Proposed northern Australia water developments pertinent to the Northern Prawn Fishery: collation and review

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2016/015 Proposed northern Australian water developments pertinent to the Northern Prawn Fishery: collation and review

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OBJECTIVES:

1. Identify available information on planned water development in northern Australia.
2. Collate the information and review these plans, providing an accessible summary.
3. Identify sources of information that might be used to evaluate impacts of water development on fisheries and ecological values.
4. Development a conceptual framework for the future elaboration of ecosystem models, addressing multispecies and ecosystem-level predictions of the impacts in the estuarine and marine environments of the water resource development.

NON TECHNICAL SUMMARY:

OUTCOMES ACHIEVED TO DATE

Provided a report to industry, management and researchers associated with the Northern Prawn Fishery (NPF) that enhances their understanding of the likely water resource development alternatives and consequences across tropical Australian catchments. The report allows NPF Industry to better understand the ecological and economic trade-offs that might eventuate from new water infrastructure placement in tropical rivers catchments that provide currently-unregulated river flows into NPF managed waters.

Provided a direction for NPF management and operators to integrate an industry perspective into the water resource planning process via an understanding of current State/Territory legislation, sources of most-recent knowledge on impact of riverflows on fishery productivity, and the possibility of engagement in the development of Water Resource Operational Plans in response to the objectives of State legislation.

Provided a recommendation to NPF management to consider that broad-scale irrigated agriculture will follow the Commonwealth-funded 'water resource assessment' studies conducted in five major catchments across tropical Australia over a ~10 year time window (2008-2018; four catchments flow into NPF managed waters). Water extraction to support agriculture will modify natural flow regimes that have supported estuarine and coastal fisheries for the past 50 years. Water Resource Operational Plans for major catchments will be updated or modified in response to the outcomes and recommendations of the water resource assessments such as the Flinders and Gilbert Agricultural Resource Assessment (FGARA) and the Northern Australia Water Resource Assessment (NAWRA). Recommendations for NPF managers include:

- Model the effects of all aspects of flow (seasonal and volumetric) on fishery production to fully understand the impacts of water extraction on fishery production, as well as considering extending any modelling to also evaluate broader marine ecosystem impacts,
- Engage in the 'water resource planning process' via stakeholder input, as possible, within the legislative framework, with the aim of **impact minimisation** using **quantitative targets** and **triggers**,
- Promote water management, infrastructure design and construction that, as much as practicable, mimics historical patterns of natural seasonal flow; only harvest water from high-volume floodflows that offer water harvest potential with low impact on downstream ecosystem services that are supported by monsoonal flow regimes.

Incorporation of up-to-date ecological research outcomes into the conceptual model of the life history of Banana Prawns (*Penaeus merguiensis*) to facilitate the development of quantitative models such as Models of Intermediate Complexity for Ecosystem assessment (MICE) models. These models are capable of quantifying the impact on each of the prawn's life-stages of modification of natural river-flows due to anthropogenic resource development. The MICE models can be deployed to investigate the effects of modification of seasonal aspects of flow and on annual series of low flows on Banana Prawn populations and yield, with improved understanding for industry and fishery management.

The project reviewed the legislation dealing with Water Resource Management in each of Queensland (QLD), the Northern Territory (NT) and Western Australia (WA) that effects the management of overland flow in catchments that empty into water managed as part of the Northern Prawn Fishery. In general, three tiers of governance exist: a Water Act which enacts legislation State- or Territory-wide, and two levels of operational water management plans that instruct the day-to-day management of water, usually at a catchment scale (or 'topographical grouping' of several rivers). Explicit provisions for the management of water that include the interests of catchment users, other than extractive users (e.g. agriculture irrigators), are incorporated at this level of water management. The formulation of management protocols for Water Resource Development (WRD) offers the opportunity for stakeholder involvement to ensure the interests of stakeholders, other than extractive users, are part of the management matrix.

In WA and QLD three levels of water management legislation are enacted: the Water Act; Water Resource Management Plans which deal with overarching aspects of the on-ground management of a catchment or group of catchments (including the issue of allocation of water to environmental flows); and Operation Plans which provide protocols and tasks to undertake the day-to-day management of water. In the Northern Territory, a key gap in legislation is the lack of or paucity of Water Resource Management Plans and Operation Plans (or equivalents). Currently, the Northern Territory is developing regional Water Allocation Plans (WAPs) and this offers an opportunity for NPF Industry to engage in the management of water allocation. To date, the Northern Territory has developed WAPs for inland urban/rural water management areas such as Alice Springs and Tennant Creek. This project suggests that the Northern Territory resource managers and legislators likely will develop WAPs for other regions, perhaps major rivers draining into the NPF.

The project also reviewed the current and future WRD in catchments and landscapes that abut the Northern Prawn Fishery. The project developed a web-accessible map portal that displays the location and scope of significant projects or infrastructure that incorporate or require WRD for their construction or ongoing operation (see https://research.csiro.au/npfnwd/). The portal provides links to websites that describe the projects or infrastructure; and links to government websites that provide regulatory provisions or other legislative oversight for the projects.

It is likely that in ~5 major river catchments, WRD will follow the recent and current water and land resource assessments funded and undertaken by the Commonwealth of Australia (including the National Water Infrastructure Development Fund). These assessments were undertaken with the long-term aim to support agricultural and infrastructure development in northern Australia. Both instream and offstream storage capacity of monsoon-driver river flows will be constructed with subsequent modification of downstream flows. Water extraction will reduce flows and poor management of flow reduction likely will have major impacts on estuarine and coastal fish species that use regulated rivers during part of their life-cycle. In addition, mining and large-scale aquaculture infrastructure in coastal environments also has the capacity to impact groundwater, overland flows and inputs to rivers and estuaries.

The modification (or development in the case of the Northern Territory) of Water Resource Plans and Resource Operation Plans (ROPs) are key windows-of-opportunity for Northern Prawn Fishery management (specifically NPF Industry) and the managers of other fisheries to engage the legislative process. The aim should be to promote downstream impact minimisation through consideration of the management of water impoundment or extraction. Management protocols should minimise the reduction or modification of historical seasonal and monsoonal flows, and the ecosystem services that they sustain in the lower river and estuary.

Workshops conducted as part of this project highlighted the need to model each life-stage of the Banana Prawn using Models of Intermediate Complexity for Ecosystem assessment (MICE) that incorporate all facets of ecosystem components and services, as well as flow, to explore abiotic and biotic drivers determining fishery catch. Project workshops concluded that models be constructed at three levels of flow; low, moderate and high, to maximise the ability to detect the impact of seasonal flows and temporal shift in flow on catch. Incorporating a suite of ecosystem components into an existing MICE model will reliably and rigorously quantify current identified uncertainties about the impacts of water extraction on the prawn and commercial fish species.

The project also identified major scientific research projects that provide quantitative information to evaluate the impacts of water development on fisheries and the ecological systems that support coastal productivity. Four major Commonwealth-funded programs were summarised:

1. Tropical Rivers and Coastal Knowledge (TRaCK)
2. Flinders and Gilbert Agricultural Resource Assessment (FGARA)
3. National Environmental Science Programme (NESP)
4. Northern Australia Water Resource Assessment (NAWRA)

NAWRA is a major project to assess the water and landscape resources of several major tropical rivers across northern Australia and will report in 2018. NAWRA will provide key outputs describing the trade-offs between WRD for irrigated agriculture (and necessary infrastructure), versus the economic impact on current industries and the depletion of ecosystem services that are sustained by the unregulated river flows. To achieve these tasks, hydrologic models will be developed to determine current and future flow regimes under unregulated and modified flow scenarios due to new water infrastructure and water resource use. Flow estimates will be modelled with catch-series from fisheries to estimate the impact of reduced water availability due to WRD on fishery catch. In conjunction, qualitative assessments of the impacts of reduced flows on key fishery and iconic species will be undertaken, as undertaken for FGARA.

While the NAWRA modelling will be informative, no ecological modelling will be undertaken.

The overall conclusion of the project is that NPF management are encouraged to take a proactive approach to the development of the water resources of tropical Australian rivers to support irrigated agriculture. They need to engage with the WRD process via stakeholder consultation processes, and promote water management protocols and infrastructure design that minimise downstream impacts on fishery production. A significant aspect purported to support proposed water extraction from tropical monsoon-driven river flows is that a relatively small percentage of annual flow will be harvested, and that only high flows will be targeted. Management protocols need to ensure that a sustainable percentage of water is extracted from high flows only. These protocols need to be legislated to be effective and also require quantitative definitions of flow and flow thresholds that can be stated clearly and withstand scrutiny by water managers and water users. Advice from hydrologists with access to historical flow series for each river is critical to flow threshold quantification.

Management adherence to the definition of flow needs to be explicit (with definitions required for each river):

- High flows as determined from examination of annual series of end-of-system flows,
- Low flows as determined from examination of annual series of end-of-system flows (which should be preserved as environmental flow),
- **Threshold levels of flow** below which water should not be harvested; water should be allowed to proceed downstream.

KEYWORDS: Water resource development, irrigated agriculture, Northern Prawn Fishery, tropical rivers.

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Some authors of this report are also involved in CSIRO's Northern Australia Water Resource Assessment and discussions and documentation undertaken as part of NAWRA assisted with concepts documented here.

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Executive Summary

The project objective was to identify and collate current and future Water Resource Development (WRD), together with infrastructure placements which impact natural flows in catchments that empty to Northern Prawn Fishery (NPF) managed waters. Further objectives were to identify sources of information to evaluate the impacts of water development on fisheries; and using best ecological information, to develop a conceptual framework for the future elaboration of ecosystem models for flow-catch prediction. These initiatives allow NPF Industry to better understand the ecological and economic trade-offs that might eventuate from new water infrastructure placement.

The project was undertaken as the remote catchments, and their historically unregulated rivers, are increasingly subject to development pressures, particularly from irrigated agriculture. Extraction of water for agriculture with modify natural flow regimes, impacting the ecosystem services that river flows provide to riverine and estuarine habitats. These same rivers and estuaries support the juvenile and adults phases of many key fishery species for the past 50 years. Environmental impacts on the inshore phase of fishery species will affect yield and economic return in adjacent coastal fisheries, including the NPF.

The project has mapped the location of WRD and linked sources of information about the irrigated agriculture or infrastructure development to the map. The map is a web-accessible portal that displays the location and scope of significant WRD using infrastructure construction, placement and ongoing operation (see https://research.csiro.au/npfnwd/). The project has summarised the likely impacts of particular WRDs on the NPF and other coastal fisheries via best-knowledge interpretations of the life history of crustaceans and fish, and likely effects from flow modification. In conjunction, the project has summarised the jurisdictional legislation that manages the way water resources are allocated to the economic projects. We summarise aspects of the State/Territory and Commonwealth legislation that protect the natural flow regimes and the ecosystem services that natural flows sustain. In addition, our research has identified recent and current research projects that have increased scientific knowledge of the impacts of modification of river flows on fishery production and eventual yield (e.g. Tropical Rivers and Coastal Knowledge (TRaCK), Flinders and Gilbert Agricultural Resource Assessment (FGARA), National Environmental Science Programme (NESP), Northern Australia Water Resource Assessment (NAWRA).

Likely, irrigated-agriculture development will follow the water and landscape resource assessments of the FGARA and NAWRA inventory projects conducted by CSIRO. Catchment 'Water Resource Plans' for rivers such as the Adelaide, Fitzroy, Flinders, Gilbert and Mitchell Rivers will be modified, updated or introduced in response to the resource assessments. In the Flinders River catchment (Queensland), the Three Rivers Irrigation Project likely has bid for water identified by FGARA and designated as unallocated. The water was released for purchase by Queensland's Department of Natural Resources Mines and Energy; subsequent to the FGARA assessment. The Three Rivers Irrigation Project plans to extract water from the Flinders River and store it off-stream.

The Mitchell River catchment (Queensland) encompasses several likely sites for a large dam and the current NAWRA resource assessment likely will identify a quantum of water that can be impounded, stored and allocated to irrigated agriculture. Similarly, the Adelaide River (Northern Territory) has a likely site for a large dam and a current pre-proposal for off-stream storage to support the water supply for the City of Darwin. In addition, wetland and groundwater resources in the Top End floodplains (eastern catchments of the 'Darwin Rivers') will be assessed for their suitability to be exploited as a source of irrigation water. While acknowledged as outside the footprint of the NPF Management Zone, the water resources of the Fitzroy River catchment will also be assessed.

Water Resource Operational Plans (ROPs) for major catchments will be updated or modified in response to the outcomes and recommendations of the water resource assessments, such as FGARA and NAWRA. NPF management should engage as a stakeholder with the reallocation of water resources as identified, and the modification of water management by State or Territory government managers and legislators. When new water management protocols are framed, NPF managers should promote, as part of the decision process and specification development, science-based best understanding of the effects of water extraction on seasonal and volumetric flows and hence impacts on fishery production. Downstream impact minimization needs to be an aim of water management. Recognizing and incorporating ecological knowledge as a key factor in the planning process will promote water management (and infrastructure design and construction) that has the capacity to mimic historical seasonal floodflows. The target is to identify and exploit floodflows that offer water harvest potential with the lowest impact on downstream ecosystem services that are supported by the natural monsoonal flow regime.

Importantly, our team and other colleagues have developed a series of conceptual models for each phase of the life cycle of the Banana Prawns (*Penaeus merguiensis*) under three flow regimes. The conceptual models list ecosystem-level interactions and subsequent impacts on Banana Prawns in their estuarine and marine habitats. From these conceptual models, a revised version of the Vance *et al*. (1985) Banana Prawn lifecycle and its adaption to a qualitative model framework that can be used to construct a dynamic framework model has been provided. Models of Intermediate Complexity for Ecosystem assessment (MICE) (Plaganyi *et al*. 2014) are discussed in this context.

This project suggests that water resource development and current flow-dependent fisheries can co-exist in Australia's wet-dry tropics if water is harvested from wet season high flows only (during January to March when >90% of annual flows occur); and if the seasonality, magnitude and duration of low flows are maintained. In the wet season, high flow volumes dominate the catchment and the capacity of in-stream or off-steam dams. If low flows are maintained as a mimic of natural flows, monsoon season high flows would overflow constructed dams or by-pass water extraction. The quantum of water reaching the estuary would be of similar magnitude to an unregulated river, supporting the historical suite of ecological services. The caveat to this best-practice water-use scenario is the stochastic nature of large floods. In Gulf of Carpentaria catchments, high flows separated by 5 to 7 y can occur, though 3 to 4 y dry periods are more common. If the harvest of high flows can sustain irrigated agriculture, then water storage capacity must be able to sustain irrigation demand over series of dry years.

Under an informed multiple-use water management regime, the maintenance of all seasonal characteristics of flow can be achieved with a result of minimal impact of downstream ecosystem services or fishery production. This report proposes seven broad management initiatives to minimise the impact of water resource development on riverflow, and hence fishery productivity and yield:

- harvest water from moderate to high flows only,
- provide environmental flows as late-dry season flows of high water quality that pass downstream,
- provide for environmental flows that allow low-flows of high water quality to pass downstream of dams and water extraction points,
- avoid creating barriers to long-stream connectivity (engineer dams to allow water offtake),
- avoid creating barriers to floodplain inundation and connectivity,
- avoid truncating estuaries or creating barriers in estuaries, and
- do not incorporate hydro-electric power stations into the design of a dam as they necessitate permanent flows through the power station and then downstream.

NPF management are encouraged to be proactive with the development of the water resources of tropical Australian rivers to support irrigated agriculture. NPF management need to engage with the WRD process via stakeholder consultation processes, and promote water management protocols and infrastructure design that minimise downstream impacts on fishery production. A significant proposition for water extraction from tropical monsoon-driven river flows is that a relatively small percentage of annual flow will be harvested and that only high flows will be targeted. Management protocols will ensure a sustainable percentage of water is extracted only from high flows. These protocols are required to be legislated to be effective. In addition, effective protocols require quantitative definitions of flow and flow thresholds; definitions that can be stated clearly and withstand scrutiny by water managers and other water users.

Keywords: Water resource development, irrigated agriculture, Northern Prawn Fishery, tropical rivers

Background

In tropical northern Australia, river flow is crucial to the ecosystem services that support the life cycles of a suite of estuarine and marine species that are important in commercial, recreational and indigenous fisheries. In recent years, the general public, not just specific interest groups, have adopted a broader perspective of the value of rivers and river flow. Increased understanding has encouraged a shift from a 'resource development' focus on water allocation for irrigation and other extractive commerce, to a more broad perspective including a range of economic, social and ecological considerations that underpin sustainable water development (Jackson *et al*. 2008). From Cape York to the Kimberley, tropical estuaries and coastal waters support a dynamic ecosystem that sustains coastal finfish, crustacean and mollusc fisheries valued at approximately $220 M per annum (Savage and Hobsbawn 2015). Ecosystem services in these habitats are sustained by the pulsed monsoonal flows within these wet-dry tropical river systems (Burford *et al*. 2012). The dynamics of populations and communities are driven and then maintained during the subsequent dry-season by wet season events (Burford *et al*. 2012, 2016). Interannual and seasonal cycles of high- and low-flows sustain both the integrity of species lifecycles and of their habitats; and these communities have co-evolved with these cycles for millennia (see discussion and references in Huey *et al*. 2014). Modification of the timing, magnitude or duration of the annual, unpredictable wet-season floods will have flow-on effects for the distribution and abundance of many species along tropical coasts.

Apart from a few mining ventures and the City of Darwin, Australian tropical coasts are remote, with minimal anthropogenic impact. However, over recent years, commercial ventures, State/Territory Governments and the Commonwealth Government are taking a greater interest in encouraging infrastructure and economic investment in these remote tropical catchments. The White Paper on Developing Northern Australia (Our North, our Future: White paper on developing Northern Australia, Commonwealth of Australia 2015) suggested that the tropical north can be vitalised to support growing human populations and economic activity across the Asian sphere; supporting Australian economic growth and market reach. Critical to this process would be the provision of water resources to support the development of agricultural production in northern Australia to 2035. Yet it has also been recognised that water should be available within the catchments and nearby coasts to support ecosystem processes: including natural variability in flows; habitat connectivity; and the delivery of water, sediment, nutrients and organic matter through river systems to the coastal zone.

The tropical Australian savannah is a hot, dry region that currently supports rangeland grazing enterprises (Petheram *et al*. 2008, 2012). However, some regions have productive soils (Petheram *et al*. 2013 a,b); and with the provision of available water for irrigated agriculture, the tropics have demonstrated the potential for the successful tillage of irrigated croplands (Department of Water 2006). Across northern Australia, many large un-regulated rivers deliver a significant annual discharge of water to the Gulf of Carpentaria, the Timor Sea and the Joseph Bonaparte Gulf (Petheram *et al*. 2008). Southern Australian rivers are managed (arguably poorly managed) to support irrigation agriculture by the regulation and diversion of flows. The estimation of sustainable levels of water storage and diversion to support economic initiatives is crucial to sustainable water management (Petheram *et al*. 2008). In addition to the allocation of water for economic development, the un-hindered flow of a quantum of water to sustain natural riverine, estuarine and coastal processes has to be ensured.

Not only is there a need to ensure ecosystems services are maintained for both natural communities and habitats; the economic value of the harvest of natural populations (e.g. fisheries) also will decline from 'present value' under water resource diversion and extraction for irrigated agriculture. Over 30 years of research into the population biology of high value tropical species has shown that the catch of commercial species is highly correlated with flow in coastal rivers and estuaries. The abundance of target species, such as Barramundi (*Lates calcarifer*), Mudcrabs (*Scylla serrata*), Threadfin (*Polydactylus macrochir*) and Banana Prawns, is dependent on the brackish ecotone within estuaries that is maintained by low flows, and migration cues provided by high floodflows (Vance *et al*. 1998; Robins *et al*. 2005; Balston 2009; Buckworth *et al*. 2014).

The Australian Government is dedicating considerable policy, economic and research resources to plan expansion of agricultural production in northern Australia (Petheram *et al*. 2013 a,b; Commonwealth of Australia 2015). For example: the White Paper on Developing Northern Australia compiled by the Office of Northern Australia (Department of Industry, Innovation and Science); and the National Water Infrastructure Development Fund which is administered by the Department of Infrastructure, Regional Development and Cities (transferred from the Department of Agriculture and Water Resources in 2017). White papers, green papers, water plans and various policy outputs by State, Territory and Federal governments, as well as private industry, comprise a large suite of plans for water use across northern Australia. Research to define the capacity of catchments to support irrigated agriculture continues to be undertaken (the magnitude of catchment runoff, the suitability of catchment soils, and the potential for instream and offstream storage, CSIRO 2016 a,b,c). In conjunction, quantitative studies of economic trade-offs have been made. For example, the trade-offs between the value of water resource development and water deployment to economic production (e.g. irrigated agriculture) vs. the values attributed to current extractive industries (including fisheries) and existing ecosystem services provided by catchment runoff (Griffiths *et al*. 2014). However, to date the studies have been restricted to a few species and catchments: ecological interactions and ecosystem level impacts also need to be evaluated (Bayliss *et al*. 2014). In addition, indigenous land users in the lower catchments of many tropical northern rivers also value water highly and strive for a water allocation that enables economic opportunity (Jackson and Barber 2013).

Estuarine production supports an abundant population of juvenile Banana Prawns (Burford *et al*. 2010), supplemented by episodic recruitment and reduced by constant predation. Together with a reduction in the abundance of estuarine meiofauna food resources, seasonal floods (low estuarine salinity) cue the emigration of Banana Prawns (Duggan *et al*. 2014). Additionally, large loads of nitrogen and phosphorus are exported on high flood-flows to the shallow coastal waters, fuelling substantial nearshore primary production with flow-on effects for fisheries, including Banana Prawns (Burford *et al*. 2016). Sediment loads deposited in the estuary and nearshore zone maintain the integrity of intertidal and supra-littoral estuarine habitats such as mangrove forests and saltflats (Asbridge *et al*. 2016). Dynamic estuaries that not only support commercial species but iconic and threatened species such as shorebirds, sawfish and freshwater sharks and rays.

Valued at $115 M in 2013–14, the NPF relies on estuarine and shallow-inshore habitats across tropical Australia for the juvenile phase of its most valuable penaeid prawn species (Rothlisberg *et al*. 1985; Dall *et al*. 1990; Dichmont *et al*. 2008). The importance of freshwater flow on coastal and estuarine fisheries catch has been well established (Robins *et al*. 2005; Buckworth *et al*. 2014). NPF Industry appreciates the importance of understanding the ecological and economic trade-offs that might eventuate from new water infrastructure placement, and water diversion for consumptive use, in Australia's tropical catchments adjacent to fished waters. Their focus is exemplified by the current NPF high priority Research Area: "Develop an understanding of ecological and economic trade-offs of the impact of existing and proposed water resource development in Northern Australia".

Currently, it is difficult to develop an appreciation of the extent of water infrastructure and development plans as there is no single listing that collates and summarises these features. As a first step in addressing this priority, our desktop research has reviewed, collated and mapped information on the water developments and infrastructure placement likely to be of interest to Australia's Northern Prawn Fishery. The information will be very relevant to other wild-capture fisheries in the wet-dry tropics of northern Australia.

Objectives

The objectives of the project were:

- Identify available information on planned water development in northern Australia.
- Collate the information and review these plans, providing an accessible summary.
- Identify sources of information that might be used to evaluate impacts of water development on fisheries and ecological values.
- Develop a conceptual framework for the future elaboration of ecosystem models, addressing multispecies and ecosystem-level predictions of the impacts in the estuarine and marine environments of the water resource development.

Methodology

The project reviewed and collated summaries of publicly-accessible information on water resource development in Australia's tropical savannah catchments flowing into the NPF's management area. The project identified what is known in terms of WRD plans, to inform management and research planning for the NPF, and in particular focused upon collation of material that will inform the operational aspects of government policy in relation to potential northern development (Table 1). The collated information linked the portal map of WRD (https://research.csiro.au/npfnwd/) to knowledge summaries of key legislation, proposals, assessment reports and consultation outputs to facilitate research and management planning. The review provides a knowledge base to better understand the ecological consequences for key fishery species to proposed water reallocation and resource development, and subsequent social and economic effects.

The project addressed the following questions:

- What are the proposed water developments in northern Australia and how will they impact natural flow?
- What species and critical habitats are within the catchment and footprint of proposed development?
- What and where are the potential impacts on the biology and ecology of the NPF and other fisheries species — threats, potential benefits and other considerations
- What cumulative impacts (i.e. in relation to other development) should be accounted for?
- Are there potential ecological interactions due to these impacts?
- Might biological and ecological impacts of proposed developments affect non-fishery stakeholders, i.e. indigenous landholders?

Additionally, the project sought to identify sources of information that might be used to evaluate impacts of WRD on fisheries and ecological values. The project identified appropriate information for the preliminary parameterisation of future ecological models as conceptualised, including ecological modelling of the impacts of WRD on the NPF's managed area. The project collated and analysed sources of previously-gathered information (such as references and information provided by Bayliss *et al*. (2014) and Petheram *et al*. (2013)), with a view to making cost savings for future research and decisions. The project provided a publicly accessible web-portal to map the location of current and potential WRD projects and infrastructure. The web-portal displays summaries of up-to-date information and data-sets where available and links to sites associated with independent northern water development project documentation and information.

The project methodology had four major components.

- review and summarise State/Territory and Commonwealth Legislation relative to water resource management for Queensland, Northern Territory and Western Australia. Under the constitution, the States have jurisdiction over water resources. However, the Commonwealth instituted a National Water Initiative to enhance an overarching cohesiveness to Australian water management; this was reviewed also,

- identify sources of information that might be used to evaluate impacts of water development on fisheries and ecological value (e.g. TRaCK (http://www.nespnorthern.edu.au/track/), FGARA (https://www.csiro.au/en/Research/LWF/Areas/Water-resources/Assessing-water-resources/Flinders-Gilbert), NESP (http://www.nespnorthern.edu.au/) NAWRA (https://www.csiro.au/en/Research/Major-initiatives/Northern-Australia/Current-work/NAWRA)) and summarise government initiatives that support WRD in northern Australia under the 'Developing Northern Australia' White Paper,

- develop a web-accessible map portal that displays the location of WRDs which may impact the NPF. The portal provides links to descriptions of these projects and relevant data. To achieve this objective, we undertook both web-based searches and person to person contacts to identify water developments in northern Australia,

- develop a conceptual framework for the future elaboration of ecosystem models (with a focus on the Banana Prawn (*Penaeus merguiensis*)), addressing multispecies and ecosystem-level predictions of the impacts in the estuarine and marine environments of the water resource development.

Table 1. Summary of initiatives taken to explore data and information relevant to WRD in tropical Australia.

Initiative	*Western Australia*	*Northern Territory*	*Queensland*	*Commonwealth*
Water Resource Legislation summary	yes	yes	yes	National Water Initiative
In-person data gathering	yes	yes	yes	no
Government initiatives providing support to WRD	yes	yes	yes	yes
Current-ongoing research outcomes	Outside NPF Management Area (but relevant)	yes	yes	Commonwealth funds
Conceptual models	overarching	overarching	overarching	overarching

Results

1. State/Territory and Commonwealth Legislation

We reviewed the State or Territory and Commonwealth legislation relative to water resource management for Queensland, Northern Territory and Western Australia. Under the constitution, the States/Territories have jurisdiction over water resources. All States/Territories have a comprehensive Water Act. However, the operational plans that actuate the Water Acts vary markedly between jurisdictions.

The Queensland legislature includes three tiers of water management: the Water Act (2000), Water Resource Plans (WRPs) and Resource Operational Plans (ROPs) (Table 2). Two tiers of operation management plans in place: one to deliver an overall operational perspective (the WRPs), and the second to define on-the-ground deployment of regulations for the consideration by water users (the ROPs).

Western Australia legislature has a similar three-tier structure: Water Acts, Water Management Plans and Surface Water Allocation Plans. In addition, Western Australia has 'environmental water provisions: monitoring and management' and 'reservoir simulations' that define further aspects of water management. These aspects are not directly targeting water usage for agriculture, urban or industrial usage. It is worth noting the Western Australia has six Water Acts differentiated by metropolitan vs. country water management; or waterway conservation. Western Australia intends to combine the six acts into one (Anon 2013 position paper).

Table 2. State/Territory-legislature enacting laws in relation to Water Resource Management within scope of the Northern Prawn Fishery. The summary of page numbers represents the size of the document, demonstrating that water management documents for some jurisdictions are more comprehensive than others.

State jurisdiction	***Western Australia***	***Northern Territory***	***Queensland***
Water Acts	YES Six Acts separated by geographic target and intent	YES (75p) 2016	YES (804p) 2000 (current 2015)
Water Resource Plans (or similar)	YES Ord River only (208p) No Kimberley rivers (unregulated rivers).	NO, 'Water Allocation Plans' for urban/rural centres Regulations (12p)	YES Cape WRP (multiple rivers) - under development Mitchell River WRP (56p) Gulf WRP (multiple rivers) (77p)
Resource Operation Plans (or similar)	YES Ord River (94p)	NO deficient	YES Mitchell River ROP (33p) Gulf ROP (multiple rivers) (55p)

The Northern Territory has a comprehensive Water Act, yet the regulation and management framework that deploys intent under the Act is poor. Primary industries are not mentioned in the Act. Northern Territory has Water Regulations that attempt to regulate water management under the Act. However, at 12 pages of text, they are scant compared to legislation in the states (with 50–200 pages of text). As described in later paragraphs, the management of impacts on environmental, fisheries and mining interests by water resource use in the Northern Territory is not stipulated in the regulations. Rather, they may be managed by an eight-person Water Resource Management panel that may or may not be appointed under the Act. The duties of this panel include aspects of environment and fisheries management as the panel members are selected with "relevant qualifications or experience in bore drilling, primary industry, secondary industry, Aboriginal affairs, public health, environmental management, fisheries and mining".

Queensland

Queensland has three levels of water management each of which is very comprehensive.

Water Act

The Queensland Water Act 2000 (current to 2015) establishes the legal framework under which surface water is managed in Queensland. The Act establishes the "allocation and sustainable management" of water and operates under the principle of ecologically sustainable development. It stipulates that decision making should integrate "long-term and short-term economic, environmental, social and equitable considerations". The Act does not mention fishing specifically, but does stipulate economic and environmental sustainability which cascades to the ecosystems and ecosystem services that sustain fisheries. The Act provides for compensation if allocated water is reduced in value or a change is made within 10 years of instigation of a WRP.

The Act stipulates environmental flow objectives and performance indicators for those objectives. The Act considers aesthetic, historical, scientific, social, and other considerations of significance, for past, present and future generations. Indigenous groups can 'take or interfere' with water for traditional activities or for cultural purposes (one reference to fishing). There were many instances of reference to overland flow (e.g. floodplain management or preventing water diversion) and riparian, but no reference to saltflat.

The Act exempts mining and petroleum activities from possible impacts of water extraction or harvest: e.g. the taking of overland flow is exempted (cross referenced to Environmental Protection Act 1994).

The Act was not read in detail – searches were undertaken on words such as environmental, indigenous, fish and fishing (one reference), floodplain, riparian, and saltflat.

Water Resource Plans

Queensland has a comprehensive array of Water Resource Plans (WRPs) often based on a single catchment (e.g. Mitchell River WRP) or series of adjacent similar catchments (e.g. Gulf WRP.) Three WRPs are relevant to the Gulf of Carpentaria catchments: the Mitchell River WRP, the Gulf WRP (southern catchments) and the Cape WRP (northern catchments — under development). The rivers included in each of the Queensland's WRPs are listed in Table 3.

As well, the Barron River WRP delivers water to the Walsh River that flows west to the Mitchell catchment. The Mitchell River WRP emphasises the Walsh River (one of the Mitchell Rivers major tributaries) as it is subject to inter-basin transfers from the Tinaroo Dam on the Barron River. The water supports the Mareeba Irrigation Area in the upper Walsh River catchment. Currently 250,000 ML of water are allocated for annual transfer from the Tinaroo Dam and about 160,000 ML are used to service about 17,000 ha of irrigated agriculture (SunWater representative, pers. comm.; August 2016).

The Mitchell River WRP specifically states that one of its "Outcomes for Sustainable Management of Water" (Chapter 3) is to "support commercial fishing in the Gulf of Carpentaria, including for example, by protecting floodflows that may deliver nutrients and water to estuarine and marine environments to stimulate growth and movement of native aquatic animals including fish, prawns and crabs" (Table 4). A second outcome is to "ensure water is available to support natural ecosystem processes".

A section on "General Ecological Outcomes for both Surface Water and Groundwater" stipulates outcomes that account for natural aspects of flow including: natural variability; connectivity; delivery of loads (nutrients, organic matter, sediment); water levels; permanence; wetlands. Specific ecological outcomes include maintenance of floodflows to estuarine and marine environments to stimulate breeding, growth and migration of native aquatic animals. Chapter 4 — Strategies for Achieving Outcomes — provides similar detail to support ecological services for downstream ecosystems.

The Gulf Rivers WRP has a similar structure and objectives at the Mitchell River WRP; Chapter 3 "Outcomes for Sustainable Management of Water" and Chapter 4 "Performance Indicators and Objectives for Surface Water". Consequently, repetition of detail will not be provided here.

The Cape WRP is currently under development and Andy Prendergast (Austral Fishing) is the NPF Industry representative as part of the consultation process. The Cape Rivers WRP encompasses river catchments on both the west coast and the east coast of Cape York; the east coast rivers being of no current consequence to the NPF.

