Knowledge for Productivity:
Phase I - Lake Wooloweyah

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In submitting this report, the researcher has agreed to FRDC publishing this material in its edited form.

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Acknowledgments

First and foremost, the authors wish to acknowledge the contribution to this project by the late Colin Creighton AM. His passion and drive for "shovel ready habitat repair" was second to none. This project came about from years of planning on Colin's behalf, and we are thankful for his knowledge and wisdom. We hope that Colin's legacy lives on through this research.

We would also like to extend our thanks to the fishing industry, and in particular, the Clarence River Fishermen's Co-operative. Danielle and her team have always been and continue to be supportive of research that is undertaken to not only improve fishery outcomes but also with environmental and community benefits.

Executive Summary

Healthy estuaries are essential for food security and the productivity and sustainability of virtually all Australia's wild professional and recreational fisheries. Currently, Australia's estuaries are heavily degraded and increasingly the community is seeking to repair estuaries to optimise their fisheries productivity. (e.g. Creighton et al. (2015)). Key coastal wetland habitats have been disconnected from the estuary across all developed estuaries in Australia due to practices such as the construction of flood mitigation works and the clearing and draining of low-lying floodplain back-swamps. Natural services, such as fisheries production, are adversely affected with a resulting economic and community cost. (e.g. Taylor and Creighton (2018) and references therein).

As a result of these adverse effects, estuarine repair is a key management priority for the NSW Government. Habitat repair of degraded estuaries is strongly linked to reinstating the tidal connectivity. While conceptually simple, the process of restoring tidal connectivity on a catchment scale is often complicated by a range of factors such as existing land use and floodplain agricultural productivity, estuarine tidal dynamics, landholder willingness, cost-benefit analysis, and future climate change uncertainty.

The value, both ecological and economic, of strategic restoration on a catchment scale can be realised by; (i) correlating habitat area/distribution with fishery health/abundance, (ii) identifying and prioritising tidal habitat restoration based on existing impact to estuarine water quality and potential restored habitat area/type and (iii) economic cost-benefit analysis of repair both now and under climate change. This multi-disciplinary approach results in a shovel-ready plan for strategic estuary-wide habitat repair applicable both in NSW and elsewhere in Australia / internationally. This project focused on a segment of the Clarence estuary: Lake Wooloweyah and associated tidal channels and wetlands, to define habitat-fishery linkages and provide strategic priorities for repair of habitat in combination with enhancement of tidal flows and resulting increases in tidal habitat, and to use it as a case study for producing similar outputs in other estuarine systems.

The principal objectives of this project are conceptualised in Figure 1 and were to:

- Determine the potential increases in fishery productivity using School Prawn (*Metapenaeus macleayi*) as readily understood community indicators of fisheries productivity.
- Link habitat with existing fisheries production by understanding the connections between habitat and hydrology
- Identify key opportunities for establishing connectivity, habitat and fisheries productivity
- Estimate the likely benefits of repair in fisheries productivity as an input to a Clarence Fisheries Productivity Investment Strategy

Methodology

Stable isotope ecology was used to prioritise habitats for fishery productivity. Sample school prawn were collected in Lake Wooloweyah along with the primary producers in each habitat type (seagrass, mangrove, saltmarsh, mud) for stable isotope analysis. Using a Bayesian mixing model, the relative contribution of each primary producer for the prawn consumers was determined.

An assessment of eco-hydrological rehabilitation options was undertaken based on the collection of extensive field data sets and detailed estuary-wide hydrodynamic modeling of tidal flows, volume and velocities. This analysis included the collection of water level and salinity field data as well as a detailed elevation survey of intertidal vegetation communities in hydrological distinct parts of the system. The surveyed vegetation elevation envelopes were then linked with the local tidal inundation and flushing regimes (i.e. hydroperiod) as inferred from the hydrodynamic model. These relationships between tidal inundation dynamics and intertidal ecosystem presence/abundance around Lake Wooloweyah served as the basis for estimating the ecological outcomes of different tidal rehabilitation options.

Guided by the hydrodynamic assessment of the system and a previous identification of low-lying land with high priority for repair across the entire Clarence River estuary, four options for intertidal habitat rehabilitation (saltmarsh and mangroves) were identified that could be activated if drainage infrastructure would be removed in strategic locations. The potential value of these new habitats to the fishery were then estimated based on the stable isotope mixing models and current and past value of the fishery. Multiple scenarios were explored, including estimating the cost/benefit of rehabilitating the habitats.

Results

Among estuarine habitats in Lake Wooloweyah, saltmarshes had the highest total value for landed prawns (\$250,000 AUD.yr^{1}) while mangroves had the lowest value (< \$100,000 AUD.yr^{-1}). The broader value of estuarine habitats was greater than \$1.6 million AUD.yr^{-1} for saltmarshes, and the combined broader value of estuarine habitats was in excess of \$3 million AUD.ya^{-1}. Sugar cane plantations appeared to have negligible contribution to the prawn food web, and so had negligible value for the system. Due to its rarity in the system, however, seagrasses had the highest per hectare landed prawn value (~\$3,000 AUD.ha^{-1}.yr^{-1}). During the 1980s the value of Wooloweyah prawn fishery was much higher, and, as a result, the value of estuarine habitats was approximately twice as high.

The hydrodynamic and eco-hydrological assessment suggests that under present day conditions, 680 – 2,155 hectares of intertidal habitats could be created by adjusting flow regimes via modifications to current drainage infrastructure. These modifications could have total flow-on values of over to \$7.2 million AUD.yr^{-1} to the prawn fishery. The rehabilitation of the low-lying lands behind the ring drain would also effectively mitigate the pronounced acid sulphate soil (ASS) and blackwater issues of these areas, thereby improving the overall eco-hydrological health of the Lake Wooloweyah hydrology unit. We highlight that the above valuations account for the school prawn fishery exclusively, and as a result these are very conservative estimates of the value of these habitats to the local economy. These projections also do not include rehabilitation of seagrasses that are harder to model.

Implications

The Lake Wooloweyah and Clarence River prawn fishery would gain value through increased landings by rehabilitating saltmarsh, mangrove and seagrass communities. Seagrass rehabilitation, however, is complex and often costly, therefore, we recommend that any rehabilitation efforts focus on saltmarshes in the area. The per-year broader value or habitat rehabilitation to stakeholders is significant (>\$7 million AUD.yr^{-1}), and since this is an underestimate of the value as it excludes other fishery species that occur in the area, we believe that the cost of this rehabilitation would rapidly be offset by benefits to the broader community. A direct cost-benefit of the four rehabilitation areas identified should be undertaken to identify the option that would provide the highest benefit at the lowest cost.

Recommendations

Explicit cost-benefit analyses of rehabilitation projects for the areas identified through hydrological models could help managers and the industry quantify the future benefit of these projects to commercial fisheries. Given the high value estimated from the potential rehabilitation area, this should be explored. This cost-benefit should include formal compensation for the purchase/loss of any farmland that would result from hydrological modifications.

Regardless of rehabilitation options, climate change and the associated sea level rise will have an impact on estuarine habitat cover. We suggest that a similar approach as that used here could also be used to outline the value that would be lost from fisheries because of sea level rise or temperature shifts.

Accurately separating the contributions of mangroves and saltmarsh succulents to the diets of prawns is difficult with stable isotopes, therefore we recommend ecological assessments that determine the trophic link between these habitats and prawn diets (e.g. through studies on zooplankton such as mysid shrimp) or the use of additional chemical tracers.

The approached outlined herein only captures value to the fishery and as a result, always underestimates the value of estuarine habitats for the broader economy through additional co-benefits. In addition, this project only considered a small component of the Clarence River system, and a broader project that examines the entire Clarence River estuary would likely provide more management options to increase value, especially given that both Lake Wooloweyah and the Clarence River systems are connected and there is likely to be nutrient flow (and therefore exchange of services) between the two. We therefore recommend follow-on projects on the broader Clarence estuary that also account for additional co-benefits such as biodiversity, blue carbon, water quality improvement, etc. to value these habitats more comprehensively. A broader valuation of these habitats in addition to the fisheries value identified here would further increase the value of these habitats and could provide further incentives to rehabilitate these environments.

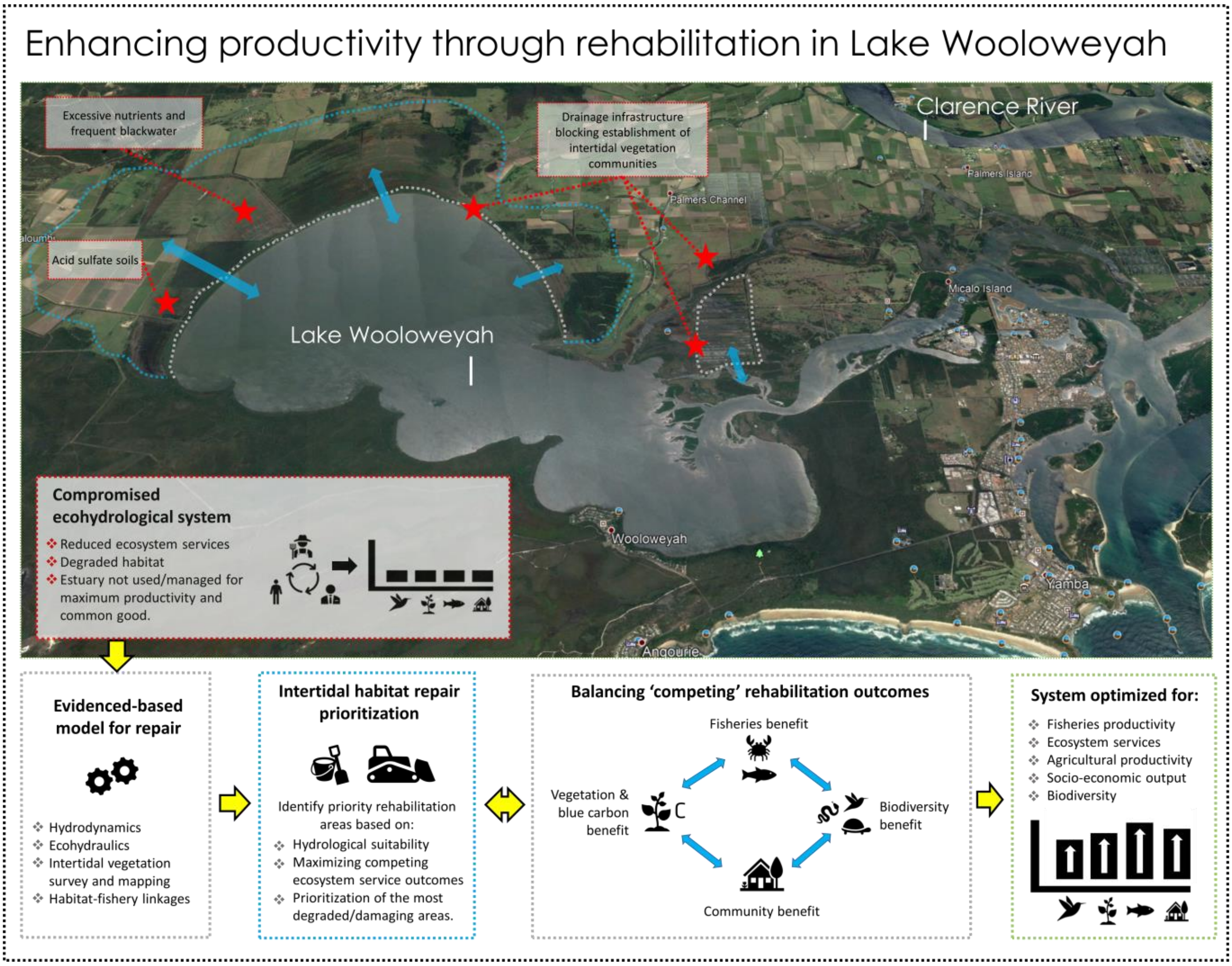


Figure 1: Conceptual diagram illustrating the key goals and outcomes of this study.

