Water resource assessment for the Roper catchment

A report from the CSIRO Roper River Water Resource Assessment for the National Water Grid

Editors: Ian Watson, Cuan Petheram, Caroline Bruce and Chris Chilcott

ISBN 978-1-4863-1905-3 (print)

ISBN 978-1-4863-1906-0 (online)

Citation

Watson I, Petheram C, Bruce C and Chilcott C (eds) (2023) Water resource assessment for the Roper catchment. A report from the CSIRO Roper River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Chapters should be cited in the format of the following example: Petheram C, Bruce C and Watson I (2023) Chapter 1: Preamble: The Roper River Water Resource Assessment. In: Watson I, Petheram C, Bruce C and Chilcott C (eds) (2023) Water resource assessment for the Roper catchment. A report from the CSIRO Roper River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

CSIRO Roper River Water Resource Assessment acknowledgements

This report was funded through the National Water Grid's Science Program, which sits within the Australian Government's Department of Climate Change, Energy, the Environment and Water.

Aspects of the Assessment have been undertaken in conjunction with the Northern Territory Government.

The Assessment was guided by two committees:

i. The Assessment's Governance Committee: CRC for Northern Australia/James Cook University; CSIRO; National Water Grid (Department of Climate Change, Energy, the Environment and Water); NT Department of Environment, Parks and Water Security; NT Department of Industry, Tourism and Trade; Office of Northern Australia; Qld Department of Agriculture and Fisheries; Qld Department of Regional Development, Manufacturing and Water

ii. The Assessment's joint Roper and Victoria River catchments Steering Committee: Amateur Fishermen's Association of the NT; Austrade; Centrefarm; CSIRO, National Water Grid (Department of Climate Change, Energy, the Environment and Water); Northern Land Council; NT Cattlemen's Association; NT Department of Environment, Parks Australia; Parks and Water Security; NT Department of Industry, Tourism and Trade; Regional Development Australia; NT Farmers; NT Seafood Council; Office of Northern Australia; Roper Gulf Regional Council Shire

Responsibility for the Assessment's content lies with CSIRO. The Assessment's committees did not have an opportunity to review the Assessment results or outputs prior to its release.

This report was reviewed by Kevin Devlin (Independent consultant).

For further acknowledgements, see page xxii.

Acknowledgement of Country

CSIRO acknowledges the Traditional Owners of the lands, seas and waters of the area that we live and work on across Australia. We acknowledge their continuing connection to their culture and pay our respects to their Elders past and present.

Photo

Looking along the Roper River at Red Rock, Northern Territory. Source: CSIRO – Nathan Dyer

7 Ecological, biosecurity, off-site and irrigation-induced salinity risks

Authors: Danial Stratford, Justin Hughes, Simon Linke, Linda Merrin, Rob Kenyon, Lynn Seo, Maxine Piggott, Peter R. Wilson, Cuan Petheram, Ian Watson

Chapter 7 discusses a range of potential risks to be considered before establishing a greenfield agriculture or aquaculture development. These include ecological implications of altered flow regimes, biosecurity considerations, irrigation drainage and aquaculture discharge water, and irrigation-induced salinity.

The key components and concepts of Chapter 7 are shown in Figure 7-1.

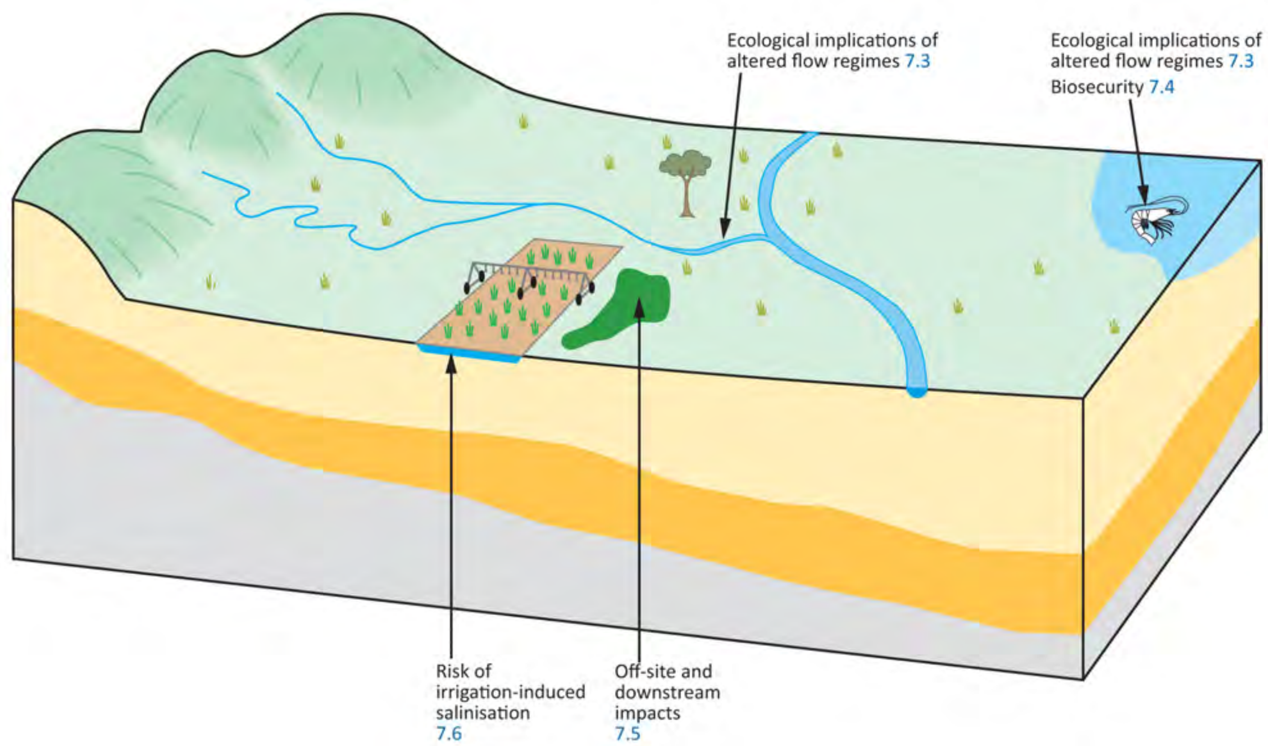

Figure 7-1 Schematic diagram of the components where key risks can manifest when considering the establishment of a greenfield irrigation or aquaculture development

Numbers in blue refer to sections in this report.

7.1 Summary

This chapter provides information on the ecological, biosecurity, off-site and downstream impacts and irrigation-induced salinity risks to the catchment of the Roper River from greenfield agriculture or aquaculture development. It is principally concerned with the risks from these developments to the broader environment but also considers biosecurity risks to the enterprises themselves.

7.1.1 Key findings

Ecological implications of altered flow regimes

The freshwater, terrestrial and near-shore marine zones of the Roper catchment contain important and diverse species, habitats, industries and ecosystem functions supported by the patterns, volumes and quality of river flows. Although irrigated agriculture only occupies a small percentage of the landscape, changes in the flow regime can have profound effects on flow-dependent flora and fauna and their habitats. These effects may extend considerable distances onto the floodplain and downstream, including into the marine environment.

Alternative future scenarios for water harvesting, instream dams and groundwater development produced a range of water volumes and patterns of flow with a variety of impacts on ecology. In summary it was found that:

- The level of impact resulting from water resource development was highly dependent on the type of development, the extraction volume and the mitigation measures implemented.
- Large instream dams and water harvesting often have a comparable mean impact to surface-flow-dependent ecology averaged across the Roper catchment, large instream dams result in significantly larger local impact to ecology in those reaches below the dam wall than water harvesting.
- Groundwater development resulted in negligible flow regime change to surface flow–dependent ecology at the catchment scale, with some moderate changes to assets occurring in some reaches of the Roper River. However, changes to groundwater levels, and hence local impacts to groundwater-dependent ecology, need specific consideration over suitable timescales of change.

Water harvesting outcomes were sensitive to the volume of extraction, but mitigation measures also changed ecology outcomes across the Roper catchment. Harvesting 100 to 660 GL of water resulted in minor changes to asset means across the Roper catchment with impacts often accumulating downstream past multiple extraction points. Threadfin, prawn species and mullet were among the ecology assets most affected by flow change for water harvesting. For low water harvest extraction volumes, providing suitable levels of end-of-system flow requirements, commence-to-pump thresholds and pump rates improved mean outcomes across ecology assets to negligible change at catchment scales compared to without these measures. This demonstrates the importance of protecting minimum flows and first flows for many of the ecology assets and that mitigation strategies have potential to reduce impacts to water dependent ecosystems.

For instream dams, the location of the dam in the catchment matters as there is potential for extreme risks of local impacts. Improved outcomes were associated with maintaining attributes of the natural flow regime. Single dams on the Waterhouse River and Flying Fox Creek each resulted in negligible mean change to assets flows at the catchment scale, but with higher local impacts. Combined, impact was greater resulting in minor change across the catchment. Under the highly unlikely hypothetical scenario of maximum development, which involved construction of five potential instream dams (including Waterhouse River and Flying Fox Creek dams), catchment-scale impacts of changed flows on ecology assets increased to moderate change. Local impacts of dams were often considerably higher with site impacts for some ecology assets reaching extreme. Impacts generally reduced further downstream with accumulating flows from other parts of the catchment. Sawfish (*Pristis pristis*), grunters (Family: Terapontidae), some of the waterbird groups and floodplain wetlands were among the ecology assets most affected by instream dams. Providing transparent flows (where some flows are allowed to 'pass through' a dam for ecological purposes) improved flow regimes for ecology at both local and catchment scales: mean outcomes for fish assets could be improved from minor to negligible mean change and for waterbird assets from moderate to minor mean change across the catchment.

Beyond flow, other impacts and considerations are also important. At catchment scales, the direct impacts of irrigation on the terrestrial environment are typically small. However, indirect impacts, such as weeds, pests and landscape fragmentation, particularly to riparian zones, may be considerable. Changes in water quality may also affect ecology and are not considered in the quantitative analysis. The combined changes of a potentially drier future climate and hypothetical water resource development produced greater impacts than did each factor on its own.

Biosecurity considerations

Northern Australia is recognised as the biosecurity frontline for many high-risk animal and plant pests and diseases. Australia has many advantages in being able to mitigate risks from pests and disease. However, serious outbreaks of diseases in agricultural and horticultural crops have occurred in recent years across northern Australia, including the fall armyworm (FAW; *Spodoptera frugiperda*) caterpillar, a serious pest of maize (*Zea mays*); and Panama disease tropical race 4 (caused by the fungus *Fusarium odoratissimum*), which affects bananas (*Musa* spp.) in northern Queensland and the NT.

Although Australia has a world-class biosecurity system, the risk of new diseases and plants entering Australia is always present due to international trade and the movement of people. Pathogens, pests and weeds have entered the NT from both natural pathways and from human activities. High-value agricultural industries tend to have had the most research investment and have the most resources to manage biosecurity, and less-valuable industries and environmental interests are likely to be in a less-favourable position. Vertebrate pests such as pigs (*Sus scrofa*) can be a significant problem for agriculture and the environment in the NT. They cause direct physical damage to crops and wetlands and can also carry and spread a range of exotic diseases, including foot-and-mouth disease (FMD). The Roper catchment has a continued risk of new weed incursions, both deliberate and accidental. Agricultural development can increase the risk of weeds becoming established. A changing climate is likely to create opportunities for new pests and diseases to move in and become established. An increase in extreme rainfall events and tropical cyclone intensity may increase the risk of pests entering via natural wind-driven pathways.

Off-site and downstream impacts

Agriculture can affect the water quality of downstream freshwater, estuarine and marine ecosystems. The principal pollutants from agriculture are nitrogen, phosphorus, total suspended solids, herbicides and pesticides. Losses via runoff or deep drainage are the main pathways by which agricultural pollutants enter water bodies. Management of irrigation or agricultural drainage waters is a key consideration when evaluating and developing new irrigation systems, and it should be given careful consideration during the planning and design process. Hence, minimising drainage water by using best-practice irrigation design and management should be a priority in any new irrigation development in northern Australia. Surface drainage networks need to be designed to cope with runoff associated with irrigation and runoff induced by rainfall events on irrigated lands. Drainage must be adequate to remove excess water from irrigated fields in a timely manner, and hence reduce waterlogging and salinisation, which can seriously limit crop yields.

In best-practice design, surface drainage water is generally reused through a surface drainage recycling system where runoff tailwater is returned to an on-farm storage or used to irrigate subsequent fields within an irrigation cycle. Hundreds of different chemicals are used in different agricultural, horticultural and mining sectors, and in industrial and domestic settings. Releasing these chemical contaminants beyond the area of target application can lead to the contamination of soils, sediments and waters in nearby environments. Some insecticides are particularly harmful to fish and to crustaceans such as prawns.

Irrigation-induced salinity

The risk of irrigation-induced salinity over much of the Roper catchment is low. The landscapes suitable for irrigation development and at risk of secondary salinisation are restricted to the Cenozoic clay plains (soil generic group (SGG 9)) occurring in drainage depressions on the Sturt Plateau. These heavy clays are naturally high in soluble salts in the subsoils. Irrigation of the clay plains or the surrounding permeable red Kandosols (SGG 4.1) may result in raised watertables and increased discharge into the drainage depressions, particularly the clay plains. Natural salinity is confined to the freshwater springs originating from the limestones around Mataranka and on the marine plains adjacent to the Gulf of Carpentaria.

7.2 Introduction

The range of environmental changes that could occur as a result of water and irrigation development is as varied as the number of potential developments. Furthermore, water and irrigation development can result in complex and in some cases unpredictable changes to the surrounding environment and communities. For instance, before the construction of the Burdekin Falls Dam, the Burdekin Project Committee (1977) and Burdekin Project Ecological Study (Fleming et al., 1981) concluded that the dam would improve water quality and clarity in the lower river and that para grass (*Brachiaria mutica*), an invasive weed from Africa that was then present at relatively low levels, could become a useful ecological element as a result of increased water delivery to the floodplain. However, the Burdekin Falls Dam has remained persistently turbid since construction in 1987, greatly altering the water quality and ecological processes of the river below the dam and the many streams and wetlands into which that water is pumped on the floodplain

(Burrows and Butler, 2007). Para grass and more recently hymenachne (*Hymenachne amplexicaulis*), an ecologically similar plant from South America, have become serious weeds of the floodplain wetlands, rendering innumerable wetlands unviable as habitat for most aquatic biota that formerly occurred there (Tait and Perna, 2000; Perna, 2003, 2004).

Thus, there are limitations to the advice that can be provided in the absence of specific development proposals and for this reason this section provides general advice on those considerations or externalities that are most strongly affected by water resource and irrigation developments. It is not possible to discuss every potential change that could occur. For this reason, the remainder of the chapter is structured as follows:

- Section 7.3 Ecological implications of altered flow regimes: examines how river regulation affects inland and freshwater assets in the Roper catchment and marine assets in the near-shore marine environment. It also examines how the impacts can be mitigated.
- Section 7.4 Biosecurity considerations: discusses the risks presented to an irrigation development by disease, pests and weeds and the risks new agriculture or aquaculture enterprise in the Roper catchment may present to the wider industry and broader catchment.
- Section 7.5 Off-site and downstream impacts: considers how agriculture can affect the water quality of downstream freshwater, estuarine and marine ecosystems.
- Section 7.6 Irrigation-induced salinity: briefly discusses the risk of irrigation-induced salinity to an irrigation development and the downstream environment in the Roper catchment.

Other externalities associated with water resource and irrigation development discussed elsewhere in this report include the direct impacts of the development of a large dam and reservoir on:

- Indigenous cultural heritage (Section 3.4)
- the movement of aquatic species (Section 5.4)
- terrestrial ecosystems within the reservoir inundation area (Section 5.4).

These externalities are rarely factored into the true costs of water resource or irrigation development. Even in parts of southern Australia where data are more abundant, it is very difficult to express these costs in monetary terms as perceived changes are strongly driven by values, which can vary considerably within and between communities and fluctuate over time. Therefore, the material in this chapter is presented as a stand-alone analysis to help inform conversations and decisions between communities and government.

It is important to note that this chapter primarily focuses on key risks resulting from irrigated agriculture and aquaculture, although the section on biosecurity considers both risks to the enterprise and risks emanating from the enterprise into the broader environment. Other risks to irrigated agriculture and aquaculture are discussed elsewhere in this report, including risks associated with:

- flooding (Section 2.5)
- sediment infill of large dams (Section 5.4)
- reliability of water supply (sections 5.4 and 6.3)
- timing of runs of failed years on the profitability of an enterprise (Section 6.3).

Material within this chapter is largely based on the companion technical reports on ecology (Stratford et al., 2022 and Stratford et al., 2023) but also draws upon findings presented in the Northern Australia Water Resource Assessment technical reports on agricultural viability (Ash et al., 2018) and aquaculture viability (Irvin et al., 2018), Further information can be found in those reports.