Table 3. List of rivers covered by Water Resource Plans or their equivalent (NPF related).

State jurisdiction	*Western Australia*	*Northern Territory*	*Queensland*
Water Resource Plans	Ord River Enhanced flow now agreed by Government and stakeholders as 'environmental' flow	No rivers included Intention to remove exemption for mining from purvey of the Act	Cape WRP Jardine to Coleman Rivers, plus Cape York east coast catchments
	East Kimberley Rivers Not included	Water Allocation Plans for urban/rural centres	Mitchell River WRP Mitchell and Walsh rivers (Baron River inter-basin transfer)
	Other rivers are unregulated	Possible future development for NT rivers?	Gulf rivers WRP Nicholson to Gilbert Rivers

Resource Operations Plans

Using the Mitchell River ROP as an example, the ROPs include reference to the same management outcomes as the WRP; such as to "support commercial fishing in the Gulf of Carpentaria, including for example, by protecting floodflows that may deliver nutrients and water to estuarine and marine environments to stimulate growth and movement of native aquatic animals including fish, prawns and crabs". The management outcomes in the ROP address key ecological principles and processes demonstrating a sound knowledge-base of the ecosystem services in GOC catchments and coastal ecosystems. Specific "ROP Rules" address each objective (e.g. the support for commercial fishing is addressed by 'regulating the take of overland flow'). Likewise, the facilitation of natural flow variability and habitat connectivity has Operational Rules such as: data collection and assessment; and performance indicators for monitoring by the chief executive.

The management outcome to "maintain flood flows to the estuarine and marine environments of the Gulf of Carpentaria to stimulate breeding, growth and migration of native aquatic animals" has specific Rules: i.e. data collection and assessment; metering; performance indicators for monitoring by the chief executive. As suggested previously, the management outcomes in the ROP demonstrate a sound knowledge-base of the ecosystem services in GOC catchments and coastal ecosystems.

There is a single reference to water to support the growth of the mining industry in the Gulf ROPs.

Table 4. Key aspects of State/Territory legislature enacting laws in relation to Water Resource Management (NPF related).

State jurisdiction	***Western Australia***	***Northern Territory***	***Queensland***
Critical statements in Water Resource Plans or Surface Water Allocation Plans	Environmental flows; fishing and fisheries	NIL; 8 member panel with relevant expertise	Environmental flows; commercial fishing in the Gulf of Carpentaria
	Stock and population measures (size classes)	Recommendations to the minister	Overland flows; longstream connectivity
Defined triggers or criteria levels	YES	NO Recommendations to the minister (if a panel is in place)	YES
	Trigger levels	Continuous assessment	Flood levels Maintenance of overland flows
Key words	Environmental impacts/implications/ management; water-dependent ecosystems		Environmental management, estuarine, marine, growth, breeding, migration, fisheries, mining

Northern Territory

The Northern Territory legislation has a reasonably comprehensive Water Act that provides consideration of environment and cultural aspects in the development and use of water resources in the NT. The NT does not have significant operations plans such as (for example) the WRPs and ROPs that exist under Queensland legislation. The regulations that prescribe the implementation of the Act are very limited and focus on the mechanics of water extraction and harvest (they run to 12 pages of text relevant to all catchments). There are no management plans specific to each catchment that might take into account peculiarities of the catchment.

The NT legislature has not developed the equivalent implementation and operation plans that take a comprehensive approach to water management; plans that consider all aspects of flow such as downstream impacts. The concept of environmental flows that might sustain ecosystem services is not mentioned.

Water Act (2016)

The Northern Territory Water Act establishes the legal framework under which surface water and groundwater is managed in the NT. The Minister may declare a 'water allocation plan' that remains in force for a maximum of 10 years with a 5 year review. Water resource management in a 'water control district' occurs in accordance with the water allocation plan. The day to day management of water is under the auspice of the Controller of Water Resources. The act defines 'beneficial users', most of which are commercial users, but one type of user is the environment — with the provision to "provide water to maintain the health of aquatic ecosystems". A second user is cultural — to "provide water to meet aesthetic, recreational and cultural needs". The commercial users are industry — to "provide water for industry, including secondary industry and a mining or petroleum activity, and for other industry uses not referred to elsewhere in this subsection". It is possible that 'fishing industry' is implicit here, but it is not explicit.

The Northern Territory Water Act defines the 'environment' (i.e. the natural environment) and incorporates the sentences "to provide water to maintain the health of aquatic ecosystems"; and (under Section 22B — Water Allocation Plans) incorporates the combination of Clause 5a "water is allocated within the estimated sustainable yield to beneficial uses" and Clause 6 "an allocation under subsection (5) (a) is to include an allocation to the environment". The Act also considers environmental implications in relation to pollution and an 'environmental offence'.

However, the regulations under the NT Act do not mention the word 'environment' or 'aquatic' or 'habitat'. There is no explicit consideration of 'sustainable management" of water or overarching principles, such as ecologically sustainable development. There is no specific mention of 'fishing' in the NT Water Act or the implication that change or interruption to flow may impact fishing activities or have other downstream impacts such as upon fish movement. The word 'migration', as in downstream fish migration, is not mentioned in the NT Act. The regulations fail to provide a framework under which the allocation of water to ecosystem services can be made.

Under the NT Act, the Minister can appoint a Water Resources Review Panel to take a range of considerations including "by instrument in writing, appoint a group of 8 persons for the purposes of subsection (2) having respectively, in the Minister's opinion, relevant qualifications or experience in bore drilling, primary industry, secondary industry, Aboriginal affairs, public health, environmental management, fisheries and mining". This section of the Act seems to be the sole section considering and supporting downstream impacts and impacts from change in natural flow regime (Table 2).

A recent proposition in conjunction with Native Title in the NT in the allocation of a quanta of the 'commercial portion' of allocated water to a Strategic Indigenous Reserve (SIR). The SIR is designed to provide economic benefits to indigenous residents within a particular catchment from the use and trade in water (Jackson and Barber 2013). Water allocation to a SIR may encompass a significant portion of catchment runoff. In approximately 2009 and progressed thereafter, a SIR was proposed for the Roper River catchment as part of the 'Mataranka Plan' (water plan). However, in 2013 with a change of government, support for SIRs evaporated. In 2016, the NT Government changed political creed again; it is possible SIRs may be re-invigorated.

Water Resources Investigation

Under NT legislation, the Controller of Water Resources has a duty "to enable effective planning for water resource development and environmental protection". As practicable, the Controller shall ensure that a continuous program for the assessment of water resources of the Territory is carried out. To undertake the Controller's duty, the assessment will include the "investigation collection, collation and analysis of data concerning the occurrence, volume, flow, characteristics, quality, flood potential and use of water resources".

Stream-flow gauging and recording, water analyses, and cooperation with the Commonwealth will facilitate data collection.

Recently, the NT Government announced its intention to remove the exemption of Mining and Petroleum activities from assessment under the water act (Water Management on Mining and Petroleum Sites; Fact Sheet). Water management on Mining and Petroleum sites will come under the Act.

Water Regulations (2008)

The NT Water Act is complemented by a set of Water Regulations (2008) which specify the permits and licences and general rules under the legislation. The regulations are a short description of the mechanics of the legislation. The Regulations under the NT Water Act do not mention the words ‘environment’ or ‘aquatic’ or ‘habitat’. Likewise, the words ‘fishing’, ‘flow’, ‘environment’ or ‘mining’ are not mentioned in the Water Regulations. Unlike in other northern State legislatures, the NT regulations are not a comprehensive water management strategy such as the Queensland WRPs or ROPs (Table 3). The regulations fail to provide a legislated framework under which the allocation of water to ecosystem services can be made.

As part of the Commonwealth’s National Water Initiative 2004, the Northern Territory provided a commitment to allocate 80% of surface water and groundwater resources to environmental and other public benefit water provision. Extraction of water for consumptive use (e.g. irrigated agriculture) will not exceed 20% of a threshold level equivalent of river flow or groundwater recharge. The commitment of 80% of surface water to ‘environmental flows’ is direct support for coastal processes and ecosystem services that sustain estuarine and coastal fisheries. The commitment was documented as the ‘***Northern Territory Water Allocation Planning Framework***’ and is sometimes called the 80:20 rule (see https://denr.nt.gov.au/land-resource-management/water-resources/legislation-and-policy/water-management-principles).

In overview, WRD in the Northern Territory exists at a lower level of water extraction or impoundment, and infrastructure placement, than in either Western Australia or Queensland. No comparable WRPs exist in the Northern Territory. No large irrigation areas exist. Darwin River Reservoir supplies urban water requirements for Darwin City. Authorities look to Manton Dam and the Adelaide River catchment for future urban water supplies. Many towns in the Northern Territory use underground water supplies as their major water source (https://www.powerwater.com.au/networks_and_infrastructure/water_services/water_supply).

During the undertaking of this project additional information has come to hand. The Northern Territory has developed Water Allocation Plans (WAPs) that determine the on-ground management of water in the Northern Territory. The WAPs are legislative instruments similar to the Queensland WRPs and improve water management in the NT. To date, three plans have been declared and the fourth plan will be declared soon: Alice Springs, Berry Springs, Katherine (declared), and Western Davenport (vicinity of Tennant Creek) (see https://nt.gov.au/environment/water/water-control-districts). Currently the WAPs deal with urban/rural water allocation in the vicinity of NT townships. No similar management initiatives are being undertaken for any of the significant river catchments in the NT, but the emphasis on water management instruments at an operational level (a level below the Water Act) shows recognition by the NT Government of the need for action in this sphere.

Western Australia

Western Australia (WA) has six Water Management Acts, complemented by two tiers of operation management plans in place: one to deliver an overall operational perspective (Water Management Plans, WMPs), and the second to define on-the-ground deployment of regulations for the consideration by water users (Surface water Allocation Plans) (Table 2). The WA government website informs that water regulators are developing/enacting new legislation to draft a universal Water Act. It is not yet in place.

WA has a series of WMPs similar to the Queensland WRPs. The geographic coverage of these plans is limited to significant areas of current and likely water development. There are no plans for large sections of the remote north of the state, such as the Kimberley. The only WMP in a catchment adjacent to the NPF is the

Ord River WMP. Other management plans in the north include the Pilbara Regional Water Plan and the La Grange Groundwater Allocation Plan.

Water Acts (1914, 1976)

The Western Australian Act establishes the legal framework under which surface water and groundwater is managed in the Western Australia. WA has six acts that are relevant to Water Resources Management and associated regulations. Currently, WA is developing/enacting new legislation as a universal Water Act. But it is not yet in place. The WA Acts are established legislation; they have been in place since the 1970s and 1980s. The principal legislation is the "Rights in Water and Irrigation" (1914) which deals with access rights and supply. This old legislation makes no reference to words such as 'sustainability', 'environment', 'migration', 'overland', 'riparian' or 'fishing'; demonstrating that issues of sustainability and environmental flows to support ecosystem services were not considered in the early 1900s. Other Acts are specific to Metropolitan Water Supply and Country Water Supply.

In 2013, a position paper "Securing Western Australia's Water Future (reforming water resource management)" was released. It is a focus point for the redrafting of WA water legislation and updates the water management conversation with 21st century concepts. The position paper deals with 'environmental water' but make no mention of 'sustainability', 'fishing', 'overland flows' or 'riparian'. Interestingly, the position paper stated explicitly that precipitation in the south-west WA has reduced by 15% since the 1970s and that the subsequent runoff has declined much more by 75% (338 GL to 75 GL). The paper predicts a continued decline in precipitation by 2030. These changes are attributed to a drying climate.

The "Waterways Conservation Act" (1976) has reference to the 'interests of navigation, fisheries, agriculture, water supply, recreation and leisure-time occupation for the benefit of the public, the natural beauty and amenity of the area, and the preservation of public rights of access'. The Act has many references to environmental protection and the development of criteria to assess environmental change or pollution.

In WA, the WMPs and WAPs provide a much more robust consideration of environmental flows and water management that considers floodplain and downstream impacts unrelated to the direct consumption of the water.

Water Management Plans

The WA Water Acts are complemented by a series of WMPs. The geographic coverage of these plans is limited to significant areas of current and likely water development. The majority of southern rivers have WMPs in place. The WMPs provide key principles and approaches to the consideration of environmental flows and maintenance of ecosystem services

There are no WMPs for large sections of the remote north of the state, such as the Kimberley. The only WMP in a catchment adjacent to the NPF is the Ord River WMP. Other management plans in the north include the Pilbara Regional Water Plan and the La Grange Groundwater Allocation Plan.

The Ord River WMP incorporates water allocation from Lake Argyle to the Ord River Irrigation Area. Roughly 14,000 ha of land are irrigated in the Ord River basin under Ord River Stage 1. Currently, 13,400 ha of land is being developed under the Ord River Stage 2 initiative (Bennett and George, 2014; Raper *et al*. 2014). Ord River Stage 3 (Cockatoo Sands) is under consideration (~6,000 ha; Smolinski *et al*. 2015). Lake Argyle is a huge water storage (10,763 GL) and it has the potential to provide 750,000 ML of water annually to downstream irrigation (Ord River ~4,400,000 ML annual discharge) (Department of Water 2006; Anon. 2013). Historically, the Ord River Irrigation Area deployed inefficient irrigation infrastructure and over the last 40 years significant runoff downstream of the irrigated area due to leakage, as well as the release of water for hydroelectric power generation has occurred.

The Ord River WMP specifies the interplay between the "needs of the riverine environment of the lower Ord, and commercial water needs of irrigation and hydro-power generation, over the next three years". The Ord River WMP contains a subject chapter on Environmental Water Provisions; considering social water values (including aboriginal cultural values), native title issues. There is consideration of environmental flows in relation to RAMSAR wetlands in the Ord River estuary and adjacent supra-littoral habitat. In all likelihood, prime Banana Prawn habitat is found adjacent to RAMSAR wetlands in the Ord River estuary; so the maintenance of RAMSAR sites will support juvenile Banana Prawn habitat. The word 'exempt' does not occur in the Ord River WMP, indicating that no sector can override another sector and gain access precedence for water.

A significant focus for the Ord River WMP is the freshwater riverine habitats: "Maintaining sufficient in-stream habitat for invertebrates and fish during the dry season" was the primary factor used to establish environmental water provisions for the lower Ord River. This was achieved by limiting the change in measures of dry season in-stream habitat; the limit point being change considered of low ecological risk. Measures of instream habitat were determined over a range of flow regimes, including the flow rates considered typical of dry season conditions since the Ord River Dam was constructed (50–60 m^3 s^{-1})".

Since the Ord River Dam and hydroelectric power station was completed in 1972, dry season flows in the lower Ord River have increased significantly. These year-round elevated flows have now been accepted by the WA Department of Environment (and hence the WA State Government) as 'environmental flows'. The flows also are accepted by local stakeholders as 'environmental flows'; in some cases they are necessary for local economic activity (e.g. guided barramundi fishing charters on the lower Ord River and the estuary). The productive estuarine fishing locations are accessed from accommodation camps on the banks of the lower Ord River. The 40 year historical duration of these flows was a major factor influencing the collaborative decision to accept elevated flow as 'environmental' flow (including community consultation, Anon. 2013). Targeted releases from Lake Argyle may supplement the environmental flows when base flows from other catchments (e.g. Dunham River) are low. Under the Ord River Surface Water Allocation Plan, in years of drought the level of environmental flow can be reduced by 12 and 23% due to restrictions triggered by low water levels in Lake Argyle (Anon. 2013).

The runoff maintains significant perennial flows in the lower Ord River and its estuary. The remainder of rivers that flow into Cambridge Gulf are typical of the wet/dry tropical Australian Rivers and either cease to flow or have very low base flow by the mid-to-end of the annual dry season. Salinities in their estuaries range from 31 to 34 (Kenyon *et al*. 2004). The constant significant flows in the lower Ord River are very non-characteristic of river flows in the Australian tropics and they drive low salinity habitats in the Ord River estuary. Low salinity in the upper Ord River estuary (<2 salinity at low tide in the upper estuary, 23.5 in the lower estuary) precludes much the estuary as prime habitat for medium to large juvenile Banana Prawns as they cannot tolerate salinity as low as <5 ppt. During September to November when most estuaries support abundant juvenile prawn populations, Banana Prawns were scarce in the Ord River estuary due to low salinity (>250 juvenile prawns 100 m^{-2} in similar estuaries compared to nil prawns caught in the upper Ord River estuary and ~10 prawns 100 m^{-2} overall in the Ord River estuary). In the case of red-legged Banana Prawns, the low salinities in the Ord River estuary impede the capacity of the estuary to act as critical nursery habitat for Banana Prawns (Kenyon *et al*. 2004).

The Ord River WMP recognises that the salinity regime of the lower reaches of the Ord River has changed in the last 30 years, but notes that other estuaries in the Cambridge Gulf complex are in near natural condition and that these estuaries should sustain species and ecosystems in a condition similar to their existence prior to dam construction. During development of the Ord WMP, the community was consulted and when considering economic issues the aim of maintaining commercial fisheries was itemised. The stated objective was to "maintain opportunity and protect fish habitat".

Section 2.5.3 of the WMP addresses Cambridge Gulf and the interests of commercial fishing. Barramundi and prawn fishing were noted; as was use of port facilities in Wyndham. The description of the use of the Ord River estuary by juvenile Banana Prawns was poorly researched and contains inaccuracies. The words 'fishing', 'flows' (environmental provision), 'environment' and 'mining' (underground mining requiring electricity)' are mentioned often in the WMP.

Water Allocation Plans (surface water and ground water)

The post-dam consideration of environmental flows is reinforced by the Ord River Surface Water Allocation Plan (2012).

The Ord River Surface WAP provides the third tier of proscribed management of Ord River catchment waters. It considers fish and fishing but with a focus on freshwater fish or catadromous and anadromous fish that spend considerable time in freshwater habitats.

The Water Corporation's storage licence stipulates that the environmental water provision for baseflow and wet season flow targets are met via the release of enough water through the Ord River and Kununurra Diversion dams to meet flow targets. A dry season baseflow of 42 $m^3 s^{-1}$ is required from the Kununurra Diversion Dam downstream to House Roof Hill. Downstream from House Roof Hill to the tidal limit, the shape of the main channel changes and the required baseflow is 37 $m^3 s^{-1}$ (5 $m^3 s^{-1}$ lower than the upstream reach). The wet season baseflow ranges from 48 $m^3 s^{-1}$ to 57 $m^3 s^{-1}$. As for the WMP, the words 'fishing', 'flows' (environmental provision), 'environment' and 'mining' (underground mining requiring electricity)' are mentioned often in the WMP.

Commonwealth legislation

Given that the States/Territories hold water management and allocation rights Australia-wide, they can be disparate and inconsistent in the deployment of best practice management. From 2004 to 2014 the Commonwealth enacted the National Water Commission (NWC) and the National Water Initiative (NWI, initiated in 2004) to provide a framework for consistent, evidence-based water management across Australia. In 2014, the NWC was abolished and its duties taken over by the Productivity Commission which continues to implement the NWI.

The NWC developed a series of documents to define best-practice water management. Chapter three outlines the NWC's principles of Sustainable Water Management, including:

- Summary of impacts
- 3.1 Understanding water resources
- 3.2 Identifying environmental objectives and water regimes
- 3.3 Returning systems to sustainable levels of extraction
- 3.4 Recovery of water for the environment
- 3.5 Increased security of environmental water
- 3.6 Environmental water management
- Summary of findings

These objectives enhance the management of water to sustain ecosystem services Australia wide. Despite the abolition of the NWC, senior management in Queensland's regional DENR office in north Queensland continue to refer to Chapter 3 for guidance on water management to sustain the environment. Other NWC initiatives that may enhance environmental flows to the benefit of the NPF are indigenous access to water which may enhance end-of-system flows and enabling State/Territory legislation that supports NWC objectives.

Currently, the Australian Government has committed policy and funds to support future development of water infrastructure for irrigated agriculture across Australia, also with an emphasis on developing northern Australia (Commonwealth of Australia, 2015 and see: Office of Northern Australia, Department of Industry, Innovation and Science; http://northernaustralia.gov.au/). Co-funding initiatives are available to State and Territory Governments to develop water infrastructure via the National Water Infrastructure Development Fund (https://infrastructure.gov.au/infrastructure/water-infrastructure/nwi-development-fund/) and the National Water Infrastructure Loan Facility (https://infrastructure.gov.au/infrastructure/water-infrastructure/nwi-loan-facility/). Successful water infrastructure placement proposals are required to be assessed and approved in accordance with Commonwealth and State/Territory environment assessments which will consider the impacts of proposed water diversion or impoundment on catchment and downstream ecosystems, communities and species.

Summary

Catchment-scale water resource management plans exist in Western Australia and Queensland, but not in the Northern Territory. Within the State's and Territory's legislative frame work, the opportunity exists for all stakeholders to have input to the development or modification of WRPs (or their equivalent). Currently, NPF Industry is engaged in the development of the Cape Rivers WRP in Queensland. Stakeholder engagement allows fishery managers to incorporate fishery-important information into the development of water resource management protocols, to provide least-impact water management strategies that service both the demand for water for irrigation purposes and the provision of environmental flows to sustain the yields of downstream fisheries.

It is likely that WRPs will be modified or adopted for major tropical river catchments in the coming years. The Commonwealth Government focus on developing northern Australia (see Commonwealth of Australia 2015) specifies several major river catchments with potential soil and water resources that can support irrigated agriculture if appropriate water storage and harvest infrastructure is provided within the catchments. In addition, the Commonwealth is funding major projects to estimate and scope the use of these soil and water resources (see CSIRO 2016 a,b,c). As has occurred for the Flinders and Gilbert Rivers, review of the water resources of these catchments will identify unallocated water resources with the potential for development to sustain irrigated agriculture (see Petheram *et al*. 2013 a,b). In each case, current WRPs for catchments identified as having water resource development capacity will be reviewed and modified to reflect the knowledge-outcomes from water assessment projects such as the Flinders and Gilbert Agricultural Resource Assessment (FGARA). In the case of the Northern Territory, the Northern Australia Water Resource Assessment (NAWRA, see CSIRO 2016 a) might instigate the development of WRPs for major NT river catchments.

NAWRA outcomes will be used to inform stakeholders of a suite of information about the potential of Australian tropical savannahs for irrigated agriculture, and the likely impacts within each catchment. In each case of active development or modification of WRPs, NPF management should engage the managers of the water resource development process as a stakeholder. NPF inputs should be cutting edge, to provide best-knowledge to the water management specification development to facilitate least impact on flow-dependent downstream fishery production.

2. Web-accessible map portal displaying Water Resource Development which may impact the Northern Prawn Fishery

We developed a web-accessible map portal that displays the location and scope of significant projects or infrastructure that incorporate or require Water Resource Development (WRD) for their construction or ongoing operation (Figure 1, and see https://research.csiro.au/npfnwd/). In many cases this WRD may impact the NPF. Not all infrastructure placement will impact the NPF. The portal provides links to websites that describe the projects or infrastructure; and links to government websites that provide regulatory provisions or other legislative oversight pertaining to the project (Figure 2).

River flow is crucial in the life cycle of a suite of estuarine and marine species important in commercial, recreational and Indigenous fisheries in northern Australia. The species include highly valuable commercial species and iconic recreational and Indigenous target species – Banana Prawns, Barramundi, Mud Crabs, Threadfin Salmon and Grunter (Barred Javelin).

Interannual and seasonal cycles of flood flows and low-flow sustain both the integrity of species' lifecycles and the integrity of habitats on which they depend. Iconic species, such as sawfish, as well as supra-littoral and coastal habitats, such as salt flats, also depend on river flows. These species and habitats have conservation and cultural value in addition to economic significance.

Currently, Australia's northern rivers support substantial economic and social value. More broadly water is a valuable commodity in other sectors. Irrigated agriculture and water development infrastructure have policy and budgetary commitments within substantive government initiatives to develop northern Australia.

This is exemplified by the recent report, "Our North, our Future: White paper on developing Northern Australia" (Commonwealth of Australia 2015), as well as other white papers, green papers, policy outputs and water plans by State, Territory and Federal governments. Government initiatives are complemented by investment proposals by private industry.

It is difficult to develop an appreciation of the extent of WRD plans, or to readily access detail, as there is no single listing, or collation that summarises facilities or infrastructure. A current NPF high priority Research Area is to "Develop an understanding of ecological and economic trade-offs of the impact of existing and proposed water resource development in Northern Australia"; underpinning the need to understand the number, type and extent of WRD initiatives. As a first step in addressing this priority, this desktop research has reviewed information, collated relevant summaries and mapped the water developments likely to be of interest to northern Australia's fisheries, principally the Northern Prawn Fishery. The project summary and infrastructure listings are presented in the 'Proposed North Australian Water Developments' portal (Figure 1).

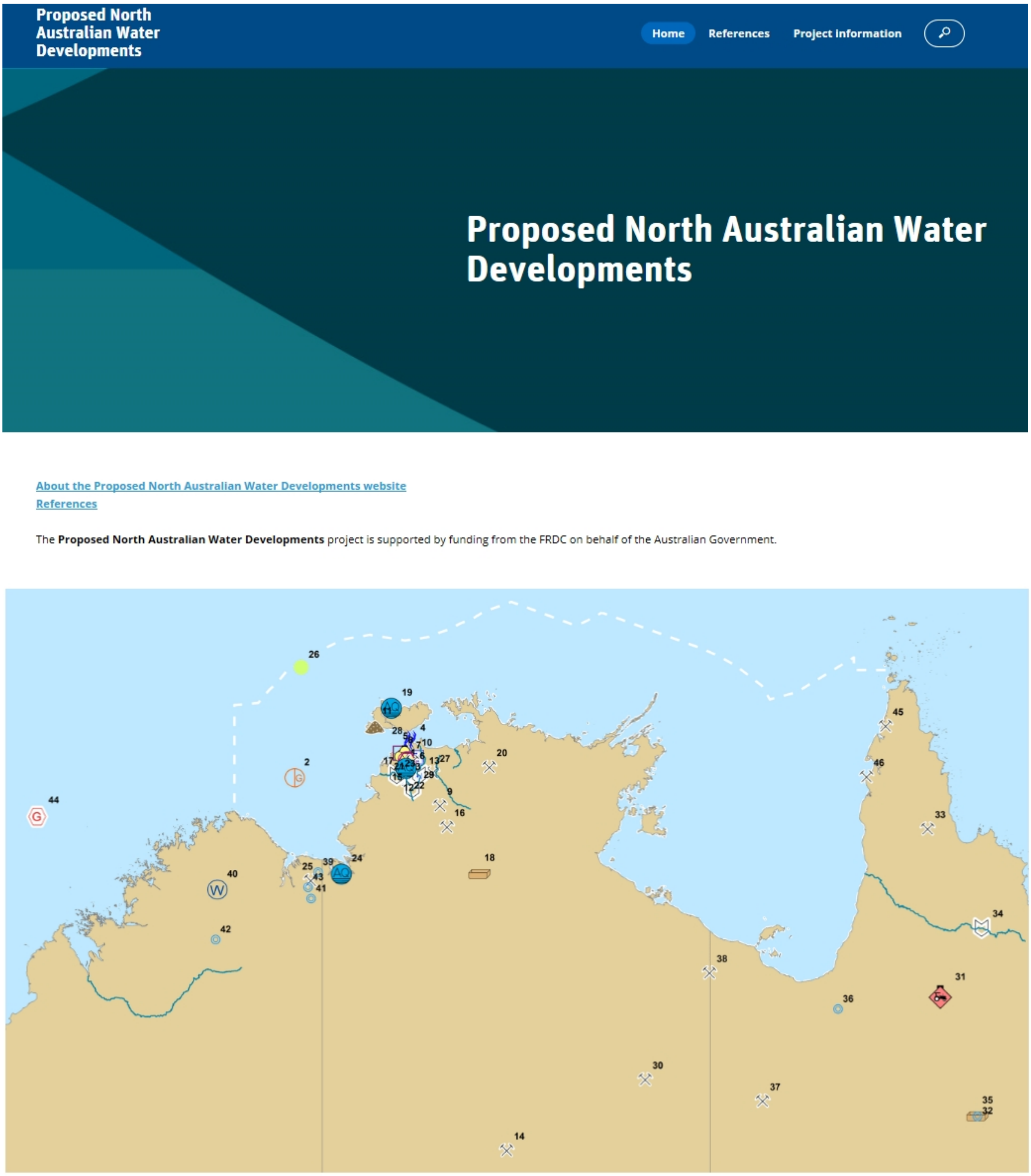

Figure 1. Portal display of proposed northern Australian water developments as captured/examined by this project (https://research.csiro.au/npfnwd/).

No	Project	Status	Latitude	Longitude	Accuracy	Type	Link
	Northern Territory						
1	Blackmore River Aquaculture Project Phelps/Panniza Holding	in construction	-12.757307	130.945262	within 20 km	Aquaculture	Link
2	Bonaparte floating LNG project	On hold status uncertain	-12.972505	128.367355	not exact	LNG	Link
3	Browns Sulphide project (expansion of Browns Oxide project) Compass Resources	On hold status uncertain	-12.995218	130.99318	exact	Mining	Link
4	Clarence Strait Tidal Energy Project	Notice of intent	-12.069396	131.045073	within 5 km	Tidal energy	Link
5	Condensate Processing Facility East Arm Darwin	On hold	-12.479436	130.913867	within 5 km	Petroleum processing	Link
6	Cosmo Deep Gold Mine	Possibly producing	-12.582295	131.094599	within 1 km	Mining	Link
7	Darwin Refinery TNG Limited	Notice of intent	-12.560844	130.971667	within 5 km	Oil	Link
8	East Point Outfall Project	Notice of intent	-12.401142	130.815471	within 1 km	Sewage Outfall	Link
9	Frances Creek Elizabeth Marion Area Mining	EIS prep	-13.614	131.734		Mining	Link
10	Howard East Borefield upgrade	planned	-12.503	131.133		Water supply	Link
11	Kilimiraka Mineral Sands Project	Notice of intent	-11.797491	130.217094	within 1 km	Sand mining	Link
12	Manton Dam return to service	planned	-12.858	131.121		Water supply	Link
13	Marrakai Dam	proposed	-12.913	131.24		Dam	Link
14	Mount Peake Mine	EOI prep	-21.63	133.283		Mining	Link
15	Mt Grace Batchelor Magnesium mine Mt Grace Resources NL	On hold	-13.048541	131.029998	within 10 km	Mining	Link
	Queensland						
31	Etheridge Integrated Agricultural Project (Gilbert River)	planned/in progress	-18.08	143.336		Agri-processing facility	Link
32	Flinders River Agricultural Precinct	CSIRO report	-20.85	144.2	not exact	Irrigation	Link
33	Minyango Coal Deposit Mining Project	feasibility study	-14.150394	143.044291	within 5 km	Mining	Link
34	Mitchell River Pinnacles Dam	unlikely	-16.469	144.292		Dam	Link
35	Off-stream storage in the Flinders River catchment	CSIRO report	-20.85	144.2	not exact	Storage	Link
36	Three Rivers Irrigation Project	planned/in progress	-18.354	140.969		Irrigation	Link
37	Valhalla Uranium Deposit	On hold	-20.482932	139.217935	within 10 km	Mining	Link
38	Westmore Uranium Deposit Laramide Ltd	Test drilling	-17.501283	137.984829	within 50 km	Mining	Link
45	Skardon River Bauxite Project	EIS prepared	-11.758981	142.070245	exact	Mining	Link
46	Amrun Mining Expansion, Bauxite Mine	EIS prepared	-12.939418	141.628714	within 20 km	Mining	Link
	Western Australia						
39	Bonaparte Plains – Ord East Kimberley Expansion – Water for Food	planned	-15.1674	128.907		Irrigation	Link
40	Bringing water from the Kimberley to Perth	unlikely	-15.572	126.57	not exact	Water transport	Link
41	Expansion of the Ord River irrigation scheme Stage 2	planned	-15.782882	128.743932		Irrigation	Link
42	Kimberley irrigated water pipeline system	white-paper option	-16.737	126.531	not exact	Irrigation	Link
43	Ord Irrigation Stage 3 – Cockatoo Sands	proposed	-15.52	128.675		Irrigation	Link
44	Shell Prelude FLNG	in construction	-13.876257	122.39294	within 50 km	Mobile gas platform	Link

Figure 2. Snapshot of tabulated data displayed via the Proposed Northern Australia Water Developments (PNAWD) portal. The tabulated data shows the project, its completion status (e.g. concept, feasibility study, in construction), its location (latitude, longitude), the type of infrastructure (e.g. an instream dam, or off-stream storage), and providing a link to third-party websites that describe the proposal, or a link to a government review-process of the water resource development project.

As well, the portal provides the location and scope of major research projects that provide key research outcomes and summary information of investigations to understand impacts of the infrastructure and activity on in-situ physical and biological systems (Figure 3).

To achieve this objective we undertook both web-based searches and person to person telephone calls with State- and Territory-based WRD managers in each of Western Australia, Northern Territory and Queensland. Our web-based searches have determined possible infrastructure, agricultural and mining construction and operation initiatives in northern Australia. Person-to-person discussions have accumulated regional-level information on Water Resource Developments in northern Australia.

To complement the data acquisition, we have undertaken data management tasks relative to data categorisation and storage.