Keywords

Trophic ecology, hydrology, rehabilitation, habitat-fishery linkage, school prawn, *Metapenaeus macleayi,* cost-benefit

Introduction

Wetlands are globally threatened as a result of human activities (Saintilan and Rogers, 2013, Whitt et al., 2020). Land reclamation, boating activities, climate change and pollution all contribute to the loss of these ecosystems (Kennish, 2002). These losses can come at a significant cost to society, as they provide various ecosystem services such as climate change mitigation, storm surge attenuation and nursery habitats to various organisms (Maltby and Acreman, 2011). The value of ecosystem services lost with these systems has driven the UN to declare 2021-2030 the decade of ecosystem rehabilitation, with explicit targets for rehabilitating habitats. However, a key difficulty in communities justifying the rehabilitation of these environments is that cost/benefit scenarios of rehabilitation are rare or have very broad uncertainty ranges. This makes it difficult to justify the often significant expenses associated with habitat repair (Bennett and Morrison, 2000, Zentner et al., 2003). Providing accurate valuations of wetland habitats should therefore be a global priority, as these will supply the justification to invest in rehabilitation projects that may be required to improve ecosystem services.

To date, wetland habitat valuation has included the use of social perceptions (van Vuuren and Roy, 1993) or ecosystem services such as climate change mitigation (Patton et al., 2015). One of the more promising avenues for valuing these environments is through direct habitat-fishery linkages (Jänes et al., 2020). As wetlands are some of the most productive environments on earth (Twilley et al., 2017), the loss of these habitats is expected to have flow-on effects to the numerous organisms that depend on this productivity for sustenance, including birds, fishes and invertebrates (Mitsch and Gosselink, 2000). Consequently, a loss of wetlands is expected to result in a direct loss of fisheries productivity because of the loss of the fishery-habitat linkages. This fishery-habitat link can be explicitly used to value habitats, if methods are used to measure the relative contribution of estuarine habitats to the food web that fisheries depend upon.

Measuring links between habitats and fisheries has primarily relied on stable isotope ecology. In general, these studies identify that saltmarshes and seagrasses have the highest contribution (and therefore, value) to the diets of commercially important species (Connolly et al., 2004, Connolly et al., 2005, Connolly and Waltham, 2015, Raoult et al., 2018, Hyndes et al., 2014, Jinks et al., 2020). The degree of contribution is strongly estuary dependent (Jänes et al., 2020), and as a result, a closer examination of the per estuary contributions is necessary to explain the underlying causes of these differences in food web contribution. An explicit understanding of fishery-habitat linkages allows for techniques that use this ecological information to explicitly value the habitats according to fishery productivity (Taylor et al., 2018), with suggestions that can be made on the value of estuarine habitat rehabilitation (Taylor and Creighton, 2018). A direct cost-benefit analysis that identifies the potential for increasing fisheries productivity by rehabilitating artificially drained floodplain areas has not been conducted using the ecosystem-based approach outlined above. This is generally hampered by a poor understanding of how modifying the hydrology of a system can help rehabilitate estuarine habitats (Rayner et al., 2021a, Sadat-Noori et al., 2021).

Estuaries are complex sedimentary coastal landforms that evolve with time primarily due to the forces exerted on estuarine water bodies via river inflows, tides, wind and waves. Intertidal vegetation communities (sometimes referred to as tidal marshes or intertidal wetlands) such as seagrasses, mangroves and saltmarshes play a key role in the nature and geomorphological evolution of estuaries through complex geomorphological feedback mechanisms (Khojasteh et al., 2021). While tidal hydrodynamics (e.g., inundation frequency, sequencing and hydroperiod) are considered the primary control for the establishment and distribution of intertidal vegetation communities (Rayner et al., 2021a, Sadat-Noori et al., 2021), other factors such as salinity, sediment type and temperature can be significant as well. Due to the strong dependence of these communities to specific degrees of tidal inundation, they are considered highly vulnerable to sea level rise, although projections vary dramatically across the literature (Sadat-Noori et al., 2021). The tidal inundation requirements of different intertidal vegetation communities are, to some extent, documented in the scientific literature (Rodríguez et al., 2017, Rogers et al., 2014, Rogers et al., 2013). For instance, Rodríguez et al. (2017) suggest that saltmarsh is predominantly limited by inundation depths larger than its height during spring tide conditions, whereas mangroves require for their pneumatophores to have access to oxygen at least half of the time. However, these 'models' were established from data for particular sites and vegetation communities, and it is uncertain whether those relationships remain valid in other estuarine systems with potentially dramatically different tidal ranges as well as flooding and oceanic surge dynamics.

Over the last century, large amounts of low-lying floodplain and back swamp areas surrounding many of the estuaries of NSW and other parts of Australia have been transformed into agricultural and sometimes urbanised areas via extensive engineered floodplain drainage systems (Tulau, 2011). In many of these areas, excessive floodplain drainage has resulted in the oxidation of acid sulfate soils and the establishment of non-water tolerant vegetation in historical wetland areas, leading to an increased frequency and magnitude of poor water quality discharge into estuaries due to acid and 'blackwater' (Tulau, 2011, Wong et al., 2011). In fact, diffuse agricultural runoff has been identified as one of the priority threats to environmental assets within the marine estate as part of the threat and risk assessment (TARA) (Fletcher and Fisk, 2017). These issues are further compounded by accelerating sea level rise, which reduces the efficiency of drainage networks as well as the frequency and magnitude of storm surges (Khojasteh et al., 2021). In recent times, the reintroduction of tidal flushing into these previously drained lands has been identified as a cost-effective strategy for not only addressing these issues, but also for creating high priority intertidal habitat such as saltmarsh and mangroves, thereby improving the overall eco-hydrological health of estuaries (Harrison et al., 2021, Tucker et al., 2020). Local NSW examples of successful implementations of large-scale tidal reintroduction with subsequent establishment of intertidal vegetation communities include Rayner et al, (2021), Sadat-Noori et al. (2021) and Glamore et al. (2014). In these examples, the estimation of vegetation outcomes of the tidal reintroduction works was based on a detailed elevation survey of the surrounding vegetation communities and corresponding tidal inundation regime. This approach has been extensively validated in practice by Sadat-Noori et al. (2021).

Rehabilitated intertidal wetlands provide a broad range of ecosystem-services to local communities. The significant potential economic benefits of tidal rehabilitation of previously drained floodplain areas are demonstrated in Harrison et al. (2019), which found that the net benefit of the remediation works outweigh the net benefit of the current dairy-focused agricultural land use 7 to 1. The report concludes that the economic benefits of tidal rehabilitation are predominantly the result of improving water quality, fisheries, and overall estuary health. Another important benefit of tidal rehabilitation is the high level of carbon sequestration occurring within all intertidal vegetation communities (i.e., blue carbon) (Macreadie et al., 2017), which is currently in the process of being included in the Australian Emissions Reduction Fund's voluntary emissions trading scheme.

Here we conducted a knowledge-based assessment of rehabilitation potential for a localised fishery: the Lake Wooloweyah school prawn fishery in the Clarence River, NSW. We combined hydrodynamic and eco-hydrological modelling of a range of tidal rehabilitation options around the lake with ecological habitat-fishery linkages. We then modelled the potential value that could be added to the Lake Wooloweyah school prawn fishery from flow-on effects that rehabilitation of these areas would provide.

Study site description

This project focuses on the Palmers Channel, Lake Wooloweyah and Oyster Channel segment of the Clarence River estuary. The Palmers, Oyster and Micalo Channels connects the Wooloweyah Lagoon to the south with the Clarence River to the north and north-west, with Oyster channel providing by far the largest hydraulic connection between the two systems. Lake Wooloweyah is of very high ecological value and is listed on the "Directory of Important Wetlands in Australia", supporting large areas of seagrasses, mangroves, and saltmarsh. Lake Wooloweyah has a local catchment of around 174 km^2 with an average annual rainfall of 1,457 mm, a very high level of inter-annual variability and a pronounced summer and autumn rainy season (Foley and White, 2007). Current land uses in the Wooloweyah Catchment are cattle grazing (55%), cane growing (24%), national parks/reserves (19%) and urban (3%) (Foley and White, 2007).

As shown in Figure 2, an extensive network of artificial drains and floodgates have been constructed to facilitate development in the Palmers Channel and Taloumbi areas. While drainage works date back to the early 1900’s, the majority of major infrastructure in this area was first constructed in 1966 by Clarence River County Council (Foley and White, 2007). Major drainage works include the Taloumbi Ring Drain and the five major radial drains that drain into it and allow agricultural uses of the low area along the banks of Wooloweyah Lagoon. This extensive drainage system consists of over 20 km of major drains and 10.2 km of levees. Due to the low-lying nature of this land, floodgates are used to prevent saline intrusion into the drainage system. Drainage works also include a small levee that was built in 1967 to provide protection in the Palmers Channel area against small flood events (Foley and White, 2007).

The Palmers Island, Micalo Island and Yamba sub-catchments are located on the right bank of the Clarence River, near its mouth. This area is characterised by a number of interconnected shallow tidal creeks and channels. Prior to flood mitigation works, Palmers Island was part of the tidal foreshore of the Wooloweyah Lagoon, however the construction of levee banks isolated Palmers Island from the lake (Council, 2010). Construction of artificial drainage networks and levees, shown in Figure 2, have enabled the expansion of sugar cane and grazing to areas that were previously wetlands, and drainage infrastructure (e.g. floodgates) have diminished available aquatic and intertidal habitat (Harrison et al., 2021).

Prior to the extensive flood mitigation works, the majority of runoff generated in the Wooloweyah catchment during wet periods accumulated in predominantly freshwater wetlands in the extensive low-lying lands behind the current Ring Drain (Foley and White, 2007). According to Foley and White (2007), up until the construction of the drainage network, these areas used to be semi-protected from tidal flushing and saline intrusion by a natural levee along the current location of the ring drain and, once filled, slowly drain into the lake via low points in the natural levee. The authors also point out that the areas to the south of the Taloumbi Ring Drain used to be brackish and featuring extensive saltmarshes. It is unclear to what extent entrance training works at the Clarence River mouth and sea level rise have influenced the tidal regime of Lake Wooloweyah since then.

Some evidence suggests that Lake Wooloweyah is slowly infilling with sediments and fine silts that are deposited here during and after floods (White, 2009). Further, the southern and south-western shoreline of the lake seems to have been accreting in recent history, as indicated by a nearly 2km wide section of about 50 relict shorelines that are clearly visible on aerial photos and Digital Elevation Models (DEMs; e.g. Figure 2). Although this process is not well documented, we believe that this accretion might be driven by local wind waves. The geometric alignment of the lake with the dominant north-easterly sea breezes (8.5km fetch length) and south and south-easterly winds (up to 5km fetch length) creating significant wave formation potential towards these shorelines, while tidal currents are minimal here.

