsen et al. 2006)<br>• Inferred through time (n=4) (Shine 1986b; Shine 1986a; Madsen & Shine 2000; Pettit et al. 2011)<br>• Inferred through space (n =) (Woinarski & Gambold 1992)<br>• Other (n=2) (Brown & Shine 2004; Sergo & Shrine 2015)<br><br>Note, rainfall is a strong correlate of floodplain inundation, hence we consider such studies 'direct' | • None: n=6 (Woinarski & Gambold 1992; Madsen & Shine 2000; Brown & Shine 2004; Madsen et al. 2006; Pettit et al. 2011; Sergo & Shrine 2015)<br>• Direct assessment: n=0<br>• Modelled: n=0 | 4 catchments, focus on NT locations with large floodplains<br><br>NT: Kakadu, East Alligator, Adelaide River, near Darwin<br><br>WA:<br><br>Qld: | Overbank flows that inundate the floodplain provide habitat for frogs and dictate the movement of reptiles (Braithwaite et al. 1991; Woinarski & Gambold 1992). Flows in the late wet drive food production on the floodplain (e.g. fish, rats) which are important prey for semi-aquatic predatory reptiles during the dry, i.e. goannas i.e. *Varanus panoptes*, *V. mertensi* and *V. mitchelli*, filesnakes and pythons (Shine 1986b; Shine 1986a; Woinarski & Gambold 1992; Pettit et al. 2011). This energy underpins the body condition and breeding of pythons and filesnakes (Madsen & Shine 2000; Madsen et al. 2006; Shine & Brown 2008; Pettit et al. 2011). Moisture in floodplain soils is also important for the survival of incubating snake eggs (Brown & Shine 2004; Shine & Brown 2008). | WRD that leads to a decline in floodplain inundation is likely to reduce the species richness of frogs, alter the movement of reptiles, such as snakes. Predatory reptiles that feed on the boom of animal production on the floodplains will likely decline in abundance. |
| 29. Mammals | Overbank<br><br>Floodplain | n=1<br><br>(Madsen & Shine 1999)<br><br>Note, Williams and Newsome (1991) and | • Direct (n=0)<br>• Inferred through time (n=1) (Madsen & Shine 1999)<br>• Inferred through space (n=0) | • None: n=1 (Madsen & Shine 1999)<br>• Direct assessment: n=0<br>• Modelled: n=0 | 0 catchments<br><br>• NT: none<br>• WA: none<br>• Qld: none | Overbank flows that inundate the floodplain support grasses that are an important food source for wallabies in the dry season, supporting their survival and reproduction (Williams & Newsome 1991; Madsen & Shine 1999; Shine & Brown 2008). Dusky rats, a species that typically only lives for 1 to 2 years, also move onto the floodplain during the dry to | Declines in wallaby abundance. Earlier movement of dusky rats on to the floodplain and faster commencement of breeding and population growth. However, gains may be short |

| Biota and/or process | Flow component and habitat | Number of studies | Flow inference | Learning about flow alteration | Spatial coverage | Knowledge summary | Impact of water resource development (primarily water extraction) |
|---|---|---|---|---|---|---|---|
| | | Shine and Brown (2008) are both reviews | | | | feed. When floodplain inundation is minimal, abundance increases as rats commence breeding earlier; however, decreases in food lead to reduced body condition later in the dry and may cause abundance to fall (Williams & Newsome 1991; Madsen & Shine 1999; Shine & Brown 2008). The abundance of other small-bodied mammals that inhabit floodplain habitats will be linked to floodplain inundation and food production (Williams & Newsome 1991). | lived as food runs out and body condition declines. |

Table A2. Evidence table that links flow-biota knowledge to 5 flow components central to the ecology of northern Australian wet-dry tropical rivers and details the expected response (e.g. increase, decrease, little change, altered) to water extraction. Responses to impoundments are shown in italics. No information is provided about the magnitude of change. Responses are separated into habitat alteration grouped by macrohabitat, and biotic impact grouped by biota. Note that cross-over exists between the 2 categories, as plants are sometimes considered as habitat but other times considered as biota (i.e. riparian vegetation). Evidence is repeated in multiple flow components if flows from multiple types are thought to be influential. Knowledge includes all relevant studies and may include reports and manuscripts that present the same information, as well as reviews. Indigenous knowledge is not included. Flow principles were adapted from Douglas et al. (2019).