Figure 3. Snapshot of the location of projects that have provided (Flinders and Gilbert Agricultural Resource Assessment) and will provide (Northern Australia Water Resource Assessment and Northern Ecosystem Science Project) significant information about the impacts of water resource development on catchments and estuaries with scope of the Northern Prawn Fishery.

Queensland

In-person data gathering (and web-search follow-up).

In particular, we spoke to Mr. Patrick Huber and Mr. Peter Siemsen (A/Manager) - Water Planning; Water Services, Natural Resources – North region; Department of Natural Resources and Mines, Queensland.

Currently, the Cape York Rivers WRP is still under development. A 'Statement of Proposals' commencing a water resource planning process' was issued in May 2016 (see www.dnrm.qld.gov.au). The Cape York WRP will be developed under the amendments of the Water Act (2000) through the Water Reform and Other Legislation Amendment Act 2014 (legislated 26 Nov 2014). The process contains a context for major issues to be addressed and a framework to shape the Plan from the State of Queensland.

Currently, the Gulf Rivers WRP is being amended and in May 2013 a tender process for 80,000 ML of un-allocated water was put in place. It is anticipated that, under the revised Gulf Rivers WRP, more un-allocated water will be released to tender following the Flinders Gilbert Agricultural Resource Assessment (FGARA) analyses and report by CSIRO (Petheram *et al*. 2013a,b). Further un-allocated water will be released under a tender process and assessment of proposals. A water budget for environmental flows will be maintained.

In the last 5 years, there have been applications made for significant irrigated agriculture projects on Cape York and in the Gulf Savannah (one has lapsed).

Three Rivers Irrigation Project

The Three Rivers Irrigation Project is being developed by the Stanbroke Pastoral Company (NAWD portal - project #36). The project scope is to develop a 15,000 ha irrigated cropping land for cotton, sourcing water from the lower Flinders River (total project area 20,422 ha). The project is located on Stanbroke's Glenore Station (234,000 ha) approximately 100 km south of Normanton and within about 100 km of the Gulf of Carpentaria coast. The capital investment in the irrigation project is >$200 M. The Project is within the scope of the Gulf Rivers WRP and the Carpentaria and Croydon Shire Councils. In May 2013, a tender process for 80,000 ML of revised-unallocated water resulted in Stanbroke acquiring 28,800 ML of water (Anon 2015). The Three Rivers Irrigation Project has been designated a Project of State Significance. As such, it is not subject to the current moratorium of the uptake of water licences for irrigation purposes. Stanbroke anticipates that, under the revised Gulf Rivers WRP, more un-allocated water will be released to tender which will supplement their needs for the Three Rivers Irrigation Project.

As of September 2017, an Environmental Impact Statement (EIS) is being prepared and will be available on the Queensland Coordinator Generals web site (see Terms of Reference at https://www.statedevelopment.qld.gov.au/). The Terms of reference were set on 8th October 2015. On the 6th April 2017 the Coordinator-General stated a new project declaration lapse date of 6th April 2018.

The Three Rivers proposed cropland irrigation plans to extract ~150,000 ML anum^{-1} from the lower Flinders River by a possible diversion structure or weir. Water will be stored in tank-dams with a combined capacity of 150,000 ML (see: https://www.statedevelopment.qld.gov.au/resources/project/three-rivers-irrigation-project/three-rivers-irrigation-project-ias.pdf). Currently, no final EIS exists and the proponent relies on CSIRO's Flinders Gilbert Agricultural Research Assessment (FGARA) analyses to predict the impact of water extraction on flows. Stanbroke Pastoral suggests that the reduction of median rivers flows (end-of-stream) would be at most 28% of median flow (Anon. 2015). They quote the CSIRO's FGARA analyses on the likely reduction in barramundi and prawn catch in response to 212 and 532 GL of water extraction from the combined flows of the Flinders and Gilbert Rivers, to justify a small impact on coastal fisheries from their irrigated croplands (<4%) (Bayliss *et al*. 2014). The water will be drawn from the river during monsoon flood events to minimise impacts on natural floodflows at other times of the year. Partial flood diversion during high flows may have little impact on aspects of flow and riverine connectivity. However, a weir of the lower Flinders River would impact natural low-flows and may reduce the baseflow and early-season low-flow contribution of freshwater inputs to the estuarine brackish ecotone, with subsequent impacts on estuarine habitats for key commercial species. As well, a weir so low down in the riverine reaches would impact the long-river connectivity for species such as Barramundi, Mullet, Freshwater Sawfish and Freshwater Whiprays.

Etheridge Integrated Agricultural Project

The Etheridge Integrated Agricultural Project (EIAP) was a large scale irrigated farm and integrated agri-processing facilities 78 kms west of Georgetown, southern Cape York. The project proponent was Integrated Food and Energy Developments Pty Ltd (IFED), a private company with the specific purpose of developing, financing and constructing large scale agricultural projects in northern Australia. The proposal included 65,000 hectares of irrigated cropping and the use of crop-trash as cattle feed. The capital investment in the irrigation project was $2 Billion.

Water for crop irrigation was to be flood harvested from the Einasleigh and Etheridge rivers and diverted into two specially constructed off-stream storages with a combined capacity of 1.6 million ML. The off-stream storages were planned to contain four (4) years irrigation capacity. The project proponent planned to harvest the peak floods only, enabling minor and low floods to pass by the offtake point. It planned to achieve this by cutting a benched offtake in a gorge upstream of the irrigated lands and channel water to its land holding. IFED proposed that a small proportion at 8.8% (550,000 ML) of the average annual discharge of water from the Gilbert River catchment would be harvested. The water would be taken from large floods only. The inconsistency of this plan was that series of years with low floodflows can extent to 5–7 years in the Gilbert River catchment which would mean the IFED water storage (4 year capacity) would fail during these dry year series. In addition, while the diversion of annual water discharge was equivalent to < 10% of the Gilbert River's average annual discharge, the average diversion of mean annual flow from the Einasleigh and Etheridge rivers was significantly higher (~ 30% and 40%, respectively).

The Coordinator General set the terms of reference for the EIS for the IFED project on 4th March 2014. On the 25th August 2015 the Coordinator-General stated a new project declaration lapse date of 5th September 2016. The EIS was not submitted and the 'coordinated project' declaration lapsed on the 5th September 2016. Currently there is no ongoing publically-known interest in the proposed development. Mr. Patrick Huber (Water planning, Queensland) suggested that there was considerable interest in the un-allocated water in the Gilbert River catchment that was previously within scope of the IFED proposal.

It is worth noting that two employment positions for project management for irrigation development in each of the Tablelands Regional Council (Mareeba) and the Etheridge Shire Council (Georgetown) were advertised in early 2017; perhaps reflecting future demand.

Other projects impacting Water Resource Development

Two new mines are in the process of development on northern Cape York in the vicinity of Weipa: the Metro Mining Bauxite Hill Mine in the vicinity of the Skardon River; and the Amrun Mine to the south-west of the Embley/Hey Rivers. This is in addition to the current Rio Tinto Mine, serviced by the town of Weipa.

The Metro Mining Mine is in the vicinity of Mapoon on the Wenlock River (http://www.metromining.com.au/resources-projects-mines/bauxite-hills-mine/environmental-impact-statement/) and in the past has been referred to as the Skardon River bauxite mine. The mine is within the catchment of the Skardon River with a barge landing on a tributary of the river. The mine proposes to extract an estimated 390 ML of water per annum (maximum) from groundwater sources rather than overland floodwater. Consequently, Metro Mining has suggested that the mine should have little impact on overland and river floodflows. The extraction of groundwater by the mine may have an impact on river baseflow; particularly during the last third of the dry-season.

The Amrun Mine to the south-west of the Embley/Hey Rivers is an expansion of the Rio Tinto bauxite mine footprint at Weipa. Initially, it was referred to as the South Weipa mine. Similar to the Metro Mine, the Amrun Mine proposes to source most of its water needs from groundwater (12 artesian bores), although there is provision of a small dam on a tributary of the Norman Creek in the northern section of the mining lease, and pumped water from the Ward River in the south.

The Amrun Mine project's water requirements range from 16 gigalitres (GL yr^{-1}) at 15 million dry product tonnes per annum (MDPTA) to 64 GL yr^{-1} at 50 MDPTA (http://www.riotinto.com/australia/environmental-impact-statement-16114.aspx). Water conservation and reuse would be deployed and used preferentially as process water: recycled from the tailings storage facilities and the mine infrastructure area. In order of preference, water would be drawn from tailings storage facilities, the mine infrastructure areas, the Norman River water supply dam, and lastly the 12 artesian bores. Supplementary water would be drawn from the Ward River (pumped).

Information published in the project's EIS suggests that the water supply dam would reduce the average annual flow in the tributary immediately downstream of the dam by 12–50%, depending on ore production rate. However, over the Norman Creek catchment, the overall decline in flow (maximum of 15%) is 'well within the normal range of river flow'. The Norman Creek is a small river that flows west to the GOC in the vicinity of Boyd Point–Thud Point.

The EIS informs that currently Rio Tinto Alcan Weipa extracts up to 9 GL per yr^{-1} of artesian groundwater under an existing water licence. Rio Tinto Alcan intends to apply to increase the allocation to a five year moving average of 12 GL per yr^{-1} with a peak extraction of 15 GL in any one year. Importantly, from an environmental sustainability viewpoint, the water supply dam on the tributary of Norman Creek/ River would be fitted with an outlet to facilitate the release of environmental flows and the spillway will be designed to allow fish passage when overflowing.

The annual volume of water pumped from the Ward River would be capped at 1% of average annual flow and the rate of pumping would be less than 20% of river flow rate at any time including low-flow periods. This scenario suggests that during the dry season, little water could be used from the Ward River; perhaps coinciding with periods of significant water demand and limited supply from the other sources? The Ward River flows south through the mining lease and enters an estuary in the vicinity of Aurukun, Cape York.

Currently, water resource development to support irrigated agriculture within the mid-to-lower Mitchell River catchment is not prominent. There is significant historical irrigated agricultural development currently deployed in the Walsh River catchment; an upper tributary of the Mitchell River. This area is the Atherton Tablelands which is managed under the Mitchell River WRP as it diverts water from the Barron River (an inter-basin transfer) to irrigate these fertile lands. Currently, the Mitchell River catchment is being studied under the auspice of the Northern Australian Water Resource Assessment which is assessing the topography, soil types and water resources of the catchment. The aim of NAWRA is to describe the potential of the currently-mostly-grazed-lands majority of the Mitchell River catchment to support irrigated agriculture and ancillary industries. There is an expectation that the catchment will be re-evaluated for agricultural development following the release of the NAWRA reports in ~2019. Presumably, un-allocated water resources will be allocated to potential irrigated land developments to facilitate their establishment.

Historical interest in irrigated lands in the Kendall River/Arukun River area exists. Currently, water licences in this region are under a moratorium pending the finalisation of the Cape Rivers WRP. In 2015, Kendall River Station owners submitted an application to clear 7800 ha of land for forage production to the Queensland Government. It was rejected. The Cape Rivers WRP encompass the intensive, irrigated banana plantations in the Lakeland Downs area in the central Cape York region. The water used on Lakeland Downs is drawn from the Normanby Rivers and tributaries of the eastern Cape catchments (flowing into Princess Charlotte Bay). As these rivers are eastward flowing, they will have no impact on NPF catchments and flows. Dry land agriculture growing other crops also occurs in the Lakeland area, together with dry land agriculture in the Archer and Leannie Rivers (the Archer being a westward flowing river). There is interest in the construction of privately-funded dams on the Laura River or its tributaries, and the upper Normanby River, to facilitate water extraction for irrigated agriculture.

The Flinders River Agricultural Precinct (http://www.frap.org.au/water/) is an Industry initiative to provide baseline information to promote agricultural development in the Flinders River and nearby catchments. The website informs that the Queensland Department of Natural Resources and Mines has recently released water under a tender process (see below).

"Friday, 28th April 2017

DNRM has now released the Tender Assessment Report to the public.
92,500 ML has been allocated in the Flinders River catchment.
2,500 ML has been allocated in the Gregory River sub-catchment.
5,000 ML has been allocated in the Lower Leichardt sub-catchment."

Information on the Lakeland Region agriculture precinct is available from the 'Cape York Sustainable Futures' website (https://www.capeyorknrm.com.au/organisation/1293) and the GULF Natural Resources Management Group (https://www.capeyorknrm.com.au/home).

Table 5. Queensland agricultural, mining and other developments that use water resources and may impact downstream species and ecosystems (numbered sequence reflects the map portal list; see https://research.csiro.au/npfnwd/)

#	PROJECT	SPECIES/CRITICAL HABITAT	POTENTIAL IMPACTS	THREATS/ BENEFITS	CUMULATIVE IMPACTS	ECOLOGICAL INTERACTION	NON-FISHERY STAKEHOLDER
31	Etheridge Integrated Agriculture (lapsed)	Estuarine Banana Prawns	Reduced baseflow and emigration cue	Reduction in optimal ecotone and flood-cued catch	Sequential years of flow modification	Reduced fluvial loads, nutrient transport, floodplume dump	Fisheries focussing on catadromous fish species
32	Flinders River Agricultural Precinct	Estuarine Banana Prawns	Reduced baseflow and emigration cue	Reduction in optimal ecotone and flood-cued catch	Sequential years of flow modification	Reduced fluvial loads, nutrient transport, floodplume dump	Fisheries focussing on catadromous fish species
33	Minyago Coal Mining Project	na	na	na	na	na	Inland mine
34	Mitchell River Pinnacles Dam	Estuarine Banana Prawns	Reduced baseflow and emigration cue	Reduction in optimal ecotone and flood-cued catch	Sequential years of flow modification	Reduced fluvial loads, nutrient transport, floodplume dump	Fisheries focussing on catadromous fish species
34	Mitchell River Pinnacles Dam, with hydroelectric power station	Estuarine Banana Prawns	Elevated baseflow and reduced emigration cue	Loss of estuarine habitat extent/ Reduction in flood-cued catch	Destruction of estuarine habitat / Sequential years of flow modification	Freshwater estuary / reduced fluvial loads, floodplume dump	Fisheries with euryhaline estuarine juvenile phase
35	Flinders River off-stream storage	Estuarine Banana Prawns	Reduced baseflow and emigration cue	Reduction in optimal ecotone and flood-cued catch	Sequential years of flow modification	Reduced fluvial loads, nutrient transport, floodplume dump	Fisheries focussing on catadromous fish species
36	Three Rivers Irrigation Project	Estuarine Banana Prawns	Reduced baseflow and emigration cue	Reduction in optimal ecotone and flood-cued catch	Sequential years of flow modification	Reduced fluvial loads, nutrient transport, floodplume dump	Fisheries focussing on catadromous fish species

37	Valhalla uranium Deposit	na	na	na	na	na	Inland mine
38	Westmore uranium deposit	na	na	na	na	na	Proposed mine in NPF catchment
45	Metro Mining Skardon River	Estuarine Banana Prawns	Reduced baseflow due to groundwater reduction	Reduction in optimal estuarine ecotone	Sequential years of flow modification	Juvenile prawn growth and survival	Barramundi and mudcrab fisheries
46	Amrun Mine Weipa	Estuarine Banana Prawns	Reduced baseflow due to groundwater reduction	Reduction in optimal estuarine ecotone	Sequential years of flow modification	Juvenile prawn growth and survival	Barramundi and mudcrab fisheries

Summary – Queensland water resource development in focus

Currently, the Three Rivers Irrigation Project (Flinders River), the Metro Mining (Skardon River) and Amrun Mines (west of Embley River) are the projects of focus in Queensland. These enterprises are either in-development or in the process of Environmental Assessment.

Research initiatives have scoped potential WRD in tropical Queensland catchments and some scenarios provided reliable water supply in >70–80% of years (Petheram *et al*. 2013 a,b)). These 'water capture and storage options' provide an indication of likely future water resource development.

CSIRO's FGARA assessment identified offstream storage (350 GL potential, delivering 175 GL pa) as an optimum method for water storage in the Flinders River catchment (Petheram *et al*. 2013a) and this is reflected by the commercial investment in the Three River Irrigation Project. In-stream dams were identified as capable of delivering a combined 80 GL of water for irrigation. The total water storage capacity could support 10,000–20,000 ha of irrigation in 70–80% of years. The FGARA assessment also identified two sites in the Gilbert River catchment for in-steam dams of approximately 500 GL and 220 GL delivering ~320 and 170 GL of water at 85% reliability (Petheram *et al*. 2013b). The water could support 20,000–30,000 ha of irrigation in 85% of years.

The current NAWRA project (CSIRO 2016c) is assessing the potential of the Mitchell River catchment to support irrigated agriculture. The project has not delivered a final report, however, it has delivered 'Methods Reports'. Three locations in the Mitchell River catchment have been identified as capable of storing >1000 GL of water for irrigation use. A component of the large in-stream storage development may be an assessment of the capacity to generate hydroelectric power from the storage. Hydro-power requires a constant flow of water to drive the turbines. As occurred in the Ord River estuary, it is highly likely that elevated downstream flows and a freshwater estuary result from hydroelectric power generation (see Kenyon *et al*. 2004; Pusey *et al*. 2011). If hydroelectric power generation eventuated, a significant longstream extent of Banana Prawn habitat in the Mitchell River estuary may be lost (Kenyon *et al*. 2004). As well, the Mitchell River catchment assessment will scope possible aquaculture development associated with irrigation infrastructure or coastal water resources. Currently, these are only prospective accounts, but point to a catchment where future WRD is likely.

Northern Territory

In-person data gathering.

We spoke to Mr. Des Yin Foo, Director - Water Assessment, to summarise publically available knowledge on current and potential water resource development in the Northern Territory (Water Resources, Northern Territory, Environment and Natural Resources (DENR) (08-8999-3615). We also spoke to Ms. Mardi Miles (Senior Planner) from NT Environment and Natural Resources.

An overview of future options for Darwin's water supply was documented by the Northern Territory Power and Water Corporation (PWC) in 2013 (Power and Water Corporation 2013). The Power and Water Corporation (a Government Owned Corporation under the Government Owned Corporations Act 2001 (NT) ('GOC Act')) has initiated discussions with DENR to submit an application to create an offstream storage facility in the mid-catchment floodplain of the Adelaide River. The off-stream storage goes by the acronym AROWS (Adelaide River Off-stream Water Storage). The reason for construction of the off-stream storage is to supply water to Darwin's future urban demand. Via AROWS, PWC would extract water from the Adelaide River during wet-season floodflows and from remnant baseflows during a portion of the dry-season. Initial perceptions of the proposal were that only high-flows would be harvested; but extraction from the declining hydrograph at the end of the wet-season would also be targeted. A bench-mark cut-off flow level below which flows would not be harvested has not been established. The site of the offstream storage is unknown to this report, but a natural landscape formation exists that can be dammed for use as an artificial storage that does not impede the natural channel of the Adelaide River. Management of natural flows would be facilitated by offstream storage as low-flows and key baseflows are easily maintained as barriers are not constructed within the river.

Historically, PWC has had an interest in building a significant dam on the upper Adelaide River (the Warrai Dam). The dam construction has been promoted since the 1980's, yet it has not eventuated to date. Construction cost, environmental approval and agreement by indigenous communities are hurdles that need to be bridged to achieve an outcome for this proposal. The current Commonwealth Government is aware of the potential of the Warrai Dam site for water resource development (CSIRO 2009).

The Power and Water Corporation delivers the water to users and they have in place a 'Water Use Management Program' with the aim of reducing water use and hence demand on new water supply in the Northern Territory.

The Manton Dam is not in-service for supplying water to Darwin and considerable cost would be incurred to upgrade it to serviceability.

Another major project discussed as in-train, with the potential to impact water resources and natural flows, was the Sea Dragon Aquaculture project. The environmental impact of Sea Dragon is described in a subsequent section. During discussions with Water Assessment, DENR, it was noted that Project Sea Dragon has received 'major project status' by the Northern Territory Government. It was noted that Sea Dragon has three footprints in the Northern Territory: Keep River, Bynoe Harbour and Gunn Point. Keep River is the major point of impact to water resources due to the extent of the grow-out ponds. The other two locations house hatchery and broodstock facilities, each with a smaller footprint.

Mr. Yin Foo also mentioned current groundwater drilling in the Cockatoo Sands basin in the west Victoria River region of the Northern Territory. He noted that the Cockatoo Sands hold groundwater and that the groundwater has been recognised as a significant water resource that may facilitate irrigation. He contrasted the groundwater potential of Cockatoo Sands with the nearby Keep River black soils plains and highlighted that no groundwater resources existed below these soils and that they were to be irrigated from Lake Argyle in Western Australia. To date, no assessment or understanding of the scope or impact of water extraction of Cockatoo Sands groundwater is available.

Overview discussions with both Mr. Yin Foo and Ms. Miles provided useful information. There was agreement that the Northern Territory did not have well-developed water resource operation plans to underpin the NT Water Act. This aspect of NT legislation was identified elsewhere in this report (and for contrast of information content, compared with the Water Resource Plans of Queensland). However, currently Water Allocation Plans (WAPs) are being developed for the Northern Territory. Three plans have been declared and the fourth plan will be declared as soon as possible: Alice Springs, Berry Springs, Katherine (3 declared), and Western Davenport (vicinity of Tennant Creek) (see https://nt.gov.au/environment/water/water-control-districts). The WAPs are statutory documents signed by the Minister.

The Northern Territory has committed to allocate 80% of surface water and groundwater resources to environmental and other public benefit water provision. Extraction for consumptive use will not exceed 20% of a threshold level equivalent of river flow or groundwater recharge. This commitment is direct support for environmental flows that support coastal processes and ecosystem services. The commitment was given as part of the National Water Initiative 2004 (see Commonwealth of Australia 2014). The commitment was documented as the '***Northern Territory Water Allocation Planning Framework***' and is sometimes called the 80:20 rule. (see https://denr.nt.gov.au/land-resource-management/water-resources/legislation-and-policy/water-management-principles, and https://denr.nt.gov.au/__data/assets/pdf_file/0006/396717/Water-Allocation-Framework.pdf). The 80:20 rule was well understood by Fisheries Division, Northern Territory Department of Primary Industry and Resources (discussions with Dr. Thor Saunders, Fisheries Research).

Currently, soil profile and fertility assessment and groundwater assessment with the aim of supporting irrigated agriculture are being undertaken on the floodplains east of Darwin as part of the NAWRA project. As part of this work, the potential for managed aquafer recharge will be assessed. Outcomes form these investigation will be provided by NAWRA reports in ~2019. It was noted that groundwater resources in the urban-rural areas south of Darwin are fully utilised and at their extraction limit.

Sea Dragon Aquaculture

The Sea Dragon Aquaculture project in the Keep River catchment likely is a going concern. The Sea Dragon proposal is for a staged aquaculture development with an initial placement of 1,080 ha of ponds (Project Sea Dragon 2016). A final placement of 10,000 ha of ponds is proposed (Figure 4). Project Sea Dragon has received major Project Status by the NT, WA and Commonwealth Governments. It has received approval for its Environmental Impact Statement/Assessment. In March 2017, Project Sea Dragon received NT Environment Protection Authority approval to proceed and two months later received Commonwealth Environmental approval. In August 2017, Project Sea Deagon gained local agreement to operate via an Indigenous Land Use Agreement from the relevant Land Council. Currently, Project Sea Dragon is attempting to raise capital to support the enterprise.

The operation will harvest seawater from the Forsyth Creek and release it back to the Joseph Bonaparte Gulf via Alligator Creek to the Keep Inlet (Anon. 2016). The effluent water will be treated and passed through an environmental protection zone (perhaps a created wetland system) so that it returns to the marine system in good condition. Releases will be made on ebb tides to ensure mixing. The project will be constructed on terrestrial lands (4.5–5 m AHD, Project Sea Dragon 2016a), not on wetland or coastal saltflat (Project Sea Dragon 2016b). The project footprint should not directly impact coastal or littoral habitat other than via the direct footprint of seawater 'extraction and return' infrastructure. Currently, there are small barrages on Alligator Creek and Forsyth Creek that separate estuarine and freshwater reaches of the waterbodies; as well as a larger dam on Forsyth Creek. Freshwater requirements for the proposed aquaculture farm are to be sourced from the dam on Forsyth Creek. No new water infrastructure or disruption is proposed. Sea Dragon have undertaken and submitted for review, their EIS requirements and documentation, and these outline aspects of the construction and operation in detail (Volume 2 – Environmental Assessment. Chapter 7 – Marine and estuarine Ecology, Project Sea Dragon 2016). (See http://seafarms.com.au/project-sea-dragon/)

Both of these waterways are prime juvenile red-legged Banana Prawn habitat with high abundances of juvenile prawns (Forsyth Creek- up to 1619.3 ± 586.9 prawns 100 m^{-2} and Keep River- up to 323.4 ± 233.4 prawns 100 m^{-2}; Kenyon *et al*. 2004), so the conservation of these habitats in the vicinity of the Sea Dragon farm is critical. It is worth noting that the EIS prepared for Project Sea Dragon does not reference Kenyon et al. (2004), despite it being the most thorough assessment of the use of mangrove/mudbank habitats in Forsyth Creek and Keep Inlet by juvenile red-legged Banana Prawns. A risk of spread of pathogens from farmed stock to wild stock prawns must be present in the vicinity of Project Sea Dragon. The climate in this region can be extreme and in the 2017 wet season, 1300 mm of rain fell in the Joseph Bonaparte Gulf region. Infrastructure design and capability must be built to withstand climate extremes such as rainfall and cyclonic conditions.

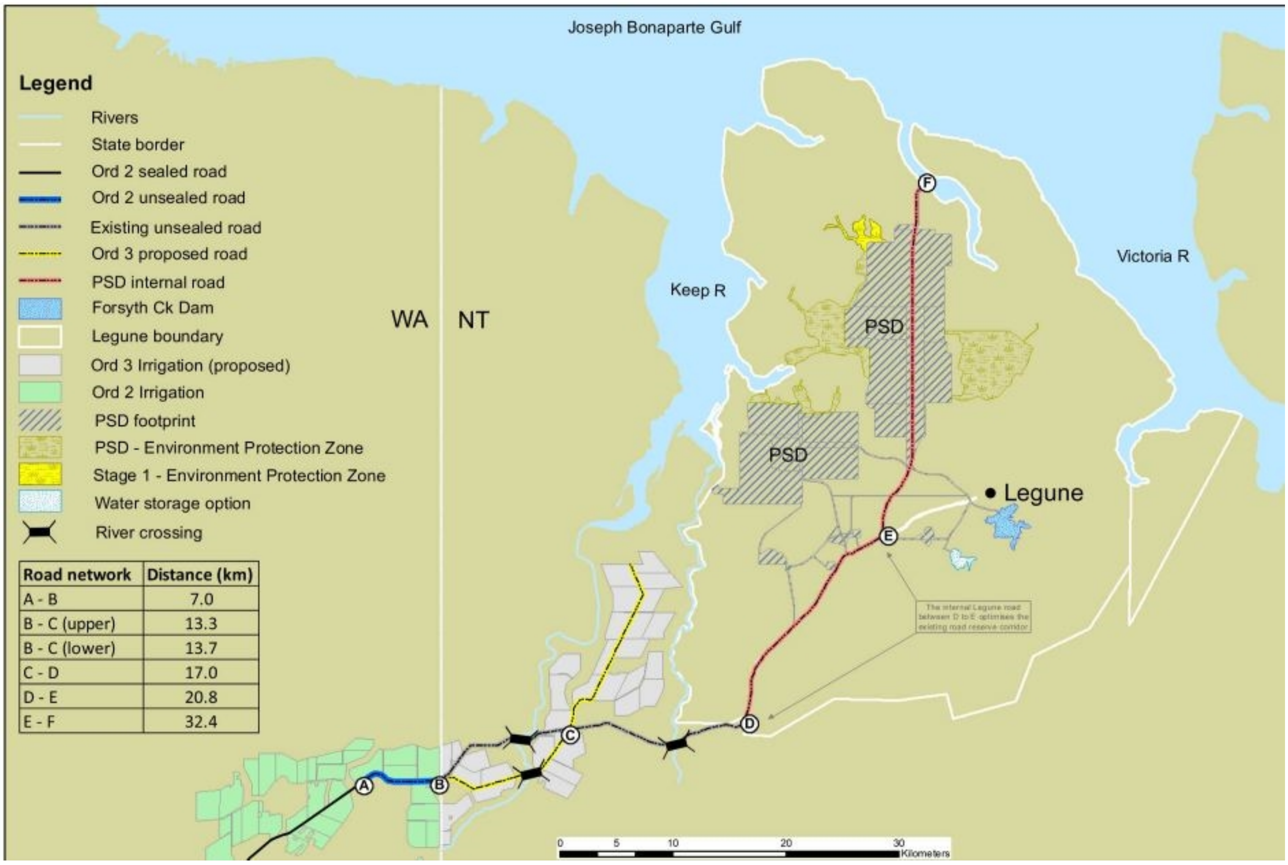

Figure 4. A representation of the proposed Sea Dragon aquaculture facility on the Legune Station lease in the Northern Territory.

Table 6. Northern Territory agricultural, mining, aquaculture and other developments that use water resources and may impact downstream species and ecosystems (numbered sequence reflects the map portal list; see https://research.csiro.au/npfnwd/).

#	PROJECT	SPECIES/ CRITICAL HABITAT	POTENTIAL IMPACTS	THREATS/ BENEFITS	CUMULATIVE IMPACTS	ECOLOGICAL INTERACTION	NON-FISHERY STAKEHOLDER
1	Blackmore River Aquaculture	Estuarine Banana Prawns and mangroves	Minor impact of near-estuary freshwater barramundi farm	minimal	Risk of pathogens	minor	Fisheries focussing finfish species
2	Bonaparte Floating LNG	Estuarine Banana Prawns, adult commercial prawns	Oil spill impacts on inshore habitats (unlikely)	Pollution of estuaries	unsure	Disruption of coastal foodwebs and ecosystem services	Coastal human communities
3	Browns Sulphide Project	na	na	na	na	na	Company in receivership
4	Clarence Strait Tidal Energy	Pelagic prawn larvae	Interrupted pelagic larval and emigration pathways	Possible attraction of fish (i.e. FAD)	na	Difficult to assess, probably minimal	Recreational fishers
5	Condensate processing – East Arm	Estuarine Banana Prawns	Habitat loss	Mangrove removal, foreshore modification	Permanent loss of habitat	Disruption of habitat, ecosystem services	Recreational fishers
6	Cosmo Deep Gold	Estuarine Banana Prawns	Reduced baseflow and emigration cue	Reduction in optimal ecotone and flood-cued catch	Sequential years of flow modification	Reduced fluvial loads, nutrient transport, floodplume dump	Fisheries focussing on catadromous fish species
7	Darwin Refinery TNG (magnetite refinery)	Estuarine community	Pollution, mangrove habitat loss	Mangrove removal, foreshore modification	Permanent loss of habitat	Disruption of habitat, ecosystem services	Recreational fishers
8	East Point Outfall	Estuarine species	Freshwater inputs to coast	Enhancement of brackish waters	Treated water	minor	Beach-users
9	Frances Creek Mining	na	Nil: inland mine	na	na	na	Ceased production

10	Howard East Borefield	Estuarine Banana Prawns	Reduced baseflow	Reduction in optimal ecotone	Sequential years of flow modification	Loss of baseflow; hypersaline estuary	Brackish ecotone estuary community
11	Kilmiraka Mineral Sands	Coastal sand habitat	Groundwater impact, minimal	Extraction of groundwater	unsure	Lower water table, soil water stress	Mineral sands mine, Bathurst Island
12	Manton Dam return to service	Estuarine Banana Prawns	Reduced baseflow and emigration cue	Reduction in optimal ecotone and flood-cued catch	Sequential years of flow modification	Reduced fluvial loads, nutrient transport, floodplume dump	Fisheries focussing on catadromous fish species
13	Marrakai Dam	Estuarine Banana Prawns	Reduced baseflow and emigration cue	Reduction in optimal ecotone and flood-cued catch	Sequential years of flow modification	Reduced fluvial loads, nutrient transport, floodplume dump	Fisheries focussing on catadromous fish species
14	Mount Peake Mine	Inland mine	na	na	na	na	na
15	Mt Grace Magnesium Mine	Inland mine	na	na	na	na	na
16	Mt Todd Gold Mine	Inland mine	na	na	na	na	na
17	Mt Bennett Dam	Estuarine Banana Prawns	Reduced baseflow and emigration cue	Reduction in optimal ecotone and flood-cued catch	Sequential years of flow modification	Reduced fluvial loads, nutrient transport, floodplume dump	Fisheries focussing on catadromous fish species
18	NT Off-Stream Storage	Estuarine Banana Prawns	Reduced baseflow and emigration cue	Reduction in optimal ecotone and flood-cued catch	Sequential years of flow modification	Reduced fluvial loads, nutrient transport, floodplume dump	Fisheries focussing on catadromous fish species
19	Barramundi Farm- Snake Bay	Estuarine Banana Prawns	Farm outflows to the estuary	Salinity shifts, pathogens	Ecotone instability, disease	Juvenile prawn growth and survival	na
20	Ranger 3 Mine	Estuarine Banana Prawns	Groundwater modification, reduced baseflow	Reduction in estuarine ecotone	minimal	minor	Brackish ecotone estuarine community

21	Rum Jungle Mine - rehabilitation	na	na	na	na	na	na
22	Rum Jungle Mine, Burton - rehabilitation	na	na	na	na	na	na
23	Rum Jungle Mine, Fitch - rehabilitation	na	na	na	na	na	na
24	Sea Dragon Aquaculture	Estuarine Banana Prawns	Farm outflows to the estuary	Salinity shifts, pathogens	Ecotone instability, disease	Juvenile prawn growth and survival	na
25	Sorby Hills Mine	na	na	na	na	na	Inland mine
26	Tassie Shoal Methanol	Offshore benthos	na	na	na	na	na
27	Toms Gully Mine	na	na	na	na	na	Inland mine
28	Tropical Tidal testing – Tenax; tidal energy	Pelagic prawn larvae; coastal habitats	Interrupted pelagic larval and emigration pathways	Possible attraction of fish (i.e. FAD)	na	Difficult to assess, probably minimal	Recreational fishers
29	Warrai Dam - Adelaide River	Estuarine Banana Prawns	Reduced baseflow and emigration cue	Reduction in optimal ecotone and flood-cued catch	Sequential years of flow modification	Reduced fluvial loads, nutrient transport, floodplume dump	Fisheries focussing on catadromous fish species
30	Wonarah Phosphate	na	na	na	na	na	Inland mine

Summary – Northern Territory water resource development in focus

Currently, the Sea Dragon Aquaculture project (Keep River) and the Adelaide River Off-stream Water Storage (AROWS) are the projects of focus in the Northern Territory.