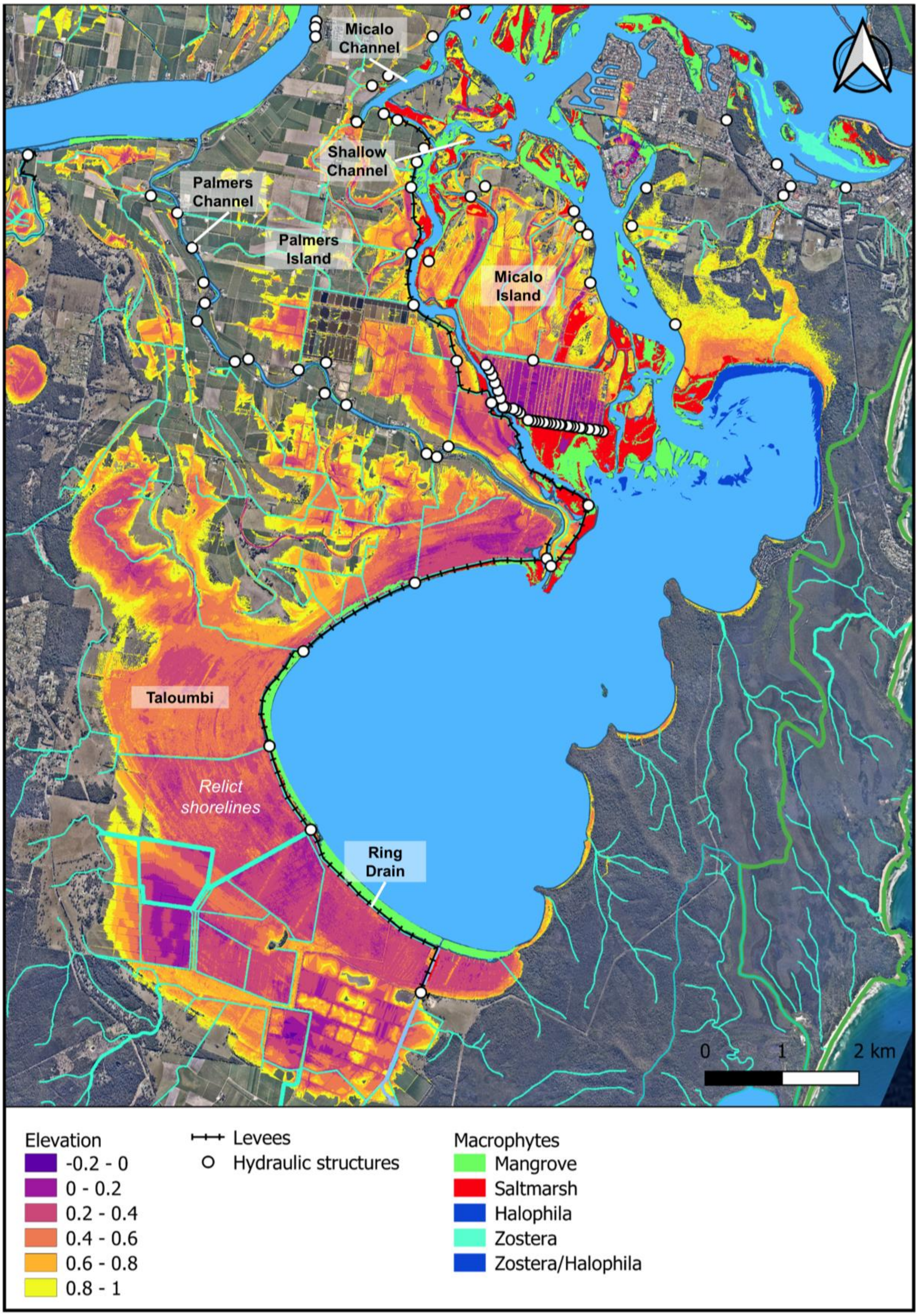


Figure 2: Overview of the Lake Wooloweyah segment within the Clarence River Estuary showing key end of system drainage structures, levees, water courses and drains, intertidal vegetation communities and elevation between -0.2 and 1m Australian Height Datum (AHD).

Objectives

The principal objectives of this project were to:

- Determine the potential increases in fishery productivity using School Prawn (*Metapenaeus macleayi*) as readily understood community indicators of fisheries productivity.
- Link habitat with existing fisheries production by understanding the connections between habitat and hydrology
- Identify key opportunities for establishing connectivity, habitat and fisheries productivity
- Estimate the likely benefits of repair in fisheries productivity as an input to a Clarence Fisheries Productivity Investment Strategy

Method

Fisheries productivity and potential enhancements

A total of 14 sites were sampled (Fig. 3) using a sled net (0.75 x 0.4 m mouth, 4 m length 26-mm diamond mesh body and 6-mm octagonal mesh cod end). A total of 6 trawls of approximately 100 m were conducted for each site and GPS locations for the beginning and end of each trawl were recorded. Prawns were bagged and labelled with their site location for processing. Each prawn had its carapace (± 0.1 mm) and weight (± 0.1 g) recorded. A random size selection was then sub-sampled for muscle tissue. These tissues were dried and ground to a fine powder using a Retsch ball mill and approximately 9mg was sent for carbon, nitrogen and sulfur stable isotope analysis.

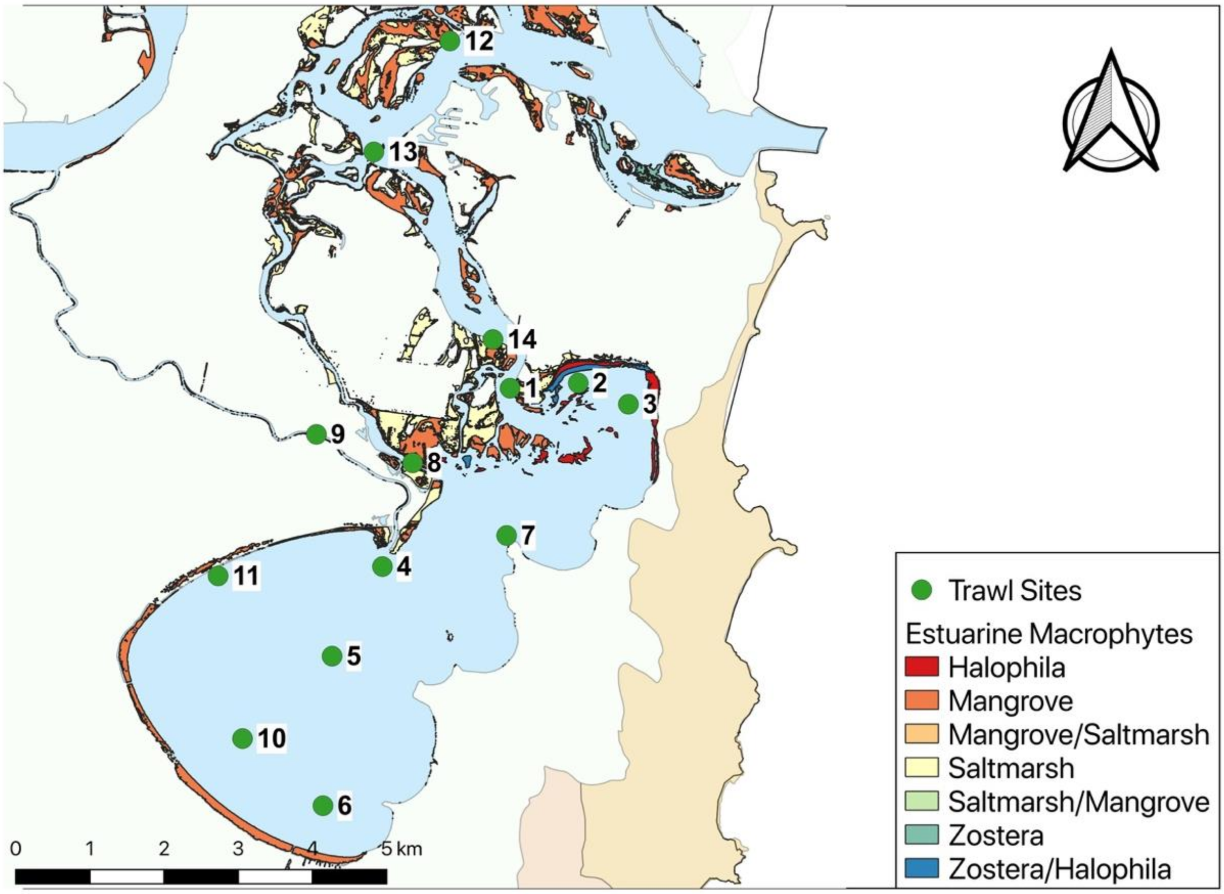


Figure 3: Location of sampling sites within Lake Wooloweyah and Clarence River. Habitat data sourced from NSW DPI Fisheries (2020).

The approach used here broadly follows that used in Raoult et al. (2018) and Hewitt et al. (2020). Stable isotope values of sources were first examine for *a priori* grouping, since sources that overlap in the isospace are indistinguishable in the model (Parnell et al., 2010). Any sources that had means and standard deviations that overlapped across all axes were grouped. This resulted in just one grouped source that included mangroves, *Sueda australis* and *Sarcocornia quinqueflora,* all other sources were independent. Contributions of these sources to the diets of School Prawn were determined using Bayesian stable isotope mixing models using MixSIAR (Stock et al., 2018) in R V. 3.6.0 (R Development Core Team, 2013). School prawn stable isotope values were adjusted to account for trophic enrichment relative to primary producers, with δ^{13}C of 1 ± 1.5, δ^{15}N of 1.95 ± 1.5 and δ^{34}S 0.5 ± 1 as per Hewitt et al. (2020). Large standard deviations for these enrichment factors were included to account for the uncertainty around these values to increase the likelihood that the 'true' enrichment factor is included in models (Bond and Diamond, 2011). Models were set to long run times with a multiplicative setting to account for within-population variability. Diagnostic criteria (Geweke and Gelman) were checked to ensure models converged.

Eco-hydrological assessment of current system conditions and options for habitat creation

The assessment of tidal rehabilitation options for the Lake Wooloweyah segment of the Clarence River Estuary was based on the following key steps:

- Eco-hydrological field survey: This involved a survey of the bottom elevation of relevant intertidal elevation communities in hydrologically different parts of the system, the installation of water level and salinity loggers, and an echo-sounding-based bathymetry survey of the Lake Wooloweyah segment.
- Hydrodynamic modeling: This involved the development, calibration, and validation of a hydrodynamic model of the entire Clarence River estuary to obtain tidal inundation dynamics for all parts of the extended Lake Wooloweyah system.
- Eco-hydrological linkages: This step involved the establishment of local site-scale linkages between tidal hydrodynamics and intertidal vegetation communities.
- Identification and modeling of rehabilitation options: This step first identified currently drained areas around the lake suitable for reintroducing tidal flushing and then estimates the likely gains in mangrove and saltmarsh areas associated with those as the basis for the fisheries benefit valuation.

Eco-hydrological field survey

Eco-hydrological field investigations were completed during five days from the 15th – 19th of June 2020. This fieldwork included an echo sounder bathymetry survey, high precision RTK GPS elevation surveys of intertidal vegetation communities in and around the lake, and the installation of water level, temperature, and salinity loggers. The GPS was also used to survey key hydraulic infrastructures such as the culvert that connects Shallow Channel with Oyster Channel. Figure 4 shows photos of the surveying set up and execution, while a map with the corresponding survey locations is provided in Figure 5. Overall, the field survey was successful and all data necessary for the related project components has been collected.

Figure 4: Photos taken during the hydrological fieldwork by the Water Research Laboratory during 15th – 19th of June 2020. Top row: RTK GPS survey of mangrove, saltmarsh and coastal upland forest communities. Bottom row: Echo-sounder set up and operation on a mud crab punt.