| Flow component, flow principle & WRD threat | Habitat alteration | Biotic impact |
|---|---|---|
| Flow component:<br><br>Within-bank flows<br><br>Flow principle:<br><br>Within-bank flows promote longitudinal connectivity and are important for the ecology of the river and its estuary. Within-bank flows can also inundate distributary creeks and deliver water to floodplain wetlands.<br><br>WRD threats:<br><br>Instream barriers including impoundments, water extraction from channel, floodplain harvesting, regulating structures on distributary creeks | River channel<br><br>• reduction in the magnitude and frequency of high flow events (Trayler et al. 2003; Cluett 2005)<br>• reduced instream depth and velocity in persistent reaches (Townsend & Padovan 2005; Chan et al. 2012; Townsend & Douglas 2014) and reduced refuges in intermittent reaches (McJannet et al. 2014)<br>• reduced scouring of channels, i.e. reduced channel-forming flows leading to a change in instream habitat complexity (bars, benches) (Erskine et al. 2003; Trayler et al. 2003; Cluett 2005) and increased sediment accumulation in the channel (Cluett 2005). Reduced movement of large wood (Pettit et al. 2013). Uncertain impacts on riffle, macrophytes and backwater habitats, as declining flows could lead to an increase (Storey & Creagh 2014) or a decrease (Storey 2002b, 2003; Chan et al. 2012).<br>• reduced channel stability if riparian vegetation is altered (Saynor et al. 2008), and increased encroachment of riparian vegetation into the channel (Cluett 2005). The loss of *Melaleuca* species and their flow-resistant roots will lead to channel widening and shallowing, causing increased instream sediment (Erskine 2002; Wasson et al. 2002)<br>• reduced hydrological connectivity and movement of materials along channel (Molinari et al. 2022), *particularly around barrier* (Morgan 2005); *however, steady releases from an impoundment can increase connectivity along the river and between the river and the estuary (Trayler et al. 2003)*<br>• reduced water quality (Brown et al. 1983; Townsend et al. 1992) including either highly acidic water and/or oxygen crashes if first flush flows are not diluted by subsequent flows (Hart et al. 1987a; Townsend 1994). Oxygen could also decline if low flows and high nutrient levels combine to cause algal blooms (Parslow et al. 2003), but this is only likely in nutrient impacted systems. I*ncreased likelihood of stratification and anoxia in impoundments (Townsend 1999)*. Saltwater intrusion may occur in lower river reaches that were formerly freshwater (Parslow et al. 2003) | Fish<br><br>• reduced movement/dispersal along the length of the river especially for diadromous species (Bishop et al. 1990; Bishop & Forbes 1991; Walther et al. 2011; Pusey et al. 2018; Crook et al. 2021b; King et al. 2021). *If an instream barrier is present fish, including the juveniles of migratory species, will be trapped below instream barrier, i.e. cherabin, barramundi and sawfish* (Bishop & Forbes 1991; Doupé & Pettit 2002; Trayler et al. 2003; Morgan 2005; Gill et al. 2006; Close et al. 2012; Whitty et al. 2014; Pusey et al. 2020a; Crook et al. 2021b). Some species will be little affected such as those that don't move much and individuals of diadromous species that are residents in freshwater i.e. resident barramundi (Heupel et al. 2011)<br>• altered assemblage structure (Storey 2002b; Stewart-Koster et al. 2011; Warfe et al. 2013b; Pusey et al. 2020a), including reduced species occurrence and abundance, particularly if depth falls below critical thresholds (Keller et al. 2019) or if macrophyte beds decline as they are important habitat for many small fish (Storey & Creagh 2014)<br>• *Where within bank flows are increased due to an impoundment (i.e. hydropower releases), changes in species richness, abundance or biomass may be relatively minor, but include an increase in estuarine species between the dam and the ocean (Trayler et al. 2003)*<br>• reproduction of wet season spawners may be delayed if the first wet season flows don't arrive (Bishop & Forbes 1991; King et al. 2021), including breeding and recruitment of sooty grunter *H. fuliginosus* (Pusey et al. 2004; King et al. 2021). However, species that recruit during low flows (Bishop et al. 2001; King et al. 2020) will increase in abundance (Stewart-Koster et al. 2011).<br>• increased opportunity for fish kills at start of wet season (Bishop 1980; Brown et al. 1983; Bishop & Forbes 1991; Townsend et al. 1992; Townsend 1994; Pidgeon 2001; Townsend & Edwards 2003) |

<table>
<tr><th>Flow component, flow principle & WRD threat</th><th>Habitat alteration</th><th>Biotic impact</th></tr>
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<ul>
<li>improved water clarity (Storey 2002b; Townsend et al. 2012b; Townsend & Douglas 2014) which should increase phytoplankton productivity (Parslow et al. 2003; Volkman et al. 2007; Townsend & Douglas 2017). However, in nutrient-limited systems phytoplankton production may decline as nutrient inputs decrease (Townsend et al. 2012b; Waltham et al. 2013).</li>
<li>increased production/biomass of macrophytes and benthic algae (i.e. primary productivity) due to a reduction in scouring flows (Rea et al. 2002; Townsend & Padovan 2005; Webster et al. 2005; Townsend & Padovan 2009; Hunt et al. 2012; Townsend & Douglas 2014).</li>
</ul>
Wetlands
<ul>
<li>reduced flow to flood runner distributary creeks and wetlands, reducing depth and water quality in these habitats (Pettit et al. 2012b)</li>
<li>initial flow-related disturbance to phytoplankton production should decline causing wetland phytoplankton to remain high (Pettit et al. 2011), but in the medium term the loss of water and nutrients is likely to lead to a reduction in primary production (Pettit et al. 2012b)</li>
<li>reduced flow disturbance to zooplankton assemblages as per phytoplankton (Tait et al. 1984)</li>
</ul>
Estuary
<ul>
<li>increased salinity (Staples 1980; McKinnon & Klumpp 1998; Vance et al. 1998; Lowe et al. 2022) and decreased sediment/turbidity (Blaber et al. 1995; Blondeau-Patissier et al. 2014; Duggan et al. 2014) due to a decline in freshwater flushing flows. However, an impoundment has been found to decrease saltwater intrusion and increased siltation (Wolanski et al. 2001) - seemingly contradictory evidence.</li>
<li>a narrowing and shallowing of estuarine reaches due to increased siltation associated with flow impoundment (Wolanski et al. 2001)</li>
<li>short term increase in benthic primary production due to reduced flood disturbance (Duggan et al. 2014; Lowe et al. 2022), but over the medium to longer term reduced nutrient/carbon inputs from the catchment (McKinnon & Klumpp 1998; Burford et al. 2011; Burford et al. 2016; Burford & Faggotter 2021; Egger et al. 2023) see Burford et al. (2012) for exception] will reduce primary production (Burford et al. 2011; Blondeau-Patissier et al. 2014; Duggan et al. 2014; Burford et al. 2016), see Burford et al. (2012) for exception]</li>
<li>altered zooplankton assemblage (McKinnon & Klumpp 1998; Duggan et al. 2008)</li>
<li>in reduced nutrient inputs should reduce algal blooms harmful to seagrass in nutrient-enriched catchments (Robson et al. 2008; Howley et al. 2018)</li>
</ul>
</td><td>
Macroinvertebrates/freshwater crabs/cherabin
<ul>
<li>reduced macroinvertebrate drift and associated recolonisation of intermittent river reaches (Dostine et al. 1998)</li>
<li>altered macroinvertebrate assemblage structure (Dostine 2000; Trayler et al. 2003; Leigh & Sheldon 2009; Warfe et al. 2013b, Humphrey et al 2016) including decline in species richness (Leigh & Sheldon 2009).</li>
<li>reduced downstream drift of cherabin larvae to estuarine nursery (Novak et al. 2015; Novak et al. 2017c) and reduced abundance of juveniles (Beesley et al. 2023)</li>
<li>altered habitat use by cherabin associated with changes in instream habitat (Novak et al. 2017b)</li>
<li>reduced downstream migration of Macrobrachium species (presumed M. australiense) (Marchant 1982)</li>
<li>reduced mussel recruitment (Humphry and Simpson 1985)</li>
</ul>
Riparian vegetation
<ul>
<li>altered plant assemblage, including the loss of flood resistant species and encroachment by terrestrial vegetation (Pettit et al. 2001; Doupé & Pettit 2002; Erskine 2002; Freestone et al. 2022). Increased tree recruitment on riverbank (Pettit et al. 2001; Freestone et al. 2022) due a reduction in scouring flows</li>
<li>altered seed dispersal (Pettit & Froend 2001; Doupé & Pettit 2002)</li>
</ul>
Food web
<ul>
<li>altered riparian vegetation could lead to a decline in riparian food (insects, fruit) that may impact fish for whom this is an important food source, i.e. terapontid grunters and fork-tailed catfish (Davis et al. 2010; Thorburn et al. 2014). Turtles are unlikely to be directly affected as riparian food is not a major component of their diet (Welsh et al. 2017); however, changes to the food web could impact them indirectly.</li>
<li>reduced inputs of riparian leaf litter could result in less food for instream fauna such as macroinvertebrates (Pettit et al. 2012a) and fish (Pusey et al. 2020b)</li>
<li>reduced aquatic and terrestrial insects (Lynch et al. 2002) could impact animals living in the riparian zone for whom this is an important food source (i.e. riparian birds, spiders, insects) (Morton & Brennan 1991; Douglas et al. 2005; Jardine et al. 2012a; Leigh et al. 2013). Decline in</li>
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| Flow component, flow principle & WRD threat | Habitat alteration | Biotic impact |
|---|---|---|
| | • sediment carbon becomes increasingly mangrove dominated due to reduced inputs of terrestrial (i.e. leaf litter) carbon from the catchment (Volkman et al. 2007) | riverine production will reduce the aquatic-terrestrial energy subsidy (Leigh et al. 2013)<br>• increased cover of submerged macrophytes (i.e. V*allisneria*) and algae (i.e. *Spirogyra*) should be beneficial to turtles that forage on these food sources (Welsh et al. 2017) as long as water depths remain high enough for turtle movement along the river.<br><br>Birds/reptiles<br><br>• reduced occurrence, abundance and species richness of riparian birds (Morton & Brennan 1991; Woinarski et al. 2000), as riparian vegetation changes, including reduced occurrence of purple-crowned fairy wren (Skroblin & Legge 2012), crimson finch (Woinarski et al. 2000) and Alligator Rivers Yellow Chat (Leppitt et al. 2022)<br>• altered diet and distribution of semi-aquatic reptiles, including goannas i.e. *Varanus panoptes*, *V. mertensi* and *V. mitchelli*, and filesnakes in line with changes in their aquatic prey (Shine 1986b; Shine 1986a)<br>• delayed hatching of the pig-nosed turtle (Doody et al. 2001) if the wet season flows that inundate their eggs and cue hatching do not arrive. Movement of female pig-nosed turtles during early wet season flows likely to also decrease (Dostine 2021)<br><br>Estuarine biota (including fish)<br><br>• altered fish assemblage (Davis 1988; Blaber et al. 1995; Pusey et al. 2016) and reduced productivity (Robins et al. 2005)<br>• altered movement of fish into tidal swamps/creeks (Davis 1985; Davis 1988). Reduced movement of diadromous fish such as sharks and sawfish that use the estuary as a nursery [255]. Reduced movement of juvenile barramundi into freshwater (Davis 1985; Walther et al. 2011) where growth is maximised (Roberts et al. 2019)<br>• reduced growth and recruitment/abundance of barramundi (Bayliss et al. 2007; Bayliss et al. 2008; Stewart-Koster et al. 2011; Leahy & Robins 2021; Crook et al. 2022) associated with declines in estuarine production. Reduced recruitment of sawfish including *Pristis pristis* (Lear et al. 2019) possibly due to pups being trapped in the estuary where they suffer high mortality. No change to the recruitment of bullsharks (Lear et al. 2020)<br>• reduced recruitment and catch of prawns (Vance et al. 1985; Staples & Vance 1986; Vance et al. 1998; Duggan et al. 2019; Kenyon et al. 2020; Turschwell et al. 2022) including reduced emigration of juvenile |