Current research initiatives are scoping potential WRD in ‘Darwin Rivers’ catchments and identified surface water and groundwater as likely WRD scenarios. These ‘water capture and extraction options’ provide an indication of likely future water resource development.

The current NAWRA project (CSIRO 2016a) is assessing the potential of the catchments of Reynolds, Finniss, Blackmore, Adelaide, McKinlay, Wildman, and West Alligator Rivers to support irrigated agriculture. The project has not delivered a final report, however, it has delivered ‘Methods Reports’. Both surface water and groundwater options are recognised. Surface water options are in the Blackmore River and Adelaide River catchments; while potential groundwater resources lie in on the flat plains east of Darwin, the Bathurst-Melville Islands, and in the Coburg Peninsula Region (CSIRO 2016a). A second information source for possible surface water development in the vicinity of Darwin is the Darwin Region Water Supply Strategy (Power and Water Corporation 2013). It also prioritises catchments of rivers like the Adelaide and Blackmore for locations on in-stream and off-stream storage. Currently, these are only prospective accounts, but point to catchments and extensive regions where future WRD is likely.

Western Australia

In-person data gathering.

We spoke to Dr. Richard George; Principal Research Scientist, Irrigated Agriculture Directorate, Western Australian Department of Agriculture and Food. Richard is a land and water scientist who has conducted many soil and hydrological studies in the Ord River Irrigation Area (see https://www.agric.wa.gov.au/richard-george).

Richard discussed the Ord Stage 1 irrigated lands which encompass about 14,000 ha. He informed us that Ord Stage 2, currently in development, increases the irrigated lands to about 27,000 ha. The footprint of Ord Stage 3 increases the irrigated area to about 60,000 ha with all possible land included (extending about 50:50 in Western Australia: Northern Territory). The majority of Ord Stages 1 and 2 are in Western Australia. Approximately 500–1000 ha of 5,000 ha of Ord Stage 2 is in the Keep River catchment in the Northern Territory. The majority of Ord Stage 3 is in the Northern Territory in the Keep River catchment. The Goomig farmlands and the Knox Irrigated Area are in the Keep River catchment (Bennett and George 2014). Therefore, under poor water management, the lower Keep River could be subject to impacts from irrigated water runoff.

Richard contrasted the improved irrigated water management in Ord Stage 2 with the older systems found in Ord Stage 1. He noted that ‘controlled tail water’ will be the base case throughout Ord Stages 2 and 3. Richard commented that irrigated agriculture research in NSW has shown that controlled tail water is crucial to successful farm management; and that Western Australia recognises the importance of tail water management. Richard predicted that there would be nil to very minimal runoff of tail water from Ord Stage 2 farms. Therefore, the downstream impacts of uncontrolled water impacts, such as are evident in the Ord River, will not be a factor for the Keep River.

Richard commented on the likelihood of nutrient loads being increased from irrigated lands. He suggested that currently, the on-farm management of nutrients and chemicals is comprehensive and that an off-footprint transport of loads from Ord Stage 1 is minimal. These practices will be continued in ORD Stages 2 and 3. Richard noted that he monitored huge loads of phosphorus and nitrogen in ~2012 in the lower Keep River as part of the Ord-expansion research scope. However, Richard proposed that the build-up of organic matter over years prior to a significant wet-season and the organic growth during a wet season are huge over the expansive area of the Kimberley catchments. He also suggested that the low-density, but widespread nutrient impacts from the pastoral industry contribute higher loads than from irrigated lands. In general, Richards’s contention was that both natural and anthropogenic factors over the huge expanse of Kimberley river catchments had a much greater impact on nutrient loads in estuaries and coastal waters than inputs from irrigated agriculture.

Richard commented that there were no mining proposals in the Western Australian portion of the NPF catchments that he was aware of.

Table 7. Western Australian agricultural, mining, aquaculture and other developments that use water resources and may impact downstream species and ecosystems

#	PROJECT	SPECIES/ CRITICAL HABITAT	POTENTIAL IMPACTS	THREATS/ BENEFITS	CUMULATIVE IMPACTS	ECOLOGICAL INTERACTION	NON-FISHERY STAKEHOLDER
39	Bonaparte Plains – East Kimberley Irrigation	Estuarine Banana Prawns	Elevated baseflow and loss of estuarine habitat	Freshwater estuaries; habitat expansion for catadromous fish	Perennial freshwater flows	Longstream shift in estuarine ecotone, reduced extent	Fisheries focussing on catadromous fish species
40	Kimberley to Perth pipeline	na	na	na	na	na	na
41	Ord River Irrigation – Stage 2	Estuarine Banana Prawns	Elevated baseflow and loss of estuarine habitat	Freshwater estuaries; habitat expansion for catadromous fish	Perennial freshwater flows	Longstream shift in estuarine ecotone, reduced extent	Fisheries focussing on catadromous fish species
39, 41. 43	Lake Argyle	Estuarine Banana Prawns	Elevated baseflow and loss of estuarine habitat; loss of emigration cue	Freshwater estuaries; habitat expansion for catadromous fish; reduced high flows	Perennial freshwater flows; impounded annual floodflows	Longstream shift in estuarine ecotone, reduced extent. Reduced emigration	Fisheries focussing on catadromous fish species; species with estuarine juvenile populations.
42	Kimberley irrigated water pipeline	na	na	na	na	na	na
43	Ord River Irrigation - Stage 3 (Cockatoo Sands)	Estuarine Banana Prawns	Elevated baseflow and loss of estuarine habitat	Freshwater estuaries; habitat expansion for catadromous fish	Perennial freshwater flows	Longstream shift in estuarine ecotone, reduced extent	Fisheries focussing on catadromous fish species
44	Shell Prelude FLNG	Estuarine Banana Prawns, adult commercial prawns	Oil spill impacts on inshore habitats (unlikely)	Pollution of estuaries	unsure	Disruption of coastal foodwebs and ecosystem services	Coastal human communities

Summary – Western Australia water resource development in focus

Currently, the Ord River Irrigation projects - Stage 2 and 3 (Ord River, Keep River) are the projects of focus in Western Australia.

Current research initiatives are scoping potential WRD in the Fitzroy River catchment and identified surface water and groundwater as likely WRD scenarios. These 'water capture, extraction and recharge options' provide an indication of likely future water resource development.

The current NAWRA project (CSIRO 2016b) is assessing the potential of the Fitzroy River catchment to support irrigated agriculture. The project has not delivered a final report, however, it has delivered 'Methods Reports'. Both surface water and groundwater options are recognised. Surface water options are suggested off-stream storage and the re-change of groundwater. Potential groundwater resources will be evaluated (CSIRO 2016b). However, the Fitzroy River catchment is not a catchment that delivers water to the NPF managed area, it is outside the NPF to the west. Consequently it is not a catchment of interest to this report.

However, these NAWRA studies are prospective accounts and point to catchments and extensive regions where future WRD is likely.

3. Sources of information that might be used to evaluate impacts of water development on fisheries and ecological value

As part of the Developing Northern Australia initiative by the Commonwealth Government, four major research projects have been undertaken (or will be undertaken) in tropical Australia to assess the economic feasibility and ecosystem impacts of irrigated cropping and other development options in northern latitudes. As well, environmental impact statements are prepared by proponents of major initiatives in the north (e.g. Sea Dragon Aquaculture; Three Rivers Irrigation).

The major scientific initiatives are past research projects (1, 2) and current research projects (3, 4):

1. TRaCK
2. FGARA
3. NESP
4. NAWRA

TRaCK produced copious volumes of information on the impact of water resource development on tropical rivers and the communities they support (see http://www.nespnorthern.edu.au/track/publications/). Key TRaCK publications imparting new knowledge for the Northern Prawn Fishery are Burford *et al*. (2010), Burford *et al*. (2012) and Burford *et al*. (2016).

The Flinders and Gilbert Agricultural Resource Assessment (FGARA) quantified the potential of the two northern catchments for successful irrigated agriculture. The water resources, soil resources, standing infrastructure and requirements, and human capital were measured and modelled. Robust hydrological models were developed using >100 year series of rainfall and river flow data and then deployed to project future water resource availability and the effects of infrastructure such as dams or water extraction on resultant flows. As well, flow projections were made under several precipitation scenarios dependent on climate trends (Petheram *et al*. 2013 a,b). Case studies provided projected future flow data given several alternative water resource development proposals; whereby a general decline in the magnitude of floodflows and modification of the wet-season hydrograph were observed. Once the changing nature of annual flow volume and trend was identified using the hydrologic models, estimates could be made on the impacts of changed flows on freshwater, estuarine and marine biota, including fishery species.

The FGARA project made quantitative and qualitative assessments of the impact of water resource development on coastal fisheries. Qualitative assessments employed expert opinion to forecast the impacts of projected flow modification on key species (Bayliss *et al*. 2014). For species with robust data series, quantitative models explored historical catch against historical flow, and then used the model to estimate the effects on catch of projected future flows under WRD scenarios (Bayliss *et al*. (2014). The models provided quantitative assessments of prospective water development impacts on Banana Prawns and Barramundi in the Flinders and Gilbert Rivers (Griffiths *et al*. 2014). The model outputs estimated that the extraction of significant quantities of water (e.g. ~250, ~550 GL) from each of the rivers would have a relatively small impact on fishery catch. Banana Prawn catch was estimated to be reduced by 3–13%, depending on future flow scenario (as modified by WRD). One prominent high extraction scenario estimated a 2–8% likely catch reduction of prawns. Barramundi catch was estimated to be reduced by 4–19%, depending on flow scenario. One prominent high extraction scenario estimated a 3–12% likely catch reduction of fish.

NESP

A current major project series, the National Environmental Science Program (NESP) will explore in more detail impacts on the ecosystem, habitats and species in these same catchments. Theme 1. 'Minimising the Risk of Land and Water Development' – will explore the environmental water needs for the Mitchell, Daly and Fitzroy Rivers; as well as the links between GOC rivers and coastal productivity (see: http://www.nespnorthern.edu.au/nesp/projects/). Currently, several reports and papers are available via the NESP portal (see: http://www.nespnorthern.edu.au/publications/).

The NESP project 1.4, component 1 - "Links between Gulf Rivers and coastal productivity" has measured the phytoplankton productivity of the community of microflora of several sites in the intertidal zone (the prime feeding zone of juvenile Banana Prawns) in the Mitchell, Gilbert and Flinders Rivers. The project measured a range of physical and chemical water quality parameters at each site (e.g. TN, TP, TSS, dissolved organic N, non-dissolved N, Chlorophyll *a*). The microflora and production of carbon in estuarine sediments provides an indicator of the baseline productivity of the foodweb available to resident juvenile Banana Prawns in each river.

In conjunction, the FRDC project 2016-47 "Addressing knowledge gaps for studies of the effect of water resource development on the future of the Northern Prawn Fishery" is making an estimate of the abundance of the estuarine Banana Prawn population in three rivers, the Mitchell, Gilbert and Flinders Rivers. During November 2016 and 2017 researchers visited the estuaries of each of the rivers and conducted multiple beam trawls in a range microhabitats in each estuary. In addition, surface set net placements provided an indication of emigration of juvenile prawns from the each of the estuaries. Together with information from NESP 1.4, links between estuarine primary productivity, the spatial extent of estuarine habitat, and prawn abundance in each of the rivers can be explored. The information will assist in understanding the contribution of particular estuaries, characterised by particular flow regimes, to the Banana Prawn fishery in the GoC.

A joint initiative of these two projects is an investigation of the geochemistry of the flesh of the Banana Prawns and the sediments on which they reside; both in the estuary, and in the nearshore and the offshore regions adjacent to the estuaries. The project is attempting to identify a chemical signature from the 'inshore' and 'offshore' life stages of the prawns that reflects the chemical signature of the sediments in each habitat. If the chemical signatures of each of the estuaries and their resident prawns differ between each estuary, then the chemical signatures of prawns that have emigrated from the estuaries may remain stable and continue to differ. If so, the chemical fingerprint of 'offshore' prawns may be able to be used to identify the estuary of origin of the sub-adult prawns in the nearshore/offshore. The overall aim of this initiative is to be able to trace the estuary of origin of prawns caught offshore and to be able to estimate the contribution of an individual river system as a component of the Banana Prawn fishery in the Gulf of Carpentaria.

NAWRA

The Northern Australia Water Resource Assessment currently is determining the quanta of annually-reliable water available to allocate to irrigation in rivers in three major catchments of tropical Australia:

- the Mitchell River, western Cape York, Queensland;

- a series of river catchments in the vicinity of Darwin, Northern Territory; and
- the Fitzroy River, Western Australia.

The NAWRA project will conduct similar baseline surveys, resources inventoried and statistical modelling and analyses as undertaken during FGARA (see: https://www.csiro.au/en/Research/Major-initiatives/Northern-Australia/Current-work/NAWRA). For each catchment, NAWRA has been tasked to:

- "evaluate the climate, soil and water resources
- identify and evaluate water capture and storage options
- identify and test the commercial viability of irrigated agricultural, forestry and aquaculture opportunities
- assess potential environmental, social and economic impacts and risks of water resource and irrigation development" (CSIRO 2016 a,b,c).

NAWRA will develop modelling that enables the provision of robust scientific hydrological information, water resource availability and flow data to support water resource planning, and the review of current WRPs. To achieve these tasks, NAWRA will develop a suite of conceptual and physically based hydrological models for each of the three study areas.

The combination of the models will allow NAWRA researchers to simulate streamflow under various new water infrastructure and water resource use scenarios. They will simulate the impacts of water extraction or dam placement on future river flow; and quantify the WRD-induced change in flow characteristics relative to historical flow patterns. The characteristics of dams located at selected sites can be determined. Dam capacity, harvestable yield (with a percent estimate of certainty) and yield can be quantified. Change in the flow regime reaching coastal estuaries can be quantitatively estimated.

Specific case studies will be developed for each catchment. For the Mitchell River, one case study examines a large in-stream water storage development (CSIRO 2016c). As well, the Mitchell River catchment assessment will scope possible aquaculture development associated with water provision from irrigation infrastructure or coastal water resources.

In the Darwin Rivers catchments, case study options of both surface water and groundwater consumption will be investigated. Surface water options in the Adelaide River catchment and groundwater resources at Wildman Station will be investigated (CSIRO 2016a).

NAWRA will report in 2018-2019 and will provide key outputs relative to trade-offs between water infrastructure placement and water use for proposed economic development, versus the economic impact on current industries and the depletion of ecosystem services that are sustained by current unregulated in-catchment flows.

As part of the ecological-impact dimension, NAWRA will model the water resources and ecological needs of aquatic and marine species in these tropical Australian river systems. The project will incorporate the impacts of WRD, together with the likely response of key species to changes in flow; including significant fishery species (CSIRO 2016 a,b,c). The numerical outputs of the hydrological models can be further modelled with catch-series from fisheries to estimate the impact on downstream fishery catch of reduced water availability due to the placement of water infrastructure. Barramundi and Banana Prawns are being modelled quantitatively. The majority of fishery species are investigated using qualitative models and expert knowledge of their biology. Moreover, the quantitative models are not ecological models; they model flow and catch; a limited selection of the suite of environmental drivers that determine species abundance.

NAWRA will provide quantitative estimates of the effects on natural flows of a range of water extraction allocations, as well as the effects of several possible dam placements with known yields. NAWRA model outcomes represent estimates of impact on a range of flow parameters: annual average flow, annual median flow, the percent reduction of high-level floods, monthly flows, days-of-no-flow, the incidence of overbank flow, and a large range of other hydrological criteria. A range of water allocation scenarios will be modelled: both relatively-low and relatively-high quanta of water relative to possible yield. Water extraction scenarios will be modelled: extraction at high river flow rates only vs. extraction from any flow levels above a relatively low river flow rate. Extraction with high capacity pumps over a short time duration vs. extraction over a longer period. A large array of possible scenario combinations will be explored. The quantitative estimates of a reduction in flow for each individual month provides an unique opportunity to examine the impact on late-dry season flows (when the juvenile Banana Prawns are abundant in optimally brackish estuaries); as well as the loss of flow during the wet season (the monsoon-driven emigration cue).

Any developments that might result from the data provided within NAWRA could result in impoundments, diversions, extraction and eventual use of water that may have significant impacts on fisheries in general and the NPF in particular. The impacts will result from substantial changes to streamflow, despite the irrigated lands occupying only a small proportion of the landscape (usually <1% of the catchment). Both water extraction and the impoundment by dams will impact late-dry season and wet season flows to different extents. In the majority of years, late-dry season flows are low-level flows, flows that would be impounded behind dam walls or flows subject to a high percent reduction as a significant volume of water would be extracted. In contrast, wet season flows are high-level flows; flows that spill-over dams and continue downstream; or flows that would be depleted by a small proportion of their water volume due to pumped extraction. For the NPF, the distinction between WRD impacts on the late-dry flows and wet season flows is very important. A high percent-reduction of late-dry low flows would have greater impact on the ecological services provided to the downstream estuarine Banana Prawn population than a low percent-reduction of wet season flows whereby downstream ecological services are mostly maintained.

As part of any review of WRPs for tropical Australian river systems, water managers will consider the best available science when providing policy advice, as well as considering the broader impacts of water security to farmers, fishers and the community. WRPs for relevant catchments will have conditions to ensure a specific volume of water reaches the end of the river system to support the life history of prawns and fish during the monsoon seasonal cycles. The NPF has the opportunity to explore science-derived facets of flow reduction under different scenarios to identify WRD that has the least impact on key flow indictors that support downstream ecological function in estuarine and coastal ecosystems. For example, water extraction or impoundment might reduce late-dry season low-level flows by 60-70% while only reducing wet season flows by 10-20%. The majority of wet season high-level floods would continue to spill over the dam. If a dam was engineered with the facility to allow environmental flows to pass the dam wall unhindered, or if water extraction occurred from high-level flows only, then late-dry season low-level flows could continue to provide ecosystem services to the downstream estuarine community. Major floods during the subsequent wet season would mostly pass unhindered and continue to provide the emigration cue to the estuarine Banana Prawn population as was the historical case. Under this scenario, the overall impact on the Banana Prawn population eventually available to be fished may be minimal. This scenario is hypothetical; yet it illustrates a situation whereby both irrigators and the NPF can benefit from a water management strategy that delivers water to off-stream users, while continuing to support the coastal ecosystem that has sustained a Banana Prawn harvest for the last 50 years.

The possibility of mutual benefit to multiple users would require a joint approach to the management of the water resources and the development of water management principles that recognise the rights of both the irrigators and the NPF. The development of a management framework that achieves this outcome would require engagement by the NPF Industry from the initiation of review of the Water Resource Plans for the rivers subject to WRD. The importance of research components and outcomes of the NAWRA project is that they will inform all stakeholders, including the fishing industry, of the likely downstream impacts on ecosystems and ecosystem services from water diversion and modified flows. The best available science-based modelling, investigation and deployed-knowledge will be provided to policy makers to inform their decisions on water management.

4. Overview of the impacts of water impoundment and diversion on aspects of the life history of Banana Prawns and other estuarine species

Effects of flow characteristics on aspects of the life history of estuarine fauna

Modification of the emigration cue

The modification or loss of floodflows has major impacts on many tropical estuarine-dependent species. Fish and crustacean species with catadromous or an estuarine juvenile component to their life histories are stimulated to emigrate from riverine to estuarine habitats or estuarine to offshore habitats. The loss of moderate to high floodflows has the potential to reduce emigration cues. Species such as Banana Prawns, Barramundi and Mullet are typical species that are cued to migrate by monsoonal floods. The estuarine juvenile phase of the Banana Prawn cannot tolerate a sharp decline in salinity to near-freshwater (<~5 ppt) (Dall *et al*. 1990) and they emigrate downstream to the lower estuary or nearshore. Small juvenile Mullet and Barramundi live in freshwater habitats, but move to estuarine and marine habitats as they grow to adulthood and to reproduce. Riverine connectivity and downstream flows facilitate their movement.

The impoundment of riverine flows by in-stream dams typifies water resource development that reduces the dimension of floodflows. The highest flows, such as 1-in-50 or 1-in-100 year floods, are little impacted by in-stream dams as the volume of water is too great—many times the volume of the dam and overwhelms the dam's capacity to block the flood's continuation downstream. Small to moderate floodflows can be trapped or reduced by large dams, especially if the dam was at a low storage level prior to the wet season. In addition, water extraction for off-stream water storage can impact small floodflows and early season flows as the volumes extracted and stored may represent a considerable portion of the volume of the flood.

Small to moderate floods, especially first-of-the-season floods may be captured by in-stream dams or off-stream storage and not reach the estuary. The connectivity and the cue for fish to emigrate from palustrine to riverine habitats; or the cue for fish and crustaceans to emigrate from the upper estuary to the lower, or from estuarine to nearshore habitats, are lost. In each situation, the anthropogenic reduction in early-season smaller flows likely causes high mortality to a portion of the local population. Remnant palustrine waterhole habitats and in-channel waterholes may dry out without early wet-season floodflows. In addition, without an emigration cue, juvenile fish and crustaceans remaining in the upper estuary are subject to higher predation rates at the high densities found in small tributaries in the mid-to-upper estuary than if they moved downstream (Wang and Haywood 1999).

Floodplain and river channel connectivity

Overbank flows (moderate to large floodflows) expand the availability of habitat to many species, particularly catadromous fish. As small juveniles, fish such as barramundi and mullet move from the estuary and main river channel to floodplain billabongs and waterholes which may be perennial but often seasonally ephemeral (wet-season). These habitats can be hotspots of productivity while wetted (Faggotter *et al*. 2013; Jardine *et al*. 2013; Ward *et al*. 2016) and support the juvenile phase of many species which return to estuaries and nearshore marine habitat as they grow. In addition, overbank flows that inundate saltflat habitats in the vicinity of an estuary, expand the area of habitat available to many species; e.g. Barramundi (Russel and Garrett 1983, 1985).

Large floods expand the connectivity and spatial extent of these habitats significantly. As mentioned previously, very large floods are minimally impacted by water resource development, as the percent of water retained is small compared to the volume of flow. During large floods, connectivity continues to be enhanced significantly. In fact, on the low relief landscape of the southern Gulf of Carpentaria, very large floods create a shallow freshwater 'lake' ecosystem for 2–3 months during a significant wet season. The 'lake ecosystem' replaces the river-floodplain-estuary-saltflat ecosystem that exists along these coasts during the dry-season and most wet-seasons (Kenyon *et al*. 2012; Burford *et al*. 2016). The fish and crustacean fauna inhabiting these ephemeral freshwater habitats has not been well studied, however, the penaeid prawn community changes from species that inhabit the euryhaline estuary (e.g. Banana Prawns *Penaeus merguiensis* and non-commercial prawns of the genus *Metapenaeus*) to a population explosion of prawns of the genus *Metapenaeus* that are tolerant of freshwater. These animals live both in the estuary and on the inundated saltflats, a much expanded habitat extent (Kenyon *et al*. 2012).

Overbank flows from a moderate flood may be reduced, particularly if a near-empty dam retains a large percentage of the volume of a first-season flood. Reduced floodplain and saltflat inundation would reduce habitat connectivity for many species. Small floods may be much reduced or negated by in-channel and offstream storage, particularly first-season floods that, unimpeded, would maintain river-channel connectivity and may reduce the salinity of the estuary with benefits for new recruits and early juveniles of many commercial species. Small floods probably don't flow overbank apart from in the upper riverine reaches, so the impact on connectivity of reduced small floodflows due to WRD for commercial species that use estuarine habitats, is minimal.

Importantly, the connectivity of remnant in-channel riverine waterholes would be impacted by reduced small floodflows. Commercial catadromous fish, such as Barramundi and Mullet survive in remnant waterholes in the river channel. Ontogenetic behaviour cues them to move from the juvenile and sub-adult habitats downstream to adult habitats in the estuary. The negation of early-season floods by WRD may block the passage of adult fish to estuarine habitats and spawning habitats at river mouths and in the nearshore marine environment. Reduction in the magnitude of small floods has the same effect, though it is likely that a continuous riverine flow would eventuate during each wet season.

Deterioration of water quality

Riverine water quality is a critical factor in the ecological health of the estuarine/marine environment. The impoundment of water in instream dams has major impacts on riverine water quality; particularly at depth within the reservoirs (Ling *et al*. 2016; Ma *et al*. 2016; Oliver *et al*. 2016). Temperature, dissolved oxygen and pH may decline with depth to levels that do not support aquatic biota, while conductivity, suspended solids and nutrient loads increase to eutrophic conditions (Ling *et al*. 2016; Ma *et al*. 2016). The release of water from impoundments as environmental flows can disrupt water quality and impact riverine floral and faunal communities downstream of impoundments. It is critical that release-waters can be sourced from a range offtake depths over the depth range of the impoundment. The indifferent release of water from the base of a dam wall may cause anaerobic/toxic water to enter an estuary with dire consequences for estuarine fauna.

Often, only the upper few meters of water within an impoundment has water with the chemical and physical parameters to support riverine biota (Ling *et al*. 2016). Impoundment structures must incorporate design and engineered features that allow multi-level release of water to facilitate the offtake of high-quality water. In most situations, water released as environmental flows must be sourced from the surface layers, via elevated engineered offtakes in the dam wall and then released downstream. In the case of water quality, water extraction and off-stream storage, rather than in-stream impoundment, may be best practise to maintain high water quality in the river channel, downstream of the WRD infrastructure.

Estuarine ecotone

The tropical Australian wet-dry climate is characterised by a ~three month wet season (January to March) and comparatively little rainfall in the other months. By September each year, little to no rain has fallen for 3–4 months and many rivers in northern catchments become a trickle or have ceased to flow. River estuaries are at marine salinity conditions and may be hypersaline. By December, near-daily tropical storms contribute sporadic rainfall in coastal zones, but usually substantial rain has not fallen in any catchment. Estuaries remain hypersaline in the lower estuary, but may have freshwater inputs to the upper estuary reducing salinity to brackish conditions. September to December also is the period of recruitment of the juvenile phase of many fish and crustacean species to tropical estuaries (e.g. Banana Prawns, barramundi, mudcrabs and mullet). During this 'pre-wet' season, hypersaline estuaries are sub-optimal for the growth and survival of many of these coastal species. Within tropical estuaries, brackish conditions (e.g. salinity of 5–25) and warm temperatures (25–30 °C) offer optimal conditions for the growth and survival of Banana Prawns, mudcrabs and mullet (Staples and Heales 1991; Ruscoe *et al*. 2004, Whitfield *et al*. 2012). Thus, first season floodflows are significant in that they reduce estuarine salinity for the recent recruits to the estuary. Early seasonal flows and initial low floodflows are critical to ensure good survival and growth of the juvenile phase of fish and crustaceans: to ensure that they grow to a larger size enabling them to survive in the nearshore zone after any flood-cued emigration later in the wet-season (Wang and Haywood 1999).

Water resource development that impounds or extracts early-season and small floodflows likely causes estuaries to remain hypersaline during the key 'pre-wet recruitment season' for juvenile fauna. Small floods would be much reduced or negated by in-channel dams and offstream storage extraction. Unimpeded, first-season floods reduce the salinity of estuaries during October to January, with benefits for the growth and survival of new recruits and the early juvenile phase of many commercial species. As the wet season gains strength, flows become consistent and increase in volume; supporting the brackish ecotone that provides optimal conditions for their growth and survival. Early low flows probably cause the down-estuary emigration of many individuals, particularly larger juveniles; while moderate to large floods increase the emigration cue and may cause the majority of a population to move to the nearshore zone. The emigration response is embedded as a cue, as the tolerance of freshwater influence decreases with the increasing size of individuals. For example, small Banana Prawns (~6–8 mm carapace length (CL)) can tolerate salinities as low as ~3, while larger sub-adult Banana Prawns (16–30 mm CL) are stressed but can tolerate salinities <20, but salinities <7 are lethal (Dall 1981). Clearly, larger prawns are cued to emigrate at higher salinities (Staples and Vance 1986), so smaller floodflows with less capacity to cause estuarine salinity to decline stimulate large juvenile prawns to emigrate while first recruits can remain in optimal conditions in the upper estuary.

In addition, mangroves distribution is dependent on the estuarine ecotone. Within an estuary, the longstream distribution of mangroves is dependent on a consistent seasonal ecotone supported by seasonal flows. Either enhancement of flows due to the release of water outside the scope of the normal pulsed wet season; or reduction of floodflows or baseflow due to water impoundment/extraction could change the longstream salinity regime in estuarine reaches, and hence mangrove distribution.

Ecosystem services and floodplume dump

Tropical coastal ecosystems in northern Australia are oligotrophic systems where estuarine food webs are dependent on carbon and nutrient fixation from phytoplankton and periphytic/epibenthic algae (Burford *et al*. 2012; Duggan *et al*. 2014). In years of high floodflows, these tropical systems support a spike in ecosystem productivity that has historically been measured indirectly as pulsed fishery catch in crustaceans and fish (Vance *et al*. 1998; Balston 2009). For some fishery species, the increased catches often are offset by a year or two due to life history characteristics (Balston 2009; Welch *et al*. 2014). Recent studies show that while nutrient loads and productivity in the tropical estuaries are not markedly enhanced during floods, hundreds of tonnes of nutrients are transferred from terrestrial sources via the estuary to nearshore flood-plume zones (Burford *et al*. 2012). During a 1-in-50 year flood in the Norman River in 2009, 4300 tonnes of N and 800 tonnes of P transited the estuary to be dumped in the nearshore zone where the nutrients likely enhanced coastal productivity and supported the populations of emigrants cued from the estuaries by the same floodflows (Burford *et al*. 2010). A reduction in flood magnitude in tropical Australian rivers would reduce the nutrient transfer from the terrestrial sources to the oligotrophic marine ecosystem; a transfer that supports the abundance of commercial species during their adult phase in the coastal marine ecosystem (where they are fished).

In the wet-dry Australian tropics, floodflows stimulate the productivity of tropical estuaries and the adjacent nearshore marine ecosystem to sustain the spike in fish and crustacean biomass that many data-series show are associated with flood events. During the pre-wet, estuarine microalgae form the basis of the food chain and support abundant populations of key commercial species; a community enhanced by a brackish estuarine ecotone. Pulsed floods that have been characteristic of these ecosystems for millennia, transfer terrestrial nutrients that enable a response from ecosystem services to sustain the increased production associated with high floodflows in these systems. The exact drivers and pathways that stimulate the ecosystem services are poorly understood. However, a reduction in either low flows or high flows in tropical Australian ecosystems will disrupt the primary and secondary production in these systems with negative impacts on key commercial species that have been sustainably harvested from tropical coasts over the last 50 years.

Supra-littoral production

The tropical Australian coastline is characterised by low-relief topography; a large percentage of the landforms being saltflat surrounding mangrove-lined estuaries and mangrove forest or coastal fringe (Danaher and Stevens 2000). While the contribution of the mangrove forest to ecosystem productivity and as critical habitat has long being recognised (Blaber, 2007; Nagelkerken *et al*. 2008; Robertson 1986; Robertson and Daniel 1989; Robertson and Daniel 2016), the contribution of the large aerial extent of saltflats is poorly known. Recent studies have shown that blue-green algae cover the saltflats as a senescent mat during the dry season. When inundated during overbank floods, the algae ‘activate’, photosynthesise and release nitrogen and phosphate to the coastal ecosystem (Burford *et al*. 2016). The duration of inundation is crucial with algal growth and primary production increasing linearly after inundation. Nutrient release occurred after 2 days and continued for 8–9 days (the duration of the experiment). While rainfall may wet the saltflats, in years of high floodflow overbank floods causing inundation for weeks, increases the productivity of flooded coastal habitats by up to 13% (Burford *et al*. 2016).

