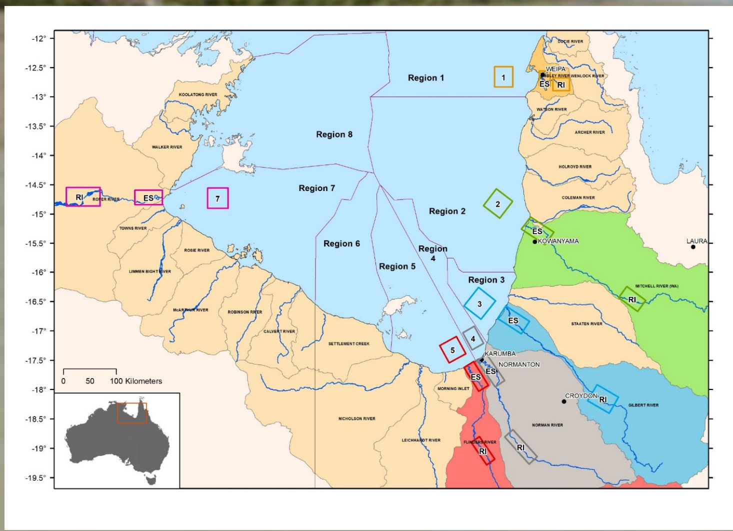
Key findings of ecological modelling of the impacts of water resource development in the Gulf of Carpentaria

Using an ecosystem modelling approach, CSIRO in conjunction with colleagues from Northern Prawn Fishery Industry (NPFI), Griffith University and Queensland Department of Agriculture and Fisheries have completed a FRDC study to quantify the impacts and risks to the Gulf of Carpentaria (GoC) ecosystem of water resource developments (WRD - anthropogenic alteration of freshwater discharge), applied in particular to the Mitchell, the Flinders and the Gilbert River catchments of northern Australia. Key model species include common banana prawns, barramundi, mud crabs, largetooth sawfish as well as mangrove and seagrass habitats



Our approach

- We built on river flow modelling undertaken as part of previous projects (e.g. NAWRA, NESP), plus drew on extensive stakeholder inputs, to investigate the impacts of 5 alternative WRD scenarios applied to freshwater catchments feeding into the GoC, covering approximately 300,000 km^2.
- Our aim was to comprehensively and dynamically quantify the way in which alterations (i.e. WRDs) to baseline freshwater river flows (end-of-system flow) may impact on a range of species that have ecological, economic, recreational and cultural importance.
- We developed a spatial MICE (Model of Intermediate Complexity for Ecosystem assessments) (Plagányi et al. 2014) to represent the population dynamics of key fishery species (common banana prawns, barramundi, mud crabs), a threatened species (largetooth sawfish) and key habitat-forming groups (mangroves and seagrass) as indicators of species with life histories that are intricately tied to changes in the magnitude, intensity, timing and nature of changes in river flows.
- Modelled species population dynamics were linked to physical drivers such as baseline flows. The dynamics of commercially targeted species were further fitted to weekly or monthly historical catch data since 1970 (or 1989 as available).
- Modelled river flows under alternative WRDs applied to the Gilbert, the Mitchell and the Flinders Rivers were input into the MICE and baseline flow simulations were used for all other catchment systems.

We then quantified changes in abundance and catch of the key species under the different WRDs.

Given uncertainties in model parameterisation and structure, we used a range of alternative plausible models to represent system dynamics.

To inform decision making, our study used a rigorous data-driven approach and accounted for uncertainties to predict impacts and risks from different levels of water allocation and catchment development inherent to WRD scenarios. These predictions account for strategies to mitigate impacts on species abundance from WRDs.