| Flow component, flow principle & WRD threat | Habitat alteration | Biotic impact |
| --- | --- | --- |
| | | prawns from the river to the marine environment (Staples 1980; Staples & Vance 1986; Vance et al. 1998). Increased upstream distribution of juvenile prawns in the late wet season associated with high salinity and low flows in the estuarine reaches of the river (Staples 1980)<br>• altered zooplankton (Duggan et al. 2008) and benthic mudflat communities (Lowe et al. 2022; Venarsky et al. 2022), including a short-term increase in meiofaunal density and macrobenthic invertebrates due to reduced disturbance from flood flows (Duggan et al. 2014; Lowe et al. 2022). Macrobenthic communities likely to decline (Venarsky et al. 2022)<br>• unknown impact on mangroves although these represent the greatest standing stock of carbon in the estuary (Duggan 2012) |
| Flow component:<br><br>Overbank (flood) flows<br><br>Flow principle:<br><br>Overbank (flood) flows facilitate lateral connectivity, maintaining the health of the riparian zone, floodplain and wetlands which support aquatic and terrestrial biodiversity that is distinct from the river channel. Overbank flood flows also recharge the aquifer via floodplain infiltration.<br><br>WRD threats:<br><br>Farm dam floodwater interception, main channel impoundment | River channel<br><br>• reduced connectivity between the main channel and floodplain habitats (Karim et al. 2016; Karim et al. 2018; Nielsen et al. 2020; King et al. 2021; Molinari et al. 2022) leading to a reduction in the delivery of riparian organic matter to the main channel (Finlayson et al. 1993; Volkman et al. 2007)<br>• a decrease in the net load of phytoplankton in the main channel because inputs of phytoplankton from floodplains wetlands decline (Townsend & Douglas 2017)<br><br>Wetlands/Floodplain<br><br>• reduced area, duration and frequency of inundation (Trayler et al. 2003; Ward et al. 2014; Karim et al. 2016; Karim et al. 2018)293, 385], with some systems more affected than others (Karim et al. 2018). *Dams can cause large reductions in floodplain inundation (Karim et al. 2018).*<br>• reduced water depth (Kennard 1995; Karim et al. 2018)<br>• an initial reduction in flow disturbance to zooplankton (Tait et al. 1984) and phytoplankton assemblages (Pettit et al. 2011), similarly a short-term improvement in oxygen due to diminished inflow of water with high benthic oxygen demand (Townsend 2006). These benefits will diminish through time.<br>• reduced primary production, including algae and macrophytes (Finlayson 1988; Finlayson et al. 1989; Finlayson 2005; Finlayson et al. 2006; Pettit et al. 2011; Traill & Brook 2011; Pettit et al. 2012b; Faggotter et al. 2013; Ward et al. 2014; Molinari et al. 2022) associated with a reduction in nutrient inputs (Hart et al. 1987b)<br>• altered algal biofilm production if the amount of submerged macrophytes and horizontal grasses decrease (Adame et al. 2017)<br>• reduced transfer of phytoplankton to the river (Townsend & Douglas 2017) | Fish<br><br>• reduced feeding (Bishop & Forbes 1991) and body condition (Luiz et al. 2019; Beesley et al. 2021) due to declines in system productivity and because fish movement into productive habitats such as floodplains and estuaries is limited (Bishop et al. 1995; Trayler et al. 2003; Crook et al. 2020; King et al. 2021)<br>• reduced species occurrence and abundance as wetland water depth declines (Kennard 1995; Trayler et al. 2003; Faggotter 2010) and as opportunities to disperse around the floodplain decrease. Predation pressure is likely to increase in isolated shrinking wetlands (Kennard 1995)<br>• reduced egg/larval survival and recruitment due to a decline in floodplain nursery habitat (Bishop & Forbes 1991)<br>• reduced abundance of species whose recruitment is linked to wet season discharge, including barramundi *Laetes calcarifer*, long tom *S. krefttii*, black catfish *Neosilurus ater* and fork-tailed catfish *Neoarius* spp. (King et al. 2021)<br><br>Macroinvertebrates/cherabin<br><br>• reduced abundance of fish on the floodplain can promote increased macroinvertebrate species richness and abundance (Trayler et al. 2003)<br>• reduced diversity of macroinvertebrates across the landscape as the number and physical diversity of wetlands decrease (Marchant 1982; Outridge 1988; Leigh & Sheldon 2009; Leigh et al. 2010) |