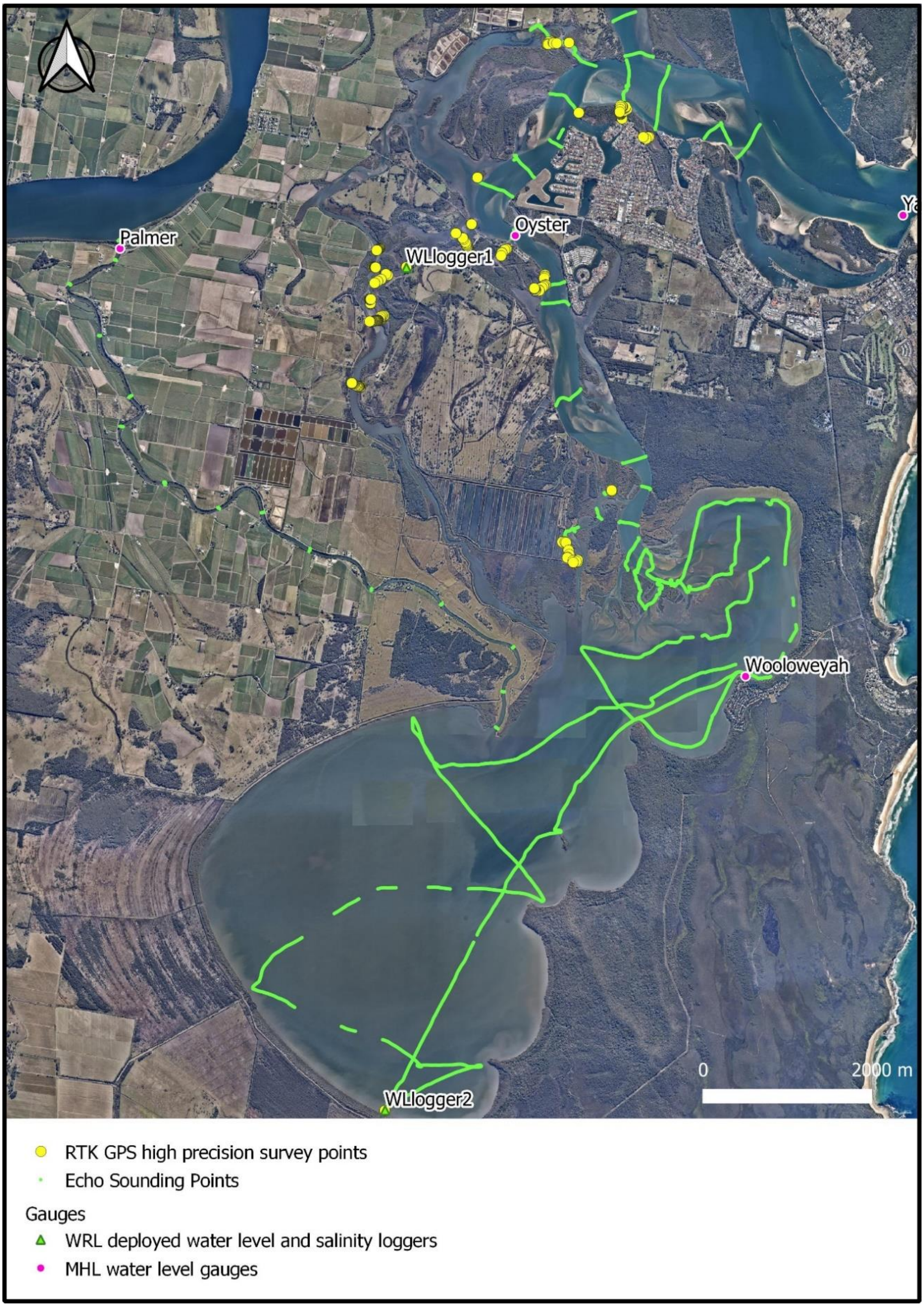


Figure 5: Overview of the hydrological data collected during the fieldwork during 15th – 19th of June 2020. The fieldwork comprised 1) a comprehensive echo-sounder bathymetry survey (see green lines) 2) RTK-GPS high precision elevation surveys across a range of intertidal vegetation communities in different parts of the system (yellow points) and 3) installation of water level and salinity loggers (green triangles).

Hydrodynamic modelling

The bathymetric and topographic data collected during the fieldwork was used to update the entire Lake Wooloweyah and Oyster channel segment of an existing UNSW-WRL hydrodynamic model of the Clarence

River Estuary (Figure 6). These segments were rebuilt entirely to represent the lake and its various feed channels with the highest possible level of accuracy. Particular attention to detail was placed on the representation of the complex Oyster, Romiaka and Micalo channel networks and their respective geomorphological features such as flood and ebb tide shoals. The hydrodynamic model is predominantly a tide model (i.e., as opposed to a flood model) that covers all of the main channels and embayments of the estuary but excludes the vast majority of vegetated intertidal wetlands as well as any floodplains (see Figure 6). In this approach, it is assumed that the volumes of water moving in an out of existing vegetated intertidal wetlands (i.e., mangroves and saltmarshes) has a negligible impact on the tidal hydrodynamics of the estuary as a whole.

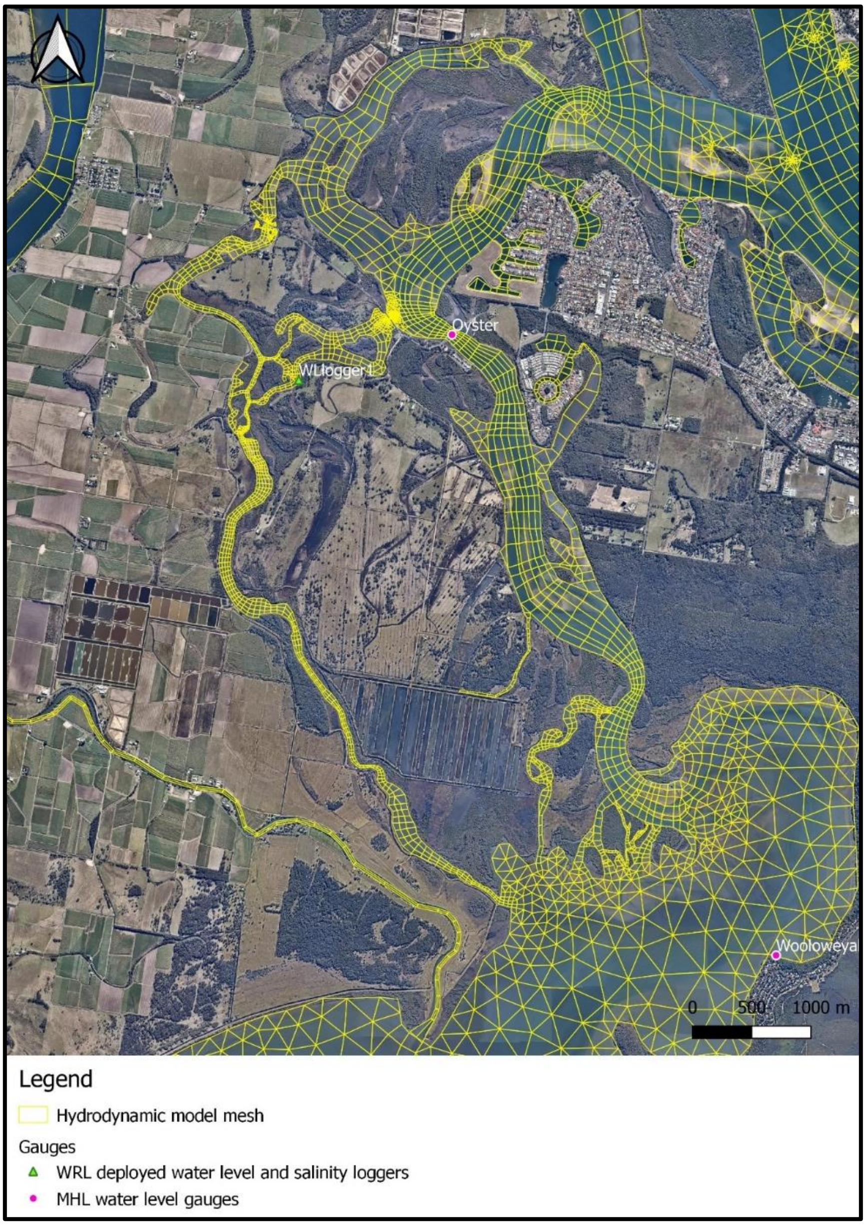


Figure 6: Illustration of the hydrodynamic modelling mesh, which was rebuilt entirely for the Lake Wooloweyah segment based on the echo sounding bathymetry and RTK GPS survey data. The mesh was highly fine-tuned to represent the complex geomorphological features in the main channels connecting the lake with the main estuary (i.e. Oyster, Romiaka, Palmers and Micalo channels, Wooloweyah flood tide delta, as well as important infrastructure bottlenecks).

The model was built using the RMA2 hydrodynamic modelling software package that solves the depth-integrated shallow water equations. This same model was subsequently also used in Harrison et al. (2021), and more details on the calibration and boundary conditions can be found in that report. The model uses inflows from all major upstream catchments as upstream boundary conditions, while data from the nearest oceanic tide gauge is used as the oceanic tidal boundary condition.

After updating the model geometry around Lake Wooloweyah based on the bathymetry data collected in the field, the model was calibrated against data from the year 1996, which included water level gauge data and a set of 24-hour flow measurements around the Clarence River Estuary conducted by MHL. We then validated the model against tide water levels in Oyster Channel and Lake Wooloweyah to determine whether it can effectively reproduce the complex tidal hydrodynamics of this part of the estuary. The calibration of the model against flow measurements in Oyster Channel (Figure 7) shows that the model reproduces the tidal flows and therefore volumes in and out of Lake Wooloweyah with a high level of accuracy.

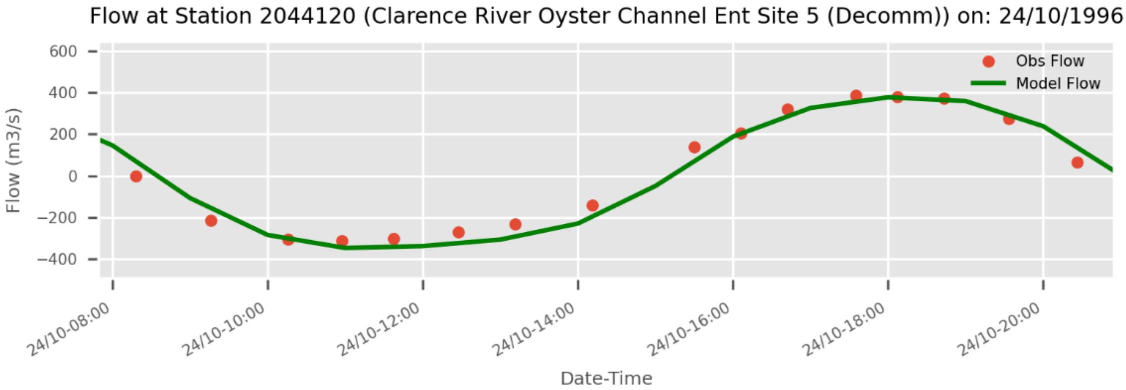


Figure 7: Calibration of the hydrodynamic model against flow data in Oyster Channel illustrating that the model is reproducing the flow volumes and velocities in Oyster channel very well. The flow data was originally collected by MHL during a survey in 1996. For this validation exercise, the model was run for the exact period during which the flow data was collected.

A validation of water levels produced by the hydrodynamic model against water levels from permanent water level gauges around the system (see location of water level gauges in Figure 5) for the year 2019 is shown in Figure 8. The tide water levels at both Oyster Channel bridge and inside Lake Wooloweyah near the Wooloweyah boat ramp are reproduced with a high level of accuracy by the model through the spring and neap tide cycles. These validations demonstrate that the model is sufficiently accurate for establishing meaningful linkages between tidal inundation dynamics and vegetation as well as for assessing the potential for tidal reintroduction in different parts of the system.

In addition to the astronomically driven harmonic oscillations of ocean tides, interannual variability in rainfall, river inflows and sea levels (i.e., surges or tidal anomalies) can significantly influence water levels and therefore the hydroperiod in different parts of an estuary. To account for some of these factors, we ran the model for a comparatively dry (2019) and wet (2013) year respectively. The hydrological reasoning behind the selection of these two years is provided in Rayner et al. (2021).

Further, sea level rise is already creating measurable impacts to the estuaries of New South Wales. White et al. (2014) analysed tidal gauges across Australia and found that the average rate of rise in mean sea levels between 1966 – 2010 in Australia was +1.4 mm/year, with a currently accelerating rate of +4.5 mm/year (White et al., 2014). Due to the high level of sensitivity of intertidal vegetation communities to changes in the mean sea level, it is therefore important to consider these accelerating trends and likely range of future projections. To provide a perspective on these sea level rise impacts, we therefore also ran the model with the same hydrological boundary conditions of 2013 and 2019 but with the addition of projected business-as-usual near future (2050, +16cm since 2020) and far future (2100, + 0.67cm since 2020) sea level rise to the oceanic boundary. A detailed explanation of the reasoning and data behind these levels is provided in Rayner et al. (2021), who adopted these same values in their analysis of floodplain vulnerability to sea level rise across the Clarence River Estuary.