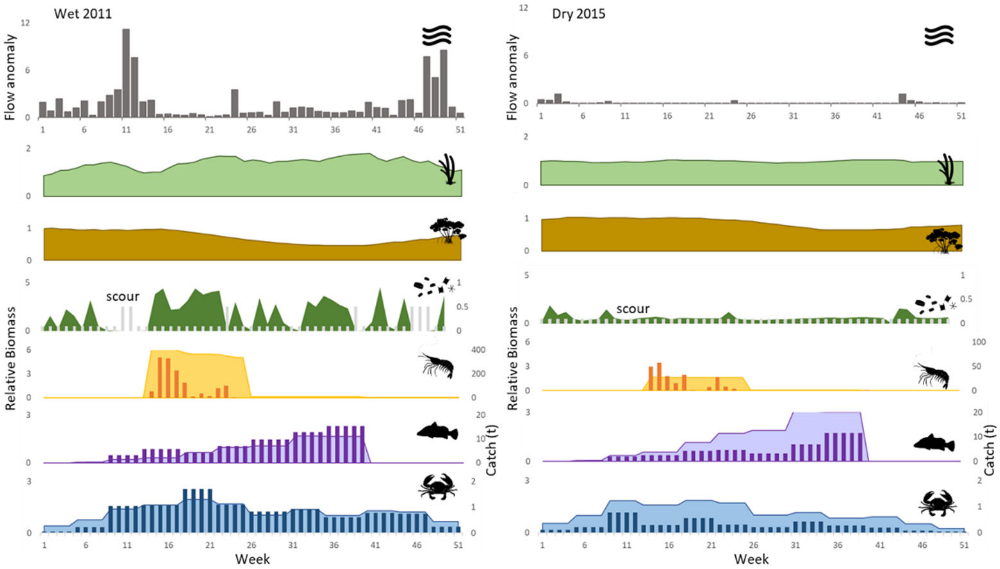


Fig. 1: Comparison of GoC river flows using Region 5 (Flinders River) as an example to illustrate changes in the intra-annual biomass and catch during (left) a wet year (2011) and (right) a dry year (2015). From top panel to bottom panel: flow, seagrass, mangroves, microphytobenthos, common banana prawn, barramundi and mud crab. For common banana prawn, barramundi and mud crab, biomass is the commercially available biomass (divided by the long-term average) and catches (tonnes) are shown on the second vertical axis.

Baseline MICE Results & Modelling Advances

1. For the fished species, we found that linking physical drivers such as river flows with population and fishery dynamics significantly improved the model's ability to predict past catches.
2. Quantification of the ways in which river flows drive estuarine and nearshore populations and habitat abundance were based on some 50 years of observations including the latest research findings and advance previous qualitative and statistical modelling of WRD in the GoC.
3. For common banana prawns, we found support for a "river portfolio effect" influencing MICE regions 2-6 (whereby regional system dynamics are influenced by a combination or portfolio of river flows). We estimated the relative contributions of different catchments to the regional fishery catches, highlighting ways in which changes in different rivers can exacerbate or mitigate changes to regional biomass and catch. This modelling approach supported previous observation-based studies also showing a river portfolio effect.
4. Our modelling of barramundi highlighted the challenges of representing a longer-lived species with a complex life history (including changing sex) and different management rules for two State-based jurisdictions (Queensland and Northern Territory). Nonetheless we were able to link in river flow as a driver to help explain variability in catches.
5. Our modelling of mud crabs advanced previous approaches highlighting sensitivity to river flows, regional differences in the strength of river flow relationships and corroborated the role of other physical drivers (e.g. temperature, etc.) influencing local populations.
6. Our large-scale representation of largetooth sawfish is the first attempt to integrate the complex life history and past population dynamics of this threatened euryhaline chondrichthyan and quantified the relative impact of alternative WRDs on sawfish recruitment and survival.
7. Our large-scale representation of vital blue carbon assets, such as GoC mangroves and seagrass attempted to model changes in these key habitats in response to changes in river flows, light levels, cyclone impacts and other physical drivers.
8. We used model ensemble averages to develop a risk assessment approach to support decision making with respect to evaluating impacts of alternative WRDs on the ecosystem and fisheries.