7.3 Ecological implications of altered flow regimes

7.3.1 Water resource development and flow ecology

The ecology of a river is intricately linked to its flow regime with species broadly adapted to the prevailing conditions under which they occur. Impacts from changes in freshwater flows are not limited to the persistence or ephemerality of rivers; they are also associated with the volumes of river flows and patterns of floodplain inundation and discharges that support species, habitats and ecosystem functions. Flow-dependent flora, fauna and habitats are defined here as those sensitive to changes in flow and those sustained by either surface water or groundwater flows or a combination of these. In rivers and floodplains, the capture, storage, release, conveyancing and extraction of water alters the environmental template on which the river functions, and water regulation is frequently considered one of the biggest threats to aquatic ecosystems worldwide (Bunn and Arthington, 2002; Poff et al., 2007). Changes in flows due to water resource development can act on both wet and dry periods to change the magnitude, timing, duration and frequency of flows (Jardine et al., 2015; McMahon and Finlayson, 2003). Impacts on fauna, flora and habitats associated with flow regime change can often extend considerable distances downstream from the source of impact and into near-shore coastal and marine areas as well as onto floodplains (Burford et al., 2011; Nielsen et al., 2020; Pollino et al., 2018).

There is an inherent complexity associated with understanding the environmental risks associated with water resource development, and particularly so in northern Australia. This is in part because of the diversity of species and habitats distributed across and within the catchments and the near-shore marine zones, and also because water resource development can produce a broad range of direct and indirect environmental impacts. These impacts can include flow regime change, loss of habitat, loss of function such as connectivity, changes to water quality and the establishment of pest species. Instream dams create large bodies of standing water that inundate terrestrial habitat and result in the loss of the original stream and riverine conditions (Nilsson and Berggren, 2000; Schmutz and Sendzimir, 2018). Storages can capture flood pulses and reduce the volume and extent of water that transports important nutrients into estuaries and coastal waters via flood plumes (Burford et al., 2016; Burford and Faggotter, 2021; Tockner et al., 2010). Further, even minor instream barriers can disrupt migration and movement pathways, causing fragmentation of populations and loss of essential habitat for species that need passage along the river (Crook et al., 2015; Pelicice et al., 2015). With water resource development and irrigation comes increased human activity, which can add pressures, including biosecurity risks associated with invasive or pest species transferring into new habitats or increasing their advantage in modified habitats (Pyšek et al., 2020).

This section provides an analysis of the risks associated with flow regime change in the Roper catchment to freshwater, estuarine and near-shore marine ecology and terrestrial systems dependent upon river flows. Impacts of the loss of habitat within potential dam impoundments and loss of connectivity due to the development of new instream barriers are discussed in Petheram et al. (2022) and impacts on groundwater-dependent ecosystems associated with changes to groundwater levels is presented in Section 5.3 of this report. Existing and other potential threatening processes for assets, including possible synergistic impacts, are discussed qualitatively in the companion report Stratford et al. (2022).

7.3.2 Ecology of the Roper catchment

The Roper River is a large perennial river that drains one of the largest catchments flowing into the western Gulf of Carpentaria (Figure 7-2). The protected areas in the Roper catchment include two national parks (Elsey and Limmen), an Indigenous Protected Area and other conservation parks. The Roper catchment also includes two sites listed in the Directory of Important Wetlands in Australia (Mataranka Thermal Pools and Limmen Bight (Port Roper) Tidal Wetlands System) (Environment Australia 2001). In the Gulf of Carpentaria are the Limmen Bight Marine Park and Anindilyakwa Indigenous Protected Area.

The ecology of the Roper catchment is shaped by the region's wet-dry climate, driven by seasonal rainfall, evapotranspiration and groundwater discharge. During the dry season, river flows are reduced with water in the catchment's streams receding, often to isolated waterholes. However, in parts of the Roper catchment water persists during the dry season, with some persistent waterholes supported by discharge from aquifers including the Tindall Limestone Aquifer and the Dook Creek Formation (Faulks, 2001; Taylor et al., 2023). The streams and waterholes that persist, including the important groundwater-feed streams between Mataranka Thermal Pools and the Red Lily Lagoon, provide critical refuge habitat for many aquatic species (Barber and Jackson, 2012; Faulks, 2001). During the wet season, flooding inundates significant parts of the catchment connecting wetlands to the river channel, inundating floodplains and driving a productivity boom. This flooding is particularly evident in the lower parts of the catchment, including the floodplains, wetlands and intertidal flats of the Limmen Bight, where floods deliver extensive discharges into the marine waters of the western Gulf of Carpentaria. These flood discharges are an important resource for marine productivity which in turn supports important fishing industries.

As discussed in Chapter 3, the Roper catchment has high species richness. It contains an estimated 270 vertebrate species (Dasgupta et al., 2019), including sawfish (*Pristis pristis*; Vulnerable), marine turtles (superfamily Chelonioidea), dugong (*Dugong dugon*) and the regionally endemic Gulf snapping turtle (*Elseya lavarackorum*; Endangered). The Roper catchment contains over 130 species of freshwater fishes, sharks and rays including freshwater, diadromous, estuarine and marine vagrant species. Owing to healthy floodplain ecosystems and free-flowing rivers (Grill et al., 2019; Pettit et al., 2017), very few freshwater fishes in the study area are threatened with extinction. The Roper catchment is an important stopover habitat for migratory shorebird species that are listed under the *Environment Protection and Biodiversity Conservation Act 1999*, including the northern Siberian bar-tailed godwit (*Limosa lapponica menzbieri*; Critically Endangered), eastern curlew (*Numenius madagascariensis*; Critically Endangered) and the Australian painted snipe (*Rostratula australis*; Endangered). Catchment flows also support high-value commercial and recreational marine fisheries, such as the Northern Prawn Fishery, as well as fisheries for barramundi (*Lates calcarifer*), mud crab (*Scylla serrata* and possibly a very small catch component of *S. olivacea*) and a suite of other species important to commercial, recreational and Indigenous fisheries (Smyth and Turner, 2019).

The ecology of the Roper catchment is further detailed in the companion report Stratford et al. (2022).

7.3.3 Scenarios of hypothetical water resource development and future climate

The ecology analysis uses modelled hydrology from a river system model (AWRA-R) to explore the possible impacts of water resource development in the Roper catchment using a range of hypothetical scenarios. The scenarios are configured to explore how different types and scales of water resource development such as instream infrastructure (i.e. large dams), water harvesting (i.e. pumping river water into offstream farm-scale storages), and groundwater extraction impact water dependent ecosystems. In evaluating the likelihood of a hypothetical development scenario occurring Section 1.2.2 should be consulted. Scenarios are also used to explore how dry, mid and wet future climates might impact water dependent ecosystems (and interactions with water resource development and a dry climate future). The scenario terminology used in the Assessment is broadly describe in Section 1.4.3 with Table 7-1 providing more specific details as related to the ecology analysis. Further details of the river system modelling are provided in Hughes et al. (2023).

The hydrology generated with the Roper AWRA-R model considers the rainfall and runoff, routing of water across subcatchments, losses, irrigation demand and diversion reservoir behaviour (Hughes et al., 2023) modelled across 28 nodes within the Roper catchment (node locations shown in Figure 7-2). A long time series of daily flow from 1 September 1910 to 31 August 2019 is generated and used (except where otherwise stated) as this provides a range of possible environmental conditions. These include periods of variability considering both low- and high-flow conditions across scales of days and inter-decadal variability and sequencing. Scenario A, representing the historical climate with current development, has been calibrated to river gauges across the catchment (Hughes et al., 2023). All impacts to ecology are considered as change relative to Scenario A_N which includes no development and represents natural conditions. In considering change, this accounts for the lag effects of existing development as well as the scenario development in the analysis. Additional analysis is performed using hydrodynamic model inputs, which provide estimates of flood extent, water depth and velocity for a sample of flood events of different magnitudes and durations as described in Kim et al. (2023).

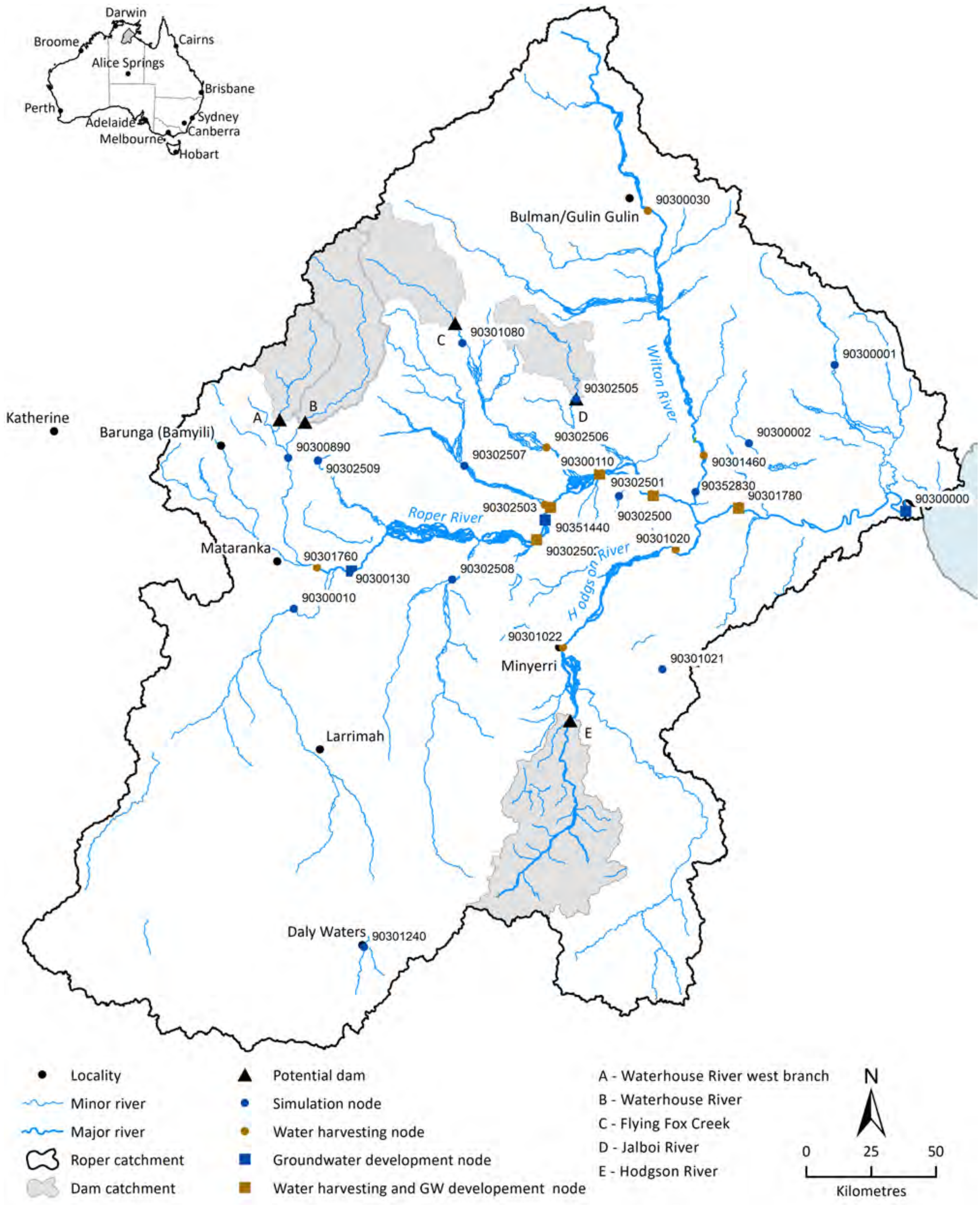

Figure 7-2 Locations of the river system modelling nodes at which flow–ecology relationships are assessed, showing the location of the hypothetical modelled dam locations (A–E), water harvesting nodes and groundwater development related changes in surface flow

The flow ecology of the environmental assets is assessed in subcatchments in which they occur, downstream of the river system nodes. The locations of ecology assets across the catchment are documented in Stratford et al. (2022).

Table 7-1 Water resource development and climate scenarios explored in the ecology analysis

Description of the river system modelling is provided in Hughes et al. (2023). FSL=Full Supply Level. EOS=End of system

SCENARIO	DESCRIPTION	VERSION (OR EXAMPLE)	DETAILS	VARIATIONS
A_N	Natural baseline	Natural (pre-2019) conditions and historical climate	Modelled daily flow from 1/9/1910 to 31/8/2019. The flow regime from which ecological change is considered	
A_{2060}	Current groundwater development to 2060 baseline	Existing groundwater development with changes modelled to year 2060	Considers the lag to 2060 associated with current levels of groundwater development impacting volumes of surface water	Modelled difference in EOS flow volumes between A_N and A_{2060} shown in Table 7-11
B-D_{WR}	Single dam	Waterhouse River dam	Waterhouse River dam 'B' in Figure 7-2 with no transparent flow. FSL = 21 m	Other single dam scenarios include Flying Fox Creek, Hodgson River, Waterhouse River west, and Jalboi River with locations shown in Figure 7-2. Changes to EOS flow volumes associated with each dam shown in Table 7-5
B-D_{WR+FFC}	Two dams	Waterhouse River and Flying Fox Creek dams (two dams)	Waterhouse River and Flying Fox Creek dams with no transparent flow	Changes to EOS flow volumes shown in Table 7-5
B-D_5	Five dams	Five dams cumulative (dams A-E in Figure 7-2)	No transparent flow	B-D_5-T (with transparent flow). Changes to EOS flow volumes of five dams with and without transparent flows shown in Table 7-6
B-W_{200}		Water harvest with irrigation target (GL)	No end-of system (EOS) flow requirement.	W – Irrigation target volume (100, 200, 330, 440 and 660 GL). Changes to EOS flow volumes shown in Table 7-10
B-E_{100}		Water harvest with EOS flow requirement (GL)	EOS flow volume required to pass EOS node before harvesting	E – EOS requirement (0, 100, 400 and 700 GL). Changes to EOS flow volumes shown in Table 7-7
B-P_{200}		Water harvest with commence to pump thresholds (ML/day)	Threshold flow at the node required before pumping	P – Pump threshold (200, 600, 1000, 1400, 1800 ML/day). Changes to EOS flow volumes shown in Table 7-8
B-R_5		Water harvest with pump capacities	Time in days required before water extraction target achieved	R – Pump capacity (5, 10, 15, 20, 30, 40 days to extract volume). Changes to EOS flow volumes shown in Table 7-9
B-G_{35}	Groundwater development	Groundwater development (35 GL from the Larrimah region in addition to A_{2060}) to 2060	Estimated changes at node 90300130 with changes propagated to downstream nodes	B-G105 105 GL groundwater extraction from the CLA to the south of Larrimah. Changes to EOS flow volumes shown in Table 7-11
C_{dry}	Future climate streamflow	Climate dry, mid and wet	Future climate scenarios to 2060	Climate mid and wet
D_{dry}-D_5	Combined future climate and WRD	Dry climate and five dams cumulative	No transparent flow and no EOS flow requirement	
D_{dry}-W_{660}		Dry climate and water harvesting	No EOS flow requirement	

It is important to note that each potential water resource development pathway results in different changes to flow regimes, considering rainfall and upstream catchment sizes, inflows, the attenuation of flow through the river system (including accumulating inflows with river confluences), and also the many ways each water resource development could unfold and be implemented and managed. The scenarios are used to explore some of these interactions between the location and the types and scale of development, and how these may influence ecology outcomes across the catchment.

Many of the hypothetical scenarios listed in Table 7-1 provide the minimum level of dedicated environmental provisions and are optimised for water yield reliability without considering policy settings or additional restrictions that may help mitigate the impacts to water dependent ecosystems. These scenarios are useful for considering impacts across different development strategies in the absence of mitigation strategies or policy settings. Further, as an artefact of the model structure, modelling dam development involves extracting water volumes 'at the dam wall' rather than conveying water for irrigation within the downstream channel. Typically, for the purpose of agricultural use, water would either be piped or extracted from conveyancing flows in the reaches below the dam; however, the model calculates and removes the extractive take at the dam node. Hence, in those scenarios with potential dams, flow volumes directly downstream of the dam are likely to have less volume than would occur in a given real-world dam setting that involves conveying water to downstream users. Further, management and regulatory requirements in a real-world setting would likely provide a range of greater safeguards for environmental outcomes, possibly establishing a combination of transparent flows (river flows that are managed to pass a regulating structure to support ecology), end-of-system requirements, extraction limits and/or minimum flow thresholds. Each of these safeguards, if implemented, would likely improve environmental outcomes. Furthermore, many of the scenarios explored, while technically feasible, exceed the level of development that would reasonably occur (see Section 1.2.2). These scenarios are included as a stress test of the system and can be useful for benchmarking or contrasting various levels of change.

The purpose of the ecology analysis is to provide information about the relative ecological risks associated with potential water resource development in the Roper catchment. The goal is to support long-term decision making and planning processes for sustainable and responsible development in northern Australia informed by scenario analysis. The development scenarios are hypothetical and are for the purpose of exploring a range of options and issues in the Roper catchment. In the event of any future development occurring, further work would need to be undertaken to assess environmental impacts associated with the specific development across a broad range of environmental considerations.

7.3.4 Ecology outcomes and implications

Changes in flow regimes can have impacts considerable distances downstream from the source of the impact, and flow needs (such as the magnitude, timing, during and frequency of both low and high flows) of different species and habitats vary. A range of modelling approaches are used to understand the impacts of flow regime change on ecological assets in the Roper catchment. These approaches are described in the companion technical report Stratford et al. (2023). Modelling considers the location of 20 ecological assets (Table 7-2) across 28 nodes in the Roper catchment including the end-of-system node for near-shore marine assets (Figure 7-2).

Table 7-2 Ecology assets used in the Roper Water Resource Assessment and the different ecology groups used in this analysis

Twenty assets are modelled in the ecology analysis; assets may be assigned to more than one group. Description of the ecology assets and their distribution is provided in Stratford et al. (2022). Analysis and interpretation for all assets is provided in Stratford et al. (2023).