| Flow component, flow principle & WRD threat | Habitat alteration | Biotic impact |
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| | Riparian zone<br><br>• Reduced magnitude (i.e. area) and duration of inundation (Karim et al. 2016; Karim et al. 2018; Canham et al. 2021a)<br>• Increased depth to water table as groundwater recharge diminishes (Lamontagne et al. 2005)<br><br>Estuary<br><br>• increased salinity (Staples 1980; McKinnon & Klumpp 1998; Vance et al. 1998; Lowe et al. 2022) and decreased sediment/turbidity (Blaber et al. 1995; Blondeau-Patissier et al. 2014; Duggan et al. 2014) due to a decline in freshwater flushing flows. *However, an impoundment has been found to decrease saltwater intrusion and increased siltation (Wolanski et al. 2001) - seemingly contradictory evidence.*<br>• *a narrowing and shallowing of estuarine reaches due to increased siltation associated with flow impoundment (Wolanski et al. 2001)*<br>• short term increase in benthic primary production due to reduced flood disturbance (Duggan et al. 2014; Lowe et al. 2022), but over the medium to longer term reduced nutrient/carbon inputs from the catchment (McKinnon & Klumpp 1998; Burford et al. 2011; Burford et al. 2016; Burford & Faggotter 2021; Egger et al. 2023) see Burford et al. (2012) for exception] will reduce primary production (Burford et al. 2011; Blondeau-Patissier et al. 2014; Duggan et al. 2014; Burford et al. 2016) see Lowe et al. (2022) for exception]<br>• sediment carbon becomes increasingly mangrove dominated due to reduced inputs of terrestrial (i.e. leaf litter) carbon from the catchment (Volkman et al. 2007)<br>• altered zooplankton assemblage (McKinnon & Klumpp 1998; Duggan et al. 2008)<br>• in reduced nutrient inputs should reduce algal blooms harmful to seagrass in nutrient-enriched catchments (Robson et al. 2008; Howley et al. 2018) | • increase in gatherer macroinvertebrates species (Leigh & Sheldon 2009); other shifts in assemblage structure (Leigh et al. 2012)<br>• reduced cherabin body condition (Novak et al. 2015) and reduced abundance in floodplain pools as depth declines (Beesley et al. 2023)<br><br>Riparian vegetation<br><br>• altered riparian assemblage structure (Pettit et al. 2001; Doupé & Pettit 2002; Trayler et al. 2003; Finlayson 2005; Franklin et al. 2007; Canham et al. 2021a) including a greater number of larger trees in areas in or close to the channel where they would not have been due to flow disturbance (Doupé & Pettit 2002). Increased cover of exotic species due to the absence flood flows which disturb these species (Doupé & Pettit 2002; Trayler et al. 2003). Reduced vegetation cover of shrubs and grasses on floodplain due to reduced inundation, particularly in lowland areas (Cluett 2005)<br>• altered seed dispersal, reducing germination and recruitment (Pettit & Froend 2001; Doupé & Pettit 2002)<br>• increased recruitment (Doupé & Pettit 2002)<br>• reduced biomass of floodplain grasses (Finlayson 1991)<br><br>Food web<br><br>• reduced transfer of energy around catchment, including between floodplain, estuarine and riverine habitats (Finlayson et al. 1993; Douglas et al. 2005; Hunt et al. 2012; Jardine et al. 2012a; Jardine et al. 2012b; Warfe et al. 2013a; Hanson et al. 2015; Villamarín et al. 2016; Pettit et al. 2017a; Venarsky et al. 2020) but see Fellman et al. (2013) as an exception]. The greatest impact is expected to occur for large-bodied species such as predatory fish and crocodiles which generally obtain considerable amounts of their energy from floodplain production (Jardine et al. 2017). Impacts likely to be greatest in areas of the river with great river-floodplain connectivity i.e. lowland reaches (Venarsky et al. 2020)<br>• reduced transfer of energy from the aquatic to the terrestrial environment facilitated by waterbirds (Morton & Brennan 1991)<br>• increased competition (dietary overlap) among fish for food (Thorburn et al. 2014), but see (Kennard 1995) as an exception<br>• uncertain impact on consumption of benthic algae by macroinvertebrates and fish (Jardine et al. 2013), especially as fatty acid composition is similar in floodplain and main-channel habitats |