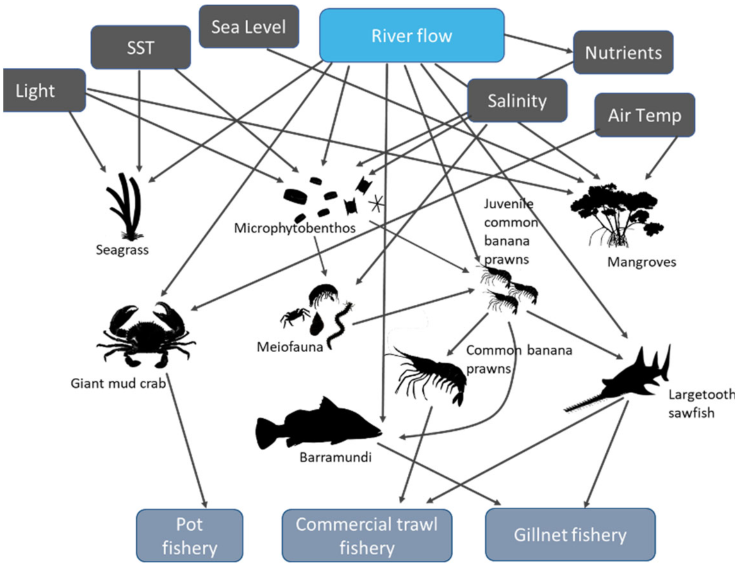


Fig. 2: Key species and linkages in the spatial Gulf of Carpentaria MICE used to test water resource development (WRDs) scenarios

Table 1: Key Water Resource Development (WRD) scenario combinations tested using MICE. TH = flow threshold; PR = pump rate; GL = gigalitres; Base line = base flows with any current water development.

WRD	Mitchell	Flinders	Gilbert
Base	Base line	Base line	Base line
WRD1	High allocation (2000 GL pa, low TH, low PR)	400 GL pa allocation	2 Dams (498 GL yield)
WRD2	Mid allocation (1000 GL pa, high TH, high PR)	160 GL pa allocation	1 Dam (172 GL yield)
WRD3	Mid allocation (1000 GL pa, low TH, high PR)	Base line	Base line
WRD4	Base line	160 GL pa allocation	1 Dam (172 GL yield)

Summary of key findings under WRD and recommendations

- Changes from baseline flows due to WRDs had variable impacts, with impacts ranging from minor through to extreme on all species and catchment regions.
- Model-predicted ecosystem impacts increased as the volume of water extracted or impounded increased, and as the number of rivers on which dams or WRD scenarios were deployed increased.
- For common banana prawns, the MICE enabled quantification of a river portfolio effect across the Mitchell, the Gilbert, the Norman and the Flinders Rivers, such that WRDs applied to a single river or different combinations of rivers had complex cumulative and synergistic effects on common banana prawn abundance and catches throughout this sub-region. Simultaneous WRD across multiple catchments negatively affected banana prawn populations from a moderate to a major degree. Lower water allocations lessened the impact, while WRD within a subset of catchments had the least impact.
- Model results corroborated previous research showing the benefits of nutrients in freshwater inputs on the primary productivity of the same river estuaries (Burford and Faggotter 2021) (which we term a productivity boost effect). This underscores the longer-term benefits to system productivity that result from ongoing productivity boosts driven by natural flow regimes. Our model predicted substantially greater reductions in local and regional banana prawn abundance and catch when accounting for the flood productivity boost effect.

- Barramundi were generally predicted to be most sensitive to the WRDs applied to the Gilbert River region, with both a single and two dams predicted to cause large declines to the local populations. Overall, the model ensemble suggested average catch would decrease up to about 20%, with a maximum decrease of around 27%, under WRDs 1 and 3.