ASSET REPORTING GROUP	ECOLOGY ASSETS
Fish	Barramundi, catfish (Order: Siluriformes), grunter, mullet (Family: *Mugilidae*), sawfish and threadfin (*Polydactylus macrochir*)
Waterbirds	Colonial and semi-colonial waders, cryptic waders, swimmers, divers and grazers, and shorebirds
Other species	Banana prawns (Genus: *Penaeus*), Endeavour prawns (Genus: *Metapenaeus*), freshwater turtles (Family: Chelidae) and mud crabs
Habitats	Floodplain and riparian vegetation, floodplain wetlands, inchannel waterholes, mangroves, salt flats and seagrass
All freshwater assets	Barramundi, catfish, colonial and semi-colonial waders, cryptic waders, floodplain and riparian vegetation, floodplain wetlands, freshwater turtles, grunter, inchannel waterholes, shorebirds, swimmers, divers and grazers and sawfish
All marine assets	Banana prawns, barramundi, Endeavour prawns, mangroves, mud crabs, mullet, salt flats, sawfish, seagrass, shorebirds and threadfin

It is important to note that this ecology analysis is broad in scale and includes significant uncertainty in results. This uncertainty is due to a range of factors including, and not limited to, incomplete knowledge, variability within and between catchments, and limitations associated with modelling processes and data. Furthermore, thresholds, temporal processes, interactions, synergistic effects and feedback responses in the ecology of the system may not be adequately captured in the modelling process. There is also uncertainty associated with the possible future climate conditions such as rainfall patterns and any additional synergistic and cumulative threatening processes that may emerge and interact across scales of space and time. The region that the Roper catchment occurs within is vast and diverse, and the knowledge base of species occurrences is limited. More broadly, the understanding of freshwater ecology in northern Australia is still developing.

Provided below are a sample of outcomes for barramundi showing the level of change in important flow metrics as measured as percentile change from the mean under Scenario A_N given the historical distribution of flows in the full model time period. Larger values represent greater change in the parts of the flow regime that are important for the asset with qualitative descriptors shown in Table 7-3. The outcomes consider the flow needs, distribution within the catchment and the range of flow conditions occurring under each of the scenarios for the ecological asset. For more details and for results on other assets see Stratford et al. (2023).

Table 7-3 Descriptive values for the flow relationships modelling as rank percentile change of the hydrometrics considering the change in mean metric value against the natural distribution observed in the modelled baseline series of 109 years. For more information see Stratford et al. (2023)

VALUE	RATING	IMPLICATION
0-2	Negligible	The mean for the assets metrics under the scenario has negligible change as considered against the modelled historical conditions and well within the normal experienced conditions at the model node. The assets hydrometrics are within 2 percentile of the historical Scenario A mean
2-5	Minor	The change is minor with the mean for the assets metrics for the scenario outside of 2 and within 5 percentile of Scenario A and the historical distribution of the hydrometrics
5-15	Moderate	The change is moderate with the mean for the assets metrics under the scenario outside of 5 and within 15 percentile of Scenario A and the historical distribution of the hydrometrics
15-30	Major	The change is major with the mean for the assets metrics for the scenario outside of 15 and within 30 percentile of Scenario A and the historical distribution of the hydrometrics
>30	Extreme	The change is extreme with the mean for the assets metrics under the scenario having extreme change as considered against the modelled historical conditions with metrics occurring well outside of typical conditions at the modelled node. The scenario mean is outside of the 30 percentile from the historical Scenario A_N mean (or equivalent to the new mean being typical of the outside 20% of observations from the historical sequence across the metrics important to the asset)

Barramundi

Barramundi are large opportunistic predatory fish that inhabit riverine, estuarine and marine waters in northern Australia, including the Roper River. Adults mate and spawn in the lower estuary and coastal habitats near river mouths during the late dry season and early wet season. Small juveniles migrate upstream from the estuary to freshwater habitats where they grow and mature, before emigrating downstream as adults to estuarine habitats where they reside and reproduce. In the Roper catchment, barramundi occupy relatively pristine habitats in both freshwater and estuarine reaches, as well as coastal marine waters. Their life history renders them critically dependent on river flows (Tanimoto et al., 2012) as new recruits move into supra-littoral estuarine and coastal salt flat habitats and juveniles occupy freshwater riverine reaches and palustrine (wetland) habitats (Crook et al., 2016; Russell and Garrett, 1983; 1985).

Barramundi are sensitive to changes in flow regime – some critical requirements affecting growth and survival are riverine–wetland connectivity, riverine–estuarine connectivity, passage to spawning habitat, and volume of flood flows (Crook et al., 2016; Roberts et al., 2019). In years of natural low flows, or flows reduced by anthropogenic activity, the range of beneficial but not essential habitat and ecosystem processes available to barramundi is reduced; hence growth and survival are reduced (Leahy and Robins, 2021; Robins et al., 2006; Robins et al., 2005).

Barramundi is an ecologically important fish species that is capable of modifying the estuarine and riverine fish and crustacean communities throughout Australia's wet-dry tropics (Blaber et al., 1989; Brewer et al., 1995; Milton et al., 2005). It is targeted by commercial, recreational and Indigenous fisheries. Barramundi is an important species for Indigenous peoples in northern Australia, both culturally (Finn and Jackson, 2011; Jackson et al., 2011) and as a food source (Naughton et al., 1986).

In the Roper catchment, barramundi were assessed at 19 nodes using flow relationships modelling (see Stratford et al. 2023). Modelling of water resource development within the Roper catchment resulted in differing degrees of impact on essential flow components for barramundi (shown in Figure 7-4 as spatial heatmap and Figure 7-5 for nodes). Mean change in important hydrometrics for barramundi was rated as minor (3.59) across the subcatchments for the cumulative five dams scenario (B-D_5), minor (4.4) for the large water harvesting up to 660 GL scenario (B-W_{660}) and negligible (0.54) for the groundwater development scenario (B-G_{35}). For single dams, both the Waterhouse River single dam (B-D_{WR}; 1.25) and the Flying Fox Creek single dam (B-D_{FFC}; 1.82) scenarios resulted in negligible change when considering the mean change across all 19 barramundi analysis nodes. In the Roper catchment, the greatest catchment-wide mean impact to barramundi water requirements from water resource development was minor (4.4) and was associated with the water harvest up to 660 GL scenario (B-W_{660}). Under this scenario, impacts to barramundi were greatest at node 90302502 (see Figure 7-2), with a moderate (11.59) percentile change from the mean of Scenario A_N in important flow requirements at this single node location. Across the catchment, two nodes had major changes resulting from the five dams cumulative scenario (B-D_5; Figure 7-4c). No nodes recorded greater-than-moderate change under the 660 GL water harvesting (B-W_{660}) or greater than negligible change under the groundwater development (B-G_{35}) scenario.

Figure 7-3 Billabong, Roper catchment

Photo: CSIRO – Nathan Dyer

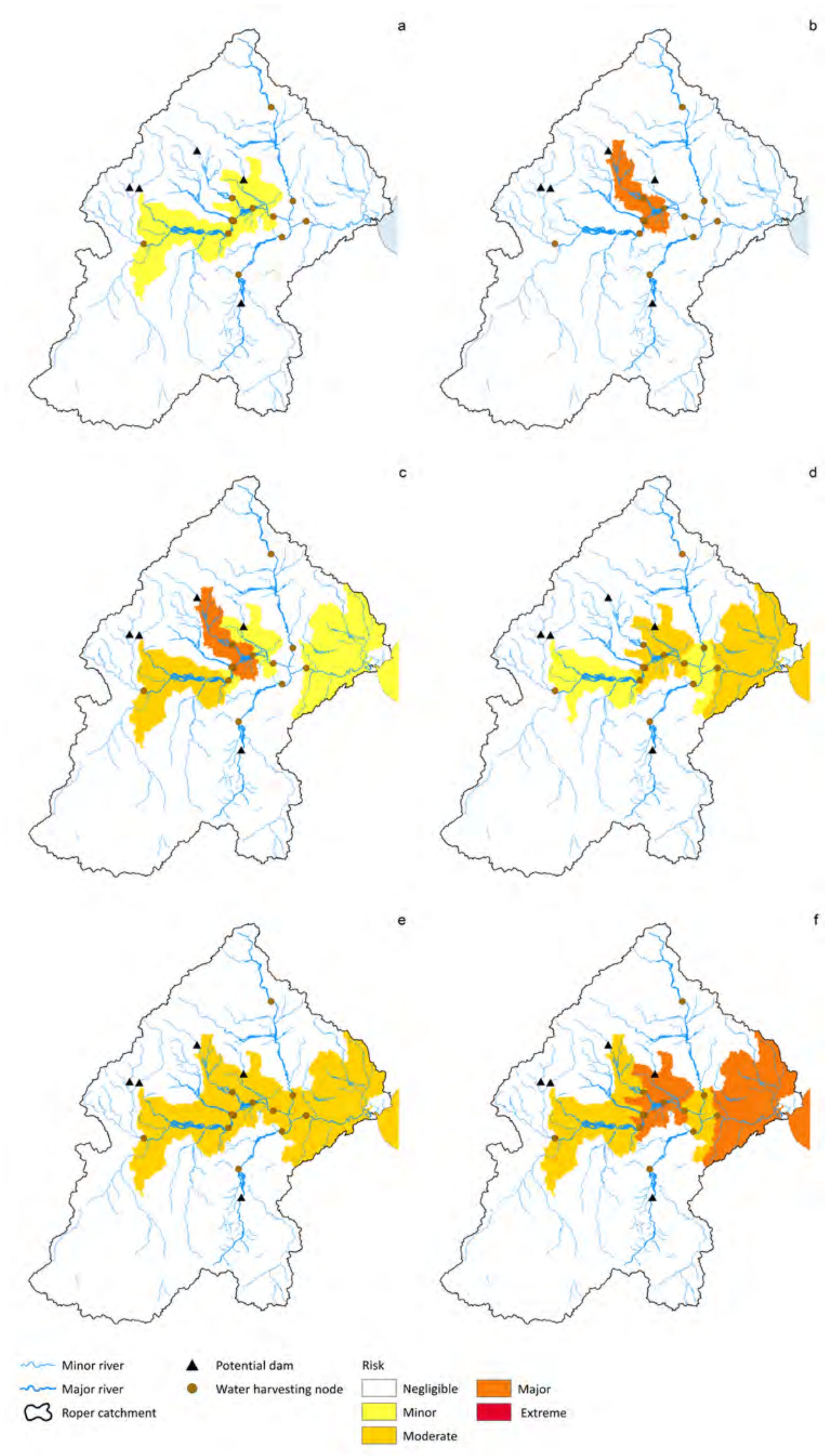

Figure 7-4 Spatial heatmap of change in important flow metrics for barramundi across the catchment

Scenarios are a) Waterhouse River dam (B-D_{WR}), b) Flying Fox Creek dam (B-D_{FFC}), c) five dams cumulative (B-D_5), d) water harvesting up to 200 GL (B-W_{200}), e) dry climate (C_{dry}) and f) dry climate and water harvesting (D_{dry}-W_{660}). Catchment shading indicates the level of flow regime change of important metrics for each asset from the upstream node, considering only the subcatchments where barramundi was assessed.

The groundwater development scenario (B-G35) resulted in negligible (1.46 and 1.26) changes at the barramundi upper catchment (90300110) and downstream (90300000) reference nodes, respectively (Figure 7-5). For barramundi, these changes from groundwater development at the downstream node were smaller than changes from both the cumulative five dam scenario (B-D5) (2.75) and large water harvesting (B-W660; 9.34) scenarios at the lower reaches of the catchment but given the smaller changes in EOS flow resulting from the groundwater development scenario this is not unexpected.

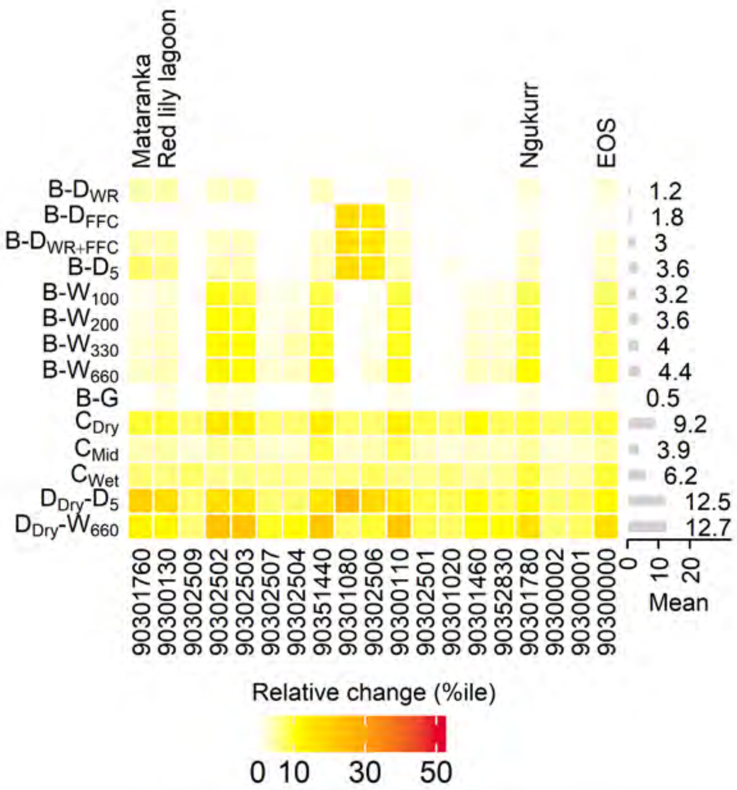

Figure 7-5 Changes in barramundi–flow relationships by scenario across the model nodes

Scenarios are listed on the left vertical axis (see Table 7-1). X-axis lists model nodes (i.e. location). Colour intensity represents the level of change occurring in the assets' important flow metrics with the scenarios at the assets' nodes. Results show the rank percentile change of each scenario relative to the distribution of the modelled natural baseline at each node. EOS=End of System. Horizontal grey bars and number correspond to the mean change across all model node locations for the asset.

Comparisons between scenarios that are roughly equivalent in terms of the overall level of changes in EOS flow volumes showed the following:

- The groundwater development scenario (B-G35) results in a similar reduction to groundwater discharge near Mataranka at 2070 as the 105 GL groundwater extraction scenario (i.e. ~1%). Groundwater development (i.e. B-G35 and B-G105) results in a lower mean impact for barramundi across the catchment with negligible (0.54) change compared to the 100 GL water harvesting (B-W100) scenario with minor (3.19) change.
- The Waterhouse River dam scenario (B-DWR) has lower impact on asset flows with negligible (1.25) change compared to the 100 GL water harvesting scenario (B-W100) with minor (3.2) change.

- The two dam scenario ($B\text{-}D_{WR+FFC}$) has lower change (minor; 3.05) than the 200 GL water harvesting ($B\text{-}W_{200}$) scenario with minor (3.6) change.
- At close to maximum feasible water harvest, the mean change across the catchment for the five dams scenario ($B\text{-}D_5$) is lower (with minor (3.59) change) than the large (up to 660 GL) water harvesting scenario ($B\text{-}W_{660}$), though also with minor (4.41) change.

Thus, for roughly equivalent scenarios, water harvesting typically had larger effects on barramundi than did dams, an outcome which varied by asset (Stratford et al. 2023).

The dry climate (C_{dry}) scenario resulted in moderate (9.2) mean percentile change across all the analysis nodes for barramundi (Figure 7-5). This indicates that the impact under Scenario C_{dry} was greater on average across all the catchment's analysis nodes than the mean change under the five dams scenario ($B\text{-}D_5$) (minor; 3.59), water harvesting ($B\text{-}W_{100}$ and $B\text{-}W_{660}$) (minor; 3.19 and 4.41, respectively), and groundwater development ($B\text{-}G_{35}$) scenarios (negligible; 0.54), although local impacts under some of the water resource development scenarios can be considerably higher. The impacts under a dry climate future in conjunction with five dams cumulative ($D_{dry}\text{-}D_5$), and a dry climate in conjunction with up to 660 GL water harvesting ($D_{dry}\text{-}W_{660}$) resulted in larger impacts up to moderate (12.5 and 12.69, respectively) when averaged across all 19 of the barramundi analysis nodes.

Some of the impacts of flow regime change on barramundi populations are related to changes in ecosystem functions. Barramundi benefit from both longitudinal and lateral habitat connectivity being maintained throughout the catchment. Barramundi are known to undertake extensive movements across inundated floodplains (Crook et al., 2019) where floodplains are likely to represent a major source of high-quality food for fish and are recognised as being important for maintaining healthy fish communities (O'Mara et al., 2022). High river flows expand the extent of habitats, increase connectivity, deliver nutrients from terrestrial landscapes, create hot spots of high primary productivity and food webs, increase prey productivity and availability, and increase migration within the river catchment (Burford et al., 2016; Burford and Faggotter, 2021; Leahy and Robins, 2021; Ndehedehe et al., 2020; Ndehedehe et al., 2021). Stream fishes including those from northern Australia are closely associated with physical habitat attributes including depth and velocity (Keller et al., 2019). Modelling of flow-habitat suitability as a function of depth and velocity preferences of barramundi showed a small reduction of maximum habitat availability across a flood event associated with dam development (Figure 7-6). Any reduction in access to upstream habitats and supra-littoral habitats associated with water harvesting or dams could contribute to impacts on barramundi populations.