Extensive saltflats surround many of the tropical estuaries in the Gulf of Carpentaria, the Top End and the Kimberley region (Danaher and Stevens 2000; Burford *et al*. 2016). When inundated, such a large area of saltflat has the capacity to contribute significant primary production to the tropical coastal ecosystem. Importantly, the ‘top-up’ to coastal productivity occurs in years of high flow when the emigration response of estuarine fauna enhances the survival, growth and abundance of many coastal species; placing demand on estuarine and coastal food webs to support more dense populations. Although not rigorously explored here, Burford *et al*. (2016) provide outputs from a simple model that relates saltflat inundation to rainfall and shows that in eleven years between 1976 and 2011, overbank flows occurred and annual primary production should have been high on the inundated saltflats surrounding the Norman River. During the same eleven ‘overbank-flow’ years, the average Banana Prawn catch in the Northern Prawn Fishery was 5120 tonnes; compared to 4170 tonnes over all years from 1976 to 2011 (Figure 5).

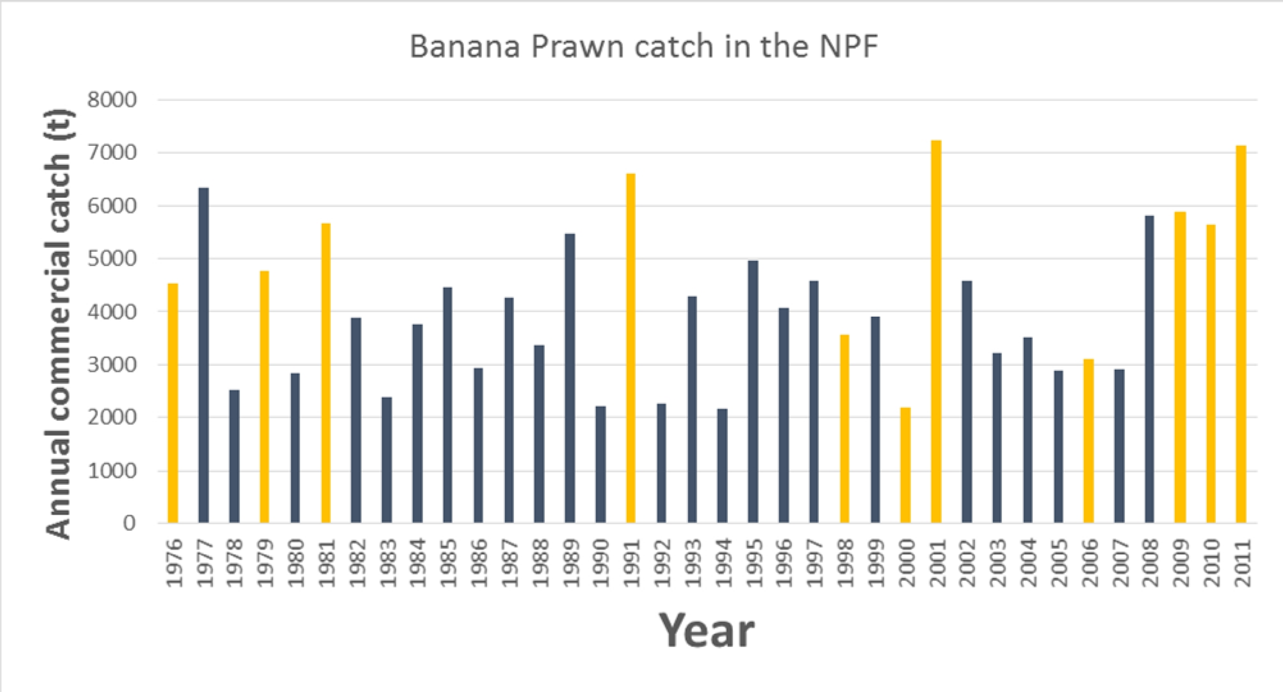

Figure 5. NPF Banana Prawn (*Penaeus merguiensis*) catch taken between 1976 and 2011 highlighting the catch in years of overbank flow (yellow bars) and catch in the remaining years (blue bars) (catch data from Laird 2016, flow data from Burford *et al*. 2016).

Moderate to large floods have the capacity to flow over-bank in the region of the estuary, inundating saltflat habitats and stimulating the senescent algae to photosynthesise. Water resource development that reduces the magnitude or frequency of high flows may reduce ecosystem primary production during the wet season. Reduction in the depth and duration of overbank flows would reduce the productivity of coastal habitats in years of high demand on ecosystem primary productivity due to the pulsed abundance of coastal fish and crustacean species that have emigrated offshore in response to pulsed flows and low estuarine salinity.

Sedimentation and soil water recharge

Mangrove habitat accretion and stabilisation due to sediment deposition is maintained by high flows (Asbridge *et al*. 2016). In the southern Gulf of Carpentaria, high floodflows increased the area of mangroves in the deltas of the rivers via river discharge and sediment deposition enhancing bank habitats and freshwater inputs expanding the ecotone habitats of mangroves. As well, high rainfall and overbank flows recharge the soil water and groundwater in coastal ecosystems, sustaining mangrove forests during the dry season. Mangroves are dependent on access to freshwater for their survival. They source freshwater from soil water or groundwater, depending on the availability of the freshest source (Ewe *et al*. 2007; Wei *et al*. 2012; Santini *et al*. 2014).

Each year at the end of the dry season (October to December), mangroves may be water-stressed due to soil water salinisation and dependent on early season and overbank freshwater flows to recharge soil-water systems. Moreover, recent evidence suggests that in drier-than-average years with high temperatures, mangroves suffer dieback due to high evapotranspiration and moisture stress due to soil water salinisation (Duke *et al*. 2016; Lovelock *et al*. 2017). Any reduction of high flows and overbank flows reduces the stability of estuarine mangrove and mudbank habitats and may result in substrate erosion and the retreat of mangroves over the longstream extent of their estuarine distribution. As well, soil water recharge will be diminished via any reduction in the duration of inundation of saltflat and floodplain habitats with subsequent reduction in water availability to mangroves during the following dry-season.

Modification of tidal exchange

The daily tidal cycle provides the shoreward tidal currents that support the advection of the postlarvae or larvae of fish and crustaceans inshore (Condie *et al*. 1999). During September to December, recently spawned and hatched Banana Prawn postlarvae move into the water column on flood tides and are transported inshore where they settle in the upper-reach mangrove-mudbank matrix of small estuarine creeks. Two aspects of the condition of the estuary are required to facilitate their immigration; an upstream movement of water via tidal exchange, and estuarine salinity levels within the tolerance range of the postlarvae.

High floodwaters leaving the estuary create a mechanical barrier that prevents the upstream movement of tidal flows and hence, prawn postlarvae. Annual monsoonal flows regularly create these conditions in a tropical estuary, however, they occur in January and February and benefit the populations of Banana Prawns. The benefit occurs because a dynamic population of juvenile Banana Prawns recruit to the estuary prior to the wet-season (i.e. September to December) and are cued to emigrate by the floodflow and the decline in salinity that results (Vance *et al*. 1998). In addition, the volume of tidal exchange is correlated with the strength of postlarval immigration (Rothlisberg *et al*. 1995; Vance *et al*. 1998). If the seasonal nature of the annual floodflows were to shift then an early freshwater flood would significantly reduce the population of juvenile Banana Prawns within the estuary. Consistent downstream flows during the September to November time window, would reduce the recruitment of postlarvae to the estuary as the outflows suppress upstream water movement as part of the daily tidal exchange. Subsequent recruitment from the estuarine population to the offshore fishery would be much reduced.

A second aspect to the presence of high floodflows to the estuary prior to the usual timing of the wet season would be the lowering of salinity to levels too fresh for juvenile prawns to tolerate. While tidal exchange may occur simultaneous with low-to-moderate floodflows, they may render the upper estuarine reaches as freshwater. Freshwater creates a barrier to the upstream movement of postlarval Banana Prawns as they cannot tolerate salinity levels below ~3 and they perish in freshwater. Thus, the postlarvae cannot not access the mid- to upper reaches of the estuary and its tributaries which support high abundances of small juveniles. As with the mechanical effects of freshwater floodflows, physiological effects also preclude the establishment of an abundant population of estuarine juvenile prawns during the key time-window for recruitment and growth prior to emigration.

It is difficult to postulate why managers of irrigation water would release high volumes of water at any time apart from during peak monsoon floods when flows spill over at high flow-volumes. Their aim is to capture water, not to release it. In particular, the pre-wet season release of water would be especially illogical as in-stream storage volumes probably would be low at the end of the dry season. Prior to the monsoon, the aim would be to capture the next wet season floods. However, the constant release of water to service a hydroelectric power station would result in freshwater flows that may freshen estuarine waters to levels below the tolerance of postlarval and juvenile Banana Prawns. Portions of the upstream extent of the nursery habitat of Banana Prawn would be lost to the juvenile population. Currently, this situation exists in the Ord River estuary in Western Australia (Kenyon *et al*. 2004). Under this scenario, while daily tidal exchange exists, the natural salinity regimes are lowered due to the constant inflow of freshwater at a time during the pre-wet when estuaries in the wet-dry tropics usually are saline or often hypersaline.

In a hypothetical 'perfect estuary', daily tides advect prawn postlarvae inshore where they settle to the mangrove/mudbank matrix in the upper reaches of creeks and tributaries. Here saline/hypersaline conditions are modified to brackish by pre-wet season flows and the juvenile prawn population flourishes in the euryhaline waters. For several months, prawn recruitment continues on the daily tidal cycle while early-season low floodflows enhance the euryhaline estuarine conditions. An abundant population of juvenile prawns establishes in the upper and lower estuary. Eventually, monsoonal high floodflows cue the juvenile prawn population to emigrate to coastal waters where they are fished.

Aspects of flow modification on the life history characteristics of selected fauna

Banana Prawns

The Banana Prawn is a short-lived species which has a larval life history strategy heavily reliant on monsoon rainfall and subsequent flows (Dall *et al*. 1990). Modification to the timing, magnitude and frequency of seasonal floodflows by in-stream dams or the reduction of both low and high flood flows by water extraction, diversion or impoundment will have a negative effect on the growth, mortality and the emigration of juvenile Banana Prawns. The impact will manifest as reduced ecosystem services within the estuary that sustain growth and survival; reduced emigration cues that support a large proportion of the estuarine population accessing offshore habitats; and the reduced capacity of the nearshore zone to support an abundant population of Banana Prawns via stimulated primary production within a nutrient-enhanced flood plume. In particular, the loss or reduction of first-season floods will impact the estuarine habitats of Banana Prawns, reducing freshwater inflows with the consequence of maintaining hypersaline conditions in the estuary. Brackish salinity, not hypersaline conditions, are optimal for the growth and survival of Banana Prawns (Staples and Heales 1991).

Banana Prawns spawn in offshore marine zones from August to December annually, and spawning is associated with increasing water temperatures (Crocos and Kerr 1983). Larvae are advected inshore by tidal currents and winds (Rothlisberg *et al*. 1996; Condie *et al*. 1999), where they settle as benthic post larvae within estuarine mangrove habitats over 80 km upstream from the river mouth (Staples 1980; Rothlisberg *et al*. 1985, Vance *et al*. 1990). However, high abundances of postlarval and juvenile Banana Prawns are associated with the mangrove-forest-mudbank matrix within tributaries of the estuary along its extent (Vance *et al*. 2002). The majority of inshore advection into estuaries occurs in the months preceding wet-season rainfall events (Staples and Vance 1985). Postlarval and juvenile prawns spend several months in the estuary between October to February, where they occupy low-velocity waters within the mangrove-fine-mud-matrix in tributaries and the main river channel. Here, they feed and shelter from predators. The highest densities of post-larval and juveniles are found within the upper reaches of small creeks within the estuary (Vance *et al*. 1998). Juveniles move into larger creeks and the main river channel as they grow (Vance *et al*. 1998; Kenyon *et al*. 2004; Burford *et al*. 2010); particularly if stimulated by a gradual decline in salinity due to low flows. The brackish conditions of tropical estuarine habitats are ideal for prawn growth (temperatures of around 28°C and salinities of 25 are optimal (Staples and Heales 1991)). In the dry-season with little rainfall, hypersaline conditions can inhibit juvenile growth until wet-season rainfall events return estuarine habitats to brackish conditions. Following the estuarine growth phase, both juveniles and sub-adult prawns migrate back to nearshore marine waters in response to seasonal floodflows. Large floodflows reduce salinity levels abruptly and induce a physiological response in the juvenile prawns to emigrate. Both large and small juveniles emigrate in response to an abrupt drop in salinity to low levels. In addition, high floodflows that reduce the salinity of estuaries to near zero also reduce the suitability of estuarine habitats to support fish and crustaceans. Under freshwater conditions, a reduction in primary production and food availability occurs in Australia's tropical estuaries (Burford *et al*. 2012; Duggan *et al*. 2014), potentially providing an extra stimuli for prawns to move offshore into habitats with greater resources

Modification of the natural timing, magnitude and duration of floodflows would have major impacts on the population stability of Banana Prawns. A reduction in early-season flows would restrict the freshwater inflow to estuaries; maintaining higher salinities within an estuary and reducing its value as juvenile habitat for Banana Prawns. Under hypersaline conditions, the growth of juvenile Banana Prawns is reduced and mortality is higher. A reduction in wet-season floodflows would reduce the emigration cue for Banana Prawns. After residing in estuarine brackish conditions for several months, large floodflows cue the abundant population of juvenile Banana Prawn to emigrate *en masse* to the nearshore zone where they rely on marine habitats for further growth and survival. Smaller floods provide a reduced emigration cue; perhaps only the larger juveniles move downstream, and perhaps to the lower estuary rather than nearshore. A correlation between the quanta of rainfall and the resultant commercial catch of Banana Prawns in the south-east GoC demonstrates the link between floodflow, emigration cue and adult prawn abundance (Vance *et al*. 2003). Importantly, a change in the seasonal distribution of flows (such as too-high, early flows) can cause estuarine salinity regimes to shift to the detriment of the juvenile prawn population (e.g. too fresh, too early into the postlarval recruitment season) and prevent the occupation of estuarine habitat by juvenile Banana Prawns

(Kenyon *et al*. 2004). Reduction and modification of the natural flow regime can reduce the estuarine population of Banana Prawns with a subsequent reduction to the offshore population and economic value of likely catch.

Mudcrabs

Mud crabs exhibit a larval life-history strategy, therefore, several stages in their development are subject to estuarine and riverflow cues in their coastal habitats. Female crabs mate, emigrate offshore and release eggs in September to November (Meynecke *et al*. 2010; Welch *et al*. 2014). After spawning, the eggs, larvae and megalopae require saline habitats (25–30 is optimal) and warm temperatures (26–30°C) to develop and survive. Pelagic zoea and bentho-pelagic megalopae in nearshore marine habitats immigrate to coastal estuaries and sublittoral habitats (Meynecke *et al*. 2010; Welch *et al*. 2014). Megalopae are tolerant of 15–45 salinity, facilitating their occupation of physically-variable inshore habitats. Chemical trace cues on daily tides and low flows may orientate immigrating larvae to nearby estuaries (Welch *et al*. 2014); though inshore advection on tides also can explain adequately their inshore movement (Condie *et al*. 1999). Conversely, large floodflows that substantially reduce the salinity of the estuarine and nearshore zones inhibit the inshore migration of megalopae.

Within the estuary, juvenile crabs are tolerant of a broad salinity range (5–45), but prefer brackish conditions (10–25) and warm waters (~20–30°C is optimal) (Welch *et al*. 2014; Alberts-Hubatsch *et al*. 2016). In tropical Australia, juvenile mudcrabs benefit from floodflows that create brackish conditions within their estuarine habitats. Mudcrabs do not emigrate to achieve ontogenetic habitat shifts from the juvenile to adult phase, thus floodflow as an emigration cue is not a driver of their distribution or survival. However, seasonal flows probably concentrate adult crabs in the lower reach of an estuary which may increase commercial catch by making them available to be caught by fishers (Robins *et al*. 2005).

Mudcrabs depend on natural flow regimes that provide ecosystem services that are supported by the monsoonal climate and pulsed flows of the tropics. Mudcrab habitat is a crucial ecosystem component that is sustained by cyclical floodflows in tropical Australia. Both the overall productivity of the coastal ecosystem and the maintenance of critical habitats are driven by the dry-season/wet-season cycles and the resultant wet-season flow regime. Mudcrabs settle within and inhabit mangrove habitats as juveniles (Alberts-Hubatsch *et al*. 2014), thus the integrity of mangrove forests is crucial. Interrupted overbank flows do not recharge the soil water and groundwater, and probably contribute to water stress in mangrove forests (Duke *et al*. 2017). As well, mangroves rely on the depositional environment sustained by sediment loads on large floods to maintain their intertidal habitat (Asbridge *et al*. 2016).

The mud crab relies strongly on estuaries to complete its life cycle. The interruption of first-season floods by in-stream dams and the reduction of both low and high floodflows by water diversion or impoundment may have a negative effect on the growth and mortality of mud crabs. In particular, the growth and survival of juveniles in the pre-wet/early season would be inhibited if first-season floods are impounded and estuaries remain hypersaline. Juvenile mud crab’s food resources are abundant in the estuarine ecotone (Duggan *et al*. 2014).

As well, in years of high floodflows, these tropical Australian ecosystems support a spike in productivity that has historically been measured indirectly as pulsed fishery catch in crustaceans, including mudcrabs (sometimes lagged by a year or two) (Vance *et al*. 1998; Meynecke *et al*. 2010). While nutrient loads and productivity in the tropical river systems are not markedly enhanced during floods, nutrients from terrestrial sources enhance primary productivity in coastal zones (Burford *et al*. 2012, 2016) and support coastal crustacean populations.

Mullet

Mullets aggregate and spawn in marine waters in the lower reaches of estuaries or adjacent coastal waters in autumn to mid-winter before moving into coastal open-water habitats (Grant and Spain, 1975b; de Silva 1980; Kailola *et al*. 1993; Halliday and Robins, 2005). The larvae enter the estuaries and small and large juveniles reside in estuarine habitats and move to upstream to freshwater reaches of the rivers (Gorski *et al*. 2015). Early juveniles move into estuaries where they use a range of estuarine and freshwater habitats (including palustrine wetlands) as they grow. Freshwater and brackish water are the preferred habitat for mullet in their juvenile and early-adult phase (ontogenetic upstream movement). Experimental studies suggest that juvenile mullet require access to fresh or brackish waters for optimal growth (Cardona 2000; Whitfield *et al*. 2012) and if these habitats cannot be accessed, their growth and survival is impacted. Adult mullet are commonly found in both estuarine and freshwater habitats; although otolith micro-chemistry shows that some individuals occupy wholly marine habitats despite available access to nearby estuaries (Gorski *et al*. 2015).

Reduction in the frequency and duration of flood events (high flows) reduces the inundation and availability of riverine floodplain and estuarine supra-littoral habitats used prolifically by juvenile mullet during the wet season. Not only is the extent of habitat reduced, but the flooded habitats often are hot-spots for productivity (Faggotter *et al*. 2013; Jardine *et al*. 2013; Burford *et al*. 2016; Ward *et al*. 2016) and enhance the productivity of the ecosystem at key stages of the life history of mullets. Flow reduction may also negatively impact mullet through a reduction in cues (e.g. flow volume, salinity) for movement out of low salinity waters to the estuary and nearshore for spawning. Therefore, a reduction in river flow of the tropical Australian monsoon-driven rivers may result in detectable changes in population size and dynamics of mullet.

Barramundi

Barramundi are a catadromous (non-obligatory) fish with a larval life history strategy. Spawning occurs in the lower estuary and adjacent coastal zone before the on-set of the wet season but can extend between September to February. Their downstream movement to these spawning areas may be stimulated by rising water temperature; increasing photoperiod and first-season low flows that connect riverine waterholes and reduce salinity in the upper estuary (Robins and Ye 2007). Larvae spend about three weeks in inshore marine waters and brackish waters optimise their development (Robins and Ye 2007); the developing juveniles move into estuaries. Although juvenile barramundi can survive as permanent estuarine residents, they thrive in semipermanent wetlands, tidal creeks and freshwater riverine habitats (Russell and Garrett 1983, 1985). Postlarvae and small juveniles attempt to access freshwater habitats adjacent to and upstream of estuaries (Russell and Garrett 1983; Halliday *et al*. 2012).

The recruitment of barramundi to nursery habitats is moderated by floodwater access to supra-littoral, lagoon and riverine habitats. Both longstream and floodplain connectivity require significant flood heights that allow fish to travel upstream or out of the river channel in search of habitats that increase their survival and growth during their juvenile stage. Peak spring tides also may facilitate access to supra-littoral habitats, supplemented by small early-season floods. Juvenile and adolescents remain in ephemeral/perennial freshwater habitats from months to years until flood-moderated connectivity liberates them to return to the river before they emigrate downstream to the estuary and nearshore zones, often as adults to spawn. The annual wet season and subsequent runoff is a major determinant of their access to juvenile habitats and connectivity back to the coastal zone. There is a correlation between seasonal floodflow and juvenile recruitment strength and subsequent adult stocks, possibly lagged by 1–5 years (Robins *et al*. 2005; Balston 2009; Halliday *et al*. 2012).

Seasonal inundation of remnant palustrine habitats and the inundation of supra-littoral habitats create freshwater hot-spots for juvenile barramundi (Faggotter *et al*. 2013; Jardine *et al*. 2013; Burford *et al*. 2016; Ward *et al*. 2016), enhancing growth and survival via seasonal food accessibility and optimal environmental conditions (Russell and Garrett 1985). Reduction in the frequency and duration of flood events (high flows) would reduce the availability of riverine floodplain and estuarine supra-littoral habitats used prolifically by juvenile barramundi during the wet season. Reduced duration of high flows would inhibit the movement of large juvenile back to the river or estuary.

The interruption of first-season floods by in-stream dams and the reduction of both low and high floodflows by water diversion or impoundment will impact emigration cues (flow and salinity) for year-old and older fish in the subsequent wet-season. Reduced flows will have a negative effect on the downstream movement of adult barramundi to spawn (Robins and Ye 2007). Physical barriers to longstream and cross-floodplain connectivity such as in-stream dams and barrages and landscape modification would interrupt barramundi movements to freshwater habitats and their return to the estuary/nearshore. Any anthropogenic reduction in river flow of the tropical Australian monsoon-driven rivers may result in detectable changes in population size and dynamics of barramundi.

Mangroves

Throughout their range, mangroves create the land/ocean interface over tens of thousands of kilometres of coastline. The accretion or retreat of the interface depends on deposition and erosion disturbance. Where mangroves are prolific, historical flow regimes have sustained the delivery of sediments from land runoff to estuaries and shores promoting larger extents of mangrove habitat and mangrove growth (Duke and Wolanski 2001; Lovelock *et al*. 2007). Sedimentation within coastal habitats changes the surface height of soils relative to sea level, extending intertidal habitat for mangrove colonisation (Gilman *et al*. 2008; Asbridge *et al*. 2016). Mangrove forests can grow rapidly on newly deposited sediments, and recovery from storms and other disturbances can be rapid, although some species are more resilient than others (Lovelock *et al*. 2012).

Mangroves are dependent on access to freshwater for their survival. Within an estuary, a sequence in mangrove species occurs both within the tidal profile (temporal inundation) and along the longstream extent of the estuary (salinity gradient) (Duke *et al*. 1998; Vance *et al*. 2002). They are capable of switching their sources of water, from soil water to groundwater, back to soil water, depending on the availability of the freshest source of water (Ewe *et al*. 2007; Wei *et al*. 2012; Santini *et al*. 2014). Freshwater flow into mangroves reduces salinity, increases the water content of soils and delivers sediments and nutrients; and creates conditions that are favourable for plant production (Smith and Duke 1987; Ball 1998; Lovelock *et al*. 2012). Mangroves are tolerant of inundation by high floodflows, even for extended periods. Over-bank floods recharge groundwater supplies following usually parched dry-season conditions in mangrove habitats, and providing a critical freshwater source for future months (see Wei *et al*. 2012; Santini *et al*. 2014).

The reduction of low to high floodflows by water diversion or impoundment will impact the terrigenous-sourced sedimentation regime and floodplain inundation of the estuarine ecosystem. Reduced sedimentation will cause coastal erosion and the loss of mangrove habitat (Asbridge *et al*. 2016). Reduced over-bank inundation will reduce the recharge of soil water and together with evapotranspiration stress during the dry-season may cause dieback and lass of mangrove forests (Duke *et al*. 2016; Lovelock *et al*. 2017). As well, a reduction in freshwater in-flow to estuaries (perhaps first-season floods) will impact the longstream salinity (brackish ecotone) and alter the extent and composition of mangrove communities with consequences for estuarine and coastal food webs.

Summary

In tropical Australian rivers, monsoon-driven flow characteristics, such as seasonality and magnitude, have supported the life histories of various estuarine fauna that have co-evolved with the natural flow-characteristics of the tropical rivers. Robust relationships between flow magnitude and the abundance of several species have been identified across northern Australia; in general, the larger the flow, the more abundant the fishery species (Table 8).

Table 8. Percent attributable to or correlation of annual catch for some commercial fish and crustacean species for which abundance in coastal ecosystems is linked to river flow. The percent of commercial catch attributable to flow often varies by river. (SOI = southern oscillation index)

Species	*Late-dry season flow*	*Wet season flow*	*Data source*
Banana Prawns	9-33%	45-70%, river dependent	Vance *et al*. 1985
	No relationship	0-68%, river dependent	Vance *et al*. 2001
	No seasonal component	12-42%, river dependent	Bayliss *et al*. 2014
Mudcrabs	No relationship	Negative – summer rain	Robins *et al*. 2005
	Not investigated	30-40%, SOI (rainfall)	Meynecke *et al*. 2006, 2010
	Not investigated	Positive – annual; Mitchell and Adelaide Rivers (lagged)	Meynecke *et al*. 2010
	Not investigated	Positive – wet season (lagged)	Meynecke and Lee 2011
Mullet	Not investigated	Positive – winter and annual	Loneragan and Bunn 1999
	Not investigated	Positive – rainfall and SOI	Meynecke *et al*. 2006
	Negative – winter flow	12-41% – total and minimum	Gillson *et al*. 2009
Barramundi	No relationship	38% – (lagged 3 to 4 years)	Robins *et al*. 2005
	Negative - extreme rainfall	Positive – annual (lagged)	Balston 2009
	52-57%- effort plus rain	48-91% – fishing effort plus flow	Halliday *et al*. 2012

Modification of flows will affect the abundance of key species via impacts on their life history requirements. Careful management of the modification of flow characteristics has the capacity to minimise the impacts on the abundance and vitality of the populations of key fishery species with a view to maintaining fishery yield. Water resource infrastructure will need to be constructed with 'environmental flow' features incorporated to support the effective management of flows, which best mimic annual and seasonal natural flow sequences that sustain ecosystem services downstream.

5. Conceptual models – ecological data

We convened a workshop (24th May 2017) to explore the components of a conceptual model for all life history stages of Banana Prawns. We chose the Banana Prawn (*Penaeus merguiensis*) as it is an animal which is one of the most studied species with an inshore/offshore – juvenile/adult in tropical Australia within the scope of the NPF (Vance and Rothlisberg, in review). Banana Prawns have both a high economic value, and have been much studied over the decades: resulting in a significant amount of information being available on each phase of their life history. Vance *et al*. (1985; and subsequent papers) developed a conceptual model of the life history of the Banana Prawn which since has well-served our understanding of the contribution of the life phases of the species to its biology and economic potential (see Figure 6). We have updated the model incorporating a compilation of results from research in the Gulf of Carpentaria since the 1990s (Figure 7). Moreover, recent studies as part of the TRaCK project, added considerable knowledge to the ecological interactions and ecosystem services that support a Banana Prawn population (Burford *et al*. 2010, 2012, 2016).

The workshop was attended by Professor Michele Burford, Dr. Leo Dutra, Rob Kenyon, Margaret Miller, Chris Moeseneder and Dr. Eva Plaganyi. Outputs from the workshop have been shared with Dr. Peter Rolthisberg and Dave Vance, retired CSIRO biologists who maintain a strong interest in the biology of Banana Prawns. In fact, Vance and Rothlisberg (in review.) recently have completed a manuscript providing a comprehensive review of all aspects of the biology and fishery production of *P. merguiensis* and *P. indicus*.

Dr Plaganyi uses 'Models of Intermediate Complexity for Ecosystem assessment' (MICE models) to explore the relationship between natural and anthropogenic drivers, and abundance and catch of fishery species. The outcome of the workshop was to develop three versions of the conceptual model graduated by floodflow regime: low flow, moderate flow and high flow versions. For each model, one aspect of complexity is removed under this strategy. The approach recognised the fact that the rivers of the GOC are very different systems under different floodflow regimes. For example, the 1-in-50 year flood of 2009 turned the estuary and surrounding floodplains and saltflats of the Norman River into a large shallow freshwater lake for a period of >2 months (Burford *et al*. 2012, 2016). The approach also recognises that the MICE models could be confounded by incorporating a continuous spectrum of flow in the model itself; better to remove a confounding variable and model three different flow regimes.

Dr Plaganyi is adapting the conceptual models to a working MICE model that provides a different perspective on multispecies and ecosystem-level predictions. On outline of the structure and links of her model is provided in Figure 8.

After follow-up discussions, the three models were split again to represent each sub-phase of the life history of the Banana Prawn:

- offshore spawner to benthic postlarvae (one model, as this phase in not flow dependent) (Figure 9);
- upper-estuary benthic postlarvae/small juveniles to lower-estuary large juveniles (Figure 10 to 12);
- lower-estuary large juveniles to nearshore adolescent/sub-adult prawns (Figure 13 to 15); and
- sub-adults to offshore adult Banana Prawns (Figure 16 to 18).

The latter three life history phases are described for low-, moderate-, and high-flow conceptual models. These models are information-rich and the ability to include all the relevant information in the draft of the conceptual model is limited. Consequently, we have annotated the flow-chart components in each of the models to refer to the scientific references that explain each aspect of the environmental drivers impacting that stage of the life history. The reference list details the publications used to stimulate our drafting of the new models. An outcome of the model revision was the need to more fully probe aspects of each stage of the Banana Prawn's life history.

The models are not as ‘linear’ as the original full life-cycle model of Vance *et al*. (1985). They lay out the impacts of environmental and biotic drivers on each life history stage; and provide a qualitative rating of each affect. The models are meant to stimulate their application to actual mathematical models ensuring that all aspects that impact the life-stage of a Banana Prawn are accounted for.

A second workshop (1st August 2017) was convened to review the outcomes of the first one. It was attended by Professor Michele Burford, Rob Kenyon, Chris Moeseneder, Dr. Eva Plaganyi and Dr. Peter Rothlisberg. The draft models (as described above) were presented to this workshop and gained broad support. An outcome of the second workshop was to develop a mimic of the linear model of Vance *et al*. (1985); updated with the last 30 years of information (Figure 7). Thus, a direct comparison of the new model with the old can be made.

At the ecosystem level, the models provide details of the impacts of flow, nutrient transport, floodplume deposition and productivity stimulation on each phase of the Banana Prawns life history. Predator species interact with Banana Prawns differently under different flow and turbidity regimes.

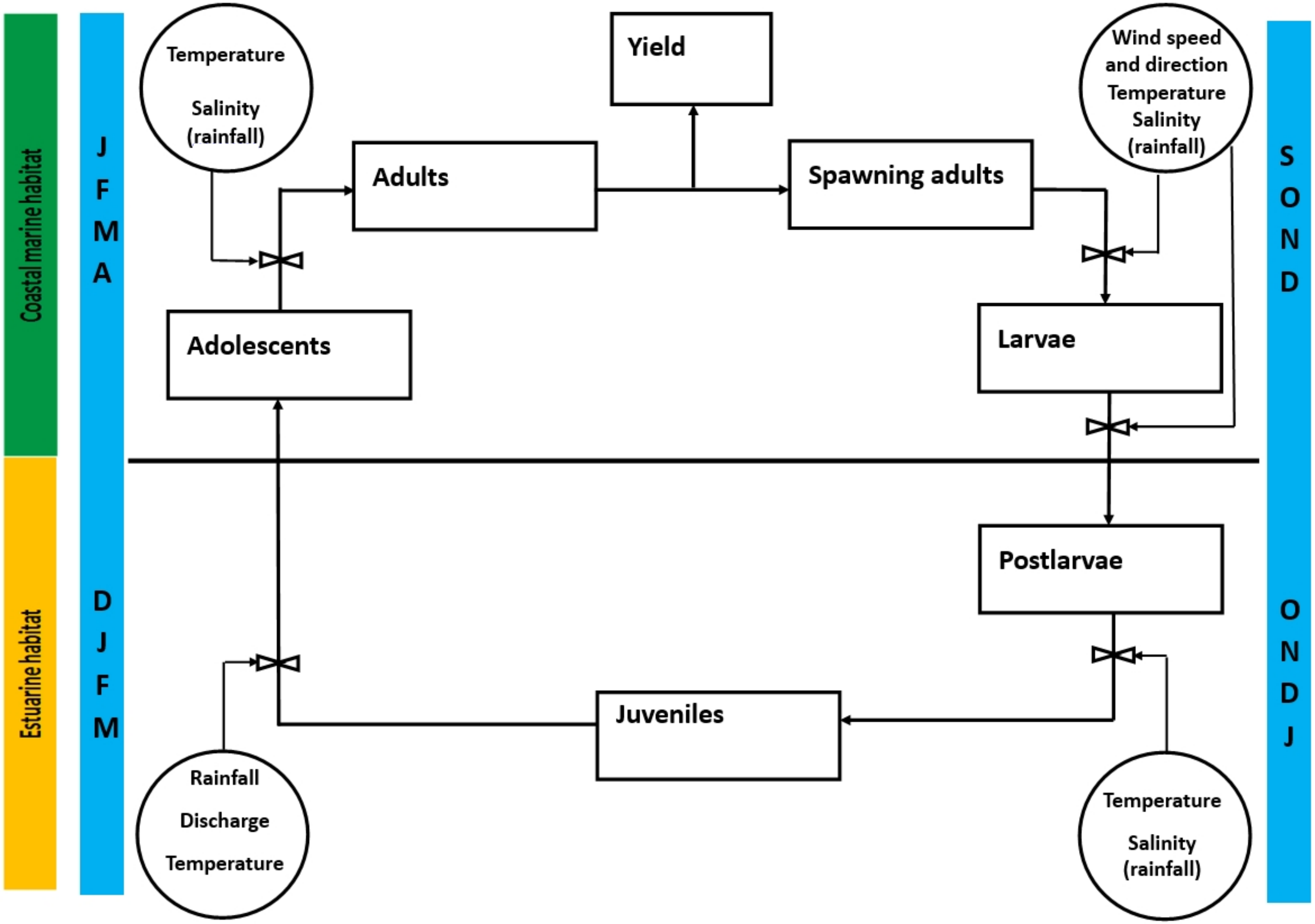

Figure 6. Life history model of *Penaeus merguiensis* showing factors that determine the abundance and survivorship of key phases the cycle, as understood in the mid-1980s (redrawn from Vance *et al*. 1985 with permission of the senior author). The letters in the blue columns represent months (the late dry season- September to December (S,O,N,D); the wet season- January to March (J,F,M).