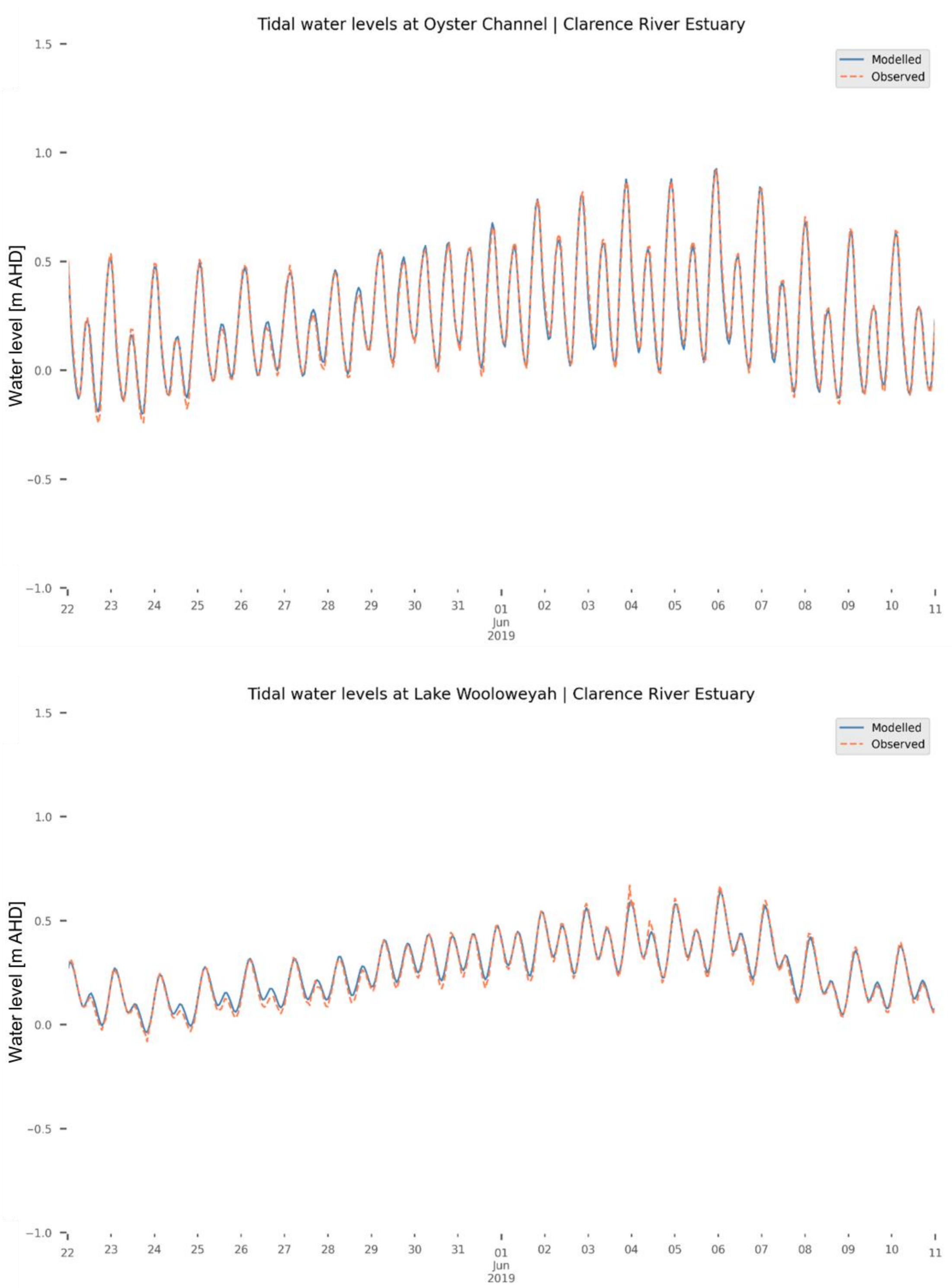


Figure 8: Result of the validation of the hydrodynamic model against permanent tide gauge data (Manly Hydraulics Laboratory) from the Oyster Channel and Lake Wooloweyah tide gauges (see Figure 5 for location of these gauges). The model is able to reproduce the complex tidal dynamics of the system through the spring tide cycle with a very high level of accuracy.

Eco-hydrological linkage modeling

The data from the GPS elevation survey were used to analyse the relationship between tidal range and hydroperiod and the vertical layering of intertidal vegetation communities. As previously mentioned, inundation depth and hydroperiod are considered the primary control for the establishment and distribution of intertidal vegetation communities, which is illustrated in Figure 9. Although a number of relatively simple rules on the habitable ranges of different intertidal vegetation communities have been suggested in the literature (e.g., Rodríguez et al. (2017)), it remains questionable whether these models are readily transferable to other sites. A detailed review of the corresponding literature is provided in Dominguez et al. (2019).

To this end, we conducted the aforementioned elevation survey of vegetation communities, where elevation was measured at ground level at the lowest end of mangrove propagules, at the interface between mangroves and saltmarsh, within saltmarsh communities and at the interface between saltmarsh and coastal upland forest. These elevation points were then clustered into four groups based on their distance from the Clarence River mouth along the centre of the river channel (i.e., thalweg) (Figure 10). For each of these four groups, we then inferred the upper and lower end of the 'habitable' ranges of mangroves and saltmarshes, taking into consideration the level of uncertainty stemming from any potential overlaps in bottom elevation across the different vegetation groups. To establish the local linkages, these habitable ranges were then compared against the long-term tidal inundation conditions at the location of each group as simulated by the hydrodynamic model. This was done separately for the dry and the wet year simulations.

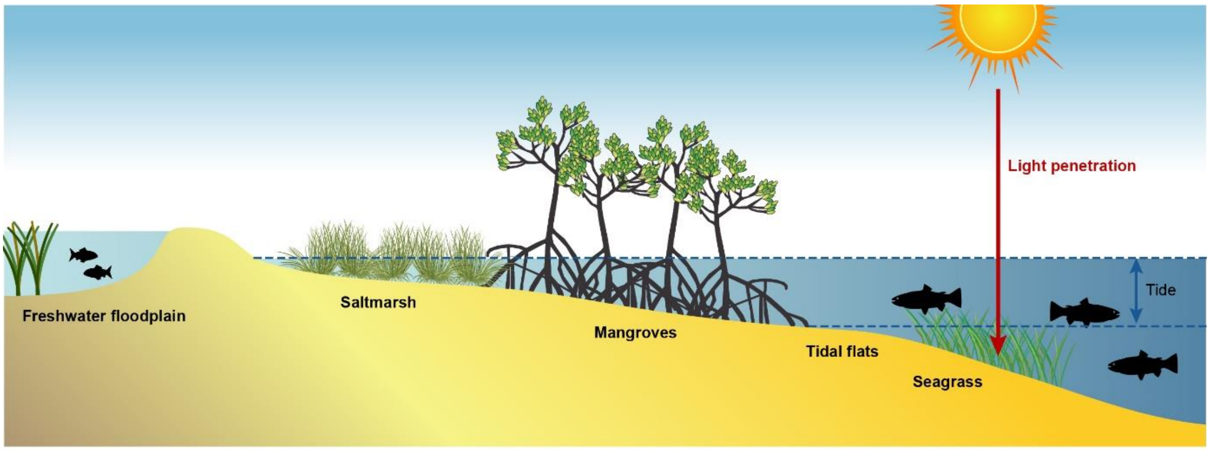


Figure 9: Schematic illustration of the relationship between tidal inundation and the vertical layering of intertidal vegetation communities, here grouped into seagrasses, tidal flats, mangroves, and saltmarshes.

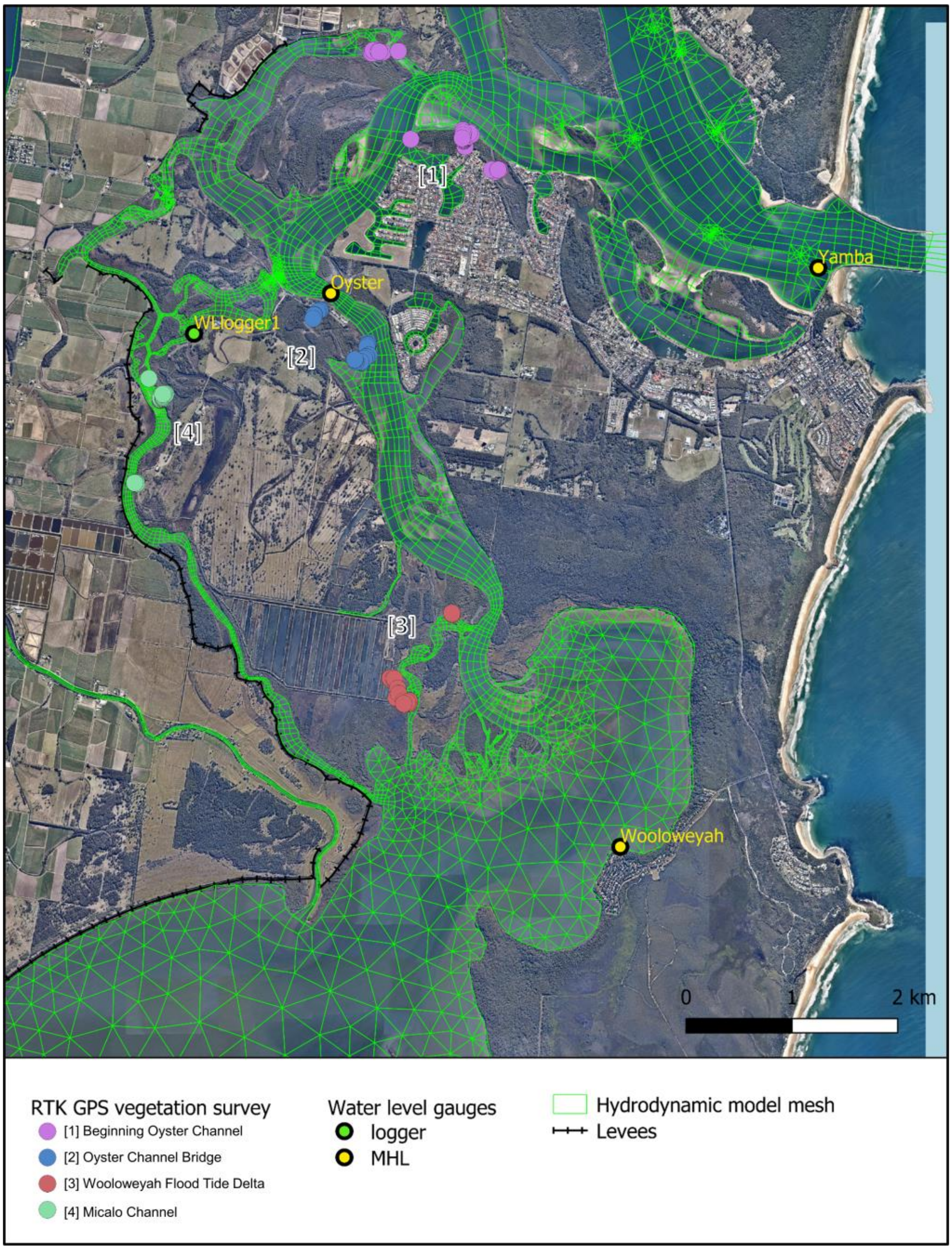


Figure 10: Overview map showing the clustering of vegetation elevation survey points into four groups.

Identification and modeling of rehabilitation options

The identification of options for rehabilitation of currently drained lands via reintroduction of tidal flows was done based on a qualitative multi-criteria analysis. In general, the single most important factor for tidal rehabilitation is the elevation of the drained land in relation to the tidal regime at the endpoint of the corresponding drainage network. This relationship drives the 'physical' (i.e., 'hydrological') feasibility for intertidal wetland creation via appropriate modification works to the existing drainage infrastructure. Other important relevant factors to consider are:

- The current land use within the drained lands as well as private land ownership. In practice, this factor is highly important since tidal reintroduction typically represents a sudden and dramatic change in the currently land use.
- Any potential adverse impacts of the currently drained lands to overall estuary health such as acid or blackwater runoff. Different floodplains within an estuary have different levels of these adverse

impacts. It is therefore sensible to start rehabilitating the most damaging floodplain areas first, since those areas will yield the highest benefit to cost ratio.
- Potential risk of flooding of upstream infrastructure of property if tidal flows are reintroduced.
- The vulnerability of the current drainage system to sea level rise. Effective drainage requires for end of system drains to discharge sufficient amounts of water into the estuary during periods of low tide. With rising mean sea levels, this ability of drainage networks to discharge sufficiently reduces, making the upstream areas increasingly vulnerable to insufficient drainage and water logging.
- The recreational and community value of existing and potential future landuse/habitat of potential areas for intertidal habitat creation.