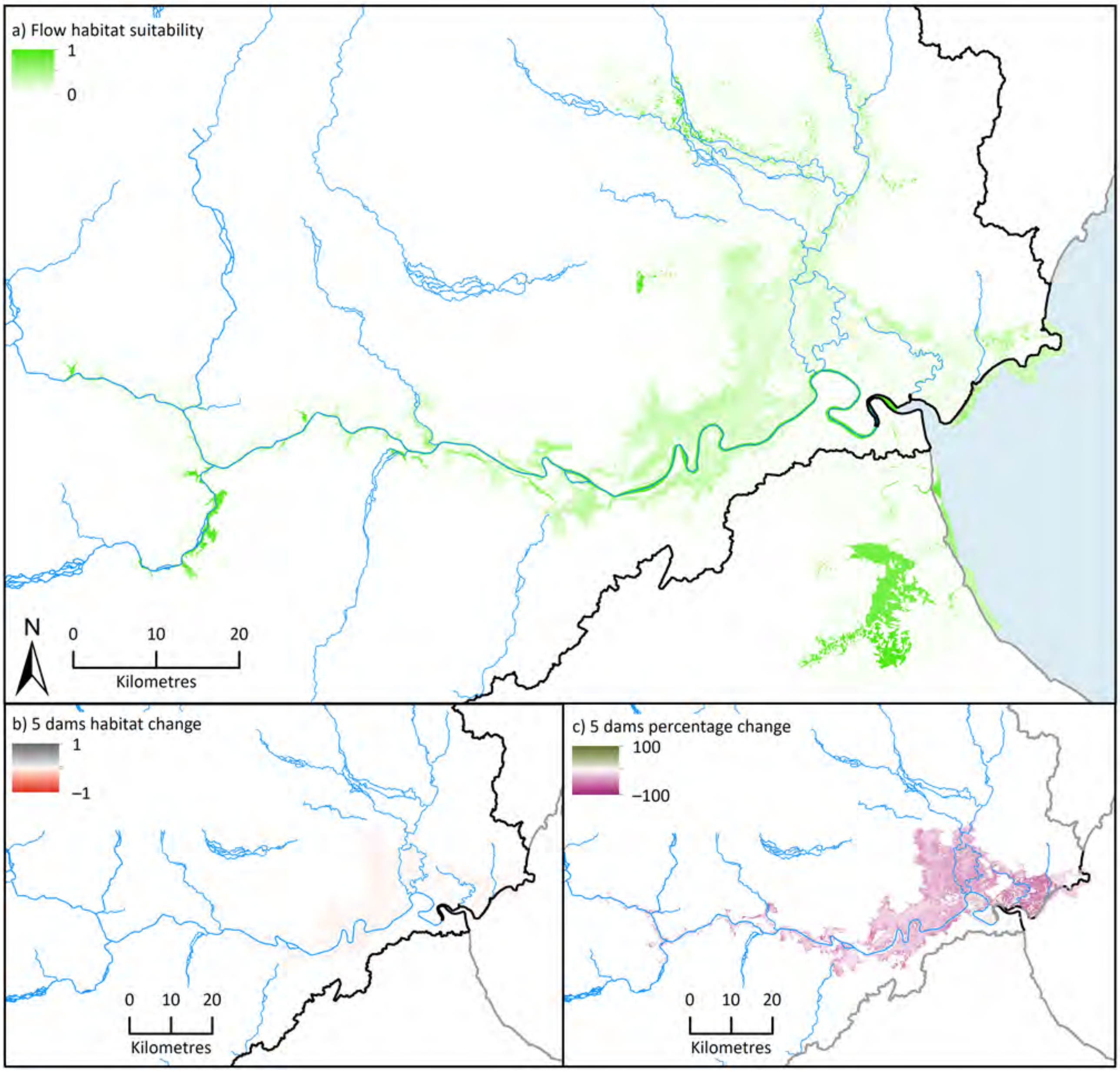

Figure 7-6 Changes in the weighted maximum flow-habitat suitability for barramundi based upon the species' recognised preferences across a 1:13 year flood event

A) Mean weighted maximum potential of preferred habitat across the modelled time period (12/2/1991 to 23/3/1991), B) difference between Scenario A and the five dams cumulative (B-D_5) scenario shown as absolute change, C) difference between Scenario A and the five dams cumulative (B-D_5) scenario shown as percentage change. More details and the flow–habitat preference relationships for barramundi are discussed in Stratford et al. (2023).

Mean catchment outcomes for ecology assets

This section provides a high-level overview of the scenarios showing aggregated results (unweighted mean of assets) and discusses specific differences driven by the scenarios in the spatial pattern and magnitude of change given the range of outcomes across the modelled environmental assets. Outcomes for specific assets vary depending upon water needs and flow ecology and are discussed with implications and interpretation of results in Stratford et al. (2023) with the example of barramundi provided above. The values associated with means include but do not show the range in outcomes across assets, where impacts for individual assets or at specific locations can be considerably higher or lower than the mean and does not consider the relative habitat area downstream of each of the assets assessment nodes.

Dams, water harvesting and groundwater development each result in different changes in flows affecting outcomes for ecology both by different magnitudes of change, but also across different parts of the catchment and in different ways (Figure 7-8 and Figure 7-9). Under the five dams scenario (B-D_5) the largest catchment mean impacts were for floodplain wetlands, grunter, inchannel waterholes and sawfish, each with mean moderate change across all their catchment nodes. The largest site-based impacts were directly downstream of dams and often resulted in node impacts with up to extreme change in asset flow conditions for assets including sawfish, shorebirds, floodplain wetlands and inchannel waterholes. Comparatively, for water harvesting under Scenario B-W_{600} the largest catchment mean change in flow regimes for assets was associated with assets located towards the end-of-system and included prawns, both tiger and Endeavour, mullet and threadfin all with moderate change across their nodes.

Figure 7-7 Roper River

Source: CSIRO – Nathan Dyer

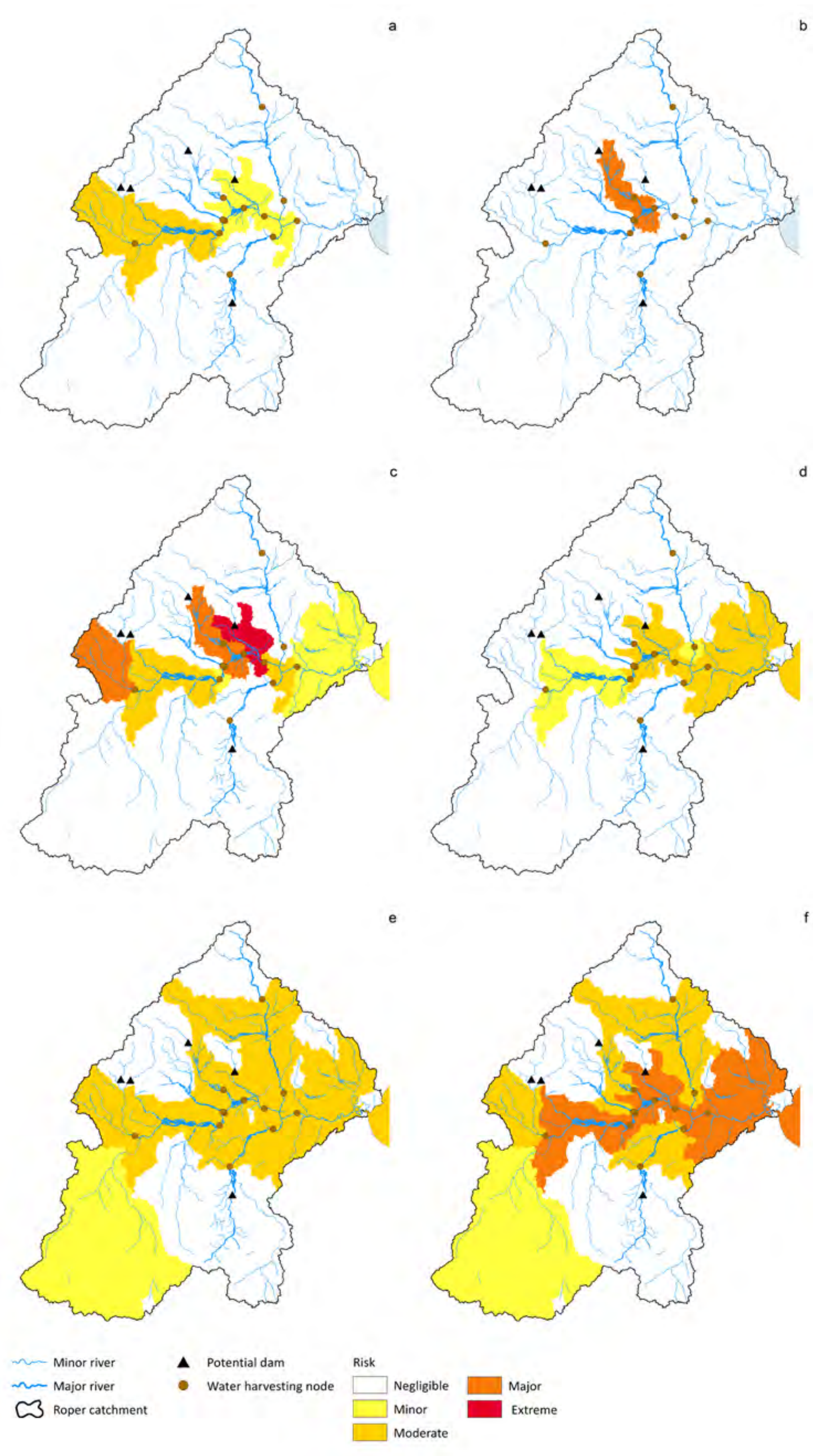

Figure 7-8 Spatial heatmap of mean asset flow regime change across the Roper catchment, considering change across all assets in the locations which each asset is assessed

Scenarios are: a) Waterhouse River dam (B-D_{WR}), b) Flying Fox Creek dam (B-D_{FFC}), c) five dams cumulative (B-D_5), d) water harvesting – soil limited (B-W_{200}), e) dry climate (C_{Dry}) and f) dry climate and water harvesting (D_{dry}-W_{660}). Catchment shading indicates the level of flow regime change of important metrics for each asset from the upstream node.

Under the maximum development scenarios explored for water harvesting (Scenario B-W_{660}) and dams (Scenario B-D_5) the impacts towards the end-of-system were greater under water harvest compared to dams for all assets excluding seagrass (Figure 7-8c and d shows mean change). This is likely not only because the water harvest scenario resulted in higher levels of extraction compared to the five dams but also that impacts from dams typically reduced with increased distance downstream from the potential dam. Impacts under scenarios with a single dam were often negligible towards the end-of-system as unimpacted tributary inflows accumulate with distance downstream from the dam (see Figure 7-8a and b). Under a dry future climate flow regime impacts on ecology occurred across the catchment (Figure 7-8e), with cumulative impacts from water resource development in combination with dry future climate often leading to the greatest catchment level impacts on flow ecology (Figure 7-8f showing D_{dry}-W_{660}).

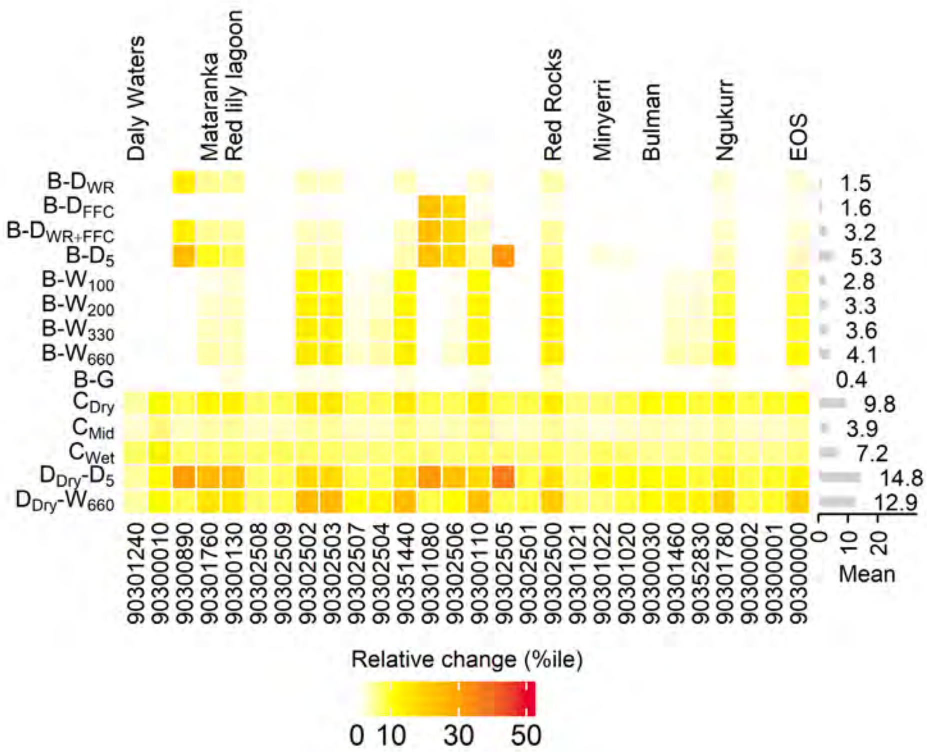

Figure 7-9 Mean of node changes in asset–flow relationships by scenario across all model nodes

Scenarios are listed on the left vertical axis (see Table 7-1). X-axis lists model nodes (i.e. location). Colour intensity represents the mean level of change occurring in the assets' important flow metrics with the scenarios. Results are the mean rank percentile change of each scenario relative to the distribution of the modelled natural baseline across all nodes for the assets. EOS = End of System. Horizontal grey bars and number correspond to the mean change across all model node locations.

7.3.5 Ecosystem functions and processes to support ecology

Lateral connectivity of floodplain habitats

Lateral connectivity is the connection of the floodplain to the river channel through inundation and is an important ecosystem function which supports many of the assets of the Roper catchment. The purpose of the lateral connectivity analysis is to understand the potential impacts that development scenarios could have on the connectivity between the river and some specific ecological assets, namely floodplain wetlands, mangroves and melaleuca (Figure 7-10) compared to Scenario A through a sample of flood events. Full results are provided in Stratford et al. (2023).

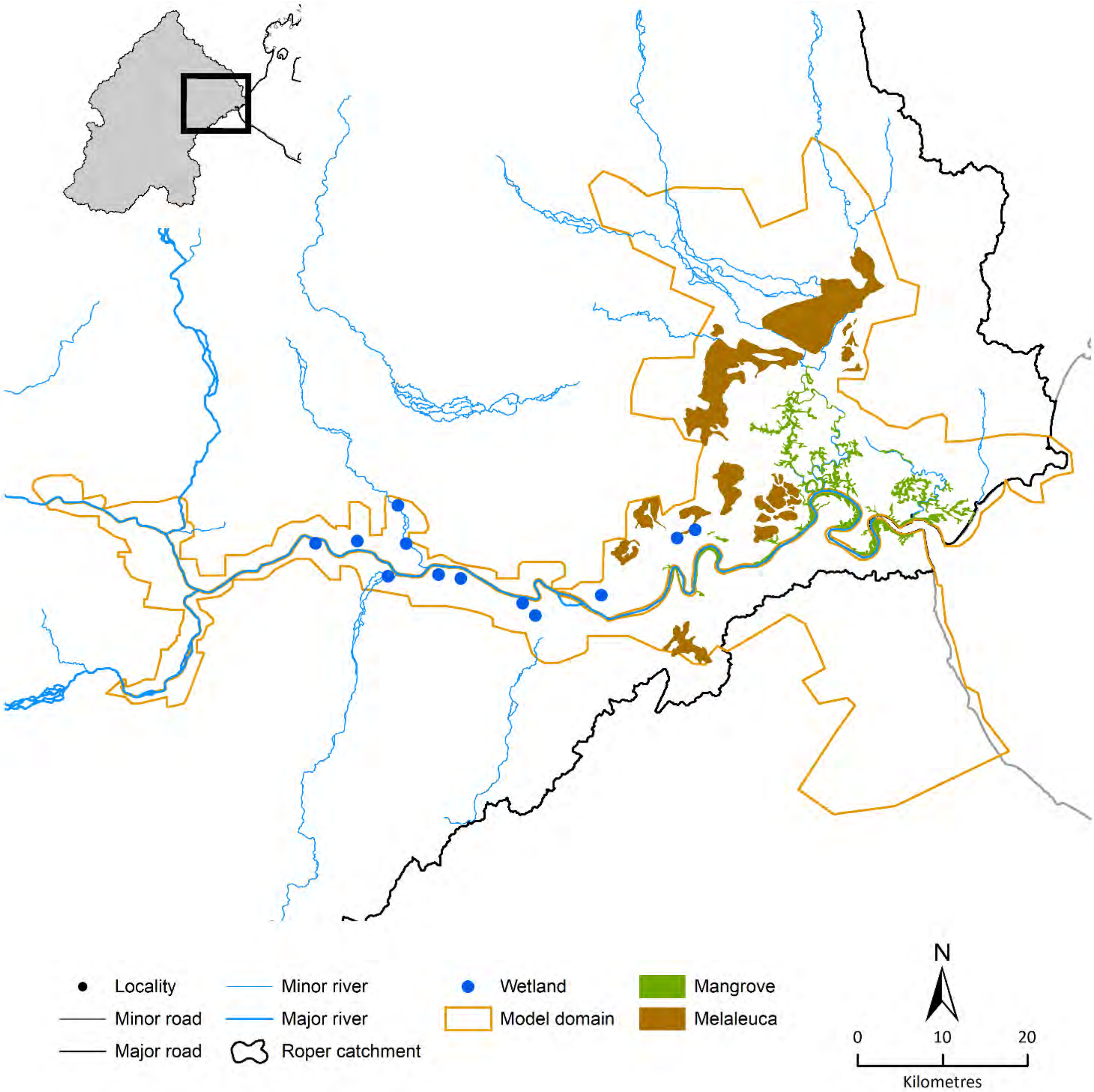

Figure 7-10 Locations of the wetland, mangrove and melaleuca habitats used to assess lateral connectivity
Wetlands are identified from imagery. Melaleuca habitats are selected from Department of Environment, Parks and Water Security (2000). Mangrove habitats are selected from Department of the Environment and Energy (2010). Minor and major roads and rivers are from Geoscience Australia (2017). The hydrodynamic model domain is described in Kim et al. (2023).