| Flow component, flow principle & WRD threat | Habitat alteration | Biotic impact |
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| | | (O'Mara et al. 2022), however a decrease in floodplain size likely will reduce energy to macroinvertebrates and fish(O'Mara et al. 2022)<br>• reduced food for macroinvertebrates, and to a lesser extent fish, if lower amounts of leaf litter are flushed into the main channel (Marchant 1982; Finlayson et al. 1993; Pusey & Arthington 2003; Leigh et al. 2010; Hunt et al. 2012; Jardine et al. 2013; Beesley et al. 2020; Pusey et al. 2020a)<br>• reductions in macrophytes unlikely to impact fish and macroinvertebrates as they are not an important food source (Pettit et al. 2011)<br>• reduced accumulation of food resources that support growth and reproduction of pig-nosed turtles (King et al. 2021)<br><br>Birds/reptiles/amphibians/mammals<br><br>• reduced nesting/recruitment of Magpie Geese due to diminished macrophyte habitat which is important for feeding, nesting, fledging and survival of yearlings (Bayliss 1989; Bayliss & Yeomans 1990; Morton et al. 1990b; Kingsford & Norman 2002; Bayliss et al. 2007; Bayliss et al. 2008; Pettit et al. 2011; Traill & Brook 2011; Bayliss & Ligtermoet 2018)<br>• delayed timing of overbank flooding in the early wet will lead to delayed timing of Magpie Goose nesting in March or April, reduced nest density and smaller clutch sizes (Whitehead & Saalfeld 2000). Decreases in maximum river height and the timing of peak river height have been found by some to have little effect on nest density (Whitehead & Saalfeld 2000), but others describe a quadratic/threshold relationship, with too little water causing problems and too much water drowning nests (Bayliss et al. 2008).<br>• reduced dispersal of Magpie Geese across the landscape and concentration in locations of permanent water and food (Bayliss & Yeomans 1990; Morton et al. 1990b; Morton & Brennan 1991; Chatto 2006; Traill et al. 2010; Traill & Brook 2011; Corriveau et al. 2020). If wet season flows are reduced such that wetland area and persistence decreases during the dry season this can impact the abundance of waterbirds that seek refuge in these habitats (Morton & Brennan 1991; Bayliss et al. 2008)<br>• reduced abundance of ducks, egrets, herons, ibises and spoonbills if persistent swamps dry out (Morton et al. 1990a, 1993b), but some birds that prefer dry floodplain habitats such as black-necked storks may become more abundant, at least in the short term (Morton et al. 1993a) |

| Flow component, flow principle & WRD threat | Habitat alteration | Biotic impact |
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| | | • reduced foraging of fish-eating waterbirds such as heron and egrets (Recher & Holmes 1982) and pelicans, cormorants and stork (Morton & Brennan 1991) if floodplain habitat declines.<br>• reduced body condition and breeding activity of Arafura filesnakes (Madsen & Shine 2000; Pettit et al. 2011) and altered survival of eggs incubating in floodplain soils (Brown & Shine 2004; Shine & Brown 2008). Altered movement of snakes (Braithwaite et al. 1991).<br>• reduced reproductive output (Madsen & Shine 2000; Shine & Brown 2008) and potentially altered diet and distribution of semi-aquatic reptiles, including goannas i.e. *Varanus panoptes*, *V. mertensi* and *V. mitchelli*, filesnakes and pythons in line with changes in their aquatic prey (Shine 1986b; Shine 1986a)<br>• potentially reduced abundance of the turtle northern snake-necked turtle *Chelodina rugosa* which occupies ephemeral wetlands/waterholes (Kennett & Tory 1996); reduced reproductive output (i.e. fewer lighter eggs in a clutch) for the pig-nosed turtle (Doody et al. 2003a). Reduced dispersal and foraging of pig-nosed turtles in floodplain habitats (Doody 2002; Dostine 2021)<br>• reduced feeding and growth of freshwater crocodiles (Webb et al. 1982, 1983b) and dispersal across the floodplain (Webb et al. 1983a; Webb 1991)<br>• reduced abundance and body condition of adult saltwater crocodiles due to reduced floodplain vegetation which is important nesting habitat (Fukuda et al. 2008; Pettit et al. 2011; Fukuda & Saalfeld 2014). Increased survival of saltwater crocodile hatchlings because nests are not drowned out by high deep floodplain inundation (Magnusson 1982; Webb 1991; Fukuda & Saalfeld 2014). Potentially increased reliance of saltwater crocodiles on terrestrial food (Adame et al. 2018).<br>• reduced species richness of frogs (Braithwaite et al. 1991; Woinarski & Gambold 1992)<br>• potentially reduced foraging on reptiles by birds of prey (Sergo & Shrine 2015) if the abundance of snakes and turtles on the floodplain decrease.<br>• increase in reproductive activity in female wallabies (Williams & Newsome 1991); however, survival and recruitment of young likely to decline due to reduced foraging on food resources (floodplain and riparian grasses) during the dry season (Williams & Newsome 1991).<br>• altered movement of the dusky rat in response to altered floodplain inundation, reduced body condition due to diminished food on the floodplain (Williams & Newsome 1991). If floodplain inundation is |

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| | | smaller populations increase, in the short term, as rats commence breeding earlier (Williams & Newsome 1991). The abundance of other small-bodied mammals that inhabit floodplain habitats is likely to track resource availability due to opportunistic life histories (Williams & Newsome 1991).<br><br>Estuarine biota (including fish)<br><br>• altered fish assemblage (Davis 1988; Blaber et al. 1995; Pusey et al. 2016) and reduced productivity (Robins et al. 2005) due to reduced food resources.<br>• altered movement of fish into tidal swamps/creeks (Davis 1985; Davis 1988). Reduced movement of diadromous fish such as sharks and sawfish that use the estuary as a nursery (Lyon et al. 2017). Reduced movement of juvenile barramundi into freshwater (Davis 1985; Walther et al. 2011) where growth is maximised (Roberts et al. 2019).<br>• reduced growth and recruitment/abundance of barramundi (Bayliss et al. 2007; Bayliss et al. 2008; Stewart-Koster et al. 2011; Leahy & Robins 2021; Crook et al. 2022) associated with declines in estuarine production. Reduced recruitment of sawfish including *Pristis pristis* (Lear et al. 2019) possibly due to pups being trapped in the estuary where they suffer high mortality. No change to the recruitment of bullsharks (Lear et al. 2020).<br>• reduced recruitment and catch of prawns (Vance et al. 1985; Staples & Vance 1986; Vance et al. 1998; Duggan et al. 2019; Kenyon et al. 2020; Turschwell et al. 2022) including reduced emigration of juvenile prawns from the lower reaches of the river to the marine environment (Staples 1980; Staples & Vance 1986; Vance et al. 1998). Increased upstream distribution of juvenile prawns in the late wet season associated with high salinity and low flows in the estuarine reaches of the river (Stapels 1980).<br>• altered zooplankton (Duggan et al. 2008) and benthic mudflat communities (Lowe et al. 2022; Venarsky et al. 2022), including a short-term increase in meiofaunal density and macrobenthic invertebrates due to reduced disturbance from flood flows (Duggan et al. 2014; Lowe et al. 2022). Macrobenthic communities likely to decline over the longer term due to reduced primary production (Venarsky et al. 2022). |
| Flow component: | River channel | Fish |