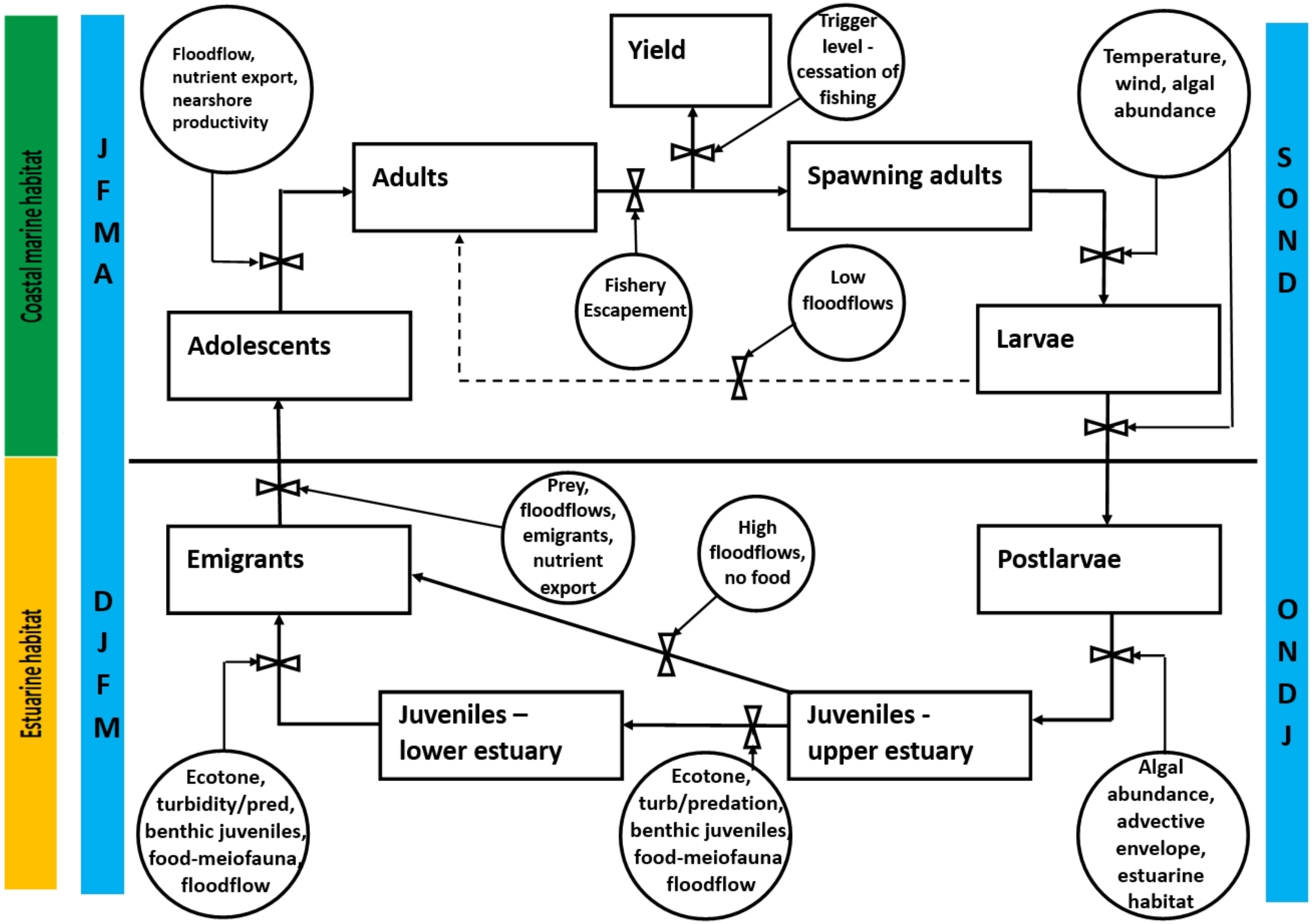

Figure 7. Life history model of *Penaeus merguiensis* showing abiotic and biotic factors that determine abundance and survivorship of key phases the cycle. (Turbidity/pred and turb/predation refer to turbidity and predation) (drawn with the benefit of concepts from Vance *et al*. (1985)). The letters in the blue columns represent months (the late dry season — September to December (S,O,N,D); the wet season — January to March (J,F,M).

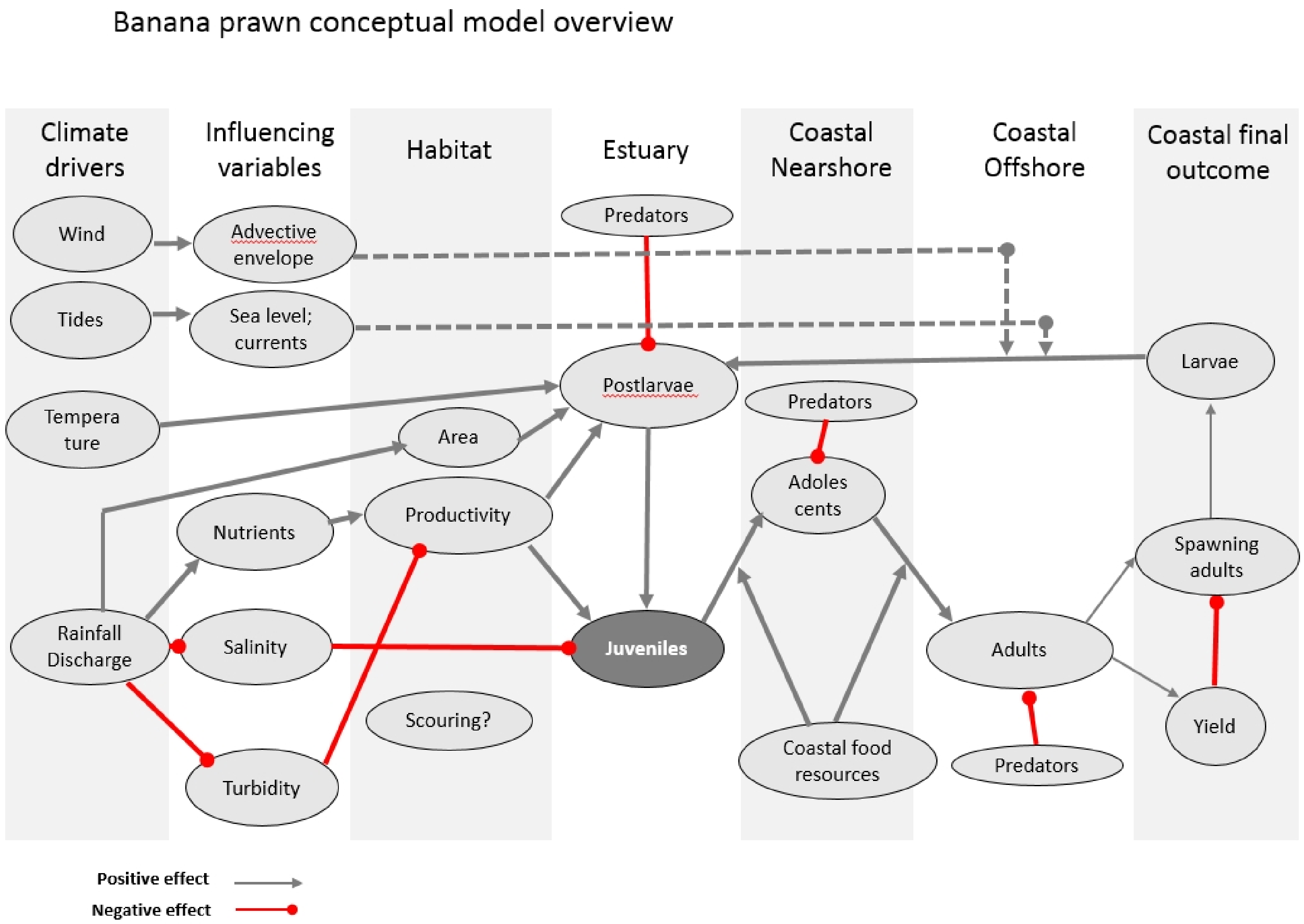

Figure 8. Representation of a Model of Intermediate Complexity for Ecological assessment model (MICE) of the life history and ecosystem interactions of *Penaeus merguiensis* showing abiotic and biotic factors that determine abundance and survivorship of key phases of the cycle.

The conceptual models shown in the following pages represent the outcome of the workshops described previously. They represent four phases within the life history of Banana Prawns; and for three phases of the prawn's life history at three levels of flood-flow. The representation of three levels of flow allow more detailed summation of the factors affecting the population of prawns within estuaries and nearshore.

The "offshore spawner to benthic postlarvae" phase is the spawning, larval development and inshore larval advection segment of the life cycle. This phase is not flow dependent; apart from when high floodflows prevent postlarvae moving into a freshwater estuary.

The "upper-estuary benthic juveniles to lower-estuary larger juveniles" phase follows the settlement of postlarvae from the pelagic to benthic environment in the mid-to-upper reaches of estuarine tributaries, the prawn's growth and movement downstream and their residence and survival in the lower estuary. These processes are depend on flood-flow and are described for low, moderate and high flows.

The "lower-estuary large juveniles to nearshore adolescent/sub-adult prawns" phase follows the movement of juvenile prawns from the upper estuary of smaller tributaries to lower estuarine reaches, often prompted by salinity reduction due to freshwater flows, but sometimes due to ontogenetic behaviour alone. This phase is an emigration phase from the estuary that is highly flow dependent. In general, high flows stimulate emigration *en masse*, while ontogenetic emigration is the primary driver of the nearshore prawn population under very low flow conditions. The exact nature of the relationship between flow-level and emigration cue (e.g. linear or stepped) remains to be fully explored.

The "nearshore sub-adults to offshore adult Banana Prawns" phase describes the movement of reproductive-aged prawns from shallower nearshore waters to deeper offshore waters where they are fished. The offshore emigration is described for low, moderate and high flows.

The conceptual models are composed of green, red and yellow component circles. The green circles represent facilitative ecological processes likely to enhance the prawn population. The red circles represent restrictive ecological processes likely to reduce the prawn population. Yellow circles represent ecological and population level outcomes that results from the interplay of the summarised ecological processes. The size of the circles is indicative of the extent of impact on each facet of the ecological processes effecting them under each of the three flow regimes.

The conceptual models are not meant to be static; they were developed to stimulate thought and comprehension of the intricacies of Banana Prawn population dynamics. The models were developed by weight of evidence drawn from peer-reviewed publications and the expertise of workshop attendees. They enhance the interpretation of the ecology of Banana Prawns to arrive at the best conclusions about the processes that determine eventual fishery abundance. The conceptual models are drafted in a way that allows them to be updated as new research outcomes improve our understanding of the habitat processes and environmental drivers that contribute to the ecological sustainability of Banana Prawns.

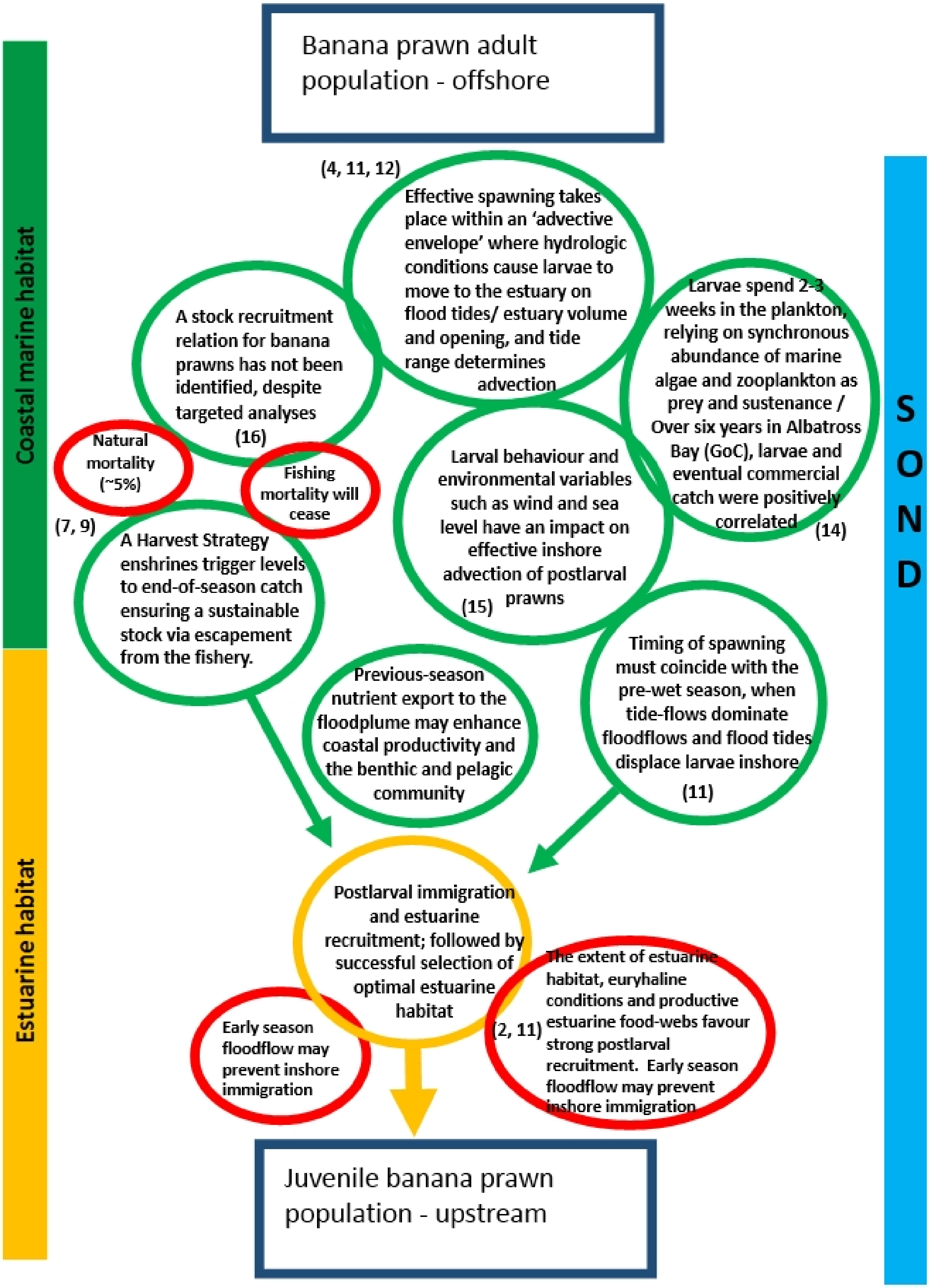

Figure 9. The life history and ecosystem interactions of *Penaeus merguiensis* showing abiotic and biotic factors that determine abundance and survivorship of offshore spawning to 'estuarine settlement as benthic postlarvae' phase of the cycle.

Literature used to reference the conceptual models.

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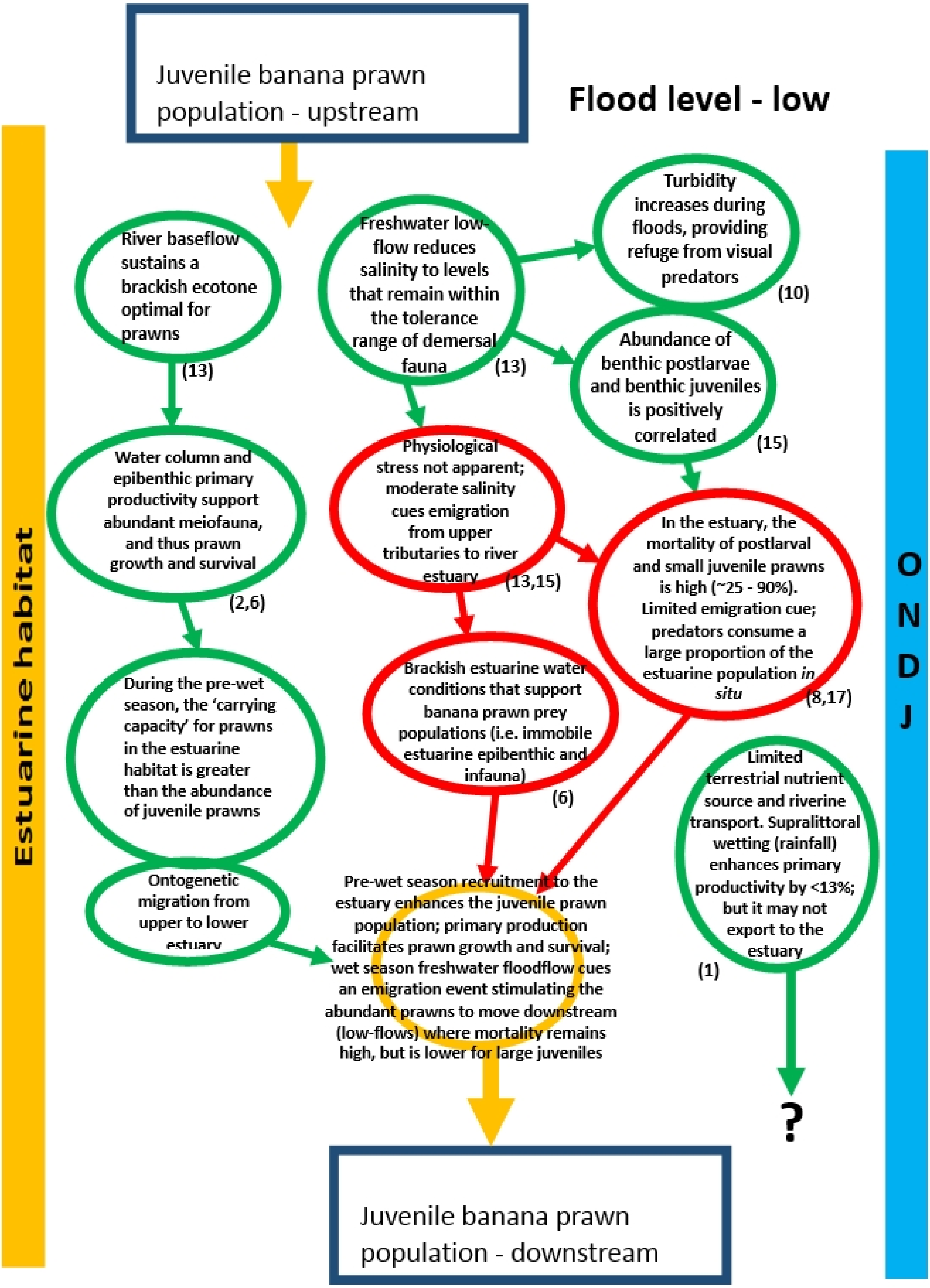

Figure 10. The life history and ecosystem interactions of *Penaeus merguiensis* showing abiotic and biotic factors that determine abundance and survivorship of the 'benthic postlarvae – upper estuary' to 'benthic juveniles - lower estuary' phase of the cycle (low floodflows).

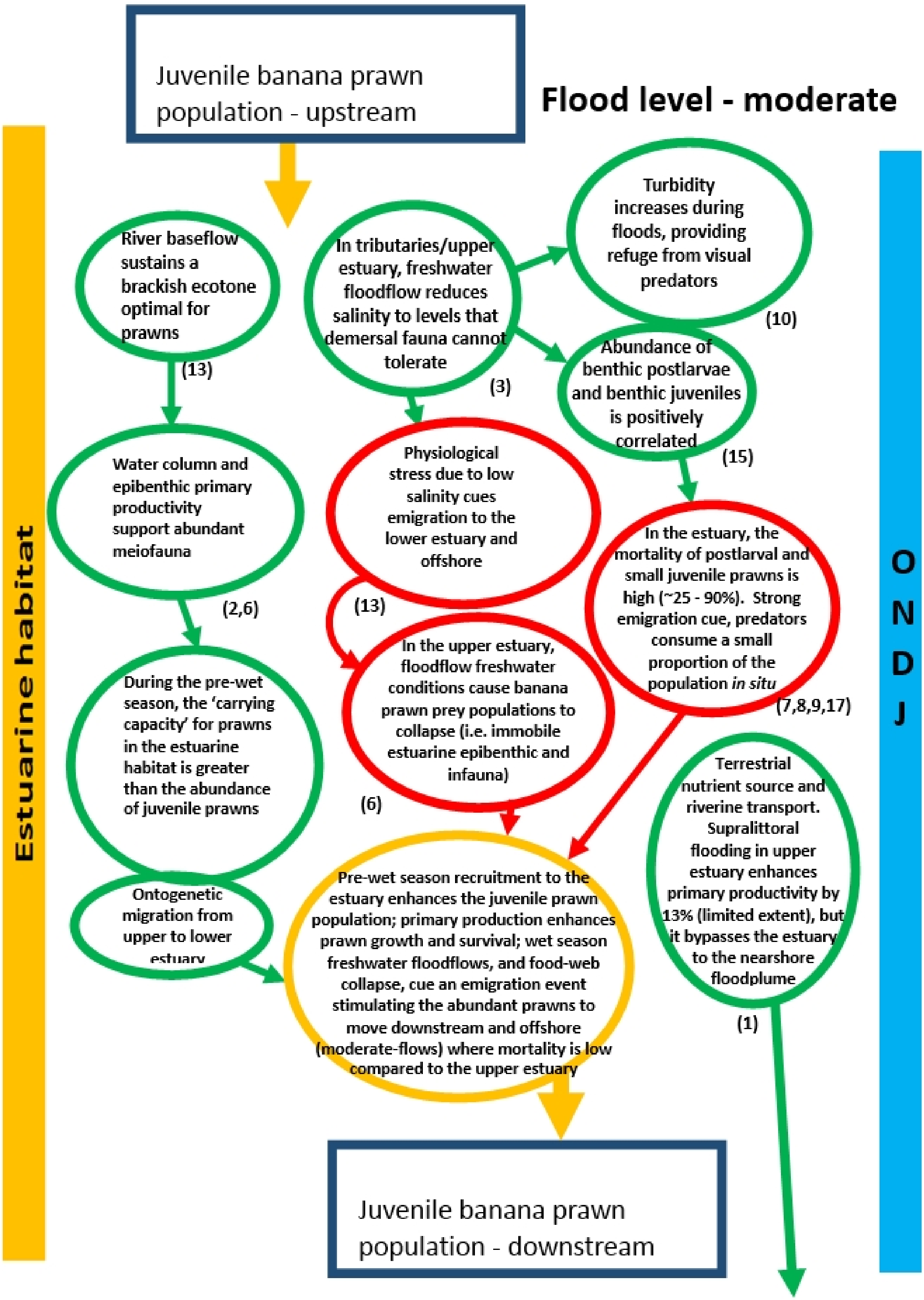

Figure 11. The life history and ecosystem interactions of *Penaeus merguiensis* showing abiotic and biotic factors that determine abundance and survivorship of the 'benthic postlarvae – upper estuary' to 'benthic juveniles - lower estuary' phase of the cycle (moderate floodflows).

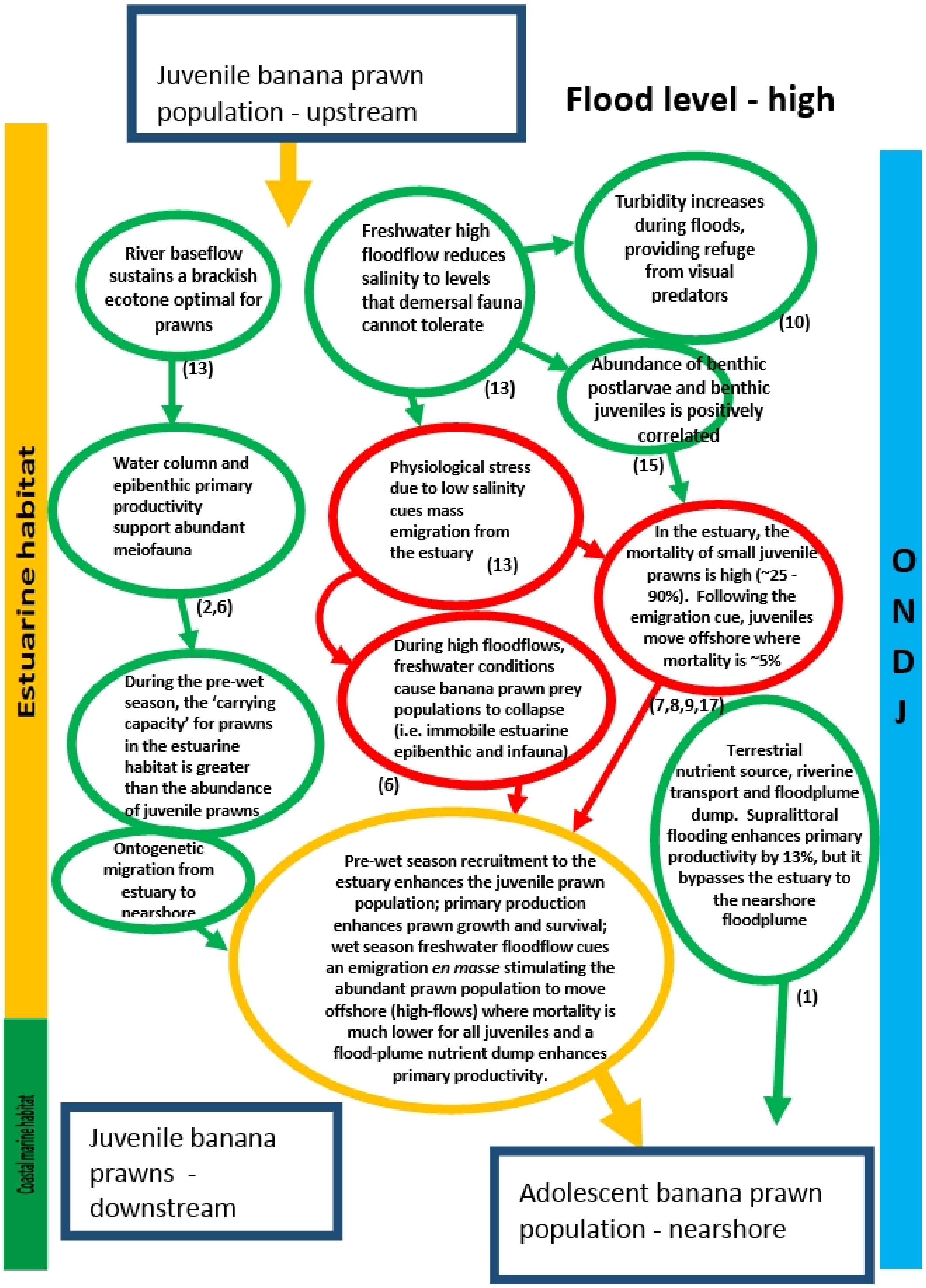

Figure 12. The life history and ecosystem interactions of *Penaeus merguiensis* showing abiotic and biotic factors that determine abundance and survivorship of the 'benthic postlarvae – upper estuary' to 'benthic juveniles - lower estuary' phase of the cycle (high floodflows).

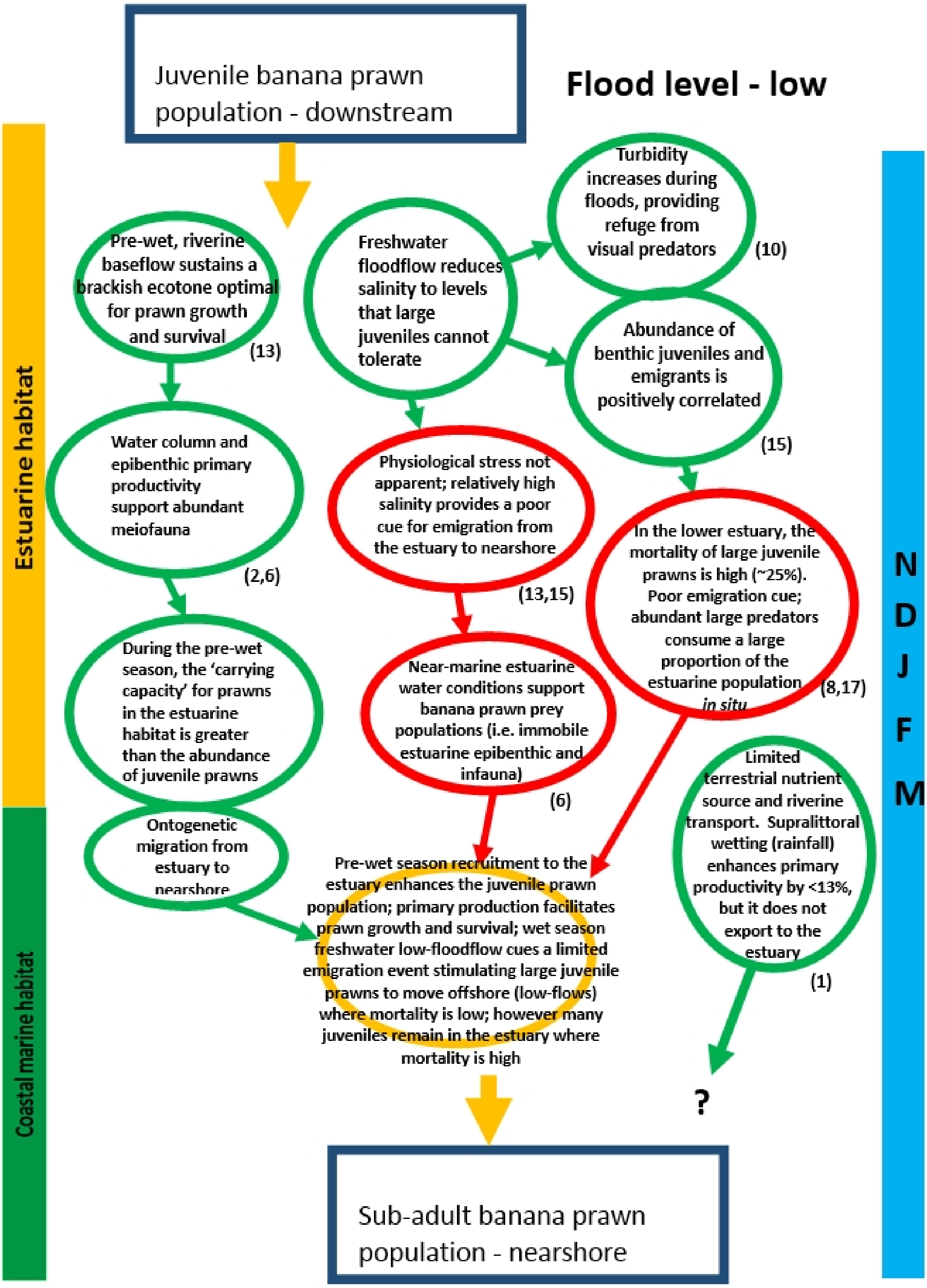

Figure 13. The life history and ecosystem interactions of *Penaeus merguiensis* showing abiotic and biotic factors that determine abundance and survivorship of the 'benthic juveniles - lower estuary' to 'emigrant sub-adults - nearshore' phase of the cycle (low floodflows).