For the assessed scenarios, a drying climate will result in the largest changes to connectivity across wetlands, mangroves and melaleuca habitats in the Roper catchment. Any reduction in high-magnitude flood events will result in greater connectivity changes to wetlands and melaleuca than to changes associated with the more frequent lower magnitude flood events, and impact these habitats disproportionately in comparison to mangrove habitats.

For wetlands, reduced connectivity affects the exchange of nutrients and carbon between the floodplain wetlands and the river channel, as well as the movement of biota, also affecting the productivity of the system (Brodie and Mitchell, 2005; Hamilton, 2010) and therefore the ecosystem services that the floodplain wetlands provide (Salimi et al., 2021). Loss of wetland connectivity will also reduce the available habitat for species such as fish and birds. Under larger levels of change there is a risk of permanent disconnection of some wetlands resulting in these wetlands transitioning more towards terrestrial environments (Kingsford, 2000; Pettit et al., 2017).

A reduction in the connectivity of melaleuca habitat can lead to a reduction in the quantity of nutrients moving from the floodplain back into the river channel, affecting primary and secondary productivity (Hamilton, 2010; Pettit et al., 2017). Melaleuca leaflitter contains high quantities of nitrogen and phosphorus, which moves back into the river channel as flood water recedes (Finlayson et al., 1993; Finlayson, 2005).

For mangroves, any reduction of the larger and less frequent flood events results in only comparatively small changes to connectivity. This is due to the mangroves dominating low-lying areas including the creek and river channels in the intertidal zone in the Roper catchment (Palmer and Smit, 2019; Smyth and Turner, 2019). Mangroves provide a range of ecosystem services, which if reduced under a future drying climate or due to water resource development would impact services such as shoreline stabilisation, carbon capture and storage, storm surge protection and provision of nutrients and suspended sediments (Palmer and Smit, 2019).

Longitudinal connectivity (flow across Roper Bar)

Biotic movement along the river channel (longitudinal connectivity) is an essential ecosystem function of river systems that enables species to access habitat, support meta-population processes and complete life-history requirements. This section provides an assessment of water levels at Roper Bar, a constructed cement crossing of the Roper River around 130 km from the river mouth. Water levels vary through time and under different water resource development scenarios and influence the ability of biota to move across the bar.

The longitudinal connectivity analysis considers three water heights over the bar (0.1m, 0.3m and 0.5m) representing low, medium and high confidence in providing biotic passage across Roper Bar. The analysis indicates that under Scenario A_N, a depth of 0.3 m at Roper Bar (representing medium confidence of enabling biotic passage) was exceeded on average 99.5 days per year. For the low confidence depth of 0.1 m, this increases to 239 days above the required threshold, and for high confidence (0.5 m) this decreases to 68 days where depth is sufficient to enable the less capable swimmers to pass (Table 7-4). For the modelled water resource development scenarios and future climate scenarios and for the three confidence levels, all except Scenario C_{wet} result in fewer days on which movement across the bar is possible compared to under Scenario A_N.

Table 7-4 The mean number of days per year with depth greater than three depth thresholds over Roper Bar representing low, medium and high confidence for allowing biotic passage

Scenario	Low confidence (0.1 m)	Medium confidence (0.3 m)	High confidence (0.5 m)
A_N	233.9	99.5	68.2
B-D_{WR}	221.1	92.7	65.3
B-D_{FFC}	229.3	94.3	66.1
B-D_{WR+FFC}	215.6	87.2	63.2
B-D_5	206.5	81.0	60.6
B-W_{100}	159.3	87.7	65.7
B-W_{200}	146.1	80.8	62.3
B-W_{330}	137.2	74.8	58.4
B-W_{660}	120.6	64.3	50.7
B-G	226.6	98.4	68.0
C_{dry}	187.7	81.6	55.5
C_{wet}	259.8	108.7	77.0
D_{dry}-D_5	161.7	66.8	48.4
D_{dry}-W_{660}	84.8	49.0	38.4

Water resource development risks not only increasing the frequency and duration of low flows, but also delaying the timing of initial wet-season flows to later in the wet-season. These changes in flow and depth may have impacts on biotic connectivity by limiting the movement of species across parts of the catchment at critical times when movement is needed as species movements or migrations may be season dependent. Water harvesting scenarios resulted in delays in connectivity at Roper Bar to later in the flow year, particularly for the low-confidence (0.1 m depth) threshold. In comparison, the high-confidence threshold of 0.5 m resulted in a much more restricted (shorter duration) but consistent period of the year (during the wet season) with suitable flows for biotic connectivity. Further, when using thresholds with greater depth, the sensitivity to changes in the scenarios was lower in terms of the impacts on the number of days above these thresholds compared to the impacts seen with the lower depth thresholds. In other words, changes to the lower depth thresholds had a more pronounced effect.

Note that if development were to affect the connectivity of the Roper Bar due to changes in flows, a range of potential mitigation strategies may be effective in restoring connectivity across the bar and enable passage of fish and other species during lower flows. The Roper Bar is modelled as it constructed now and because it may also be an indicator for other changes to longitudinal connectivity elsewhere in the river system. Impacts to longitudinal connectivity in the Roper catchment would have impacts to assets including fish and turtle species.

7.3.6 Management of impacts on ecology

The magnitude and spatial extent of ecological impacts arising from water resource development are highly dependent on the type and location of development, the extraction volume and how the type of changes in the flow regime impact different aspects of flow–ecology. Mitigation measures seek to protect important parts of the flow regime and can be important for sustaining ecology under water resource development. This section explores the effectiveness of different mitigation measures including providing transparent flows for dams, different rules for water harvesting and different overall targets for water extraction.

Instream dam development

Five individual dams were assessed resulted in varying levels of impact to ecology flow dependencies with none resulting in changes greater than negligible averaged for all assets across the catchment (Table 7-5), although local impacts can be considerably higher. Not all dams are the same size, have similar inflows or capture similar volumes, and the location of the dam in the catchment influences outcomes. Dam sites closer to the end-of-system may have higher impacts on end-of-system flow and connectivity compared to dams in headwater catchments, but when considering impacts, the ecology flow changes may affect a smaller proportion of the catchment overall. Impacts directly downstream of modelled dams are often high and may cause extreme changes in ecology flow dependencies. Areas further downstream have contributions from unimpacted tributaries that help support natural flow regimes. Impacts are not equivalent across assets and large local impacts may lead to changes in ecology across other parts of the catchment due to the connected nature of ecological systems.

The cumulative impacts of multiple dams (two dams and five dam scenarios) are greater than those of individual dams considering both change in EOS flow volumes and ecology flow dependencies, as shown in Table 7-5. Cumulative impacts to ecology may be associated with a combination of a larger portion of the catchment being affected by changes in flows across multiple parts of the catchment, as well as residual flows being lower due to the overall greater level of abstraction (Table 7-5 and Figure 7-8c compared to a and b). Assets with higher change associated with altered flow regimes from dams include grunters, sawfish, colonial and semi-colonial nesting waterbirds, cryptic waders, shorebirds and floodplain wetlands (more details are provided in Stratford et al. (2023)).

Table 7-5 Scenarios of instream dams showing end-of-system (EOS) flow and mean impacts for groups of assets across each asset's respective catchment assessment nodes

SCENARIO	DESCRIPTION	EOS NET REDUCTION IN FLOW (GL/YEAR)	ALL ASSET MEAN	FISH	WATER BIRDS	OTHER SPECIES	HABITATS	FRESHWATER ASSETS	MARINE ASSETS
A_N	Natural baseline	0	0	0	0	0	0	0	0
B-D_{WR}	Waterhouse River	130.9	1.3	1.3	1.7	1.4	1.0	1.5	1.1
B-D_{FFC}	Flying Fox Creek	103.7	1.4	1.8	1.8	1.0	1.3	1.9	1.2
B-D_{HR}	Hodgson River	64.3	0.4	0.4	0.2	0.6	0.3	0.2	0.6
B-D_{WW}	Waterhouse West	72.4	0.8	1.0	1.0	1.0	0.6	1.0	0.8
B-D_{JR}	Jalboi River	66.4	1.1	1.1	1.3	1.0	0.9	1.3	0.8
B-D_{WR+FFC}	Two dams	227.5	2.5	2.6	3.3	1.9	2.1	3.2	1.8
B-D_5	Cumulative 5 dams	409.2	3.9	3.8	5.6	2.9	3.6	5.3	2.6

Higher values represent greater change in flows important to the assets of each group. Values are asset means across their respective catchment assessment nodes. Some assets are considered in multiple groups, where the mean across the nodes is used. Asset means include values from all nodes that the asset is assessed (see Stratford et al. 2023) including in reaches that may not be affected by flow regime change. EOS net reduction in flow includes changes resulting from evaporative losses from dams.

Instream dams with environmental flows

Measures to mitigate the impacts of large instream dams, such as transparent flows (inflows let to pass the dam wall for environmental purposes), resulted in improved ecological outcomes for ecology broadly across all assets, with particularly strong benefits from transparent flows for fish and waterbird assets (Table 7-6). Instream dams capture inflows and change downstream flow regimes. Transparent flows are a type of environmental flow provided as releases from dams that mimic or maintain natural flows, and can be successful in replicating smaller to moderate flood events during periods when natural runoff is entering the dam impoundment. Modelling transparent flows uses inflow thresholds on dams and was designed primarily to preserve lower flows during periods of natural inflow. Inflow thresholds used in the transparent flows analysis were similar to the commence-to-pump thresholds used in water harvest, facilitating comparison. Transparent flows are provided across all five dams in the five dam scenario (Hughes et al., 2023).

Table 7-6 Scenarios of dams with management of environmental flows showing end-of-system (EOS) flow and mean ecological change on flows for groups of assets across each asset's respective catchment assessment nodes

SCENARIO	DESCRIPTION	EOS NET REDUCTION IN FLOW (GL/YEAR)	ALL ASSET MEAN	FISH	WATER BIRDS	OTHER SPECIES	HABITATS	FRESHWATER ASSETS	MARINE ASSETS
A_N	Natural baseline	0	0	0	0	0	0	0	0
B-D_5	Five dams cumulative without transparent flows	409.2	3.9	3.8	5.6	2.9	3.6	5.3	2.6
B-$D_{5\text{-}T}$	Five dams cumulative with transparent flows	356.5	2.3	1.6	3.4	2.0	2.3	2.9	1.7

Higher values represent greater change in flows important to the assets of each group. Values are asset means across their respective catchment assessment nodes. Some assets are considered in multiple groups, where the mean across the nodes is used. Asset means include values from all nodes that the asset is assessed (see Stratford et al. 2023) including in reaches that may not be affected by flow regime change.

Water harvesting

For water harvesting, providing an end-of-system (EOS) flow requirement of 100 GL improved outcomes from minor at the catchment scale to negligible, considering asset means across all their assessment nodes (Table 7-7). Larger volumes of water provided additional benefit; however for smaller irrigation targets, the largest gain was achieved with the initial 100 GL requirement. EOS flow requirements provide for a specified volume of water to pass through the last node in the river system model before pumping for water harvesting can commence. The outcome associated with providing end-of-system flow requirements occurs by delaying the start of pumping to later in the wet season, thus retaining initial wet-season flows while also reducing the period of time available for water harvest (Hughes et al., 2023). In this analysis, different end-of-system flow requirement volumes were modelled (ranging from 0 to 700 GL).

Table 7-7 Scenarios of water harvesting with the benefits of end-of-system (EOS) annual flow requirements

SCENARIO	DESCRIPTION	EOS NET REDUCTION IN FLOW (GL/YEAR)	ALL ASSET MEAN	FISH	WATER BIRDS	OTHER SPECIES	HABITATS	FRESHWATER ASSETS	MARINE ASSETS
A_N	Natural baseline	0	0	0	0	0	0	0	0
B-E_0	No EOS	53.5	2.5	3.1	1.6	3.8	1.6	1.8	3.2
B-E_{100}	EOS 100 GL	48	0.2	0.2	0.2	0.4	0.2	0.2	0.3
B-E_{400}	EOS 400 GL	46.8	0.1	0.1	0.1	0.2	0.1	0.1	0.2
B-E_{700}	EOS 700 GL	46.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Higher values represent greater change in flows important to the assets of each group. Values are asset means across their respective catchment assessment nodes. Some assets are considered in multiple groups, where the mean across the nodes is used. Asset means include values from all nodes that the asset is assessed (see Stratford et al. 2023) including in reaches that may not be affected by flow regime change.

Providing minimum flow pump start thresholds improved ecology outcomes across increasing threshold levels (Table 7-8). Modelled minimum flow thresholds varied from 200 to 1800 ML/day (Table 7-8) and are provided by requiring that flow volume in the river exceeds required thresholds before pumping commences. Increasing pump start threshold to 600 ML/day results in significant reduction in modelled mean impact (i.e. 2.5 to 1.1). Increasing the pump start threshold above 600 ML/day results in incremental ecological improvements without any notable substantial improvement to ecology flow dependencies above 1400 ML/day for smaller irrigation targets. The outcomes achieved were not as significant as those arising from provision of end-of-system flow requirements (Table 7-7), even for the highest minimum flow threshold of 1800 ML/day.

Table 7-8 Scenarios of water harvesting with different minimum flow pump start thresholds (ML/day)

SCENARIO	DESCRIPTION (ML/DAY PUMP START THRESHOLD)	EOS NET REDUCTION IN FLOW (GL/YEAR)	ALL ASSET MEAN	FISH	WATER BIRDS	OTHER SPECIES	HABITATS	FRESHWATER ASSETS	MARINE ASSETS
A_N	Natural baseline	0	0	0	0	0	0	0	0
B-P_{200}	200	53.5	2.5	3.1	1.6	3.8	1.6	1.8	3.2
B-P_{600}	600	55.1	1.1	1.3	0.8	1.5	0.9	0.8	1.4
B-P_{1000}	1000	55.4	1.0	1.1	0.7	1.1	0.7	0.7	1.1
B-P_{1400}	1400	55.4	0.7	1.0	0.5	0.9	0.5	0.6	0.9
B-P_{1800}	1800	55.4	0.7	0.9	0.5	0.9	0.4	0.5	0.8

Higher values represent greater change in flows important to the assets of each group. Values are asset means across their respective catchment assessment nodes. Some assets are considered in multiple groups, where the mean across the nodes is used. Asset means include values from all nodes that the asset is assessed (see Stratford et al. 2023) including in reaches that may not be affected by flow regime change.

Setting pump capacity limits on the rate that water can be extracted showed that ecology outcomes associated with water harvest are improved when pump rates are slower (Table 7-9) despite only minimal reductions in the total water extracted for the irrigation target modelled. As water can only be extracted when river flow exceeds the minimum pump threshold, this limits the volume of water that can be extracted during a wet season and reduces impact at commencement of pumping (i.e. on any day the extraction volume is limited but pumping may extend to later in the season). The outcomes achieved were not as significant as those arising through provision of end-of-system flow requirements (Table 7-7) or by providing minimum flow thresholds (Table 7-8), even for the slowest pump rate (of 40 days of flow above the threshold before water harvest). Additionally at larger extraction volumes, limiting the pump capacity often resulted in lower total volumes of water extracted (Hughes et al., 2023) which would further limit the extent of change for ecology.

Table 7-9 Scenarios of water harvesting with different pump capacities (pump rate as days of flow above the threshold required to take the extraction target from the river)

SCENARIO	DESCRIPTION (DAYS TO PUMP TARGET)	EOS NET REDUCTION IN FLOW (GL/YEAR)	ALL ASSET MEAN	FISH	WATER BIRDS	OTHER SPECIES	HABITATS	FRESHWATER ASSETS	MARINE ASSETS
A_N	Natural baseline	0	0	0	0	0	0	0	0
$B\text{-}R_5$	5 (fastest pump rate)	53.5	2.5	3.1	1.6	3.8	1.6	1.8	3.2
$B\text{-}R_{10}$	10	53.5	2.4	3.0	1.5	3.7	1.5	1.7	3.1
$B\text{-}R_{15}$	15	53.6	2.4	3.0	1.5	3.7	1.5	1.7	3.1
$B\text{-}R_{20}$	20	53.5	2.2	2.8	1.4	3.5	1.4	1.6	2.9
$B\text{-}R_{30}$	30	53.5	2.0	2.6	1.2	3.1	1.2	1.4	2.6
$B\text{-}R_{40}$	40 (slowest pump rate)	53.4	1.8	2.3	1.1	2.6	1.1	1.3	2.2

Higher values represent greater change in flows important to the assets of each group. Values are asset means across their respective catchment assessment nodes. Some assets are considered in multiple groups, where the mean across the nodes is used. Asset means include values from all nodes that the asset is assessed (see Stratford et al. 2023) including in reaches that may not be affected by flow regime change.