- For mud crabs, substantial negative declines in abundance and catch were predicted for the Flinders and Gilbert catchments under both medium and high-impact WRDs (WRD2 and WRD1 respectively) and for all five model versions in the MICE ensemble, but almost no change was predicted for the Mitchell catchment given the very weak flow relationship estimated by the model for this region.
- Predicted changes in catch particularly for barramundi and mud crabs under WRDs were similar to the magnitude of change observed in historical catches between wet, intermediate and dry years.
- Across each of the modelled species, the incorporation of a low river flow extraction threshold value (TH) as part of the pumped-water extraction regime caused a much more substantial negative impact on model-predicted catches and abundance. A significant decline in catch associated with water extraction at low-levels of river flow was consistent with previous studies pointing to the need to maintain flows well above an ecosystem-minimum level. Maintaining low-level river flows, especially early season flows, enhances the estuarine ecosystem by re-establishing estuarine/riverine connectivity , inputting a new source of nutrients, and ameliorating high salinity conditions after a prolonged dry season.
- As the Mitchell River is a perennial system that exhibits less environmental extremes than the Gilbert and the Flinders Rivers, WRDs for the Mitchell River were predicted to have a less extreme impact on barramundi, mud crabs and prawns.
- Our model implicitly accounts for the timing of river flows (and early wet season flows in particular) that are critical for most species, and hence model results to evaluate the impact of alternative WRDs include integration of changes in intra-annual flow levels evaluated using either a weekly or monthly time step.
- Across a range of alternative parametrisations, we found that decreases in river flows translated into substantial decreases in population abundance of largetooth sawfish because their life-history characteristics mean they are unable to compensate or rapidly bounce back in response to any negative impacts on their productivity.
- Largetooth sawfish were predicted to show high sensitivity to almost all WRDs tested. Water extractions and flow modification within multiple catchments (e.g. WRD1 and WRD2) were predicted to result in extremely large local population declines. Sawfish model results differed in a number of ways from those for prawns, barramundi and mud crabs as changes to WRD settings such as river flow extraction threshold value and pump rate did not result in mitigation of the impacts on sawfish as was the case for some of the other species.

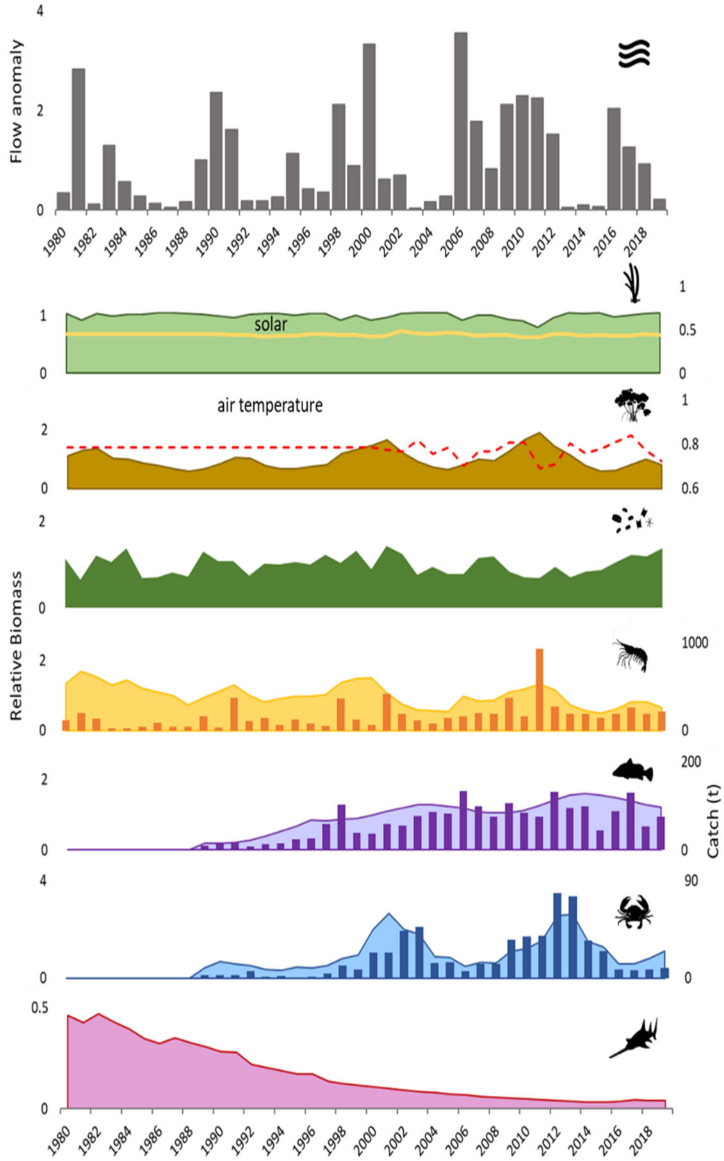


Fig. 3: Example of MICE physical drivers and changes in the relative biomass and catch (t) of the model groups under baseline flow for Region 4 (Norman River) to illustrate interannual variability over 1980 to 2019.