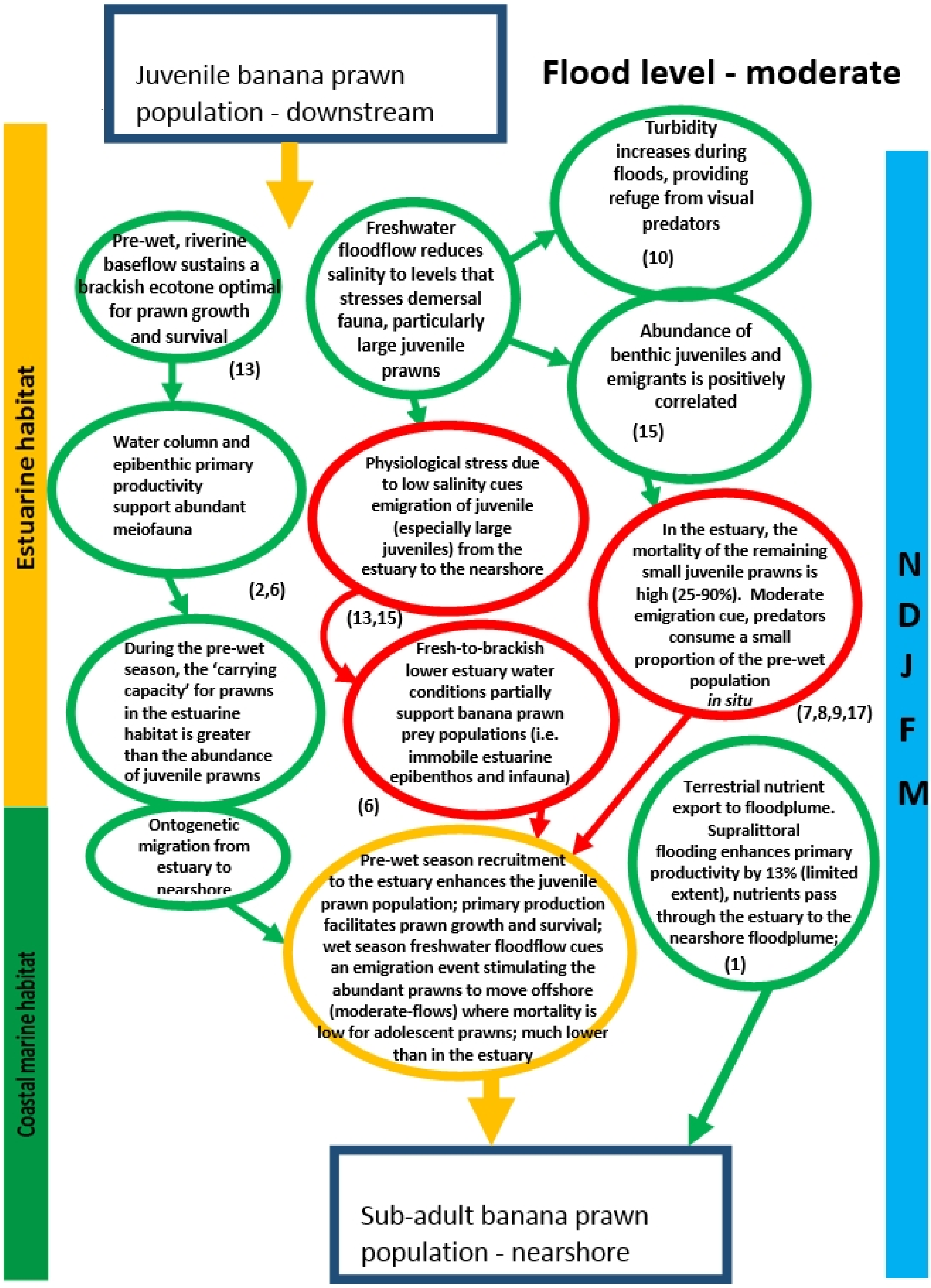

Figure 14. The life history and ecosystem interactions of *Penaeus merguiensis* showing abiotic and biotic factors that determine abundance and survivorship of the 'benthic juveniles - lower estuary' to 'emigrant sub-adults - nearshore' phase of the cycle (moderate floodflows).

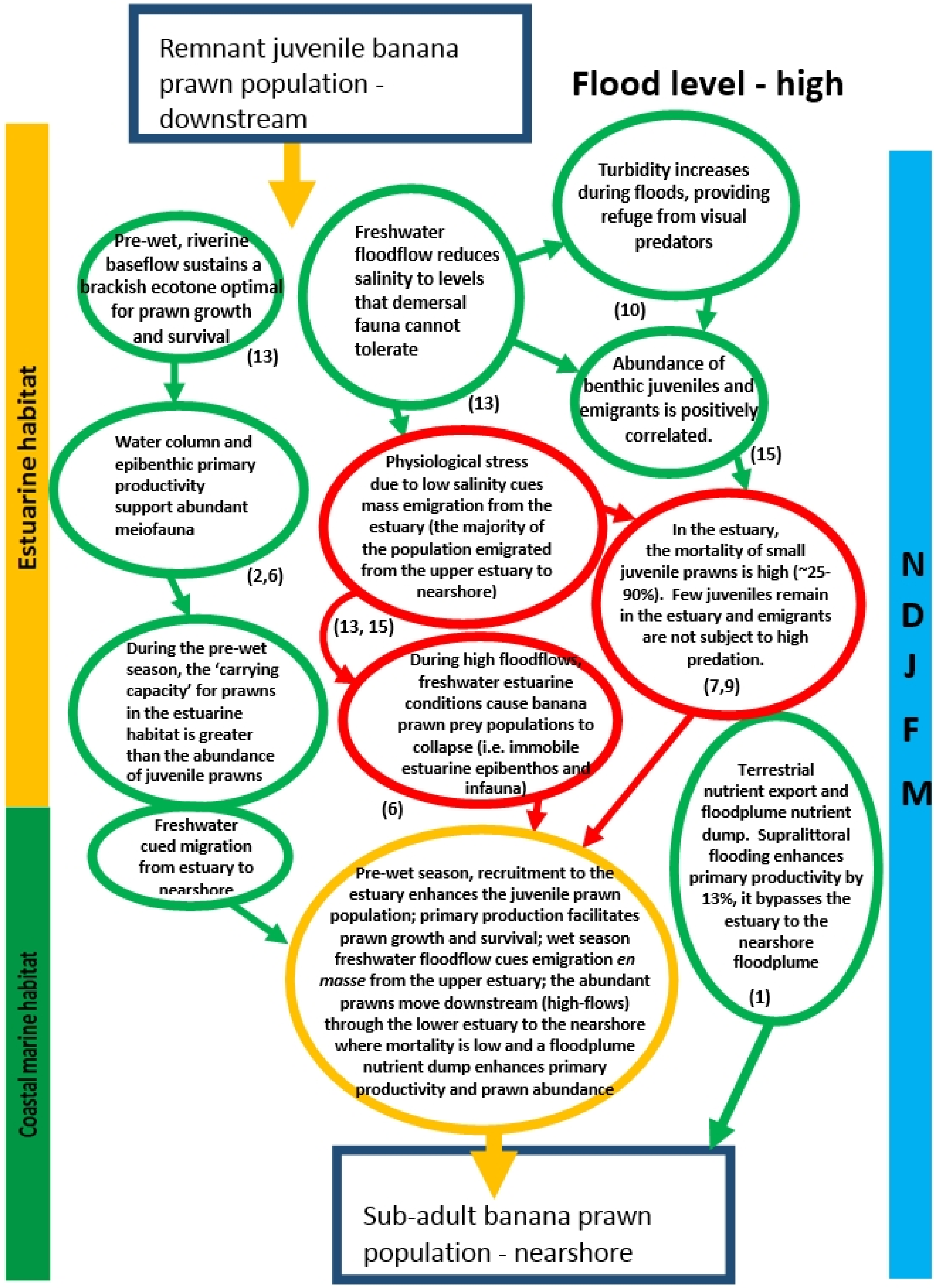

Figure 15. The life history and ecosystem interactions of *Penaeus merguiensis* showing abiotic and biotic factors that determine abundance and survivorship of the 'benthic juveniles - lower estuary' to 'emigrant sub-adults - nearshore' phase of the cycle (high floodflows).

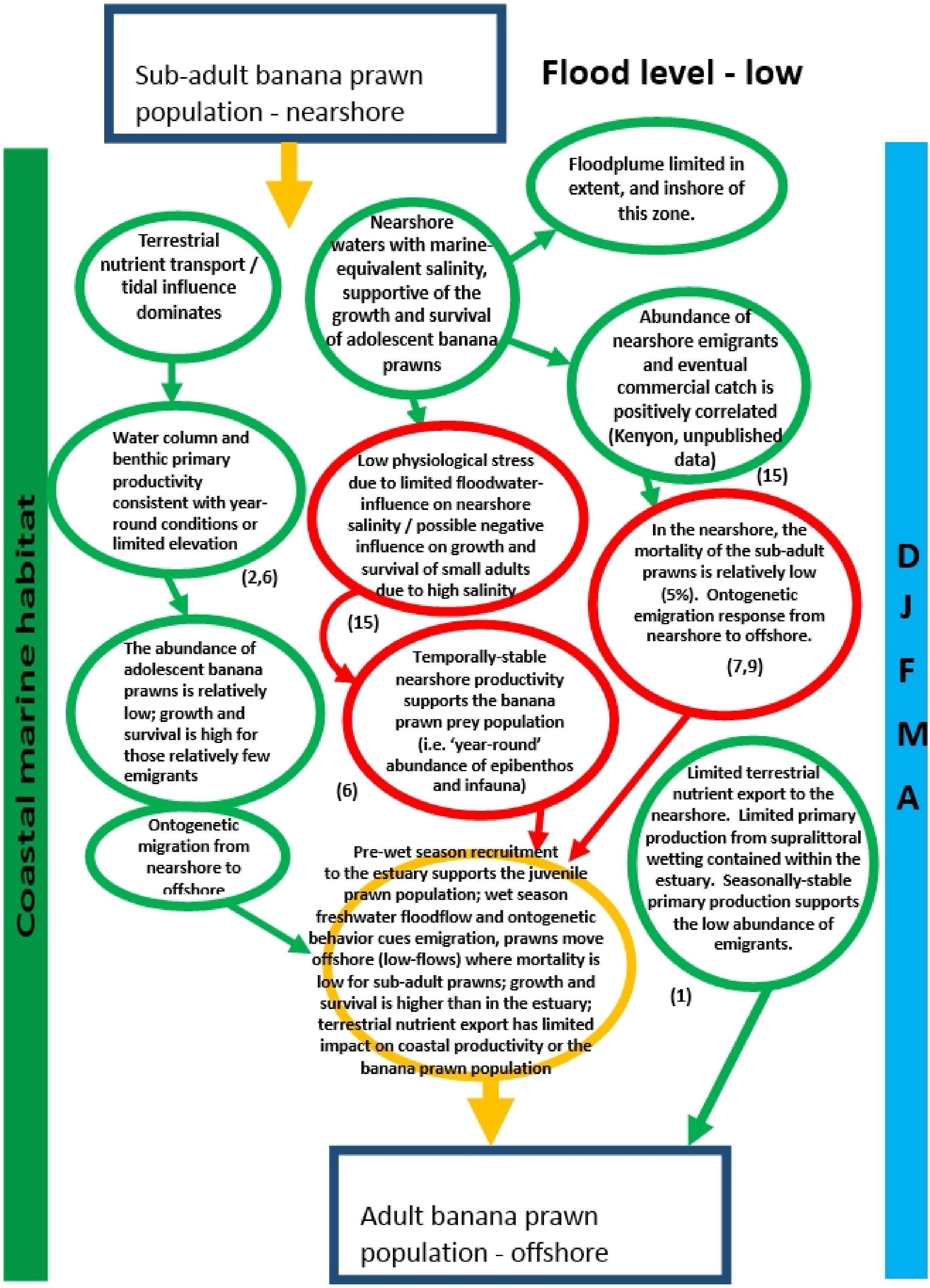

Figure 16. The life history and ecosystem interactions of *Penaeus merguiensis* showing abiotic and biotic factors that determine abundance and survivorship of the 'sub-adults - nearshore' to 'adults – offshore' phase of the cycle (low floodflows).

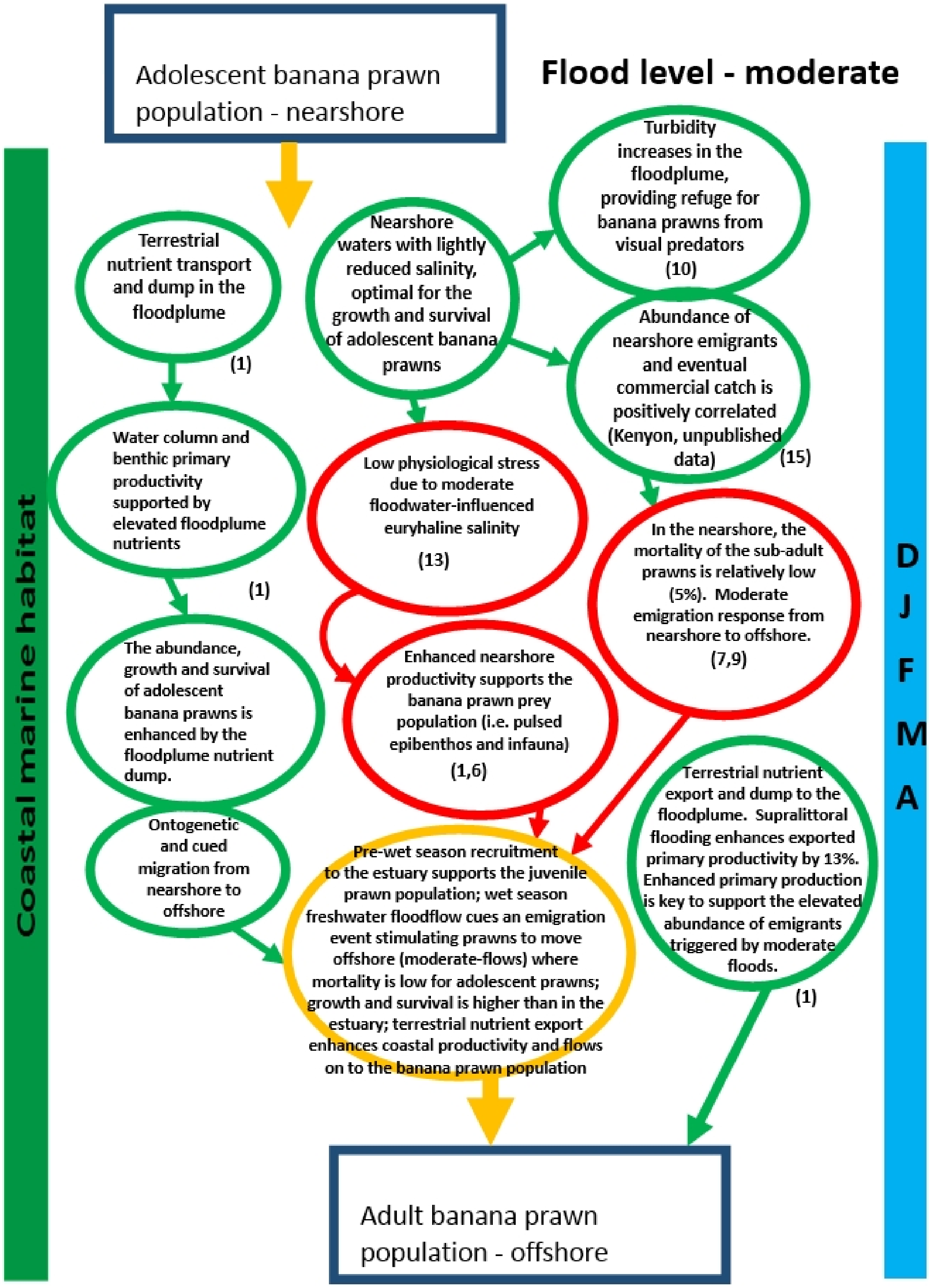

Figure 17. The life history and ecosystem interactions of *Penaeus merguiensis* showing abiotic and biotic factors that determine abundance and survivorship of the 'sub-adults - nearshore' to 'adults - offshore' phase of the cycle (moderate floodflows).

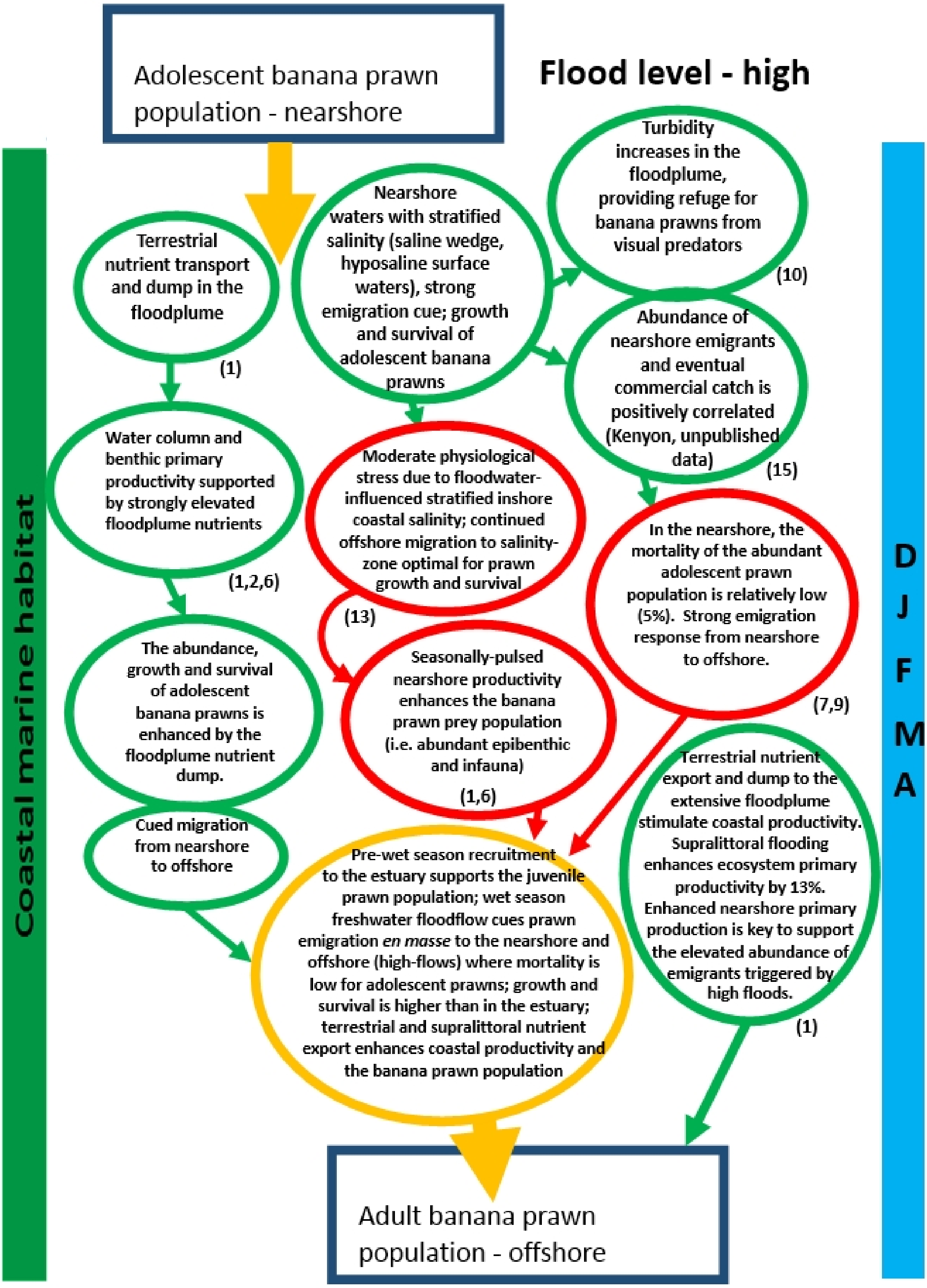

Figure 18. The life history and ecosystem interactions of *Penaeus merguiensis* showing abiotic and biotic factors that determine abundance and survivorship of the 'sub-adults - nearshore' to 'adults – offshore' phase of the cycle (high floodflows).

Discussion

The study identified four types of infrastructure development proposed within catchments and near-coasts of the NPF that have a clear risk to natural catchment flows and water cycles. Disruption to natural overland and river-channel flows has the ability to impact the sustainability of prawn fisheries and other fisheries that are dependent on highly seasonal, monsoon flows that have supported ecosystem services in tropical estuarine and coastal marine habitats for millennia. These infrastructure developments are:

- Water resource development,
- Coastal aquaculture placements,
- Mining infrastructure placement and operation, (water extraction and the footprint of port infrastructure), and
- Hydro-electric power generation associated with in-stream water storage.

Water resource development operates under three main categories:

- In-stream storage, particularly large dams as well as barrages and other infrastructure. The impacts of dams are amenable to hydrologic modelling and reduction in flows or change in flow characteristics can be estimated accurately,
- Off-stream storage; benched or pumped off-take, benched off-take operates during high flows, but pumping from low flows is possible,
- Groundwater extraction and recharge (including enhanced recharge during the wet season).

Large-scale aquaculture development has four significant aspects that may impact water flows or coastal habitats (in addition, the road and transport infrastructure as described below for mining is relevant for aquaculture):

- Possible in-stream or off-stream storage to supply freshwater requirements,
- Day-to-day release of tail-water from pondage to the natural environment (via water quality treatment),
- Escape of pathogens and pollution such as anaerobic toxic sediments,
- Large pondages with risk of wall-breach that would allow the escape of large volumes of water (and farmed prawns) to estuaries and coasts.

Mining infrastructure and operation impact both riverine and groundwater sources, as well as having a coastal-and-foreshore port operations footprint that likely removes and modifies coastal habitats. The main potential mining impacts are:

- Mines require water to operate and extract it from overland-riverine flows. Usually, small in-stream dams are built to store river flows, and in the wet-dry tropics, the only volumes of water feasible to harvest are wet-season floodflows,
- Groundwater may provide a large proportion of a mine’s water requirements. Groundwater harvest may lower the local water table and may impact river baseflows during the dry season in response to a low water table,
- In remote tropical Australia, road infrastructure is sparse and if available, not bituminised. Access for large equipment, volumes of freight and the local transport of mine equipment is often via coastal waters and a local port or barge landing. Port construction necessitates the removal of intertidal and sub-littoral habitats, often within sheltered estuaries. Ore transhipment requires large scale ports which can be coastal or estuarine. The impacted habitats often are mangroves, seagrasses and corals; all productive habitats for the juvenile phase of fishery species. In conjunction, estuaries may require dredging and spoil dumping to facilitate deep-draft shipping; perhaps modifying local tidal flows and

advective processes, with possible impacts on estuarine immigration of the larval phase and emigration of the juvenile phase of fish and crustaceans.

Hydroelectric power generation requires a consistent quantum of water under high pressure to drive the turbines and armatures that generate electricity:

- Turbines to drive hydroelectric generation require consistent water flow. Water requirements can be met by the transfer of water from a large dam through the turbine and eventual release below the dam into the original river channel. The ecological implications of a consistent elevated flow of water below the dam are considerable. As highlighted in this report, rivers in the Australian wet-dry tropics often have very low baseflow or cease to flow during the dry season. Perennial (year-round) water release to sustain electricity generation elevates river flow downstream, including the estuary, and can decrease estuarine salinity to level below the physiological tolerance of the juvenile phase of fishery species. Currently, this situation occurs in the estuary of the Ord River where salinities <5 render much of the upper- to mid-estuary uninhabitable for red-legged Banana Prawns (or inhabited at low densities); nearby estuaries have abundant populations of Banana Prawns (Kenyon *et al*. 2004). Pusey *et al*. (2011) estimate that water flow in the Ord River below Lake Argyle is elevated by 430% year round. The last third of the dry season is the critical period of recruitment of the postlarvae and juveniles of many fishery species to estuarine nursery habitats and if salinity is too low early in the season, their physiological tolerances will prevent entry to the estuary. In addition, constant outflow of water may limit the tidal exchange in an estuary and prevent the immigration of postlarvae and early juveniles by mechanical means; a down-estuary current.

(Note also that the situation of perennial elevated flows is now incorporated as 'ecological baseflow' into the legislated instrument — the Water Operation Plan that governs the water allocation and management in the Ord River catchment (Department of Water. 2006; Anon 2013). This case is discussed in more detail elsewhere in this report.)

A short description of the hydrodynamic impacts of WRD follows:

In-stream storage

The degree of modification of natural flows by in-stream storage can be well researched and for a specific dam, well understood. Hydrologic models quantify the disruption or reduction in the seasonality and magnitude of floods. Based on the outcomes of the hydrologic analyses, water allocations for natural flows and urban/industrial requirements are made. Flow volumes in excess of these requirements can be allocated to economic initiatives such as irrigated agriculture.

In-stream dams have little impact on major floods, the total volume of the floodwater event is much greater than the volume of the dam — they pass over the dam spillway. In-stream dams have considerable impacts on early wet-season flows and low to moderate floods, and the way baseflow tails off at the end of the wet-season. The seasonal pattern of floodflows is interrupted by in-stream dams; i.e. the shape of the annual flow hydrograph. Under 21st century water management initiatives, environmental flows are instigated to reinstate natural cycles. Modern dam construction incorporates facilities that allow the release of water to sustain those natural cycles. Once constructed, the dam operators are required to release water to mimic the natural seasonality of floods, such as early wet-season floodflows. If dam levels are below spillway level, early wet-season floods are trapped in the dam.

During the pre-wet, tropical Australian estuaries are marine-salinity, if not hypersaline. High salinity is not optimal for the growth and survival of some estuarine species, such as Banana Prawns (Staples and Heales 1991). Banana Prawn postlarvae recruit to the mid-upper estuary of tropical rivers and their tributaries during September to March each year. Early season low flows (e.g. November–December) prior to the onset of the wet season may reduce upper-estuarine salinity by 10–15 units; conditions that support the juvenile phase of Banana Prawns. If these early season floods are captured by a dam, then the estuary remains hypersaline and the conditions for growth and survival of juvenile Banana Prawns are non-optimal. The seasonal cycle of a brackish estuary supporting an abundant population of fast-growing juvenile Banana Prawns that eventually are cued to emigrate by a large flood during the wet season is interrupted. The large flood may occur, but the population of prawns available to emigrate is much reduced.

Low to moderate floods are reduced by the retainment of water in in-stream dams. The emigration cue that they provide to species such as Banana Prawns and barramundi is reduced, thus reducing the proportion of the estuarine population that moves downstream to the lower estuary or offshore (Vance *et al*. 1998; Bayliss *et al*. 2014). During low-magnitude floods, mostly the large juvenile prawns emigrate (>~10–12 mm CL) and they may move to the lower estuary as well as to the nearshore; in contrast during high-magnitude floods the whole population emigrates to the nearshore (Staples and Vance 1986).

Offstream storage

The diversion of high floodflows only (perhaps via a benched offtake) and delivery to off-stream storage is a common water-capture strategy associated with recent large irrigated-agriculture proposals in Queensland's tropical regions (e.g. iFED and Three Rivers). The water diversion proposals are promoted as low-impact on natural flow cycles as they divert high flows only and capture a low percentage (often <10%) of total end-of-system flows. In the wet-dry tropics, high flows are naturally highly variable in frequency and magnitude; as a consequence it is suggested that a 10% loss of average annual flow is 'not missed'. Two issues arise: the first is that the variability of natural flows is very high and while the reduction in mean annual flow might be low, the percent flow reduction in any one year might be much higher. The second issue is that rainfall and resultant flow is stochastic in the Australian tropics and the 100-year flood hydrograph shows that time gaps of 5–7 years between medium to large floods are common. When irrigators are caught short of water after four dry years, they will be forced to access low flows in subsequent years; reducing the total volume of water available for environmental flows. Under both of these scenarios, in any one year flow reduction in tributaries and at the end-of-system may be much greater than the low-impact reduction (~10%) stated during the regulatory approval process. In short, the annual demand for harvest water is consistent, despite year-to-year capacity of catchments to deliver that water being absent.

As for the case of in-stream storage, when off-stream extraction reduces the magnitude of low to moderate flows, it reduces the estuarine ecotone that sustains the populations and the emigration cue for estuarine dependent species to stimulate them to move offshore to their sub-adult habitats.

Groundwater

The impact of groundwater extraction on riverflow is a likely reduction in river baseflow due to lower groundwater levels feeding less water into the river channel. Baseflow sustains a brackish estuarine ecotone during the late dry-season supporting optimal conditions for the growth and survival of recently-recruited estuarine species. A reduction in baseflow may reduce the population of estuarine dependent species such as Banana Prawns, as estuaries remain hypersaline, reducing growth and increasing the mortality of key species. Baseflow also sustains the riparian zone along the river channel. If the riparian zone is degraded, erosion in subsequent high-flow years may cause sediment deposition within the estuary and degradation of habitats used by estuarine inhabitants.

Groundwater recharge is an initiative suggested for some tropical catchments (CSIRO 2016). One suggested method of groundwater recharge is the placement of a barrage within a river channel; not to impound water alone, but sand and water. The water is stored within the permeable sand matrix; and protected from evaporation by the upper layers of sand. Slowly, it percolates into the groundwater. The river barrier both reduces and negates baseflow, and breaks the connectivity of the river channel. The physical barrier is not an impediment to estuarine species such as Banana Prawns; but it impacts the populations of catadromous fish (e.g. barramundi) and TEP species, such as freshwater sawfish and whiprays.

Discussion of aspects of flow modification on the life history characteristics of estuarine fauna

The effects of flow characteristics on aspects of the life history of estuarine fauna, including Banana Prawns, has been discussed in detail in the Results section of this report. The impacts of modification of natural flows were categorised under eight headings:

- modification of emigration cue,
- floodplain and river channel connectivity,
- deterioration of water quality,
- estuarine ecotone,
- ecosystem services and floodplume dump,
- supra-littoral production,
- sedimentation and soil water recharge, and
- modification of tidal exchange.

This report has identified seven water management initiatives that can minimise the impacts of water resource development on crustaceans and fish, and the economic benefit that the harvest of these species supports. The initiatives fall into broad categories:

- harvest water from moderate to high flows only,
- provide environmental flows of high quality water that allow early-season flows to pass downstream,
- provide environmental flows of high quality water that allow low-flows past dams and water extraction points,
- avoid creating barriers to a long-stream connectivity,
- avoid creating barriers to floodplain inundation and connectivity,
- avoid truncating estuaries or creating barriers in estuaries, and
- avoid constructing hydroelectric power stations as they create freshwater estuaries.

The simple interaction of these flow modifications and water management initiatives for each of four fishery species and one habitat community is outlined in Table 9. Clearly, many negative impacts of flow modification will occur if water impoundment and harvest are not managed. However, selective water harvesting and facilitating key seasonal and environmental flows have the capacity to much reduce the impact of water resource use for irrigation and economic initiatives on the juvenile and adult population of fishery species. As well, the minimal use of barriers to long-stream and floodplain connectivity much reduces the loss of related ecosystem services.

Table 9. Measures that can be undertaken to minimise the impacts of WRD on fisheries, including the crustacean species that support the NPF (and an iconic whipray). Water management initiatives that would minimise the impact of water impoundment or extraction on flows, and hence, ecosystem services are listed as follows: modification of emigration cue (a); floodplain and river channel connectivity (b); deterioration of water quality (c); estuarine ecotone (d); ecosystem services and floodplume dump (e); supra-littoral production (f); sedimentation and soil water recharge (g); modification of tidal exchange (h). The columns of the table are populated with the letter representing the ecosystem service that effects the fishery species listed within the table.

Water management initiative	*Harvest water from moderate to high flows only*	*Provide environmental flows of high quality water that allow early-season flows to pass downstream*	*Provide environmental; flows of high quality water that allow low-flows to pass dams and water extraction points*	*Avoid creating barriers to long-stream connectivity*	*Avoid creating barriers to floodplain inundation and connectivity*	*Avoid truncating estuaries or creating barriers in estuaries*	*Avoid constructing hydroelectric power stations*
Banana Prawns	a, e, f, g, h	c, d, e	c, d, e	-	f, g	b, d, e, h	c, d, e, h
Mudcrabs	e, f, g, h	c, d, e	c, d, e	-	f, g	b, d, e, h	c, d, e, h
Mullet	a, b, c, e, f, g, h	b , c, d, e	b , c, d, e	b	b, f, g	b, d, e, h	b, c, d, e, h
Barramundi	a, b, c, e, f, g, h	b , c, d, e	b , c, d, e	b	b, f, g	b, d, e, h	b, c, d, e, h
Mangroves	d, e, f, g, h	c, d, e	c, d, e	-	f, g	b, d, e, h	d, e, h
Freshwater whiprays	a, b, c, d, e, f, g	b, c, d, e	b, c, d, e	b	b, f, g	b, d, e, h	b, c, d, e

However, the co-operation of the managers of water allocation and the irrigated lands is critical to achieve the water management initiatives that minimise impacts on fisheries and ecosystems. Without their cooperation, the un-structured harvest of water will have serious deleterious impacts on estuarine ecosystems and the resident fauna therein.

This report highlights the fallibility of some of the recent proposals for water extraction and use for irrigation proposed for north Queensland.

The Three Rivers Irrigation Project proposes to extract water from the Flinders River at a volume that their Initial Advice Statement (IAS) suggests will have minor impacts on the catchments lower ecosystem (Anon 2015). The IAS suggests that <28% of the median flows will be harvested (150,000 ML anum^{-1}) from the lower Flinders River with a <4% impact on fisheries production (specifically each of Banana Prawns and barramundi). However, the IAS makes no mention of the seasonality of flows and how disruption to seasonal flows might impact fishery catch. Likewise, the 28% water extraction is an average of all flows including the highest flows. No consideration of the consistency of the annual monsoon-driven floodflows is provided. The CSIRO's Agricultural Resource Assessment for the Flinders Catchment predicts water yield at 85% reliability, not 100% (Petheram *et al*. 2013a), so water scarcity over dry years deserves consideration. Perusal of the 120 year flood hydrograph shows years-series of low flow of 4–5 years occur on decadal scales (see historical flow series in Petheram *et al*. 2013a or at http://www.bom.gov.au/qld/flood/brochures/flinders/flinders.shtml). As discussed elsewhere in this report, the stochastic nature of Australia's tropical flows will result in years when stored-water volumes for irrigated lands are critically low. In these years, the pressure from irrigators to harvest water from low flows and early-season flows will be extreme. The impacts on estuarine ecosystems and fisheries of 'high-percent water diversion' at critical times of the year, are well-explained elsewhere in the report.