| Flow component, flow principle & WRD threat | Habitat alteration | Biotic impact |
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| Recessional flows<br><br>Flow principle:<br><br>Recessional flows assist the movement of animals to refuge habitats and assist others to complete life history migrations. They are also important for maintaining key habitats, particularly during the dry season.<br><br>WRD Threats:<br><br>Instream barriers including impoundments, water extraction from channel | • reduced instream depth and velocity in persistent reaches (Townsend & Padovan 2005; Chan et al. 2012; Townsend & Douglas 2014)<br><br>Wetlands/Floodplain<br><br>• reduced flow to flood runner distributary creeks and wetlands, reducing depth and water quality in these habitats (Pettit et al. 2012b)<br><br>Riparian<br><br>• No information<br><br>Estuary<br><br>• No information | • Reduced migration to refuges, including from floodplain habitats back to the main channel (Bishop et al. 1995; Crook et al. 2020).<br><br>Macroinvertebrates/cherabin<br><br>• reduced upstream migration of juvenile cherabin (Novak et al. 2015; Novak et al. 2017a).<br><br>Riparian vegetation<br><br>• No information<br><br>Food web<br><br>• No information<br><br>Birds/reptiles<br><br>• Potentially an earlier start to dry season nesting for northern snake-necked turtle *Chelodina rugosa* (Kennett 1999).<br>• Reduced breeding of pythons and filesnakes if late wet season flows are reduced because these flows are mainly responsible for the duration of floodplain inundation which determines the abundance of prey items i.e. fish, rats (Madsen & Shine 2000; Madsen et al. 2006; Shine & Brown 2008).<br><br>Estuary<br><br>• No information |
| Flow component:<br><br>Groundwater / Low flows<br><br>Flow principle:<br><br>Groundwater storages, including bank storage and aquifers are important in maintaining subterranean habitats, wetlands, riparian zones and springs, and | River channel<br><br>• reduced water depth, velocity and hydrologic persistence (Storey 2002b; Townsend & Padovan 2005; Webster et al. 2005; Chan et al. 2012; Townsend et al. 2012b; Hermoso et al. 2013; Keller et al. 2019) causing a decline in the number and size of refuge pools (Dostine et al. 1998; Close et al. 2012; Beesley et al. 2023).<br>• reduced channel stability if riparian vegetation is altered (Saynor et al. 2008).<br>• *where water is released from an impoundment during dry season low flows there can be an unnatural increase in water depth, water velocity and water* | Fish<br><br>• increased strength of competition and predation (Woinarski & Gambold 1992; Kennard 1995; Storey 2002b; Pusey et al. 2018; Turschwell et al. 2019; Lear et al. 2021), increased physico-chemical stress (Woodland & Ward 1992; Waltham et al. 2013; Gleiss et al. 2017).<br>• reduced body condition (Beesley et al. 2021; Lear et al. 2021).<br>• altered assemblage structure (Woodland & Ward 1992; Storey 2002b, 2003; Stewart-Koster et al. 2011; Warfe et al. 2013b; Pusey et al. 2018; Pusey et al. 2020a), including reduced species occurrence and abundance for many species including large species such as |