- Sawfish results suggested greater sensitivity to WRD scenarios involving water extraction compared with water impoundment i.e. dams (assuming free movement of the animals was not negatively impacted). Anything other than very low extraction amounts were predicted to have substantial negative impacts on sawfish, across a range of alternative water extraction threshold and pump rate settings.
- Our preliminary investigations for largetooth sawfish provided guidance as to which river systems are likely to be most sensitive to flow modification (e.g. the Flinders River) and the type of impacts (extraction WRDs performed worse than impoundment scenarios, i.e. dams). In addition, the models shed light on recommended settings for future WRDs if these were to be implemented.
- Model results were fairly robust to alternative model structures that included explicit representation of the dependence of barramundi and largetooth sawfish on estuarine prey availability (using common banana prawns as a proxy) albeit that this could worsen predicted impacts of WRDs in some scenarios.
- In contrast to all the other MICE groups, seagrasses were predicted to marginally increase in abundance/distribution under some WRDs for some time periods, with minor impacts (up to a 7% decline in seagrass abundance relative to base levels) across most scenarios. Seagrass habitats are typically geographically separated from freshwater flows compared with estuarine habitats.
- Model results suggest that WRDs may have a dramatic effect on mangroves with water impoundment predicted to result in large declines in mangrove abundance in affected areas if flows influence growth rates and carrying capacity. This significant finding requires on-ground validation.

- There were no suitable data to confirm model results that outcomes for mangroves under the same extraction allocation could be substantially worse if using a low river flow extraction threshold value (TH) and longer pump duration compared with a less impactful scenario extracting at higher river flow levels and over a short pump duration. A low river flow threshold allows the pumping of low-level flows whereby a large proportion of river flow is extracted and significantly less water passes downstream. In addition, a longer pump duration necessitates water extraction from flows other than peak flows, resulting in a higher proportion of the non-peak flows being extracted. Both pump routines disturb the pattern of river flow during low-level flows when water extraction disproportionally affects river flow volumes and downstream ecosystem service provision.

- For commercially fished species, model results suggested minor to large changes in average catches. Economic analyses corroborated that the maximum modelled decline in any year is likely to be of more interest to fishing industry stakeholders. The latter rely on regular annual income and may not be able to withstand even a few years of low catch or periods when the fishery becomes economically unviable.
- Our MICE framework is a useful tool for quantifying the impacts of WRDs across a range of species, catchment systems, time-scales and model parameter settings. Given adequate data, the MICE could readily be extended to include other species or systems. There is considerable scope to gradually increase the complexity of the modelled systems such as to account for a range of inter-specific interactions, connectivity scenarios, other fishery sectors (e.g. recreational species such as king threadfin salmon); as well as to investigate what the additional effects of climate change might impose on this ecosystem (beyond the scope of this study).
- Accurately representing ecosystem dynamics, species with different life histories, multiple users and jurisdictions, as well as the impacts of WRDs is complex as there are often more than one driver at play. We therefore acknowledge that our MICE framework has limitations such as not fully representing connectivity between all regions, not explicitly modelling the oceanographic and wind-driven dynamics of the GoC, not including multiple other species that are linked by trophic webs to our key species and may be similarly impacted by river flows (e.g. king and blue threadfin salmon, grunter), not accounting for species composition and species-specific life history characteristics of the habitat-forming groups and using best-estimate relationships to represent complex mechanistic processes.
- Although additional complexity can be added to the MICE, the current version is consistent with the MICE philosophy of starting with a first approximation and finding the 'sweet spot' at which the uncertainty in policy indicators is minimised.

Research is urgently required to gain a better understanding of largetooth sawfish population status and ecology in rivers that are likely to be impacted by water extraction and upstream dams. Our study underscores key gaps including data on the natural mortality, status and connectivity of sawfish. This is being partially addressed through a CSIRO close kin mark-recapture research study (on narrow sawfish). We also highlight the need for further targeted field-based research.