Ecology outcomes associated with water harvest are worse with larger irrigation targets; this applies broadly across all asset groups and throughout the range of explored irrigation targets (Table 7-10). Larger extraction volumes resulted in mean outcomes up to moderate change across the catchment’s ecology assets. Some assets, including floodplain wetlands and some waterbird groups, experienced major change at some locations. While improvements are likely to occur in conjunction with providing either minimum flow thresholds or end-of-system requirements, greater extraction equates to a greater level of change in important ecology flow metrics.

Table 7-10 Scenarios of water harvesting with different river system irrigation targets (GL/year)

SCENARIO	DESCRIPTION (IRRIGATOIN TARGET GL/YEAR)	EOS NET REDUCTION IN FLOW (GL/YEAR)	ALL ASSET MEAN	FISH	WATER BIRDS	OTHER SPECIES	HABITATS	FRESHWATER ASSETS	MARINE ASSETS
A_N	Natural baseline	0	0	0	0	0	0	0	0
$B\text{-}W_{50}$	50	53.5	2.5	3.1	1.6	3.8	1.6	1.8	3.2
$B\text{-}W_{250}$	250	242.3	4.1	4.7	2.9	6.6	2.6	3.2	5.0
$B\text{-}W_{650}$	650	613.9	5.0	5.4	3.7	8.3	3.3	3.8	6.1
$B\text{-}W_{1050}$	1050	969.3	6.0	6.0	4.3	10.2	4.2	4.3	7.5
$B\text{-}W_{1450}$	1450	1301.1	6.9	6.6	5.0	11.8	5.2	4.9	8.8
$B\text{-}W_{2250}$	2250	1885.2	8.1	7.3	6.2	13.6	6.4	5.8	10.3
$B\text{-}W_{3050}$	3050	2396.1	9.2	8.0	7.4	15.0	7.7	6.7	11.6

Higher values represent greater change in flows important to the assets of each group. Values are asset means across their respective catchment assessment nodes. Some assets are considered in multiple groups, where the mean across the nodes is used. Asset means include values from all nodes that the asset is assessed (see Stratford et al. 2023) including in reaches that may not be affected by flow regime change.

Groundwater development

Groundwater development explored two scenarios relative to the natural baseline (A_N) shown in Table 7-11. The first, A_{2060}, was current groundwater development extrapolated to the year 2060 and the second, B-G_{35}, included an additional 35 GL of water extraction from the Larrimah region in addition to the current groundwater development to 2060. The additional 35 GL groundwater development extractions resulted in small decreases in ecology outcomes compared to the current levels of development projected to the year 2060. Groundwater development effects on mean annual flow were relatively modest at a catchment scale (Hughes et al., 2023), and the resulting impacts to ecology were negligible at the catchment scale, although impacts of some species including grunter (which require riffle habitat for some life-stages) were moderate at some sites. Groundwater development impacts on hydrology included changes in low flows, particularly in areas downstream of Mataranka. This analysis is limited to exploring changes to surface water ecology (through changes in modelled streamflow) and not changes to groundwater levels. Hence local impacts to groundwater-dependent ecology need specific consideration with suitable timescales of change.

Table 7-11 Scenarios of groundwater development

SCENARIO	DESCRIPTION	EOS NET REDUCTION IN FLOW (GL/YEAR)	ALL ASSET MEAN	FISH	WATER BIRDS	OTHER SPECIES	HABITATS	FRESHWATER ASSETS	MARINE ASSETS
A_N	Natural baseline	0	0	0	0	0	0	0	0
A_{2060}	Current levels of development to year 2060	7	0.4	0.6	0.3	0.6	0.2	0.4	0.5
B-G_{35}	35 GL additional groundwater development in the Larrimah region	7.6	0.5	0.7	0.4	0.6	0.3	0.4	0.5

Higher values represent greater change in flows important to the assets of each group. Values are asset means across their respective catchment assessment nodes. Some assets are considered in multiple groups, where the mean across the nodes is used. Asset means include values from all nodes that the asset is assessed (see Stratford et al. 2023) including in reaches that may not be affected by flow regime change.

7.4 Biosecurity considerations

7.4.1 Introduction

Northern Australia is recognised as the biosecurity frontline for many high-risk animal and plant pests and diseases due to its proximity to neighbouring countries. This is particularly true for the northern islands in the Torres Strait, which are only a few kilometres from Papua New Guinea. Other considerations unique to the region include ecological and climate conditions that are conducive to the introduction and establishment of exotic pests and disease, and the size, remoteness and sparse population of this region. Australia has many advantages in being able to mitigate risks from pests and disease through sound regulatory processes controlling translocation, technological knowledge and capability, and the greater geographic spread between farming operations in many regions. However, serious outbreaks of pests and diseases have occurred in agricultural and horticultural crops in recent years across northern Australia, including the fall armyworm (FAW) caterpillar, a serious pest of maize; the American serpentine leafminer (ASL; *Liriomyza trifolii*), affecting vegetables and ornamentals; the rice blast fungus (*Magnaporthe oryzae*), affecting rice (*Oryza sativa*) production in the Ord River Irrigation Area; Panama disease tropical race 4, affecting bananas in northern Queensland and the NT; and banana freckle (*Phyllosticta cavendishii)* in the NT. Although Australia has a world-class biosecurity system, the risk of new diseases and plants entering Australia is always present due to international trade and the movement of people.

From a biosecurity point of view, risk is defined as the product of the likelihood of an invasion by a pest or pathogen and the impact that species will have. With both likelihood and impact there is a great deal of uncertainty, and it is difficult to make clear predictions. Although certain exotic pests are prioritised nationally as high risk, based on their potential impact on industry, the environment and the community, there are many pests of biosecurity concern. Each industry will have their priority pest list and preparedness plans for the potential arrival of exotics pests. The best defence against pests and diseases is to understand the potential disease, pest and weed risks for the industry and implement sound biosecurity practices to reduce and mitigate this risk. The three main fronts for achieving good biosecurity outcomes are:

- Prevention – minimising the likelihood of entry and establishment of new pests through monitoring and on-farm biosecurity measures
- Eradication – detecting and reporting pests and diseases, containing and eliminating significant pests where possible
- Management – reducing the impact of established pests on the economy, environment and community such as through pesticide management and integrated pest management.

7.4.2 Agricultural biosecurity

This section examines biosecurity risk from an agricultural perspective, with the discussion structured around:

- the biosecurity risk to new farming enterprises in the Roper catchment
- the biosecurity risk that new farming enterprises in the Roper catchment may present to the broader industry across Australia.

Agricultural production systems can be threatened by generalist or specialised pests. A range of endemic pests and pathogens in the NT require management strategies.

Generally, both dryland and irrigated cropping systems have relatively well-developed pest management protocols, and the economics of such systems are such that they can bear the cost of controlling the pests that are of concern to them. This is especially the case for high-value crops. In addition, research and funding has been invested in high-value crops to produce pest-resistant varieties. Less-intensive agricultural industries and environmental interests are likely to be in a less-favourable economic position when it comes to pest management. Thus, irrigation and other intensive agricultural industries can increase the risks that less-intensive industries and the natural environment face from pests. Many exotic pests and diseases that are not in Australia but are present in neighbouring countries pose a serious threat to agriculture in northern Australia. On-farm biosecurity measures can reduce the risks posed by endemic and exotic diseases, pests and weeds entering and becoming established on farms. A farm biosecurity management plan can build biosecurity practices into day-to-day activities to reduce the risk of pests and diseases entering a property.

Pathways of entry

Pathogens, pests and weeds can enter a catchment via human activities or natural pathways. Recent exotic biosecurity incursions into the NT from natural pathways are predominantly insects, including FAW, ASL and mango shoot looper (*Perixera illepidaria*). Whereas human activities have most likely contributed to the entry of a wider range of pests and pathogens such as browsing ant (*Lepisiota frauenfeldi*), guava root knot nematode (*Meloidogyne enterolobii*), citrus canker (*Xanthomonas citri* subsp. *citri*) and banana freckle. Many of these pests and diseases were initially detected in the peri-urban regions of Darwin. Biosecurity risks for the Roper catchment are likely to enter from within the NT or interstate. For example, FAW was initially detected in Darwin and subsequently in the Katherine and Douglas–Daly regions (Piggott et al., 2021).

Human activities include road transport, ships and planes, and the ‘carriers’ (e.g. humans, animals, plants, machinery) that facilitate the movement and incursion of new pests, diseases and weeds. Published work has shown that the most likely human-facilitated pathway for bringing invasive species is either general trade, or live plant or animal trades. While it is not currently possible to determine the actual or relative risk to the Roper catchment from these forms of human-facilitated trade, it is possible to look at the historical rate of invasions (also referred to as incursions) in Australia. Studies have shown that the incursion rate in Australia for four orders of insects (beetles, bugs, flies, and moths and butterflies) has been about 15 species/year. Given the low human population in the Roper catchment, it is not likely that the catchment will be exposed to regular incursions facilitated by humans. However, incursions do occur, so surveillance, preparation and on-farm biosecurity are critical to prevent pests and diseases entering and becoming established.

Pests and diseases

Current risks to broad-scale cropping in the NT include three species recently detected in the NT: FAW, ASL and guava root knot nematode. FAW prefers tropical environments and has now been detected throughout northern Australia as well as in southern Australia. Adults can fly long distances in a night and can also spread through the transport of infested produce. FAW has a broad host range; it predominantly affects maize crops but is also a pest on cotton (*Gossypium* spp.), sorghum (*Sorghum bicolor*), rice and sugarcane (*Saccharum officinarum*). FAW has high levels of resistance to synthetic pyrethroids. ASL is a pest fly species, and the larvae of these flies burrow between the upper and lower layers of leaves of vegetables and soft-leaved decorative plants. This pest poses a serious threat to Australia’s horticulture, nursery production and agricultural plant industries. Guava root knot nematode is one of the most damaging root knot nematodes in the world. It is a particularly high risk for sweet potato (*Ipomoea batatas*) but can also affect crop yields of vegetables, fruit and crops such as cotton and soybean (*Glycine max*).

Movement of pests and disease out of the Roper catchment into other locations is most likely to occur as a result of human activities. Cotton pests found in the Ord River Irrigation Area and NT include pink bollworm (*Pectinophora gossypiella*), herbicide-resistant barnyard grass (*Echinochloa* spp.) and fungal pathogens in the *Alternaria* genus. These cotton pests are not found in southern Australia. Cotton grown in the NT is currently shipped to Queensland gins for processing, which could transport pests and disease into Queensland. A local gin located in Katherine has been promoted to service the local industry, which would also reduce movement between the NT and Queensland cotton-growing areas.

Pigs can be a significant problem for agriculture in the NT. In addition to indirect damage, for example by carrying weed seed from watercourses to open country, they can also cause direct and major physical damage to a wide range of crops and even to cultivated ground. Pigs have a daily water requirement, which means that during the dry season their range is generally restricted to areas relatively close to water. As the dry season progresses, areas of irrigated crops become increasingly attractive. Pig control is expensive and so selection of crops not attractive to pigs (e.g. cotton) is desirable where their numbers are high.

In addition to directly damaging crops and being agents of weed dispersal, pigs can carry and spread a range of exotic diseases. Exotic livestock diseases of concern carried by pigs include African swine fever, foot-and-mouth disease (FMD) and Japanese encephalitis (JE), which has already been detected across the Top End including the Roper River catchment. FMD is of particular concern to the northern cattle industry. Swine brucellosis affects pigs, cattle and horses and can cause serious illness in humans. It has been detected in feral pigs in the NT, and cattle and horses may potentially pick up infection from open waters visited by feral pigs.

Diseases spread by mosquitoes, ticks and midges include FMD, lumpy skin disease (LSD) and JE, and are one of the major risk pathways to the livestock industry. These diseases are usually not of concern for human health, except for JE. FMD has been detected in countries close to Australia. The risk of an FMD outbreak is increasing and estimated at 11.6% in the next 5 years. Spreading by feral pigs is considered a high risk if FMD enters Australia because pigs produce large quantities of the virus. LSD is another serious disease in cattle, water buffalo (*Bubalus bubalis*) and banteng (*Bos* spp.). It has been recently detected in Indonesia and continues to spread through Asia. This disease can be spread by insects as well as remaining active on surfaces such as equipment and animal hides.

Cattle tick (*Rhipicephalus australis*) is a serious pest present in the NT; it can affect a range of hooved animals including cattle, water buffalo and horses. There are controls on cattle movement implemented by the NT Government depending on which zone cattle are leaving and the zone they are going to. Inspection and treatment are required for movement between cattle tick zones. The Roper River sits in the ‘The Infected Zone, and livestock require inspection and supervised treatment with endorsement from an approved inspector before being moved to another zone.

Johne’s disease is a serious bacterial wasting disease in cattle caused by *Mycobacterium avium paratuberculosis* and has no known treatment. This disease is not present in the NT but has been detected when infected animals have been brought in from interstate. Johne’s disease is found in dairy cattle in south-eastern Australia, but it can also occur in beef cattle.

Weeds

The Roper catchment, along with other parts of northern Australia, is at a continued risk of new weed incursions and the spread of existing weeds by the deliberate and accidental actions of people. Riparian zones and other more mesic parts of the landscape are prone to a greater variety of weeds than elsewhere, but even drier parts of the landscape provide niches for some invasive species. Greater levels of disturbance, such as those that occur in association with any cropping system, provide opportunity for particular types of weeds. Nine weeds in or at risk of entering the Katherine region are under statutory management plans that landholders must follow (Department of Environment, Parks and Water Security, 2021) including gamba grass (*Andropogon gayanus*), prickly acacia (*Vachellia nilotica*), mimosa (*Mimosa pigra*) and grader grass (*Themeda quadrivalvis*). Several of these weeds (e.g. mimosa, prickly acacia and grader grass) can affect the environment and pasture production, whereas other weeds can affect livestock directly, such as the toxic bellyache bush (*Jatropha gossypiifolia*), which is widespread along watercourses. Gamba grass is a highly invasive Weed of National Significance that creates high fuel loads and make fires hotter and more destructive, which can result in a high fire risk to the environment. In addition to direct competition with crops, weeds can also be reservoirs for diseases and insects. For example, weeds can act as a reservoir for the cucumber green mottle mosaic virus (*Tobamovirus*).

Greenfield development

Accessing new and uncleared areas for agricultural and industrial development can have positive economic and social outcomes. However, clearing, creating vehicle access and agricultural expansion into natural habitats can create new and unexpected biosecurity threats through new pathways or new hosts for pests and diseases. Roads can increase access and movement of people and goods as well as feral animals. Increased movement and travel create opportunities for the introduction of pests, diseases and weeds into new areas. Weeds especially can colonise cleared ground quickly. Natural habitat may contain existing pests and diseases, act as reservoirs and create new pathways for agricultural pests and disease. The tropical dry season can act as a natural control for agricultural pests and diseases. However, improved water access for irrigation throughout the dry season may help to maintain conditions that favour these pests and diseases. Irrigation may also increase the risk of vector-borne diseases for livestock with a consistent supply of water, as well as increasing the risk of aquatic weeds entering local river systems. Introducing pests, weeds and diseases via agricultural expansion into natural habitat may reduce the resilience of the environment to pests and diseases. For example, crossover of pathogens between cultivated and wild species may occur; this has been identified as a potential risk in wild rice (Khemmuk et al., 2016). Many exotic pests and pathogens of concern in the primary industry context, such as the bacteria in the genus *Xylella* and exotic ants, will also have major impacts on the environment. Therefore, understanding biosecurity risk is important for sustainable agricultural expansion in the Roper catchment.

7.4.3 Climate change

A changing climate is likely to create opportunities for the movement and establishment of new pests and diseases. An increase in extreme rainfall events and tropical cyclone intensity may increase the risk of pests entering via natural wind-driven pathways. A changing climate could create conditions that facilitate the establishment or spread of pests, infectious diseases and vectors. Warmer temperatures can create more favourable conditions for mosquitoes, increasing their threat as carriers of potential pathogens (Russell, 2009). This may have implications for vector-borne diseases of livestock such as FMD, LSD and JE.

7.5 Off-site and downstream impacts

7.5.1 Introduction

Agriculture can affect the water quality of downstream freshwater, estuarine and marine ecosystems. The principal pollutants from agriculture are nitrogen, phosphorus, total suspended solids, herbicides and pesticides (Lewis et al., 2009; Kroon et al., 2016; Davis et al., 2017). Losses via runoff or deep drainage are the main pathways by which agricultural pollutants enter water bodies. Climate, location (e.g. soils and topography), land use (e.g. cropping system) and management (e.g. conservation and irrigation practices) influence the type and quantity of pollutants lost from an agricultural system.

Most of the science in northern Australia concerned with the downstream impacts of agricultural development has been done in the eastern-flowing rivers that flow into the Great Barrier Reef lagoon. Comparatively little research on the topic has been done in the rest of northern Australia. The development of agriculture in northern Australia has been associated with declining water quality (Lewis et al., 2009; Mitchell et al., 2009; De'ath et al., 2012; Waterhouse et al., 2012; Thorburn et al., 2013; Kroon et al., 2016). Pollutant loads in north-eastern Australian rivers (typically those in which agriculture dominates as a land use) are estimated to have increased considerably since European settlement in the 1850s for nitrogen (2 to 9 times baseline levels), phosphorus (3 to 9 times), suspended sediment (3 to 6 times) and pesticides (~17,000 kg) (Kroon et al., 2016). Degraded water quality can cause a loss of aquatic habitat, biodiversity, and ecosystem services. Increased nitrogen and phosphorus can cause plankton blooms and weed infestation, increase hypoxia (low oxygen levels) and result in fish deaths. Suspended sediment can smother habitat and aquatic organisms, reduce light penetration and reduce dissolved oxygen levels. Pesticides may be toxic to aquatic organisms (Pearson and Stork, 2009; Brodie et al., 2013; Davis et al., 2017).