For the purpose of this assessment, the hydrological feasibility was considered as the primary factor for identifying areas suitable for habitat rehabilitation. This was done intentionally in order to capture the upper range of fisheries benefits that can be achieved for this system. In practice, most of the other factors will likely be considered carefully in order to guide potential on-ground rehabilitation works and further information on these aspects is provided in the following section. To facilitate the prioritisation of potential rehabilitation efforts in practice, we split the hydrologically feasible area for tidal rehabilitation into four eco-hydrologically distinct segments and ran all further calculations in accordance with this segmentation.

The hydrological feasibility for tidal reintroduction-based habitat creation was assessed using a GIS-based local wetland scale bathtub modelling approach. In this approach, tidal planes in the estuary are extrapolated across the adjacent low-lying lands, without considering hydrodynamic losses. In general, this approach is not recommended to be used at the estuary scale, since tidal regimes can vary dramatically across different parts of an estuary (Khojasteh et al., 2021), as is the case for Lake Wooloweyah. However, previous tidal reintroduction works undertaken by the Water Research Laboratory have shown that this approach can lead to sufficient levels of accuracy at a local wetland scale, if accurate tidal boundary conditions can be obtained for a nearby point in the estuary (e.g., Rayner et al, (2021), Sadat-Noori et al. (2021)).

The DEM used for this analysis was the *"BARE POINT 2010-04-28 2kmx2km 1 metre Resolution Digital Elevation Model"* from the NSW Government Spatial Services obtainable via the ELVIS data platform (https://elevation.fsdf.org.au/). In densely vegetated areas such as saltmarshes, LiDAR derived DEMs can suffer from minor vertical inaccuracies. To test this, we compared the saltmarsh bottom elevation points collected near the Lake Wooloweyah flood tide delta with the elevations of the DEM (Figure 11). This experiment showed that for this group of points, there was a consistent difference in bottom elevation of about 15cm (median).

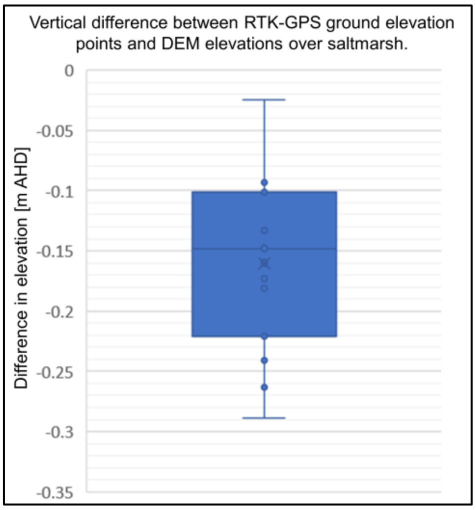


Figure 11: Difference in elevation between RTK-GPS measurements of bottom sediment elevation in saltmarsh areas around the Lake Wooloweyah flood tide delta (see Figure 10 for location) and the elevations over those same locations as indicated by the 1x1m resolution Digital Elevation Model (DEM).

To account for uncertainties and inaccuracies in the vegetation survey data, the hydrodynamic model and the DEM, we adopted three distinct scenarios for modelling the hydrological and ecological outcomes of potential tidal rehabilitation works. The three scenarios were designed to reflect the range of uncertainty present in both the input datasets as well as uncertainties associated with the eco-hydrological modeling method. It is important to mention here that although more sophisticated methods such as detailed high resolution hydrodynamic modelling have been proposed in the past for assessing tidal reintroduction options (e.g., Rodríguez et al. (2017)) these approaches are equally affected by inaccuracies in the input datasets as well as other factors such as a lack of data for calibrating and validating these models or complex groundwater surface water interactions.

Floodplain rehabilitation around Wooloweyah in the context of overall estuary health

As previously mentioned, it is important to place any potential rehabilitation efforts around the Lake Wooloweyah segment in the context of improving the overall health of the Clarence River estuary. In this context, the hydrological state and in particular the presence and abundance of acid sulfate soils and blackwater generation risk of the drained areas around Lake Wooloweyah have previously been assessed as part of the Clarence River Floodplain Prioritisation Study (Harrison et al., 2021). The assessment is based on extensive modelling and field campaigns and the underlying methodology is described in detail in Rayner et al. (2021b). Figure 12 shows the acid sulfate soil priority ranking for 15 sub-catchments in the Clarence River estuary. The area behind the Taloumbi Ring Drain was identified to have a high ASS priority, meaning that it is a high priority area for addressing ASS issues in the Clarence River estuary.

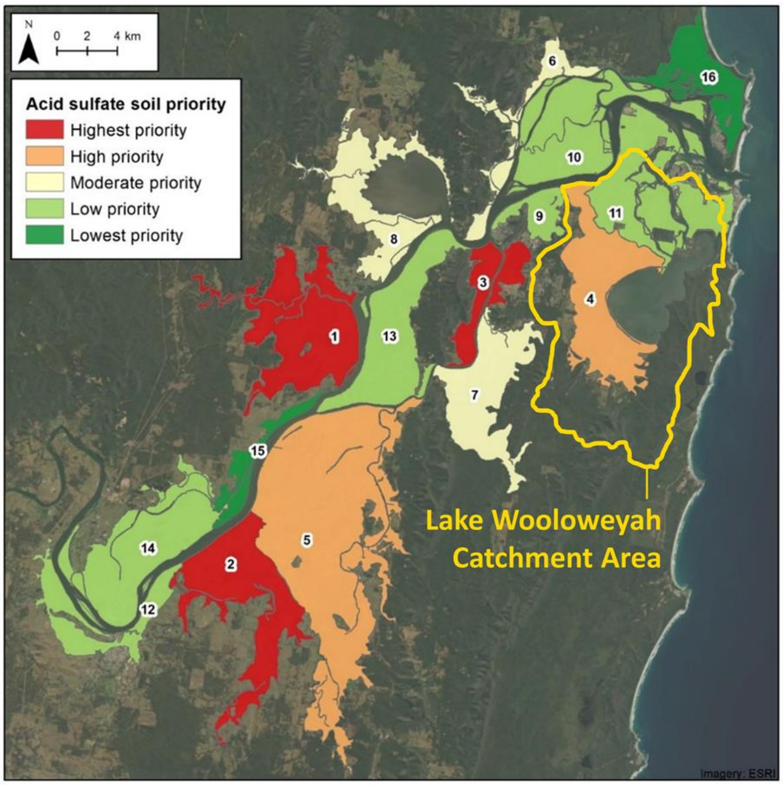


Figure 12: Clarence River floodplain subcatchment rankings of the acid prioritisation assessment (source: Harrison et al. 2021).

Figure 13 shows the 'blackwater priority' of floodplains across the Clarence River Estuary, which was again identified as high for the Taloumbi sub-catchment (Harrison et al., 2021). Lastly, the study also assessed the vulnerability of drainage systems and the corresponding floodplain areas to end of century sea level rise of +0.67cm as of 2020 (Figure 14). Not surprisingly, the low lying Taloumbi area was identified to be at high risk of more frequent and severe flooding and reduced drainage efficiency.

Jointly, these estuary-wide assessments illustrate that in the context of improving the overall health of the Clarence River Estuary via floodplain rehabilitation, the Lake Wooloweyah, and in particular the Taloumbi

Ring Drain segment, represents one of the priority areas for repair. In other words, floodplain rehabilitation works in these areas are characterised by a high 'return on investment' in terms of restoring eco-hydrological health of the Clarence River estuary.

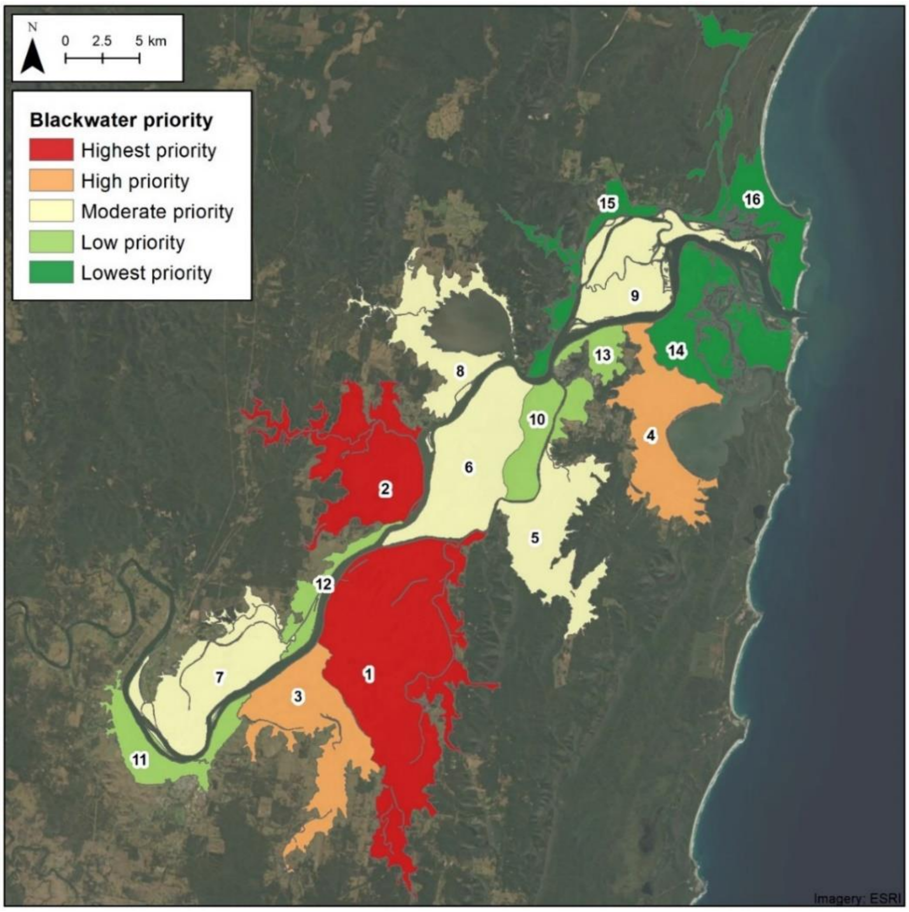


Figure 13: Clarence River floodplain subcatchment rankings of the blackwater prioritisation assessment (source: Harrison et al. 2021).

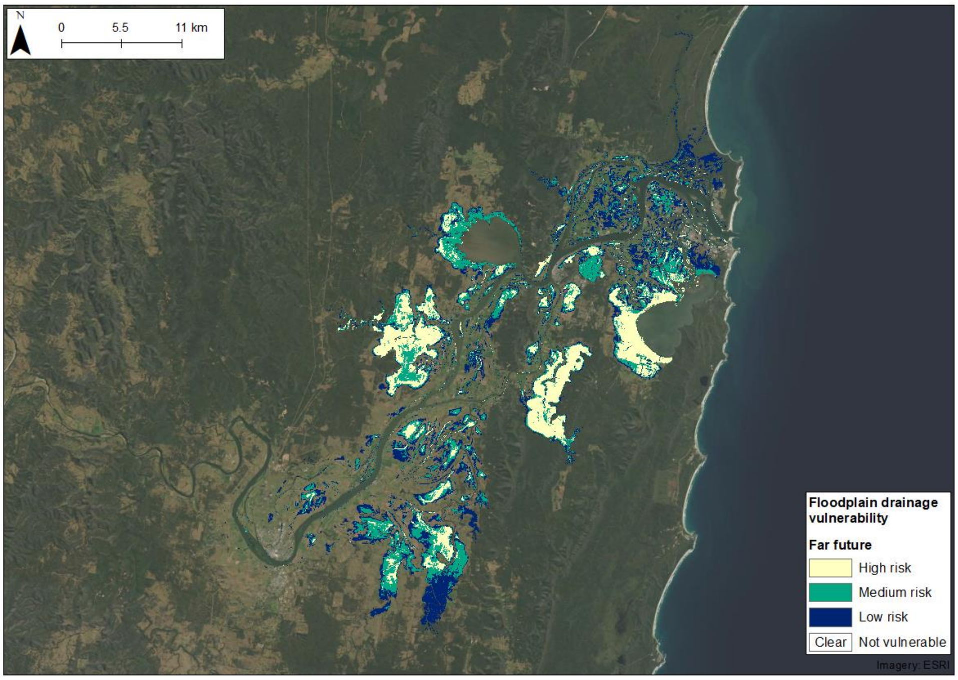


Figure 14: Clarence River floodplain vulnerability with sea level rise (far future, ~80cm of sea level rise between 1996 and ~2100). (source: Harrison et al. 2021).