Ecological and fisheries risk assessment

- Our risk assessment classified WRD1 (highest water allocation and multi-catchment WRD) as the highest risk development, with moderate to intolerable risks predicted for all species and groups (except for seagrass), including both population-level risk and fishery risk. WRD2 and WRD4 scenarios (lower water allocation or single catchment WRD) were predicted to have high risks to threatened species populations (e.g. sawfish) and fisheries (prawn, barramundi, mud crabs). WRD3 was assessed less risky because it assumes no development on the Flinders and Gilbert River catchments.
- Largetooth sawfish had the greatest sensitivity to WRDs (due to their low productivity life-history characteristics) with risks ranked as intolerable across a broad range of alternative water extraction or impoundment scenarios.
- For common banana prawns, the Flinders River catchment emerged as the most sensitive to WRDs, consistent with previous findings from estuarine productivity studies (Burford and Faggotter 2021).
- We quantified the probability of alternative WRDs increasing the baseline economic risks to the common banana prawn sub-fishery of the

NPF by computing the relative probability of occurrence of major risks (defined as risk of an unacceptable or bad year), severe risk (two successive bad years) and intolerable risk (fishery operations becoming unviable due to three or more consecutive bad years). We predicted that the risk of a bad year may more than double under some WRD scenarios.

- The Gilbert River catchment emerged as the riskiest scenario overall for barramundi abundance and catches.
- For mud crabs, the Flinders and Gilbert River catchments emerged as most vulnerable to WRDs with risks often as high as the severe risk category.
- The MICE predicted major to severe risks to mangrove habitats under some WRD scenarios, but negligible risks to seagrass, although we did not account for potential increases in nutrient levels and turbidity that may be associated with WRDs.