Northern Australian river systems are distinctive as they have highly variable flow regimes, unique species composition, low human population densities and, in some cases, naturally high turbidity (Brodie and Mitchell, 2005). Primary influences on water quality include increased sediment loads associated with land clearing, grazing, agriculture and late dry-season fires, and nutrient pollution from agricultural and pastoral land use (Dixon et al., 2011).

7.5.2 Managing irrigation drainage

Surface drainage water is water that runs off irrigation developments as a result of over-irrigation or rainfall. This excess water can potentially affect the surrounding environment by modifying flow regimes and changing water quality. Hence, management of irrigation or agricultural drainage waters is a key consideration when evaluating and developing new irrigation systems and should be given careful consideration during the planning and design processes. Regulatory constraints on the disposal of agricultural drainage water from irrigated lands are being made more stringent as this disposal can potentially have significant off-site environmental effects (Tanji and Kielen, 2002). Hence, minimising drainage water through the use of best-practice irrigation design and management should be a priority in any new irrigation development in northern Australia. This involves integrating sound irrigation systems, drainage networks and disposal options so as to minimise off-site impacts.

Surface drainage networks must be designed to cope with the runoff associated with irrigation, and also the runoff induced by rainfall events on irrigated lands. Drainage must be adequate to remove excess water from irrigated fields in a timely manner and hence reduce waterlogging and potential salinisation, which can seriously limit crop yields. In best-practice design, surface drainage water is generally reused through a surface drainage recycling system where runoff tailwater is returned to an on-farm storage or used to irrigate subsequent fields within an irrigation cycle.

The quality of drainage water depends on a range of factors including water management and method of application, soil properties, method and timing of fertiliser and pesticide application, hydrogeology, climate and drainage system (Tanji and Kielen, 2002). These factors need to be taken into consideration when implementing drainage system water recycling and also when disposing of drainage water to natural environments.

A major concern with tailwater drainage is the agricultural pollutants derived from pesticides and fertilisers that are generally associated with intensive cropping and are found in the tailwater from irrigated fields. Crop chemicals can enter surface drainage water if poor water application practices or significant rainfall events occur after pesticide or fertiliser application (Tanji and Kielen, 2002). Thus, tailwater runoff may contain phosphate, organic nitrogen and pesticides that have the potential to adversely affect flora and fauna and ecosystem health, on land and in waterways, estuaries or marine environments. Tailwater runoff may also contain elevated levels of salts, particularly if the runoff has been generated on saline surface soils. Training irrigators in responsible application of both water and agrochemicals is therefore an essential component of sustainable management of irrigation.

As tailwater runoff is either discharged from the catchment or captured and recycled, it can result in a build-up of agricultural pollutants that may ultimately require disposal from the irrigation fields. In externally draining basins, the highly seasonal nature of flows in northern Australia does offer opportunities to dispose of poor-quality tailwater during high-flow events. However, downstream consequences are possible, and no scientific evidence is available to recommend such disposal as good practice. Hence, consideration should be given to providing an adequate understanding of the downstream consequences of disposing of drainage effluent, and options must be provided for managing disposal that minimise impacts on natural systems.

7.5.3 Chemical contaminant risk to aquaculture and the environment

Hundreds of different chemicals, including oils, metals, pharmaceuticals, fertilisers and pesticides (i.e. insecticides, herbicides, fungicides), are used in different agricultural, horticultural and mining sectors, and in industrial and domestic settings, throughout Australia. Releasing these chemical contaminants beyond the area of target application can contaminate soils, sediments and waters in nearby environments. In aquatic environments, including aquaculture environments, fertilisers have the potential to cause non-point source pollution. Eutrophication is caused by nutrients that trigger excessive growth of plant and algal species, which then form hypoxic 'dead zones' and potentially elevated levels of toxic un-ionised ammonia (Kremser and Schnug, 2002). This can have a significant impact on the health and growth of animals in aquaculture operations, as well as in the broader environment.

Of concern to aquaculture in northern Australia are the risks posed to crustaceans (e.g. prawns and crabs) by some of the insecticides in current use. These are classified based on their specific chemical properties and modes of action. The different classes of insecticides have broad and overlapping applications across different settings.

The toxicity of organophosphate insecticides is not specific to target insects, raising concerns about the impacts on non-target organisms such as crustaceans and fish. Despite concerns about human health impacts and potential carcinogenic risks, organophosphates are still one of the most broadly used types of insecticide globally, and they are still used in Australia for domestic pest control (Weston and Lydy, 2014; Zhao and Chen, 2016). Pyrethroid insecticides have low toxicity to birds and mammals, but higher toxicity to fish and arthropods. Phenylpyrazole insecticides also pose risks to non-target crustaceans (Stevens et al., 2011). Neonicotinoid insecticides are being used in increasing amounts because they are very effective at eliminating insect pests, yet they pose low risks to mammals and fish (Sánchez-Bayo and Hyne, 2014). Monitoring data from the Great Barrier Reef catchments indicate that the concentration of neonicotinoid insecticides in marine water samples is rapidly increasing with widespread use. One significant concern for aquaculture is the risk that different insecticides, when exposed to non-target organisms, may interact to cause additive or greater-than-additive toxicity.

7.5.4 Aquaculture discharge water and off-site impacts

Discharge water is effluent from land-based aquaculture production (Irvin et al., 2018). Discharge water is water that has been used (culture water) and is no longer required in a production system. In most operations (particularly marine), bioremediation is used to ensure that water discharged off-farm into the environment contains low amounts of nutrients and other contaminants. The aim is for discharge waters to have similar physiochemical parameters to the source water.

Discharge water from freshwater aquaculture can be easily managed and provides a water resource suitable for general or agriculture-specific irrigation. Discharge water from marine aquaculture is comparatively difficult to manage, with limited reuse applications. The key difference in discharge management is that marine (salty) water must be discharged at the source, whereas the location for freshwater discharge is less restrictive and potential applications (e.g. irrigation) are numerous. Specific water discharge guidelines vary with species and jurisdiction. For example, Queensland water discharge policy minimum standards for prawn farming include minimum standards for physiochemical indicators (e.g. oxygen and pH) and nutrients (e.g. nitrogen, phosphorus and suspended solids) and total volume (EHP, 2013).

The volume of water required to be discharged or possibly diverted to a secondary application (e.g. agriculture) is equivalent to the total pond water use for the season minus total evaporative losses and the volume of recycled water used during production.

A large multidisciplinary study of intensive Australian prawn farming, which assessed the impact of effluent on downstream environments (CSIRO, 2013), found that Australian farms operate under world best practice in regards to the management of discharge water. The study found that discharge water had no adverse ecological impact on receiving water and that nutrients could not be detected 2 km downstream from the discharge point.

While Australian prawn farms are reported as being among the most environmentally sustainable in the world (CSIRO, 2013), the location of the industry adjacent to the World Heritage listed Great Barrier Reef and related strict policy on discharge has been a major constraint to the industry's expansion. Strict discharge regulation, which requires zero net addition of nutrients in waters adjacent to the Great Barrier Reef, has all but halted expansion in the last decade. An example of the regulatory complexity in this region is the 14-year period taken to obtain approval to develop a site in the Burdekin shire in north Queensland (APFA, 2016). Over the last decade, increases in production have been due to improvements in production efficiency rather than any expansion of the industry footprint.

In a report to the Queensland Government (Department of Agriculture and Fisheries Queensland, 2013), it was suggested that less-populated areas in northern Australia, which have less conflict for the marine resource, may have potential as areas for aquaculture development. The complex regulatory environment in Queensland was a factor in the decision by Project Sea Dragon to investigate greenfield development in WA and NT as an alternative location for what would be Australia's largest prawn farm (Seafarms, 2016).

Today most farms (particularly marine) use bioremediation ponds to ensure that water discharged off-farm into the environment contains low amounts of nutrients and other contaminants. The prawn farming industry in Queensland has adopted a code of practice to ensure that discharge waters do not result in irreversible or long-term impacts on the receiving environment (Donovan, 2011).

7.6 Irrigation-induced salinity

Salinity is a measure of the concentration of soluble salts in soils or water. Soil salinity is the result of the complex interactions of geophysical and land use factors such as landscape features (geology, landform), climate, soil properties, water characteristics and land management. Salinity becomes a land use issue when the concentration of salts adversely affects plant establishment and growth (crops, pastures or native vegetation) or degrades soil or affects water quality (Department of Environment and Resource Management, 2011).

The natural salts in the landscape are derived from rainfall, weathering of primary minerals and the origin of the geology (such as marine sediments). Most salinity outbreaks result from the imbalances in the hydrological systems of a landscape, including secondary salinisation due to human-related activities such as clearing of native vegetation, cropping and irrigation.

Naturally occurring areas of salinity (primary salinity) occur in the landscape with ecosystems adapted to these conditions. Natural salinity in the Roper catchment is confined to the freshwater springs originating from the limestones around Mataranka and on the marine plains adjacent to the Gulf of Carpentaria. The mound springs and associated discharge areas into drainage lines around Mataranka have very high salt concentrations (mainly calcium salts) on the soil surface and are unsuitable for development.

In the dryland salinity (non-irrigated) hazard mapping of the NT, Tickell (1994) determined that the dryland salinity hazard over most of the NT is low, predominantly due to the relatively low amount of salt stored in the landscape, which is mainly derived from small salt inputs from rainfall.

In Australia, excessive root zone drainage through poor irrigation practices, together with leakage of water from irrigation distribution networks and drainage channels, has caused the watertable level to rise under many intensive irrigated areas. Significant parts of all major intensive irrigation areas in Australia are currently either in or approaching a shallow watertable equilibrium condition (Christen and Ayars, 2001). Where shallow watertables containing salts approach the land surface (in the vicinity of 2 to 3 m from the land surface), salts can concentrate in the root zone over time through evaporation. The process by which salts accumulate in the root zone is accelerated if the groundwater also has high salt concentrations.

In the case of irrigation-induced salinity in the Roper catchment, the landscapes suitable for irrigation development and at risk of secondary salinisation are restricted to the Cenozoic clay plains (SGG 9) occurring in drainage depressions on the Sturt Plateau. These heavy clays are naturally high in soluble salts in the subsoils. Irrigation of the clay plains or the surrounding permeable red Kandosols (SGG 4.1) may result in raised watertables and discharge into the drainage depressions, particularly the clay plains. Other soils are generally not at risk from irrigation-induced salinity.

Further investigations on salinity processes and monitoring of watertables are necessary if these areas are to be developed.

7.7 References

APFA (2016) Productivity Commission inquiry into the regulation of Australian marine fisheries and aquaculture sectors. Viewed 2 June 2023, https://www.pc.gov.au/__data/assets/pdf_file/0008/197522/sub023-fisheries-aquaculture.pdf.

Ash A, Bristow M, Laing A, MacLeod N, Niscioli A, Paini D, Palmer J, Prestwidge D, Stokes C, Watson I, Webster T and Yeates S (2018) Agricultural viability: Darwin catchments. A technical report to the Australian Government from the CSIRO Northern Australia Water Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments. CSIRO, Australia.

Barber M and Jackson S (2012) Indigenous water management and water planning in the upper Roper River, Northern Territory: History and implications for contemporary water planning. CSIRO, Darwin.

Blaber S, Brewer D and Salini J (1989) Species composition and biomasses of fishes in different habitats of a tropical northern Australian estuary: their occurrence in the adjoining sea and estuarine dependence. Estuarine, Coastal and Shelf Science 29(6), 509-531.

Brewer D, Blaber S, Salini J and Farmer M (1995) Feeding ecology of predatory fishes from Groote Eylandt in the Gulf of Carpentaria, Australia, with special reference to predation on penaeid prawns. Estuarine, Coastal and Shelf Science 40(5), 577-600.

Brodie JE and Mitchell AW (2005) Nutrients in Australian tropical rivers: changes with agricultural development and implications for receiving environments. Marine and Freshwater Research 56(3), 279–302.

Brodie J, Waterhouse J, Maynard J, Bennett J, Furnas M, Devlin M, Lewis S, Collier C, Schaffelke B, Fabricius K, Petus C, Zeh D, Randall L, Brando V, Mckenzie L, Brien DO, Smith R, Warne M, Brinkman R, Tonin H, Bartley R, Negri A, Turner R, Davis A, Mueller J, Alvarez-romero J, Henry N, Waters D and Tracey D (2013) Assessment of the relative risk of degraded water quality to ecosystems of the Great Barrier Reef. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), James Cook University, Townsville.

Bunn SE and Arthington AH (2002) Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management 30(4), 492-507.

Burdekin Project Committee (1977) Resources and potential of the Burdekin River Basin, Queensland. Main report and 5 volumes of appendices. Australian Government Publishing Service, Canberra.

Burford M, Valdez D, Curwen G, Faggotter S, Ward D and Brien KO (2016) Inundation of saline supratidal mudflats provides an important source of carbon and nutrients in an aquatic system. Marine Ecology Progress Series 545, 21-33.

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

Burford MA, Revill AT, Palmer DW, Clementson L, Robson BJ and Webster IT (2011) River regulation alters drivers of primary productivity along a tropical river-estuary system. Marine and Freshwater Research 62(2), 141-151. DOI: 10.1071/MF10224.

Burrows DW and Butler B (2007) Determining end-point goals and effective strategies for rehabilitation of coastal wetlands: examples from the Burdekin River, north Queensland. In: Wilson AL, Dehaan RL, Watts RJ, Page KJ, Bowmer KH and Curtis A (eds) Proceedings of the 5th Australian Stream Management Conference. Charles Sturt University, Thurgoona, New South Wales, 49–54.

Christen EW and Ayars JE (2001) Subsurface drainage system design and management in irrigated agriculture: best management practices for reducing drainage volume and salt load. Technical report 38/01. CSIRO Land and Water, Griffith.

Crook D, Buckle D, Allsop Q, Baldwin W, Saunders T, Kyne P, Woodhead J, Maas R, Roberts B and Douglas M (2016) Use of otolith chemistry and acoustic telemetry to elucidate migratory contingents in barramundi Lates calcarifer. Marine and freshwater research 68(8), 1554-1566.

Crook DA, Buckle DJ, Morrongiello JR, Allsop QA, Baldwin W, Saunders TM and Douglas MM (2019) Tracking the resource pulse: Movement responses of fish to dynamic floodplain habitat in a tropical river. Journal of Animal Ecology 2020(89), 795–807.

Crook DA, Lowe WH, Allendorf FW, Erős T, Finn DS, Gillanders BM, Hadweng WL, Harrod C, Hermoso V, Jennings S, Kilada RW, Nagelkerken I, Hansen MM, Page TJ, Riginos C, Fry B and

Hughes JM (2015) Human effects on ecological connectivity in aquatic ecosystems: Integrating scientific approaches to support management and mitigation. Science in the Total Environment 534(2015), 52-64.

CSIRO (2013) The environmental management of prawn farming in Queensland – worlds best practice. Viewed 2 June 2023, https://era.daf.qld.gov.au/id/eprint/2064/2/1._Prawn_farming_environmental_research_1995-2002-sec.pdf http://apfa.com.au/wp-content/uploads/2015/01/CSIRO-Research-summary.pdf.

Dasgupta S, Blankenspoor B, Herzog T and Davies A (2019) Terrestrial biodiversity indicators. DOI:https://datacatalog.worldbank.org/dataset/terrestrial-biodiversity-indicators (2019). Viewed 10 October 2019.

Davis AM, Pearson RG, Brodie JE and Butler B (2017) Review and conceptual models of agricultural impacts and water quality in waterways of the Great Barrier Reef catchment area. Marine and Freshwater Research 68, 1–19. DOI: 10.1071/MF15301.

De'ath G, Fabricius KE, Sweatman H and Puotinen M (2012) The 27-year decline of coral cover on the Great Barrier Reef and its causes. Proceedings of the National Academy of Sciences of the United States of America 109, 17995–17999. DOI: 10.1073/pnas.1208909109.

Department of Agriculture and Fisheries Queensland (2013) About biosecurity. Department of Agriculture and Fisheries. Queensland.

Department of Environment and Resource Management (2011) Salinity management handbook. Department of Environment and Resource Management, The State of Queensland, Brisbane. Viewed 2 June 2023. https://www.publications.qld.gov.au/dataset/salinity-management-handbook/resource/529b12b0-8e23-4cd3-a1cd-7659d0b9b3b4.

Department of Environment, Parks and Water Security (2000) Melaleuca Survey of the Northern Territory. Viewed 7 June 2023 http://www.ntlis.nt.gov.au/metadata/export_data?type=html&metadata_id=2DBCB7711FE606B6E040CD9B0F274EFE.

Department of Environment, Parks and Water Security (2021) Katherine Weeds Strategy 2021–2026, Northern Territory Government.

Department of the Environment and Energy (2010) A Directory of Important Wetlands in Australia (DIWA) Spatial Database. [spatial] CSIRO, Canberra. Viewed 8 December 2018, https://www.environment.gov.au/water/wetlands/australian-wetlands-database.