Potential return on investment

The approach used here largely reflected that used in Taylor et al. (2018) and Taylor and Creighton (2018), but also used this approach to examine historical and potential future trends that would be associated with changes in habitat cover as a result of rehabilitation. Briefly, the approach uses stable isotope mixing model outputs (contributions of each habitat to the diets of school prawns in Lake Wooloweyah collected above) to attribute value of fisheries landings to estuarine habitats. This first required regrouping of primary producer sources contributing to the diets of prawns that were included in the stable isotope model to account for which habitat they belonged to, with the assumption that each source in a group contributes equally (i.e. the two saltmarsh succulents contribute 2/3 of the 'Mangrove and others' group contribution). Because particulate organic matter (POM) and fine benthic organic matter (FBOM) have no distinct habitat, and therefore they do not consist of a habitat that could be attributed a value, they were not included in the valuation process (their contribution to the value was effectively 'lost'). Using a Monte Carlo Markov Chain approach that accounts for uncertainty within the model outputs rather than just using mean or other summary statistic (here assumed to be a normal distribution using the standard deviations around the means) from the inter-annual variability in the landings of prawns, the value per kg of prawn product, the uncertainty in the contributions of the habitats, the direct market value of the school prawn product arising from the habitats was estimated with 5000 simulations. Catch data from NSW DPI Fisheries was used to determine the value of the fishery and included all school prawn-specific landing data within the Clarence River estuary (since there is uncertainty about location data in logbook records) from 1978 to 2009, after which data were only available for 2019 and 2020. Logbook records prior to 1978 were available, however, they did not differentiate between prawn species and could include species that do not draw their nutrition from within the estuary itself (i.e. large eastern king prawns), and as a result those data could not be used reliably.

To attribute a value that accounts for the rarity of the habitats, the posterior estimates of habitat values for the Lake Wooloweyah school prawn fishery were then divided by the areal extent (in hectares) of each habitat to obtain a value per hectare per year estimate. Two potential scenarios were explored that could highlight the potential financial return on investment into estuarine habitat rehabilitation:

1. A fisheries-productivity based assessment that assumes that areal extent of habitats will remain stable, but the 'quality' of those habitats (productivity and trophic role) improves to produce fishery landings of school prawn similar to peak levels (1980s). This would be relevant for habitats that are degraded (e.g. cattle feeding on saltmarshes) but whose areal extent would not change under rehabilitation projects, and assumes all the loss in fishery landings are a result of habitat degradation rather than direct loss of habitat area or other factors like pollution.
2. A habitat rehabilitation approach that adds value to the fishery based on current per hectare value determined above, and adds value to the estuary-wide valuation based on the possible area of each habitat that may be repaired using the hydrological model in objective 3. Since there is uncertainty around the extent of each habitat that would be rehabilitated as a result of changes in hydrological patterns, different scenarios were explored (mangrove/saltmarsh/seagrass rehabilitation only). Estimates for the cost of rehabilitation were obtained from the literature to provide a cost/benefit analysis.

Results

Fisheries productivity and potential enhancements

A total of 728 *Metapenaeus maclaeyi* were processed from the trawls with an average carapace length of 5.9 mm (± 3.6 mm S.D.) and an average weight of 0.16 g (± 0.4 g S.D.). Of the 14 sites sampled, there were five sites with abundant prawns and five sites with zero abundance (Fig. 15). Site 10 had the highest abundance of 213 prawns 100 m^{-2}.

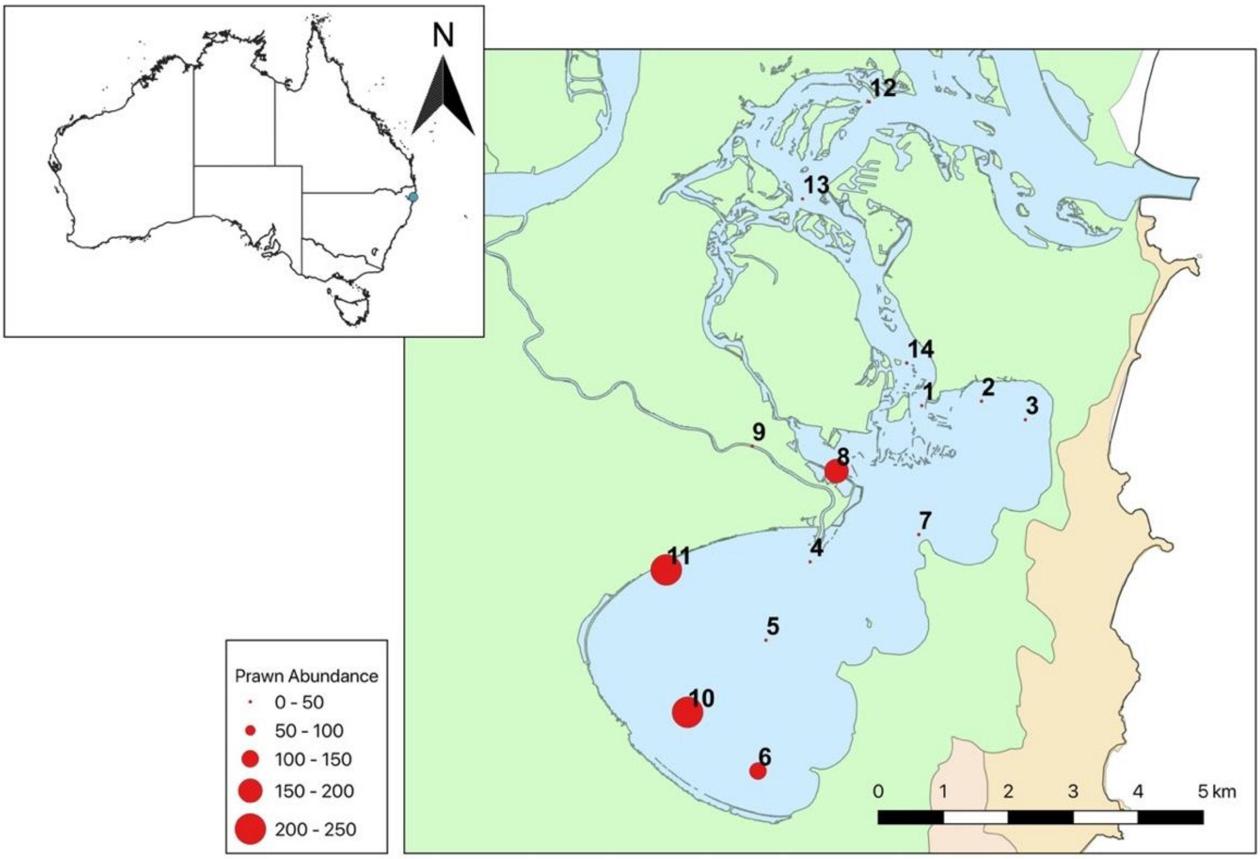


Figure 15 Prawn abundance (per 100 m2) at each of the sites sampled

The length frequency distribution of the prawns most likely indicates a single juvenile cohort with a few larger adults who evaded capture from the previous harvest (Fig. 16). There is little variation in median size between the sites.

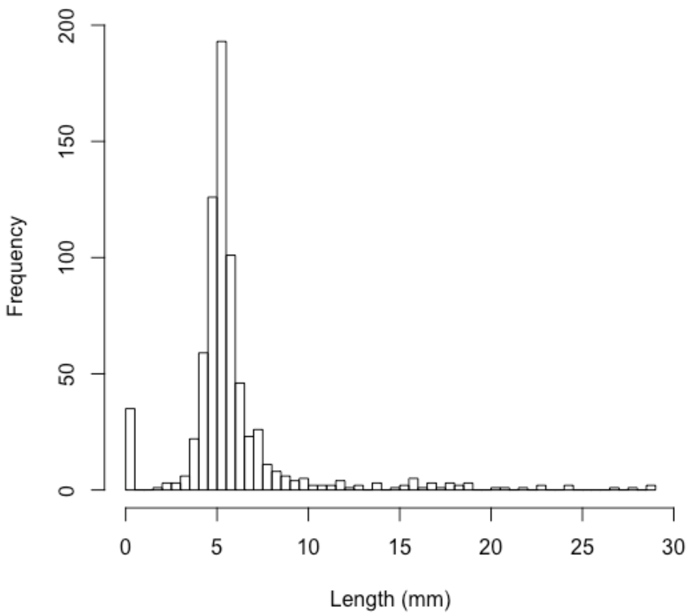


Figure 16 Size frequency histogram for prawns caught across all sites.

Stable isotope values of sources of primary production were generally well distributed within the isospace across the three isotopic tracers (Figs. 17, 18, 19). The exception was for mangroves and saltmarsh succulents, which had to be grouped for subsequent analyses to improve model outputs. Sugar cane and fine benthic organic matter were highly ^{34}S depleted and distinct from the rest of the primary producers. The $\delta^{15}N$ range of values for school prawns was very broad suggesting variability in diet choice within the population (Fig. 17, 19).

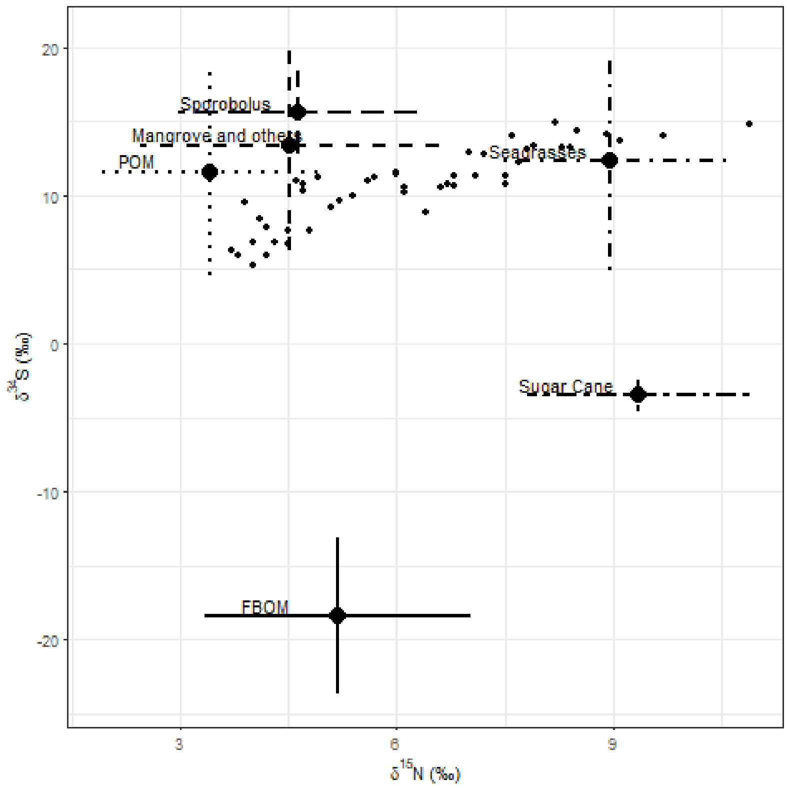


Figure 17 Isospace plot for sulfur and nitrogen stable isotopes for various sources and school prawns (small circles) sampled in Lake Wooloweyah. Source values have been adjusted to account for trophic enrichment. POM – particulate organic matter, FBOM – fine benthic organic matter.