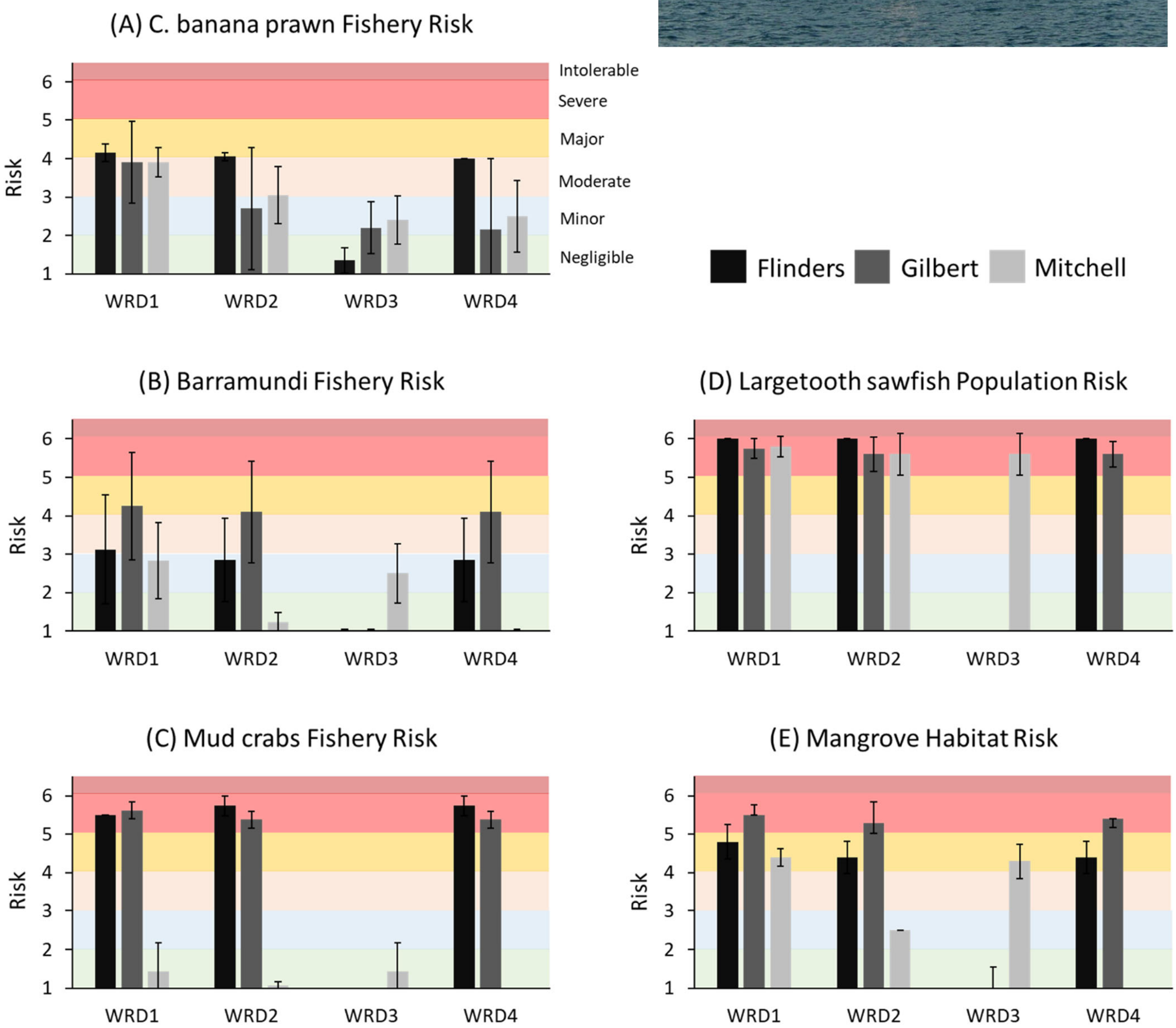
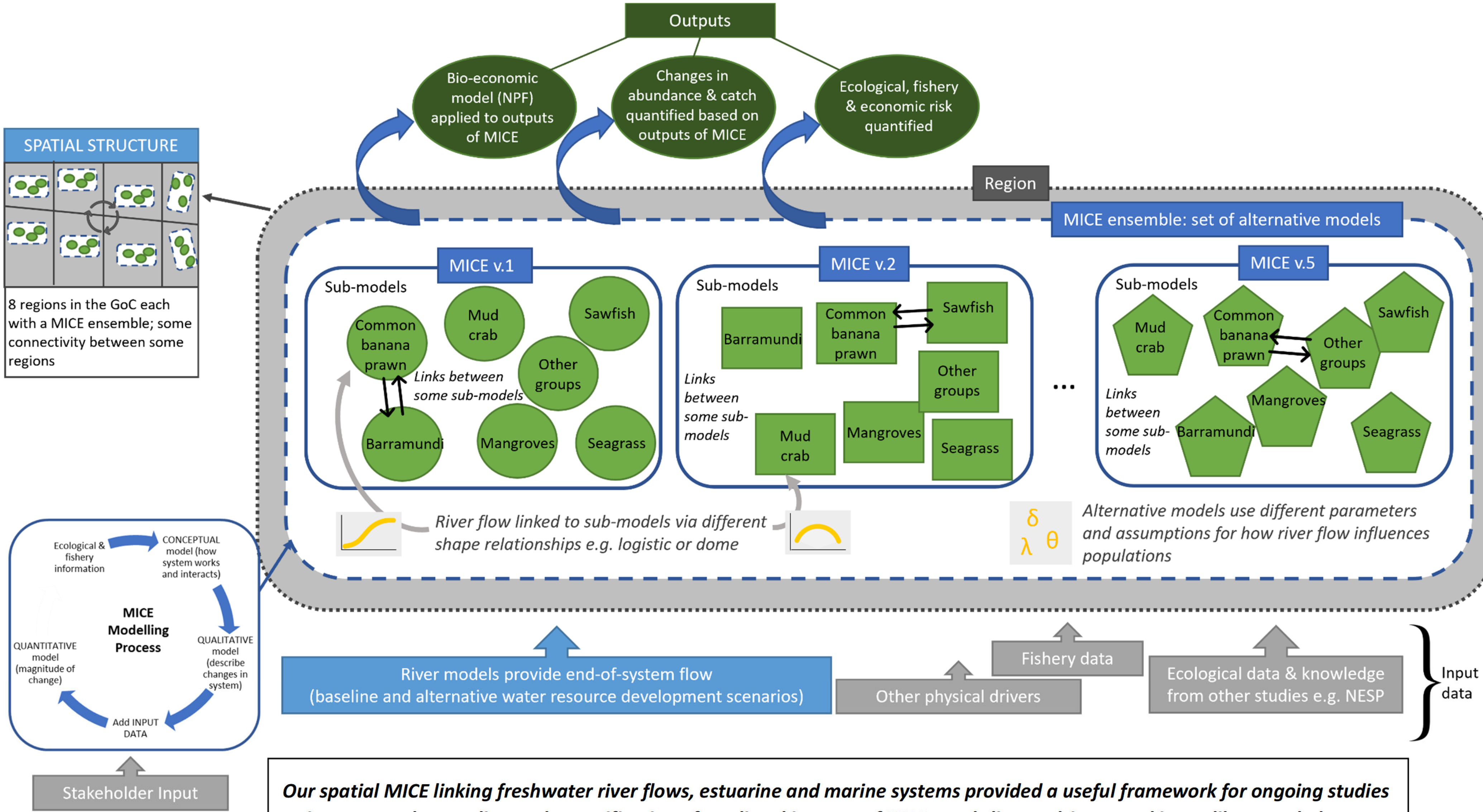