| Flow component, flow principle & WRD threat | Habitat alteration | Biotic impact |
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| can provide dry season flow that supports runs, riffles and pools in the river channel.<br><br>WRD Threats<br><br>Impoundment.<br><br>Groundwater pumping, water extraction from main channel or from wetlands. Reduced groundwater recharge on floodplain and in main channel due to farm dam floodwater interception and impoundments<br><br>Impact:<br><br>reduced water table | *permanence, changing the flow regime from intermittent to perennial (Trayler et al. 2003).*<br>• declining water quality, i.e. increased nutrients, temperature and turbidity, and reduced oxygenation as flows subside and pools shrink (Hart & McGregor 1980; Storey 2002b; Faggotter et al. 2013; Leigh 2013; Gleiss et al. 2021) most stressful conditions occur in disconnected pools/waterholes (Waltham et al. 2013). However, in rivers with perennial flow, flow reduction may cause a decrease in turbidity (Storey 2002b).<br>• reduced in-channel backwater habitats (Storey 2002b).<br>• increased photosynthesis and primary production as water velocity slows, i.e. phytoplankton, algal biofilm, filamentous algae (e.g. *Spirogyra*) (Rea et al. 2002; Townsend & Padovan 2005; Webster et al. 2005; Townsend & Padovan 2009; Townsend et al. 2011; Hunt et al. 2012; Burrows et al. 2020). However, these increases may diminish through time if low flows are protracted (Rea et al. 2002; Townsend & Padovan 2005; Webster et al. 2005; Townsend & Padovan 2009) see Robson (2010) as an exception] as slow flows can reduce the ability of primary producers, particularly phytoplankton, to uptake nutrients required for growth (Robson 2010; Townsend et al. 2012a). However, slowing flow may have little effect on primary production in clear water systems, such as the mid reaches of the Daly River, if primary production is nutrient rather than light or scour limited (Townsend et al. 2011; Townsend et al. 2012b) although some clear systems appear both light and nutrient limited (Hunt et al. 2012).<br>• reduced reliance of the instream aquatic food web on ancient carbon in groundwater (Fellman et al. 2014; Pettit et al. 2017b)<br>• a decline in macrophyte beds particularly for species that prefer high velocity flows such as *Vallisneria nana* (Rea et al. 2002; Storey 2002b; Erskine et al. 2003). If falls in water depth are sudden and expose macrophyte beds, macrophytes can suffer mortality (Rea et al. 2002; Storey 2002b).<br><br>Wetlands/Floodplain<br><br>• Reduced depth and persistence of groundwater-fed wetlands and creeks<br>• declining water quality, i.e. increased nutrients, temperature, turbidity (Tait et al. 1984; Pettit et al. 2012b; Wallace et al. 2017)<br>• diminished cover of macrophytes and water-loving herbs as wetlands dry (Finlayson 2005; Pettit et al. 2012b; Waltham et al. 2013)<br>• simplification of zooplankton assemblage (Tait et al. 1984)<br><br>Riparian<br><br>• increased depth to water table (Lamontagne et al. 2005) | barramundi, sawfish and fork-tailed catfish (Chan et al. 2012) associated with increasing competition and predation in shrinking pools, particularly if depth falls below critical thresholds (Keller et al. 2019).<br>• decreased abundance of sooty grunter (Chan et al. 2012; Crook et al. 2021b) and other species that prefer riffle habitat (King et al. 2021).<br>• local extirpation if pools dry completely.<br>• altered distribution and abundance of small fish/juvenile fish as shallow nursery habitats within the main channel disappear (Storey 2002b), reduced spawning of low-flow spawning specialists (King et al. 2020; King et al. 2021).<br>• reduced foraging of sawfish in shallow 'run' habitats (Whitty et al. 2017).<br>• *artificial flows from a dam that increase the permanence of the lower reaches and estuarine-river connectivity increase the number of estuarine species in lower river reaches (Trayler et al. 2003). They can also increase fish average size (Trayler et al. 2003) as natural extirpation processes are missing.*<br><br>Macroinvertebrates/freshwater crabs/cherabin<br><br>• diminished abundance of aerial aquatic insects if stream reach dries out (Lynch et al. 2002).<br>• altered macroinvertebrate assemblage structure (Dostine 2000; Storey 2002a; Trayler et al. 2003; Humphrey et al. 2008; Leigh & Sheldon 2009; Waltham et al. 2013). This includes a decline in flow-dependent macroinvertebrate taxa as flows recede (Storey 2002a; Storey & Lynas 2007; Dostine & Humphrey 2012; Leigh 2013), i.e. a shift from filterers and grazers to gatherers (Leigh & Sheldon 2009). Decreases in species richness as aquatic habitats contract have been found by many (Marchant 1982; Outridge 1988; Storey 2002a; Leigh 2013; Waltham et al. 2013), although some report little change (Trayler et al. 2003). Declines are also thought to be linked to low oxygen levels at the bottom of thermally stratified pools (Outridge 1988).<br>• decreased mussel abundance (survival) if oxygen levels decline (Humphrey and Simpson 1985).<br>• reduced macroinvertebrate production in the late dry (Marchant 1982; Outridge 1988; Pettit et al. 2011; Garcia et al. 2015). Declines especially likely if macrophyte habitat decreases (Marchant 1982). |

| Flow component, flow principle & WRD threat | Habitat alteration | Biotic impact |
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| | Estuary<br><br>• increasing salinity (McKinnon & Klumpp 1998). *Note that salinity can reduce if an impoundment or irrigated agriculture is creating a dry season flow release (Kenyon et al. 2004)*<br>• increased saltwater intrusion (Kenyon et al. 2004)<br><br>Hyporheos<br><br>• Reduced habitat impacting hyporheic biota such as microcrustaceans (Dostine et al. 1998) | However, crabs and many invertebrates will survive by aestivating in the riverbed or bank (Marchant 1982).<br>• altered instream macroinvertebrate taxa in response to a decrease in riparian canopy cover (Leigh & Sheldon 2009).<br>• decline in crab abundance as the water table falls (Waltham et al. 2013; Waltham 2016).<br>• reduced abundance of cherabin in macrophyte beds (Storey 2002b). Reduced cherabin body condition (Novak et al. 2015).<br>• impacts to stygofauna if groundwater falls or is contaminated due to high groundwater connectivity across the region (Oberprieler et al 2021).<br><br>Riparian vegetation<br><br>• reduced access to groundwater (Lamontagne et al. 2005; O'Grady et al. 2006b; Canham et al. 2021b) likely causing increased water stress to trees situated low in the landscape close to the river, such as Melaleucas (O'Grady et al. 2006b; O'Grady et al. 2006a).<br>• altered plant assemblage, including the loss of flood resistant species and encroachment by terrestrial vegetation (Erskine 2002; Freestone et al. 2022). A decline in species richness has been reported (Trayler et al. 2003)<br>• *reduced seed germination in the main channel due to unnaturally high flows, i.e. lack of moist soil as it is underwater (Doupé & Pettit 2002)*<br><br>Food web<br><br>• reduced inputs of ancient, bioavailable dissolved organic carbon into streams/rivers/springs (Fellman et al. 2013).<br>• reduced aquatic and terrestrial insects (Lynch et al. 2002) which can provide a food subsidy for animals living in the riparian zone (e.g. riparian birds, spiders, insects) (Morton & Brennan 1991; Pusey & Arthington 2003; Douglas et al. 2005; Leigh et al. 2013), and for fish that consume terrestrial insects such as archerfish and rainbowfish (Jardine et al. 2012a).<br>• reduced inputs of leaf litter from riparian vegetation which is an important food source for macroinvertebrates (Pusey & Arthington 2003; Leigh et al. 2010; Pettit et al. 2012a; Fellman et al. 2013; Beesley et al. 2020) and some fish such as bony bream (Pusey et al. 2020b) and grunters (Davis et al. 2010); but not in some systems (Hunt et al. 2012). |