Currently, no EIS for the Three Rivers Irrigation Project exists, and presumably these issues will be addressed as part of that process. However, this report highlights that unless a much more informed and integrated approach to water harvest is taken, then the impact of fishery production in the Flinders River estuary could be significant and much higher than the 4% predicted. For example, it is proposed that a weir on the lower Flinders River may need to be constructed to impound sufficient water to be pumped to off-stream storage. A barrage would be a major disruption to the longstream connectivity of this currently un-regulated river. A barrier would impact natural low-flows and may reduce the baseflow and early-season low-flow contribution of freshwater to the estuarine brackish ecotone, with subsequent impacts on estuarine habitats for key commercial species. As well, a weir low down in the riverine reaches would impact the long-river connectivity for other commercial species such as Barramundi, and iconic species such as Freshwater Sawfish and Whiprays.

The possible skewed optimism about low water 'percent off-take' for irrigation and limited subsequent downstream effects is highlighted by the promotion of the iFED irrigated agriculture infrastructure. In ~2014, the senior author of this report attended a presentation by a representative of the iFED group to NPF managers and the content of the presentation highlighted the problems. iFED stated that the capacity of their off-stream storage (1.6 GL) could sustain their irrigation needs for four years; yet the flood hydrograph for the Gilbert River showed gaps between significant floods of 5–7 years. During these extended dry periods, the iFED water infrastructure would not support cropping via an ongoing supply of irrigation water. The option to divert water from low-to-medium floods would be considered as the only source of water to maintain the irrigation-dependent enterprise. Water extraction may breach permits and protocols that were enacted so as to maintain environmental flows. During years of critically low water levels, if water was extracted from low-flows, the percent diversion of the floodflows would be much greater than 10%. Consequently, a high percentage of flows diverted from low-flows would have a much greater impact on ecosystem processes in the estuary, and hence fishery production, than the projected impacts suggested by the irrigators during the pre-development phase of the projects.

A significant component of iFED's water-diversion guarantee was that only high flows would be harvested with only a small downstream impact due to the irrigation enterprise. An engineered benched off-take was to be constructed as an artificial 'ravine' cut into the wall of a natural high-sided constriction in the channel topography of the Einasleigh River. The high-flow bench level was to be 'set in stone', literally. The cut through the natural river-wall was a deep cut several kilometres long through rock, leading to an engineered channel many kilometres long that eventually emptied into the offstream storage tanks. The construction of the river-wall cut and the lengthy channel was a major engineering initiative involving blasting of rock through the near-river landscape and the construction of ~30 km of channel across the farmland landscape. Significant capital costs and equipment were required. It was clear that due to high cost and equipment demand, the construction of the off-take and delivery channels were a once-only enterprise; it wouldn't be re-engineered in the future.

The highlighted guarantee that the water diversion was limited to high flows was that the bench-level of the off-take would be measured and cut in the river-wall at a level hydro-dynamically modelled and known to be exceeded by floods of an agreed high-flow magnitude. However, questions on the day showed that while the initial cut could be engineered so that the off-take bench on the river might be set at a height that harvested high-flows only, a short distance into the artificial ravine, the cut could be made at a lower level that would transport water at low-to-medium flood levels. In the event of future demand for reliable irrigation water, the initial cut could be re-blasted over only a small distance, allowing access to water harvest at low flood levels. Given the high capital investment proposed by iFED (~$2B), the critical need for reliable irrigation water, and the stochastic nature of flows in the wet-dry tropics of northern Australia, flexibility in regard to extraction and use of water in these hot, demanding catchments would be critical. Once a proposal like iFED was a going concern, during a series of dry years with stored water at critical lows, adherence to pre-development guarantees about water harvesting is questionable for renegotiation. Both the seasonal distribution of water extraction (e.g. extraction during early-season flows), and the percent volume extracted from low flows (much higher than pre-development guarantees) would change. Modification of seasonal and volumetric characteristics of river flows would lead to downstream impacts, such as a much reduced brackish ecotone within estuaries during critical seasonal recruitment of juvenile fishery species, or a much reduced emigration cue later in the wet-season during already dry years. While remaining within a legal water allocation by annual volume, the characteristics of water extraction relative to season trends and percent-of-flood-volume extracted would change.

Experience to date suggests that the promotion of agricultural irrigation initiatives by the proponents; both via written documentation and verbal accounts (via the media and in person) focus on the relative low percent of mean annual flows that is sought for water extraction and diversion. In years of high floodflows, this representation might be accurate. However, these simplistic accounts do not take into scope aspects of seasonal flow, or critical low flows that might be heavily impacted by water extraction. Moreover, to date the modelling of the impacts of flow reduction on fishery catch also do not adequately incorporate assessment of impacts on seasonal flow or extended years of low flows on ecosystem stability and the dependent yield of commercial species.

Quantitative studies of the trade-offs between water resource development and impacts on fishery catch has been restricted to a few species and a few catchments; the relationship suggests a decline in existing ecological services that support fishery production (Bayliss *et al*. 2014). To date, the modelling of the response of fish and crustacean catch to anthropogenic modification of flows has used coarse-scale data like annual end-of-system flow volume and fish catch at 30 nm scales to explore the relationship. The need to extend the modelling to explore ecological interactions and ecosystem level impacts at smaller spatial scales has been identified (modelling and interpretation undertaken for the FGARA project, Bayliss *et al*. 2014). In addition, modelling to date has not taken into account the seasonality of floodflows (the importance of which is explained in this report), or the impact of water extraction from low-flows that may much reduce their contribution to ecosystem services and estuarine processes. The lack of information about the impacts of water extraction over a series of low-flow years has been highlighted as a significant knowledge gap by previous studies (Bayliss *et al*. 2014). As well, the contribution of nearby rivers to the catch statistics used in the current modelling has not been evaluated.

Despite current robust models predicting minimal impacts of water harvest on fishery catch, change in the seasonality of flows and the modification of early-season low flows may have much greater impacts on catch than estimated by these models. Future work should adapt tools such as “Models of Intermediate Complexity for Ecosystems assessments” (MICE; Plaganyi *et al*. 2014) and Ecosim (a dynamic extension to Ecopath: Griffiths 2010). MICE have the ability to provide rigorous multispecies predictions that can be used to support decision making. Further, by coupling existing high resolution hydrodynamic models developed by CSIRO with a whole-of-ecosystem Ecosim model, system level responses to altered water flows and impacts on broader ecological groups and key species can be evaluated.

During the workshops reported here, Dr. Plaganyi highlighted the use of MICE models to explore the flow-catch relationships at finer temporal and spatial scales. The compartmentation of the life history of Banana Prawns into 4 phases and the documentation of all aspects of flow, temperature, turbidity, predation and nutrient transport that might affect Banana Prawn’s growth and survival provides a platform to develop MICE models. The conceptual models developed scenarios for each life history phase and three flow levels: low, moderate and high. Initial representations of MICE models of phases of the life history and ecosystem interactions of *Penaeus merguiensis* have been developed. The models show abiotic and biotic factors that determine abundance and survivorship of key phases of Banana Prawns, as dependent on flow. A future project will develop these conceptual MICE models to fully-developed statistical tools.

Dr Plaganyi and Professor Burford, with inputs from others, developed this representation to map the linkages between different research components and projects to highlight the gaps; as well as facilitate sharing of data and model outputs so as to ensure that the various studies complement each other (Figure 19).

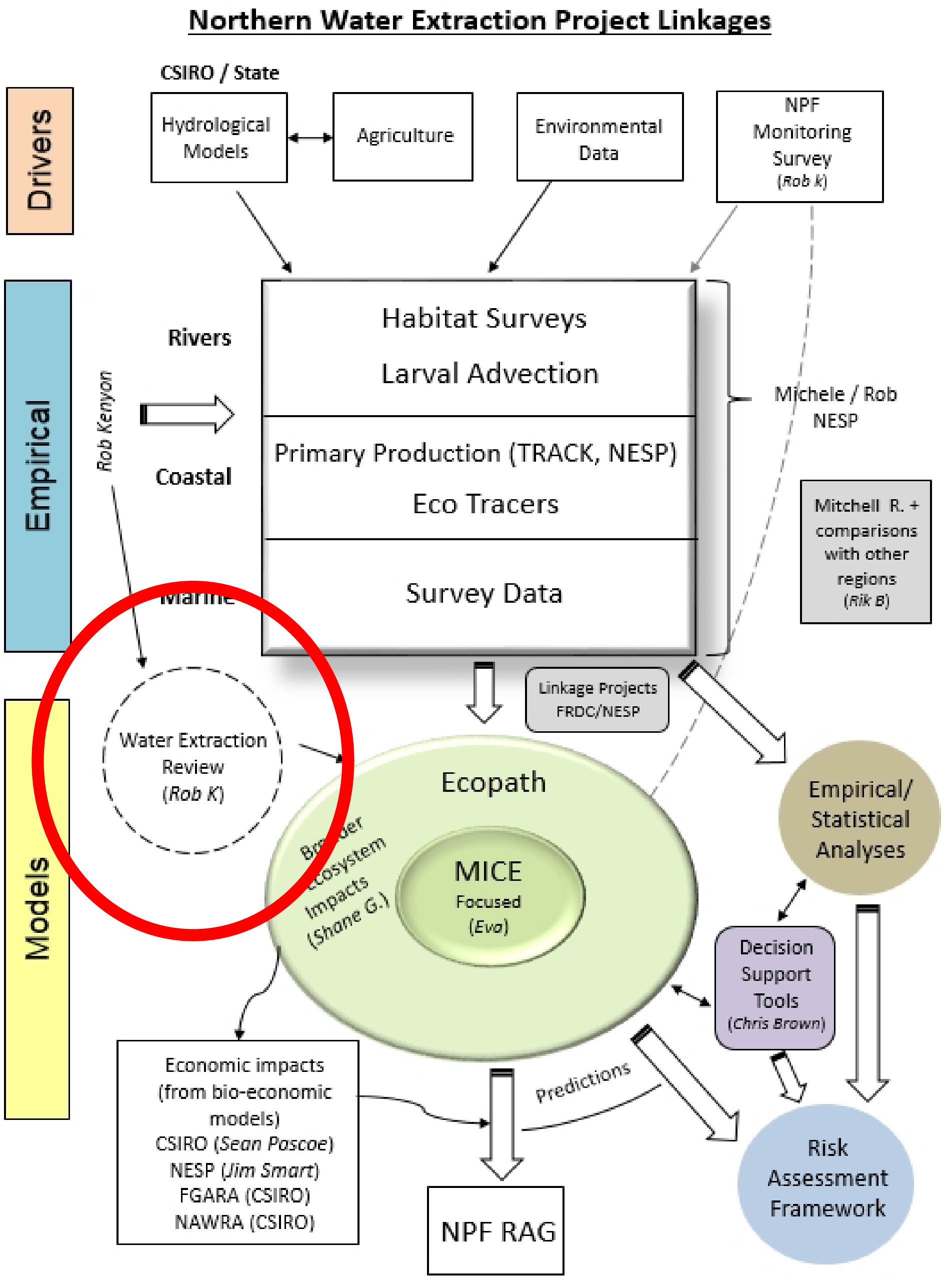

Figure 19. Research components and projects that map knowledge gaps in understanding the relationship between environmental drivers, yield and sustainability in the NPF; facilitating advice to management.

The current project (highlighted in the red circle) represents a small portion of the totality of these knowledge-generating interactions. The representation shows the need for continued development on these themes and processes. MICE models are the next step to generate new knowledge and illuminate future paths to a better understanding of productivity processes that contribute to better yield in the NPF.

Historical analyses of the relationship between river flow and catch (which controlled for fishing effort) have shown that fishing effort, rather than flow, contributed the majority the variation in catch (Vance *et al*. 2003; Bayliss *et al*. 2014). While flow was a significant determinant of catch, the contribution of effort can be up to 70% of catch variation. However, the contribution of fishing effort is a circular argument as both aeroplanes and echo-sounders are used to locate aggregations of Banana Prawns; so effort shows that prawns were found during searching in locations where they were stimulated to emigrate to by flows. The FGARA modelling (Bayliss *et al*. 2014) did not incorporate a seasonal component to the analysis of catch. The flow statistics used were end-of-system (EOS) flows from the 1st of October to the 30th of September annually; and the annual catch of both Banana Prawns and barramundi. Thus, seasonal aspects of flow were not modelled. As highlighted during this report, early season flows are critical to optimal habitats for juvenile prawns in estuarine habitats. Historical modelling of spring (September to November) and summer (December to February) rainfall (as a proxy for flow) has shown significant positive effects of late dry season 'early-rainfall' on catch in some rivers but not in others (Vance *et al*. 2003). Wet season (summer) rainfall shows a stronger positive relationship between flow and commercial prawn catch (Vance *et al*. 2003). The consideration of early season flows and the cumulative effect of successive years of low-flows is critical to fully understanding the impacts of flows on catch.

Subsequent modelling of Banana Prawn catch with flows, including seasonal aspects of flow, continues to show the importance of flow as a determinant of subsequent commercial catch; but again highlighting that less than 50% of the variation in commercial catch is attributable to flow (Mischa Turschwell, pers. comm.). As well, flow analyses for rivers in the vicinity of Darwin show that higher dry season flows are positively correlated with a higher prawn catch in the subsequent fishing season (Mischa Turschwell, pers. comm.). Higher dry season baseflows have the capacity to enhance the estuarine ecotone in the estuary, benefiting the prawn population. Baseflows at higher levels would lower salinity from possible hypersaline levels at the end of the dry season to enhance the growth and survival of juvenile prawns during the late dry-season when pelagic postlarvae are recruiting to the estuary as the benthic phase and them growing to become juveniles.

These most recent modelling results highlight the need for more robust analyses that separate early season flows (estuarine recruitment season) from bulk-year flows. Importantly, Bayliss *et al*. (2014) show that only 2–5% of annual flows occur 'early-wet-season' (October to December), while 85–90% of annual flows occur during January to March, and ~7% are late-wet flows (April and May). One to four percent of flows occur during the dry season. Our conceptual models demonstrate the importance of an optimal estuarine ecotone during the juvenile phase of fishery species. Both growth and survival of several species are enhanced in euryhaline, rather than hypersaline estuarine conditions. As they are such a small percentage of all flows, maintenance of the early wet-season flows during the recruitment window is critical for estuarine habitats. A euryhaline estuary is conditioned by baseflows and early-season low-floodflows that reach the estuary after dry-season cessation. As well, early season flows may increase the turbidity of the estuary, reducing predation on prawns and juvenile fish by large visual predators.

In addition, the impact of a series of annual low-flows requires more detailed flow-catch analyses. The impact of water extraction on low floodflows may be critical by extending the series of 'dry years'. Historically, series of dry years are common in the stochastic precipitation conditions within the tropical north. Impoundment of, or extraction from riverflows may exacerbate and extend the duration of consecutive low-flow years. While tropical species have evolved over millennia to cope with dry years, anthropogenic extension of dry-year series may stress the dynamics of prawn reproduction and resilience that allow populations to span poor years. When large flows remain intact, early season flows may decline, large flows may not contribute to support populations and emigration if the small and early flows are not in place to support the population as per historical trend.

Conclusion

The impoundment or extraction of water modifies natural flows with downstream effects for the stability of the estuarine fauna community, as well as for environmental drivers that cue the behaviour of crustaceans and fish. Water can be diverted or extracted in ways that minimise the impacts on natural flow regimes. Water management protocols that extract or impound water only from monsoon-season high flows may have little impact on natural flows and key flow parameters identified as supporting ecosystem services in the catchment and downstream fisheries production. The utilisation of low flows would have the opposite effect; possibly reducing seasonal flow by 50-80%. Low flows during the mid- and late-dry season sustain riverine habitats under water stress due to the reduction in the extent and depth of pools. These flows also modify estuaries to a brackish condition, habitat best suited to support the annual recruitment pulse of the juvenile phase of many key fish and crustacean species, including fishery and TEP species. The loss of low flows would be devastating for riverine and estuarine habitats. Importantly, only 10-15% of annual flows occur during the dry season (April to December) and 2-5% of flows occur from October to December (Petheram *et al*. 2012; Bayliss *et al*. 2014), so by avoiding harvest during the dry season little water would be forgone to consumptive use. However, the stochastic nature of rainfall and riverflow in the wet-dry tropics means the temporal and volumetric reliability of flows is unpredictable. If attempts are made to increase the reliability of water supply through opportunistic or continuous harvest of flows, then Australia's tropical rivers will suffer modified seasonal and annual flows to the detriment of ecosystem services and downstream users.

Proponents of irrigated agriculture sourcing water from catchments in the wet-dry tropics promote the minimal use of natural flows. They quote the concept that a small percentage of end-of-system flows (e.g. 10%) is required to sustain their water needs. However, water requirements as a percentage of overall flow does not convey full consideration of the suite of possible impacts on flow. It is both the timing of water extraction and the proportion extracted from all flows that is critical to the modification of ecosystem services that sustain fish and fisheries. Extraction or impoundment of early-season flows may remove 90–100% of the flow volume, thus negating estuarine inflows and the brackish ecotone that sustains species' growth and survival downstream. Likewise, extraction or impoundment of low floodflows may reduce the flow-volume by >50%; downstream estuarine salinity might remain high during the 'wet' season, removing an emigration cue for key fishery species. In these cases, significant modification of the ecosystem services that sustain fishery production would occur with detrimental impacts on eventual catches and landed value.

Water management protocols for extraction or impoundment that allow key seasonal flows to pass WRD infrastructure unhindered will maintain ecosystem processes key to sustain fishery production. The prohibition of water extraction below defensible trigger levels; or the release of 'late-dry season' and 'environmental' flows during the wet season are key to successful water management to support multiple stakeholders conducting a variety of economic activity in the wet-dry tropics. Water infrastructure such as dams will need to be designed and engineered to allow the offtake of high quality water for release downstream.

The FGARA project identified ~200 ML of water available for extraction in the Flinders River and ~500 ML of water available in the Gilbert River for extraction; likely for irrigated agriculture. The topography of the Mitchell River catchment suits the placement of a large dam with subsequent allocation of impounded water and modification of the Mitchell River WRP. The NAWRA project will scope case studies of new water infrastructure and unallocated water from the Mitchell River. We consider it likely that proponents of irrigated agriculture will bid for water allocations that are identified as available as part of the FGARA and NAWRA projects recently and currently being conducted by CSIRO. The Three Rivers Irrigation Project likely has bid for water allocation from the Flinders River, sold by tender under a revised Gulf Water Plan (2007) and water allocation in 2016/17 (see: http://www.frap.org.au/images/pdfs/26April2017-gulf-uaw-tender-assessment-report-final-sml.pdf). The NPF Industry needs to be proactively involved as part of the process of WRP revision, modification and new water allocation.

The NAWRA project will offer a crucial opportunity for all stakeholders including NPF Industry to engage in the assessment and approval process for proposed water infrastructure development. Knowledge derived from NAWRA will inform the WRPs that provide the water management protocols for each catchment and potential

WRD project. WRPs will include protocols and trigger conditions that ensure specific volumes of water (as seasonal river flows) reach estuarine systems to maintain habitats and environmental cues that support the life history stages of fishery species. The NAWRA project will scope a greater range of water extraction and dam placement scenarios than what will be reported; so the opportunity may exist for stakeholders to interact with hydrologists and ecologists to more fully explore a broad range of impacts on flows.

In addition to the environmental impact assessment under State and Territory laws, water development co-funded by the Commonwealth's National Water Infrastructure Development Fund and the National Water Infrastructure Loan Facility will be assessed under Commonwealth legislation, including the Environment Protection and Biodiversity Conservation Act (http://www.environment.gov.au/epbc/about). State/Territory and Commonwealth legislation will require water management protocols that sustain habitats and ecosystem services for key species. NPF Industry need to be part of this process to ensure key seasonal flow parameters identified as critical to estuarine crustaceans are maintained to support their fishery.

NPF Industry and Management should be active stakeholders in the revised management of catchment water resources which may be the result of water resource development in landscapes adjacent to the NPF. They should seek to:

- influence constructed infrastructure to incorporate design features that allow the maintenance of seasonal flows of high water quality to provide key ecosystem services to downstream species,
- rigorously define seasonal flow levels that are key drivers of downstream fishery productivity in Australia's wet-dry tropics,
- define trigger levels of flow below which seasonal river flows should not be impounded or extracted,
- define flows that are defensible under scrutiny based on statistically robust modelling of historical hydrology, flow impacts on/relationships with catch series, and predicted impacts of change-in-flow due to water resource development,
- explore extraction or impoundment regimes that deliver water to other users while best-maintaining ecosystem services downstream.

The need to extend flow-catch modelling to explore ecological interactions and ecosystem level impacts at finer temporal and spatial scales is critical. To date, the reported modelling has not taken into account the seasonality of floodflows, or the impact of water extraction from low-flows (in particular, a series of years with low flows) that may much reduce the contribution of key riverine inputs to ecosystem services and estuarine processes. Neither has the most recent flow-catch modelling incorporated food availability, mortality, turbidity or stepped-levels of primary productivity as factors into model. Models of Intermediate Complexity for Ecosystems assessments (MICE) and Ecosim have the capacity to incorporate the dynamics of seasonal flows and extended series of low flows, as well as other biotic and abiotic factors in model outputs. MICE have the ability to provide rigorous multispecies predictions that can be used to support decision making. Coupling outputs from existing high resolution hydrodynamic models developed by CSIRO with MICE models highlights the capacity to predict ecosystem level responses to altered water flows and impacts on key fishery species and broader ecological groups.

This project has developed conceptual models for 'whole of life-history' scenarios, as well as for each of four life history stages and at three flow levels: low, moderate and high. These conceptual models provide a sound foundation to inform future development of MICE models representing the different phases of the life history and ecosystem interactions of *Penaeus merguiensis*. The conceptual models show abiotic and biotic factors that determine the abundance and survivorship of key phases of Banana Prawns are dependent on flow. A future project to develop these conceptual models to dynamic MICE and/or Ecosim models would be a comprehensive response to the outputs from this current project. A preliminary MICE model has been developed and a more comprehensive extension could now be built using the data and information collated as part of this study, as well as the conceptual models summarising the current state of understanding of the system. The next step in the modelling process is therefore, to turn the qualitative model framework into a dynamic framework capable of quantifying outcomes under alternative scenarios.

Implications

The outcomes of the project demonstrate a clear increase in anthropogenic pressure on the ecosystem services provided by natural flows that have historically remained unhindered and unregulated since the instigation of northern fishing enterprises in the 1960 and 70s. Specific initiatives have been mapped over a continent-wide scale across tropical northern catchments.

NAWRA and NESP are focussed in river catchments with potential for WRD to support irrigated agriculture. In the case of FGARA, the rivers that were in focus currently are the subject of private enterprise 'irrigated-agriculture' development. The Three Rivers Irrigation Project proposes a 150 ML extraction from the Flinders River using FGARA outcomes to support their proposal. In their initial 'statements of intent', they quote from both a water availability perspective and a response to environmental impact considerations when documenting their case for water extraction. The Mitchell River, the 'Darwin Rivers' and the Fitzroy River catchments likely will be subject to private enterprise 'irrigated-agriculture' development as an outcome of the NAWRA project.

The Darwin Rivers likely will develop a WRP equivalent (as per WAPs) to manage the outcomes of the NAWRA assessments. The Mitchell River Water Resource Plan will be updated in response to the NAWRA outcomes; and if a dam is constructed, completely modified to account for the water resource storage and delivery potential. In both cases, NPF Industry should engage with the process of WRP modification based on the experience and contacts Andy Prendergast has achieved with the Cape WRP. Identifying the engagement process for the Northern Territory is critical to achieve fishery-orientated inputs to water management in many catchments.

As expressed by the conceptual models of each stage in the life history of an estuarine dependent species, the 2017 exploration and summation of the drivers of fishery productivity highlight the complex set of abiotic and biotic factors determining population dynamics. Most recent modelling for Banana Prawns demonstrates that riverflow as a juvenile emigration cue is very important to adult abundance. Again however, after significant deployment of expertise, the models continue to show that only a portion of abundance measured as fishery catch is attributable to the emigration cue provided by floodflows (mostly high-floodflows). Our conceptual models complement the information gap highlighted by the latest modelling. Our models include estuarine food resources (also dependent on flow), predation (dependent on location within the estuary), turbidity (modifying predation rate) supported by early season low-flows, and supra-littoral primary production; ecosystem processes together impacting prawn population dynamics. Each of these aspects is a likely driver of the proportion of catch that the latest models show is not attributable to high flows.

The workshops conducted as part of this project highlighted the need to model each life-stage of the Banana Prawn using Models of Intermediate Complexity for Ecosystem assessment (MICE) that incorporate all facets of ecosystem services listed in the previous paragraph, as well as flow, to elucidate the totality of drivers determining fishery catch. Facilitating this exploration, our workshops concluded that models be constructed at three different levels of flow; low, moderate and high, to maximise the ability to detect the impact of seasonal flows and temporal shift in flow on catch. Incorporating a suite of ecosystem components into an existing MICE will reliably and rigorously quantify current identified uncertainties about the impacts of water extraction on the prawn and commercial fish species. Moreover, depending on data availability, the MICE could be extended to include several other representative species groups to evaluate the broader marine ecosystem effects of water extraction.

Most importantly, NPF Industry needs to engage the Water Resource Planning process 'armed' with latest outputs from modelling that provide the most up-to-date information about the impacts of modified flow on fishery production. Components of this information can be gained from the NAWRA and NESP projects. However, the broad ecosystem effects of water extraction will only be understood fully by commissioning MICE models to explore all aspects of ecosystem drivers (including seasonal and low flow series), that are modified by upstream water extraction or impoundment.

Recommendations

- The Water Resource Development to support irrigated agriculture in northern rivers such as the Flinders, Gilbert, 'Darwin Rivers' and Mitchell Rivers that will occur over the next 10–15 years is of relevance to the Northern Prawn Fishery Management (NPF Industry and the Australian Fisheries Management Authority). Downstream impacts on estuarine and coastal fisheries will occur as flows are modified by water impoundment or extraction.

- NPF Management are encouraged to develop a 'response plan' to engage with the State/Territory and Commonwealth legislators and irrigation development proponents to achieve **impact minimisation** for the NPF. The stakeholders will provide inputs to the development of the water infrastructure and management protocols. The scope of these protocols will determine the capacity and plasticity of both infrastructure and management to optimise the conflicting interests of water harvest against the maintenance of environmental flows and downstream ecosystem services. The response plan should include a suite of water management protocols that can be put to State/Territory water managers for incorporation into Water Resource Plans for optimal water delivery to all sectors, including fisheries. The protocols need to include precise definitions and trigger levels of flow based on rigorous knowledge that supports explicit decision-making.

- NPF Management are encouraged to engage with the process of Water Resource Plan development or modification, and the design and construction of water resource infrastructure, to ensure that both management protocols and water infrastructure incorporate capacity to deliver environmental flows that optimise estuarine processes and fishery production, given constraints from water extraction. The aim would be to include specific clauses in Water Resource Plans that protect downstream fisheries.

- As part of the 'response plan' NPF Management need to develop and promote clear protocols for water management that support downstream fishery production, while allowing water extraction. Suggestions for the basis of the protocols include:

    - harvest water from moderate to high flows only,
    - provide environmental flows that allow late-dry season flows of high water quality to pass downstream,
    - provide environmental flows that allow low-flows of high water quality past dams and water extraction points,
    - engineer dams to allow water offtake at multiple levels over the depth range of the impoundment, and incorporate fish ladders in dam design,
    - avoid creating barriers to a long-stream connectivity,
    - avoid creating barriers to floodplain inundation and connectivity,
    - avoid truncating estuaries or creating barriers in estuaries, and
    - avoid constructing hydroelectric power stations as they disrupt natural tidal cycles and seasonal cycles of flow.

- Protocols require quantitative definitions that can be clearly stated and promoted during management meetings that develop Water Resource Plans for each catchment. Management adherence to these definitions needs to be explicit (definitions are required for each river):

    - High flows as determined from examination of annual series of EOS flows (from which water can be harvested) (collaboration with hydrologists - historical flow series),

    - Low flows as determined from examination of annual series of EOS flows (which should be preserved as environmental flow) (collaboration - CSIRO hydrologists - flow projections),

    - **Threshold levels of flow** below which water should not be harvested; water should be allowed to proceed downstream.

- It would be useful to conduct modelling of the effect of early season flows and sequential low flow series on commercial catch to fully understand the impacts impoundment or extraction of water would have on natural flows, with subsequent impacts on fishery populations. Modelling should include biotic and abiotic ecological relations as factors that, as well as flow, drive subsequent catch. To date, the majority of modelling that has demonstrated positive relationships between flow and catch has used coarse time-scales: annual flow with no allowance for the effects of seasonal aspects of flow. Some models have included seasonal flows such as 'pre-wet flows' and have demonstrated significant relationships between seasonal flow (e.g. September to November) and catch. However, the flow-catch relationship is significant for a minority of rivers and the relationship is not consistent for each season. Yet our conceptual models suggest pre-wet season river flows should be important to provide estuarine conditions optimal to juvenile Banana Prawns; ecological models may provide the power to better test the flow-catch relationship. The exact nature of the flow-catch relationship needs to be fully explored and documented to be able to defend a 'fishery-supportive' position when the management protocols and water infrastructure designs are developed and adopted.
- The conceptual and qualitative models developed as part of this study are useful in synthesizing understanding and functioning of the system. However, in order to quantify the impacts of water extraction on fisheries production, as well as broader ecosystem influences, quantitative ecosystem models are needed. Future work could draw on an existing preliminary MICE as well as EwE (Ecopath with Ecosim) models for the region and extend these as necessary. To reliably and rigorously quantify and account for uncertainties of the impacts of water extraction on the prawn and commercial fish species, the most appropriate model would be MICE. Economic components are also able to be incorporated and extended in the existing MICE. Moreover, depending on data availability, the MICE could be extended to include several other representative species groups to evaluate the broader marine ecosystem effects of water extraction. However, to explore the ecosystem impacts on a much larger suite of species, it would be preferable to also develop the EwE model. Both types of model could be forced with environmental variables from the hydrological models. The spatial and temporal structure and domain of both models would also be informed by the results of this study. However, given limited data on all species groups, a whole of ecosystem model such as EwE would likely use a larger spatial domain for the entire region, whereas MICE can be tailored to any scale to address more specific questions. Both models should also draw on the latest research as to system understanding, as summarised in this report, and should further highlight remaining key knowledge gaps, and evaluate the sensitivity of model results to such gaps.

Further development

Engage with hydrologists to examine annual flow data for tropical rivers to develop definitions of 'high', 'moderate' and 'low' flows for specific rivers with the aim of determining trigger levels of flow, below which water harvesting should cease. Flow data such as these, are available from projects such as FGARA and NAWRA. CSIRO hydrologists have custody of historical flow series and flow projections using various hydrological models. The NAWRA project will model a greater range of water extraction and dam placement scenarios than reported; so pursue the opportunity to interact with hydrologists and ecologists to more fully explore a broad range of impacts on flows.

Model the effect of early season flows and sequential low flow series on commercial catch to fully understand the impacts impoundment or extraction of water from natural flows would have on subsequent fishery catch. Include biotic and abiotic ecosystem components in the models to best explore the links between low flows and catch; historic indications of significant relationships between early-season flow and catch have been inconsistent across river catchment/location and require further investigation.

Extension and Adoption

Presentation to the NPRAG in November, 2016 (Brisbane) discussing project progress.

Presentation to the NPRAG in May, 2017 (Brisbane) verbal discussion of project progress.

Presentation to the NPRAG on December 5th, 2017 (Brisbane) discussing the completion of the project and the project outcomes and recommendations, and Industry responses and likely opportunities. The RAG took stock of our recommendations and had an immediate response to CSIRO staff on the day.

Presentation to the NORMAC on February 22nd, 2018 (Brisbane, by Dr Trevor Hutton, as R. Kenyon was in the Gulf of Carpentaria) discussing the project outcomes and recommendations, and Industry responses and likely opportunities.

The presentation to the RAG prompted further consideration of research on the impact of reduction in flows due to water resource use and to invite a CSIRO O&A team to submit a project proposal to a May RAG with the view to support 'Models of Intermediate Complexity for Ecosystem assessment' (Eva Plaganyi). The project proposes using the ecosystem model to continue exploring the impacts of the reduction in rivers flows in general, in particular seasonal aspects of flow on prawn catch.

The RAG clearly recognised the need to engage with the WRP process and the need to have 'environmental flow' projections and proposals that will sustain the fishery and withstand the scrutiny of water managers and the proponents of water diversion for irrigation.

At the NORMAC meeting, the request for a project proposal to use 'Models of Intermediate Complexity for Ecosystem assessment' Ecosystem model to explore the impacts of water resource development of river flow and downstream ecological services was restated and reinforced (for consideration by the May NPRAG meeting).

Project materials developed

The project created the Proposed North Australian Water Developments Portal (https://research.csiro.au/npfnwd/). It houses an inventory of current and proposed water resource development for catchments spanning Queensland, the Northern Territory and Western Australia; catchments flowing north through Australia's tropical savannahs to receiving waters in the management scope of the Northern Prawn Fishery.

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Appendices

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