Fig. 4: Risk scores averaged across five MICE versions (± standard deviation) for key species/groups across three rivers (Flinders, Mitchell and Gilbert) under four WRD scenarios.



Our spatial MICE linking freshwater river flows, estuarine and marine systems provided a useful framework for ongoing studies to improve understanding and quantification of predicted impacts of WRDs and climate drivers, and is readily extended to represent WRDs applied to other catchments, acknowledging that there remains considerable scope for improving our modelling approach as new information becomes available.

GLOSSARY

Allocation: Water resource allocations (GL/year) which are either extracted by pumping or impounded i.e. via dams.

Baseline flow: Base river flows which include current water development but no future water development

Bio-economic model: Separate model for Northern Prawn Fishery to which MICE outputs are applied

Input data: Other studies or sources used directly in model or to develop relationships to model variables such as seasonal changes in light, quantify impact of cyclones (this study)

MICE: Model of Intermediate Complexity for Ecosystem Assessments – includes subset of species (sub-models) and their linkages, informed by input data, accounts for uncertainty

MICE ensemble: A set of alternative MICE model versions that are similar but may differ in model structure or use different input parameters, or may have different underlying assumptions e.g. how river flow affects population dynamics

PR: Pump rate – river flow extraction pump rate measured as the number of days taken to pump water

Qualitative model: A model that describes the system status and functioning and e.g. direction of a change rather than magnitude of change

Quantitative model: A model that quantifies the system and processes and e.g. the magnitude of a change

River flow: End of system river flow computed using river models; standardised flow measures or flow residuals are the flow amounts divided by the average or median flow

River model: External set of river models updated and extended to provide river flow as input to MICE (this study)

Spatial structure: The way in which the MICE was set up to capture spatial differences for species/groups and associated drivers. In this case, the Gulf of Carpentaria was divided into different spatial regions, with a separate customised MICE for each region and with some connectivity between regions via the sub-models (e.g. prawns)

Sub-models: a model for each species or group, which may be linked. Modelled using DYNAMIC population models that capture changes over time, plus capture NON-LINEAR relationships and feedbacks unlike static statistical models e.g. correlations, general linear models (GLMs)

TH: Threshold – river flow extraction threshold value (ML/day). Water can only be extracted when river flow surpasses this value

WRD: Water Resource Development – the anthropogenic alteration of natural river flow regimes implemented by allocating water for either extraction or impoundment (i.e. dams) for use in agriculture and/or other industries

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Species scientific names: Common (or white) banana prawns *Penaeus merguiensis*; barramundi *Lates calcarifer*; giant mud crab *Scylla serrata*; largetooth (previously freshwater) sawfish *Pristis pristis.*

Photographs Source: Prawn trawler **–** Rob Kenyon, Mangroves – F.P.C. Blamey, Sawfish – Derek Fulton.

References cited: Burford & Faggotter (2021) Marine Pollution Bulletin, 169, 112565; Plagányi et al. (2014) Fish and Fisheries, 15(1), 1-22.

See also: FGARA Overview and findings - CSIRO; NAWRA - CSIRO; Roper River Water Resource Assessment - CSIRO; https://www.nespnorthern.edu.au/nesp/

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