| Flow component, flow principle & WRD threat | Habitat alteration | Biotic impact |
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| | | • uncertain impact on consumption of benthic algae by macroinvertebrates and fish (Jardine et al. 2013).<br>• reduced quality of food sources and complexity of the aquatic food web (Pettit et al. 2017b)<br><br>Birds/reptiles/mammals<br><br>• reduced occurrence, abundance and species richness of riparian birds (Morton & Brennan 1991; Woinarski et al. 2000), including threatened species such as the purple-crowned fairy wren (Skroblin & Legge 2012), crimson finch (Woinarski et al. 2000) and Alligator Rivers Yellow Chat (Leppitt et al. 2022) as riparian habitat changes and diminishes.<br>• reduced abundance of waterbirds that will remain during the dry season as refuge wetlands dry up (Bayliss et al. 2008)<br>• reduced body condition and abundance of turtles as habitats contract and food sources diminish. For example, declines in aquatic algae, riparian leaves and fruit, could impact the northern snapping turtle *Elseya dentata* (Kennett & Tory 1996; Townsend & Padovan 2009; Welsh et al. 2017). Similarly, declines in the macrophyte *Vallisneria* and molluscs will lead to reduced body condition of pig-nosed turtle *Carettochelys insculpta* (Georges et al. 2002; Erskine et al. 2003; Welsh et al. 2017; Dostine 2021; King et al. 2021). The movement of pig-nosed turtles are also likely to be impacted if the main channel dries into pools (Georges et al. 2002) and declines in sand moisture will lead to reduced nesting (Georges et al. 2002; Doody et al. 2003b).<br>• reduced turtle nesting success. For instance, declines in water depth and permanence may impact nesting of the northern long-necked turtle *Chelodina rugosa* which creates underwater nests in ephemeral wetlands (Kennett 1999). Reduced groundwater inputs (i.e. thermal springs in the riverbed) may impact turtle body condition and breeding success of pig-nosed turtles (Doody & Georges 2002; Dostine 2021).<br>• increased movement of freshwater crocodiles (*Crocodylus johnstoni*) upstream (Webb et al. 1983a). Reduced suitability of channel sandbars/riparian zones freshwater crocodile nesting (Somaweera & Shine 2013; Hipsey et al. 2021) and embryo survival if the water table falls and soil becomes too dry (Webb et al. 1983c; Hipsey et al. 2021).<br>• reduction in saltwater crocodile nesting if permanent aquatic habitats dry (Webb et al. 1983c; Harvey & Hill 2003), freshwater swamps/billabongs sustained by groundwater in the lower reaches of rivers are particularly important nesting grounds (Webb 1991). *Dams* |

| Flow component, flow principle & WRD threat | Habitat alteration | Biotic impact |
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| | | *that create artificial high dry season flows (e.g. Ord) may impact the nesting success of freshwater crocodiles if they drown nests.*<br>Estuarine biota<br>• increased immigration of post larval prawns into the lower reaches of the river in the late dry season due to high salinity and low flows (Staples & Vance 1986). *Prawn immigration and abundance can decrease if unnatural dry season flows from an impoundment are decreasing salinity (Kenyon et al. 2004; Duggan et al. 2019).*<br>• altered benthic communities (Lowe et al. 2022; Venarsky et al. 2022) |
| Flow component:<br>Antecedent conditions<br>Flow principle:<br>Antecedent hydrological conditions, i.e. flow regime over a range of temporal scales, have an important influence over the ecology of the system. | River channel<br>• reduced persistence of in-channel waterholes if groundwater recharge isn't sufficient in the prior wet season (Waltham et al. 2013)<br>• potentially little change in the water quality of dry season refuge pools if wet season flows vary (Gleiss et al. 2021)<br>Wetlands/Floodplain<br>• reduced wet season inundation will reduce GW recharge that may sustain some wetlands (Waltham et al. 2013)<br>• size of prior wet affects the amount of wetland habitat (Karim et al. 2018; Beesley et al. 2023{Karim, 2015 #205)}<br>Riparian<br>• no information<br>Estuary<br>• no information | Fish<br>• the abundance of juvenile sooty grunter is lower when flows were more variable during the wet season two years prior (Stewart-Koster et al. 2011) probably because highly variable flows reduce spawning and recruitment of the species in riffle habitat.<br>• the abundance of barramundi is positively linked to the magnitude of the wet prior (Stewart-Koster et al. 2011; Turschwell et al. 2019), the year before that i.e. 2 yrs prior (Bayliss et al. 2008; Stewart-Koster et al. 2011) and also three years before (Bayliss et al. 2008), probably because higher flows improve food in the estuary which enhances the survival and recruitment.<br>• fish assemblages in perennial tributaries/rivers different from those in intermittent ones (Stewart-Koster et al. 2011; Warfe et al. 2013b; Pusey et al. 2018; Turschwell et al. 2019; Pusey et al. 2020a).<br>• Changes to the flow regime will impact fish populations for multiple subsequent years (Stewart-Koster et al. 2011)<br>Macroinvertebrates/cherabin<br>• historical hydrological connectivity was a key driver of macroinvertebrate assemblage structure and functional feeding groups of main channel and floodplain pools (Leigh & Sheldon 2009).<br>• improved dry season macroinvertebrate richness due to reduced wet-season flow stress (Leigh 2013).<br>Riparian vegetation<br>• no information |

| Flow component, flow principle & WRD threat | Habitat alteration | Biotic impact |
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| | | Food web<br><br>• As the dry season progresses, fish become less reliant on energy from the floodplain and increasingly reliant on energy produced locally in the main channel (Venarsky et al. 2020).<br><br>Birds/reptiles/mammals<br><br>• reduced reproduction, recruitment and abundance of magpie geese (Bayliss 1989; Bayliss et al. 2008), flows more than 1 year prior to nesting have little impact on nest density (Whitehead & Saalfeld 2000)<br>• increased survival of saltwater crocodile hatchlings if preceding wet season flows are lower because nests are not drowned out (Fukuda & Saalfeld 2014)<br>• reduced breeding in pythons and filesnakes if wet season is smaller the preceding year due to shortened floodplain inundation as it drives the abundance of prey (i.e. fish for filesnakes and rats for pythons) (Madsen & Shine 2000; Shine & Brown 2008).<br>• reduced reproductive output (i.e. fewer lighter eggs in a clutch) for the pig nosed turtle if the wet season the year or two before were small (Doody et al. 2003a).<br>• delayed timing of overbank flooding in the early wet will lead to delayed timing of Magpie Goose nesting in March or April, reduced nest density and smaller clutch sizes (Whitehead & Saalfeld 2000). The size of wet season flooding affects their food resources/foraging the following dry season (Bayliss 1989; Bayliss et al. 2008; Pettit et al. 2011; Traill & Brook 2011; Bayliss & Ligtermoet 2018) which in turn affects their dispersal across the landscape (Bayliss & Yeomans 1990; Morton et al. 1990b; Morton & Brennan 1991; Chatto 2006; Traill et al. 2010; Traill & Brook 2011; Corriveau et al. 2020).<br><br>Estuarine biota<br><br>• no information |