Dixon I, Dobbs R, Townsend S, Close P, Ligtermoet E, Dostine P, Duncan R, Kennard M and Tunbridge D (2011) Trial of the Framework for the Assessment of River and Wetland Health (FARWH) in the wet–dry tropics for the Daly and Fitzroy Rivers, Tropical Rivers and Coastal Knowledge (TRaCK) research consortium. Charles Darwin University, Darwin.

Donovan D (2011) Environmental code of practice for Australian prawn farmers. Viewed 2 June 2023, https://ntepa.nt.gov.au/__data/assets/pdf_file/0019/290080/appendix3.pdf.

EHP (2013) Operational policy marine prawn aquaculture. Department of Environment and Heritage Protection, Queensland Government. Viewed 2 June 2023, https://www.ehp.qld.gov.au/assets/documents/regulation/pr-op-wastewater-prawn-farm.pdf.

Environment Australia (2001) A directory of important wetlands in Australia. Third edition. Environment Australia, Canberra. Viewed 5 June 2018, http://www.environment.gov.au/system/files/resources/18f0bb21-b67c-4e99-a155-cb5255398568/files/directory.pdf.

Faulks JJ (2001) Roper River Catchment: An assessment of the physical and ecological condition of the Roper River and its major tributaries. Technical Report No. 36/2001. Natural Resources Division. Department of Lands, Planning and Environment. Katherine, NT.

Finlayson C, Cowie I and Bailey B (1993) Biomass and litter dynamics in a Melaleuca forest on a seasonally inundated floodplain in tropical, northern Australia. Wetlands Ecology and management 2, 177-188.

Finlayson CM (2005) Plant ecology of Australia's tropical floodplain wetlands: a review. Annals of Botany 96(4), 541-555.

Finn M and Jackson S (2011) Protecting Indigenous Values in Water Management: A Challenge to Conventional Environmental Flow Assessments. Ecosystems 14(8), 1232-1248. DOI: 10.1007/s10021-011-9476-0.

Fleming PM, Gunn RH, Reece AM, and McAlpine JR (eds) (1981) Burdekin project ecological study. CSIRO and Department of National Development and Energy, Canberra.

Geoscience Australia (2017) GEODATA TOPO 250K Series 3 Topographic Data. Viewed 1 October 2018, http://pid.geoscience.gov.au/dataset/ga/64058.

Grill G, Lehner B, Thieme M, Geenen B, Tickner D, Antonelli F, Babu S, Borrelli P, Cheng L, Crochetiere H, Macedo HE, Filgueiras R, Goichot M, Higgins J, Hogan Z, Lip B, McClain ME, Meng J, Mulligan M, Nilsson C, Olden JD, Opperman JJ, Petry P, Liermann CR, Sáenz L, Salinas-Rodríguez S, Schelle P, Schmitt RJP, Snider J, Tan F, Tockner K, Valdujo PH, Soesbergen Av and Zarfl C (2019) Mapping the world’s free-flowing rivers. Nature 569(2019), 215-221.

Hamilton SK (2010) Biogeochemical implications of climate change for tropical rivers and floodplains. Hydrobiologia 657(1), 19-35.Hughes J, Yang A, Marvanek S, Wang B, Petheram C and Philip S (2023) River model calibration and scenario analysis for the Roper River catchment. A technical report from the CSIRO Roper River Water Resource Assessment to the Government of Australia. CSIRO, Australia.

Hughes J, Yang A, Marvanek S, Wang B, Petheram C and Philip S (2023) River model calibration and scenario analysis for the Roper catchment. A technical report from the CSIRO Roper River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Irvin S, Coman G, Musson D and Doshi A (2018) Aquaculture viability. A technical report to the Australian Government from the CSIRO Northern Australia Water Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments. CSIRO, Australia.

Jackson S, Finn M, Woodward E and Featherston P (2011) Indigenous socio-economic values and river flows. Darwin, Northern Territory: CSIRO Ecosystem Sciences, 127.

Jardine TD, Bond NR, Burford MA, Kennard MJ, Ward DP, Bayliss P, Davies PM, Douglas MM, Hamilton SK, Melack JM, Naiman RJ, Pettit NE, Pusey BJ, Warfe DM and Bunn SE (2015) Does flood rhythm drive ecosystem responses in tropical riverscapes? Ecology 96(3), 684-692.

Junk W, Bayley P and Sparks R (1989) The flood pulse concept in river-floodplain systems. In: Dodge D (ed.), Proceedings of the International Large River Symposium. Canadian special publication of Fisheries and Aquatic Sciences.

Keller K, Allsop Q, Brim Box J, Buckle D, Crook DA, Douglas MM, Jackson S, Kennard MJ, Luiz OJ, Pusey BJ, Townsend SA and King AJ (2019) Dry season habitat use of fishes in an Australian tropical river. Scientific Reports 9(5677), 1-14.

Khemmuk W, Shivas RG, Henry RJ and Geering ADW (2016) Fungi associated with foliar diseases of wild and cultivated rice (Oryza spp.) in northern Queensland. Australasian Plant Pathology 45, 297–308.

Kim S, Hughes J, Ticehurst C, Stratford D, Merrin L, Marvanek S and Petheram C (2023) Floodplain inundation mapping and modelling for the Roper catchment. A technical report from the CSIRO Roper River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Kingsford RT (2000) Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. Austral Ecology 25(2), 109-127.

Kremser U and Schnug E (2002) Impact of fertilizers on aquatic ecosystems and protection of water bodies from mineral nutrients. Landbauforsch Völkenrode 52(2), 81–90.

Kroon FJ, Thorburn P, Schaffelke B and Whitten S (2016) Towards protecting the Great Barrier Reef from land-based pollution. Global Change Biology 22, 1985–2002. DOI: 10.1111/gcb.13262.

Leahy SM and Robins JB (2021) River flows affect the growth of a tropical finfish in the wet-dry rivers of northern Australia, with implications for water resource development. Hydrobiologia 848(18), 4311-4333.

Lewis SE, Brodie JE, Bainbridge ZT, Rohde KW, Davis AM, Masters BL, Maughan M, Devlin MJ, Mueller JF and Schaffelke B (2009) Herbicides: a new threat to the Great Barrier Reef. Environmental Pollution 157, 2470–2484. DOI: 10.1016/j.envpol.2009.03.006.

McMahon TA and Finlayson BL (2003) Droughts and anti-droughts: the low flow hydrology of Australian rivers. Freshwater Biology 48(2003), 1147–1160.

Milton D, Yarrao M, Fry G and Tenakanai C (2005) Response of barramundi, Lates calcarifer, populations in the Fly River, Papua New Guinea to mining, fishing and climate-related perturbation. Marine and freshwater research 56(7), 969-981.

Mitchell A, Reghenzani J, Faithful J, Furnas M and Brodie J (2009) Relationships between land use and nutrient concentrations in streams draining a wet-tropics catchment in northern Australia. Marine and Freshwater Research 60, 1097–1108. DOI: 10.1071/MF08330.

Naughton JM, O'Dea K and Sinclair AJ (1986) Animal foods in traditional Australian aboriginal diets: polyunsaturated and low in fat. Lipids 21(11), 684-690.

Ndehedehe CE, Burford MA, Stewart-Koster B and Bunn SE (2020) Satellite-derived changes in floodplain productivity and freshwater habitats in northern Australia (1991–2019). Ecological Indicators 114, 106320.

Ndehedehe CE, Onojeghuo AO, Stewart-Koster B, Bunn SE and Ferreira VG (2021) Upstream flows drive the productivity of floodplain ecosystems in tropical Queensland. Ecological Indicators 125, 107546.

Nielsen DL, Cook RA, Ning N, Gawne B and Petrie R (2015) Carbon and nutrient subsidies to a lowland river following floodplain inundation. Marine and Freshwater Research 67(9), 1302-1312.

Nielsen D, Merrin L, Pollino C, Karim F, Stratford D and O'Sullivan J (2020) Climate change and dam development: Effects on wetland connectivity and ecological habitat in tropical wetlands. Ecohydrology 2020, 13pgs. DOI: 10.1002/eco.2228.

Nilsson C and Berggren K (2000) Alterations of riparian ecosystems caused by river regulation. BioScience 50(9), 783-792.

O'Mara K, Venarsky M, Stewart-Koster B, McGregor G, Schulz C, Marshall J, Bunn SE and Kainz MJ (2021) Trophic transfer of lipids and fatty acids across habitats in tropical river food webs. Freshwater Biol. 2022(00), 1-19.

Palmer C and Smit N (2019) Limmen Bight Marine Park: Marine and coastal biodiversity values. Department of Environment and Natural Resources, Northern Territory Government.

Pearson R and Stork NE (2009) Catchment to reef: water quality and ecosystem health in tropical streams. In: Stork N and Turton S (eds) Living in a dynamic tropical forest landscape. Blackwell Publishing, Carlton, 557–576. DOI: 10.1002/9781444300321.ch45.

Pelicice FM, Pompeu PS and Agostinho AA (2015) Large reservoirs as ecological barriers to downstream movements of Neotropical migratory fish. Fish and Fisheries 2015(16), 697-715.

Perna C (2003) Fish habitat assessment and rehabilitation in the Burdekin Delta distributary streams. Report 03/22. Australian Centre for Tropical Freshwater Research, James Cook University, Townsville.

Perna C (2004) Impacts of agriculture and restoration of the habitat values, water quality and fish assemblages of a tropical floodplain. MSc Thesis, James Cook University, Townsville.

Petheram C, Yang A, Seo L, Rogers L, Baynes F, Devlin K, Marvanek S, Hughes J, Ponce Reyes R, Wilson P, Stratford D, Philip S (2022) Assessment of surface water storage options and reticulation infrastructure in the Roper catchment. A technical report from the CSIRO Roper River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Pettit NE, Naiman RJ, Warfe DM, Jardine TD, Douglas MM, Bunn SE and Davies PM (2017) Productivity and Connectivity in Tropical Riverscapes of Northern Australia: Ecological Insights for Management. Ecosystems 2017(20), 492-514.

Piggott MP, Tadle FPJ, Patel S, Gomez KC and Thistleton B (2021) Corn-strain or rice-strain? Detection of fall armyworm, Spodoptera frugiperda (JE Smith) (Lepidoptera: Noctuidae) in northern Australia. International Journal of Tropical Insect Science 41, 2607–2615.

Poff NL, Olden JD, Merritt DM and Pepin DM (2007) Homogenization of regional river dynamics by dams and global biodiversity implications. PNAS 104(4), 5732-5737.

Pollino C, Barber E, Buckworth R, Cadiegues M, Deng R, Ebner B, Kenyon R, Liedloff A, Merrin L, Moeseneder C, Morgan D, Nielsen D, O'Sullivan J, Ponce Reyes R, Robson B, Stratford D, Stewart-Koster B and Turschwell M (2018) Synthesis of knowledge to support the assessment of impacts of water resource development to ecological assets in northern Australia: asset analysis. A technical report to the Australian Government from the CSIRO Northern Australia Water Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments. CSIRO, Canberra.

Pyšek P, Hulme PE, Simberloff D, Bacher S, Blackburn TM, Carlton JT, Dawson W, Essl F, Foxcroft LC, Genovesi P, Jeschke JM, Kühn I, Liebhold AM, Mandrak NE, Meyerson LA, Pauchard A, Pergl J, Roy HE, Seebens H, van Kleunen M, Vilà M, Wingfield MJ and Richardson DM (2020) Scientists' warning on invasive alien species. Biological Reviews 2020(95), 1511–1534. DOI: 10.1111/brv.12627.

Roberts BH, Morrongiello JR, King AJ, Morgan DL, Saunders TM, Woodhead J and Crook DA (2019) Migration to freshwater increases growth rates in a facultatively catadromous tropical fish. Oecologia 191(2), 253-260.

Robins JB, Halliday IA, Staunton-Smith J, Mayer DG and Sellin MJ (2005) Freshwater-flow requirements of estuarine fisheries in tropical Australia: a review of the state of knowledge and application of a suggested approach. Marine and freshwater research 56(3), 343-360.

Robins J, Mayer D, Staunton-Smith J, Halliday I, Sawynok B and Sellin M (2006) Variable growth rates of the tropical estuarine fish barramundi Lates calcarifer (Bloch) under different freshwater flow conditions. Journal of Fish Biology 69(2), 379-391.

Russell D and Garrett R (1983) Use by juvenile barramundi, Lates calcarifer (Bloch), and other fishes of temporary supralittoral habitats in a tropical estuary in northern Australia. Marine and freshwater research 34(5), 805-811.

Russell D and Garrett R (1985) Early life history of barramundi, Lates calcarifer (Bloch), in north-eastern Queensland. Marine and freshwater research 36(2), 191-201.

Russell RC (2009) Mosquito-borne disease and climate change in Australia: time for a reality check. Australian Journal of Entomology 48(1), 1–7.

Salimi S, Almuktar SA and Scholz M (2021) Impact of climate change on wetland ecosystems: A critical review of experimental wetlands. Journal of Environmental Management 286, 112160

Sánchez-Bayo F and Hyne RV (2014) Detection and analysis of neonicotinoids in river waters – development of a passive sampler for three commonly used insecticides. Chemosphere 99, 143–151. DOI: 10.1016/j.chemosphere.2013.10.051.

Schmutz S and Sendzimir J (eds) (2018) Riverine Ecosystem Management Science for Governing Towards a Sustainable Future. Springer Open.

Seafarms (2016) Seafarms group – project sea dragon. Viewed 6 June 2018, https://seafarms.com.au/project-sea-dragon/

Smyth C and Turner J (2019) Natural values and resource use in the Limmen Bight Marine Region. Australian Marine Conservation Society.

Stevens MM, Burdett AS, Mudford EM, Helliwell S and Doran G (2011) The acute toxicity of fipronil to two non-target invertebrates associated with mosquito breeding sites in Australia. Acta Tropica 117(2), 125–130. DOI: 10.1016/j.actatropica.2010.11.002.

Stratford D, Kenyon R, Pritchard J, Merrin L, Linke S, Ponce Reyes R, Blamey L, Buckworth R, Castellazzi P, Costin B, Deng R, Gannon R, Gilbey S, King D, Kopf K, Kopf S, McGinness H, McInerney P, Perna C, Plaganyi E and Waltham N (2022) Ecological assets of northern Australia to inform water resource assessments. A technical report from the CSIRO Roper River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Stratford D, Merrin L, Linke S, Kenyon R, Ponce Reyes R, Buckworth R, Deng RA, McGinness H, Pritchard J, Seo L and Waltham N (2024) Assessment of the potential ecological outcomes of water resource development in the Roper catchment. A technical report from the CSIRO Roper River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Tait J and Perna C (2000) Fish 450orth450t management challenges on an intensively developed tropical floodplain: Burdekin River 450orth Queensland. RipRap 19, 14–21.

Tanimoto M, Robins JB, O'Neill MF, Halliday IA and Campbell AB (2012) Quantifying the effects of climate change and water abstraction on a population of barramundi (Lates calcarifer), a diadromous estuarine finfish. Marine and freshwater research 63(8), 715-726.

Tanji KK and Kielen NC (2002) Agricultural water management in arid and semi-arid areas. Irrigation and drainage paper 61. Food and Agriculture Organization of the United Nations, Rome.

Taylor AR, Crosbie RS, Turnadge C, Lamontagne S, Deslandes A, Davies PJ, Barry K, Suckow A, Knapton A, Marshall S, Hodgson G, Tickell S, Duvert C, Hutley L and Dooley K (2023) Hydrogeological assessment of the Cambrian Limestone Aquifer and the Dook Creek Aquifer in the Roper catchment, Northern Territory. A technical report from the CSIRO Roper River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Thorburn PJ, Wilkinson SN and Silburn DM (2013) Water quality in agricultural lands draining to the Great Barrier Reef: a review of causes, management and priorities. Agriculture, Ecosystems and Environment 180, 4–20. DOI: 10.1016/j.agee.2013.07.006.

Tickell SJ (1994) Dryland salinity hazard mapping Northern Territory [online]. In: Water Down Under 94: Groundwater Papers. Preprints of papers. National conference publication (Institution of Engineers, Australia), no. 94/14. Institution of Engineers, Australia, Barton, ACT, 745–748.

Tockner K, Pusch M, Borchardt D and Lorang MS (2010) Multiple stressors in coupled river–floodplain ecosystems. Freshwater Biology 55, 135-151.

van Dam R, Bartolo R and Bayliss P (2008) Identification of ecological assets, pressures and threats. Environmental Research Institute of the Supervising Scientist: Darwin, Australia, 14-161.

Ward JV and Stanford J (1995) Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated rivers: research & management 11(1), 105-119.

Waterhouse J, Brodie J, Lewis S and Mitchell A (2012) Quantifying the sources of pollutants in the Great Barrier Reef catchments and the relative risk to reef ecosystems. Marine Pollution Bulletin 65, 394–406. DOI: 10.1016/j.marpolbul.2011.09.031.

Weston DP and Lydy MJ (2014) Toxicity of the insecticide fipronil and its degradates to benthic macroinvertebrates of urban streams. Environmental Science & Technology 48(2), 1290. DOI: 10.1021/es4045874.

Zhao J and Chen B (2016) Species sensitivity distribution for chlorpyrifos to aquatic organisms: Model choice and sample size. Ecotoxicology and Environmental Safety 125, 161–169. DOI: 10.1016/j.ecoenv.2015.11.039.