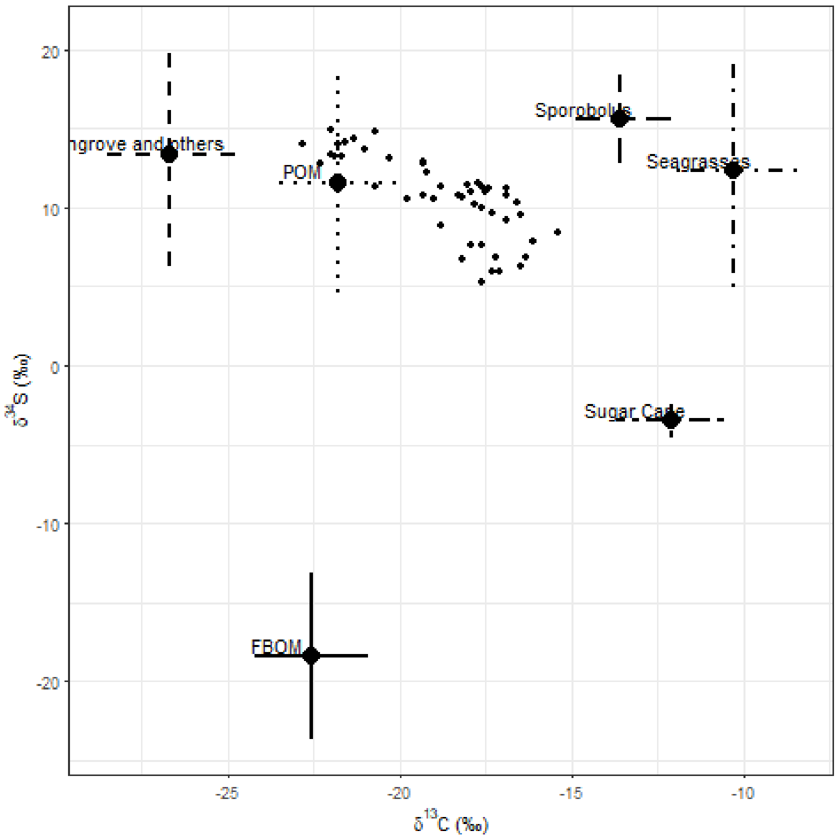


Figure 18 Isospace plot for sulfur and carbon stable isotopes for various sources and school prawns (small circles) sampled in Lake Wooloweyah. Source values have been adjusted to account for trophic enrichment. POM – particulate organic matter, FBOM – fine benthic organic matter.

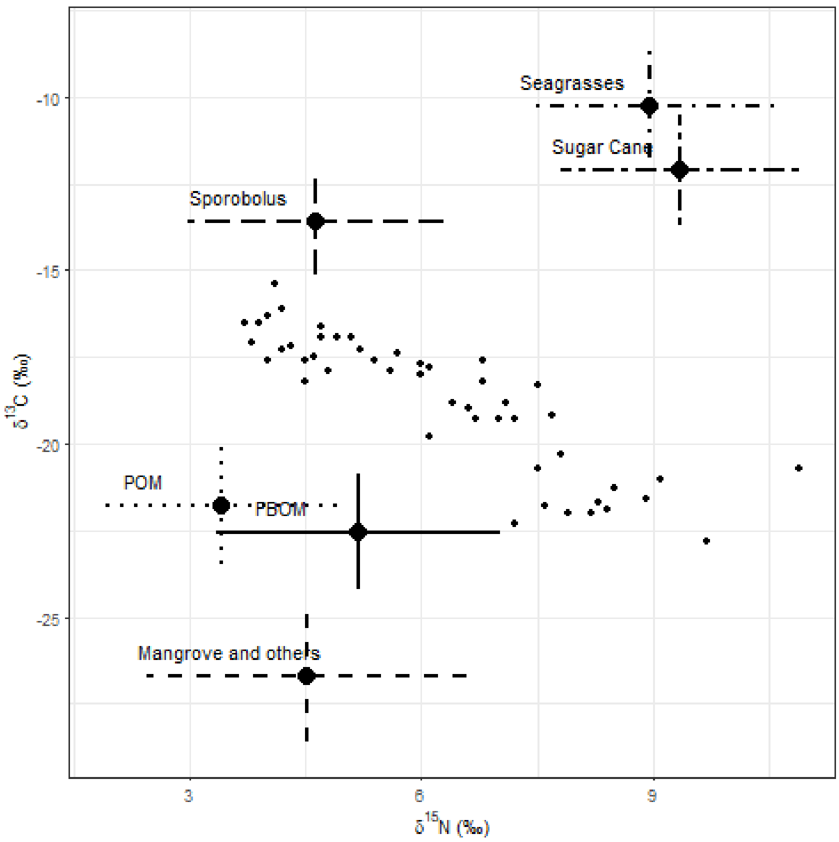


Figure 19 Isospace plot for carbon and nitrogen stable isotopes for various sources and school prawns (small circles) sampled in Lake Wooloweyah. Source values have been adjusted to account for trophic enrichment. POM – particulate organic matter, FBOM – fine benthic organic matter.

Mangroves and saltmarsh succulents had the highest contribution to the diets of school prawns (35%), followed by seagrasses (25%). The posterior distributions from all sources were generally broad, indicative of high variability within the school prawn population. The most constrained distribution (with the highest certainty) was that of fine benthic organic matter (FBOM) which also had the lowest contribution to the diets of school prawns (Fig. 20).

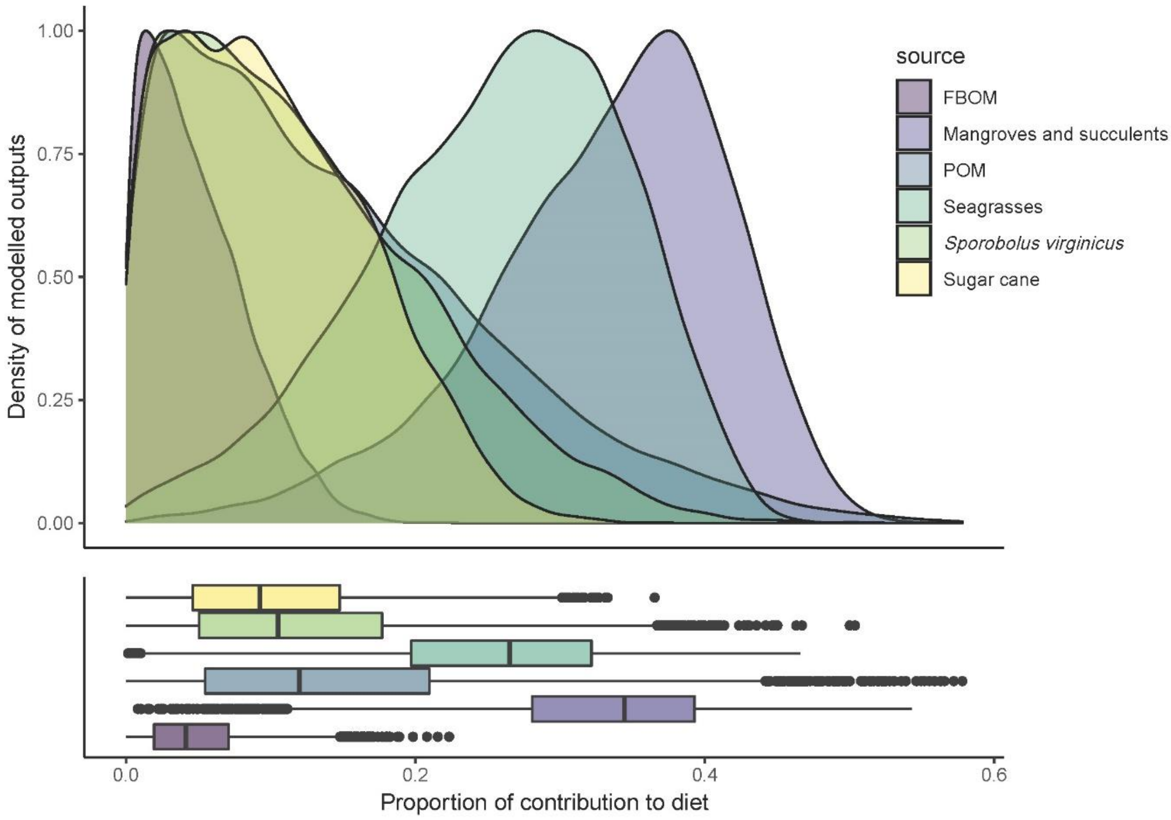


Figure 20 Posterior distributions of estimated contributions to diets of school prawns from various estuarine sources of primary productivity, as estimated from Bayesian stable isotope mixing models.

Tidal Hydrodynamics

The Lake Wooloweyah segment has a highly attenuated and complex tidal regime. To illustrate, we analysed water level data from four permanent tide gauges in and around Lake Wooloweyah. Figure 21 shows time series plots for selected time periods for four gauges located at the mouth of the Clarence River at Yamba, at Oyster Channel bridge, inside Lake Wooloweyah and near the confluence of Palmers Channel and the Clarence River (see Figure 5 for location of gauges). Figure 22 shows time series of water levels for a longer time period, including the entire year of 2018 and 2019 for the lake Wooloweyah gauge. The yearly plots further show key low and upper end percentiles and the 50th percentile.

It can be seen that Lake Wooloweyah exhibits a dramatically reduced tidal range of around 20-30 cm as well as an increased mean sea level of around 0.2 m AHD. Tides in the lake lag behind the oceanic tides with low tide roughly coinciding with the incoming mid tide at Yamba, and high tide coinciding with the outgoing mid tide at Yamba (e.g., Figure 21 centre panel). Another important feature of the tides inside the lake is that experiences significant spring tidal pumping, characterised by an increase in the mean water level of a tidal basin during larger tidal forcing during spring tides (McLean and Hinwood, 2011). This spring tidal pumping can be seen particularly well in the top panel of Figure 22. This increase in the mean water level also occurs during elevated water levels in the Clarence River during floods as seen in the bottom panel of Figure 21. As a result of the significant levels of tidal pumping, the mean water level in the lake fluctuates greatly throughout any given year and this is illustrated well in the centre and bottom panel of Figure 22.

The tidal dynamics of Lake Wooloweyah are influenced by variability in flows in the Clarence River as well as spring and neap tide cycles, which poses challenges for a traditional harmonic tidal constituent and tidal plane analysis. Instead of tidal planes, we therefore use water level percentiles here, which indicate the percentage of time that water levels are below the level of a particular percentile over the analysed data period. This approach is illustrated in Figure 23, which shows tidal duration distribution plots (i.e., water level probability density plots) for the period of February 2016 to March 2020 for three key tide gauges in the system. For instance, the 10th percentile (i.e., water levels are below this only 10% of the time over the three-year period), is about -0.4 m at Yamba, -0.2m at Oyster Channel Bridge and just above 0 m within Lake Wooloweyah, which shows an elevated mean water level of 15cm. The upper end percentiles (i.e., 90-99th) exhibit an opposite pattern, decreasing by about 20-40cm from Yamba into the Lake.

The high level of tidal attenuation from the Clarence River into Lake Wooloweyah is further exemplified in Figure 24 which shows key water level percentiles (obtained from the hydrodynamic model runs) plotted along the estuary centreline from the mouth (0km) through Oyster Channel (5-12.5km) through Lake Wooloweyah from the flood tide delta to the north to the Taloumbi Ring Drain to the south (12.5-20 km). The percentiles illustrate the dramatic tidal attenuation that occurs through the Oyster Channel segment, in particular around Oyster Channel bridge. Minor attenuation continues towards the flood tide delta, after which the lake essentially behaves like a bathtub, as illustrated by no further modification of the percentile-based tidal planes.

Figure 24 also shows that above-average annual rainfalls such as those that occurred in 2013 have a measurable impact on the tide water levels in and around the Lake Wooloweyah segment (compare top vs. bottom panel, which represent a wet vs. dry year). This is particularly apparent for the upper end percentiles (i.e., 99th percentile), which are representative of the water levels during comparatively rare flood events. This is of relevance since these water levels occur for about 1% of the time in any given year and can be important for driving saltwater higher up into floodplains thereby preventing the establishment of vegetation communities that are less tolerant to high salinity levels.

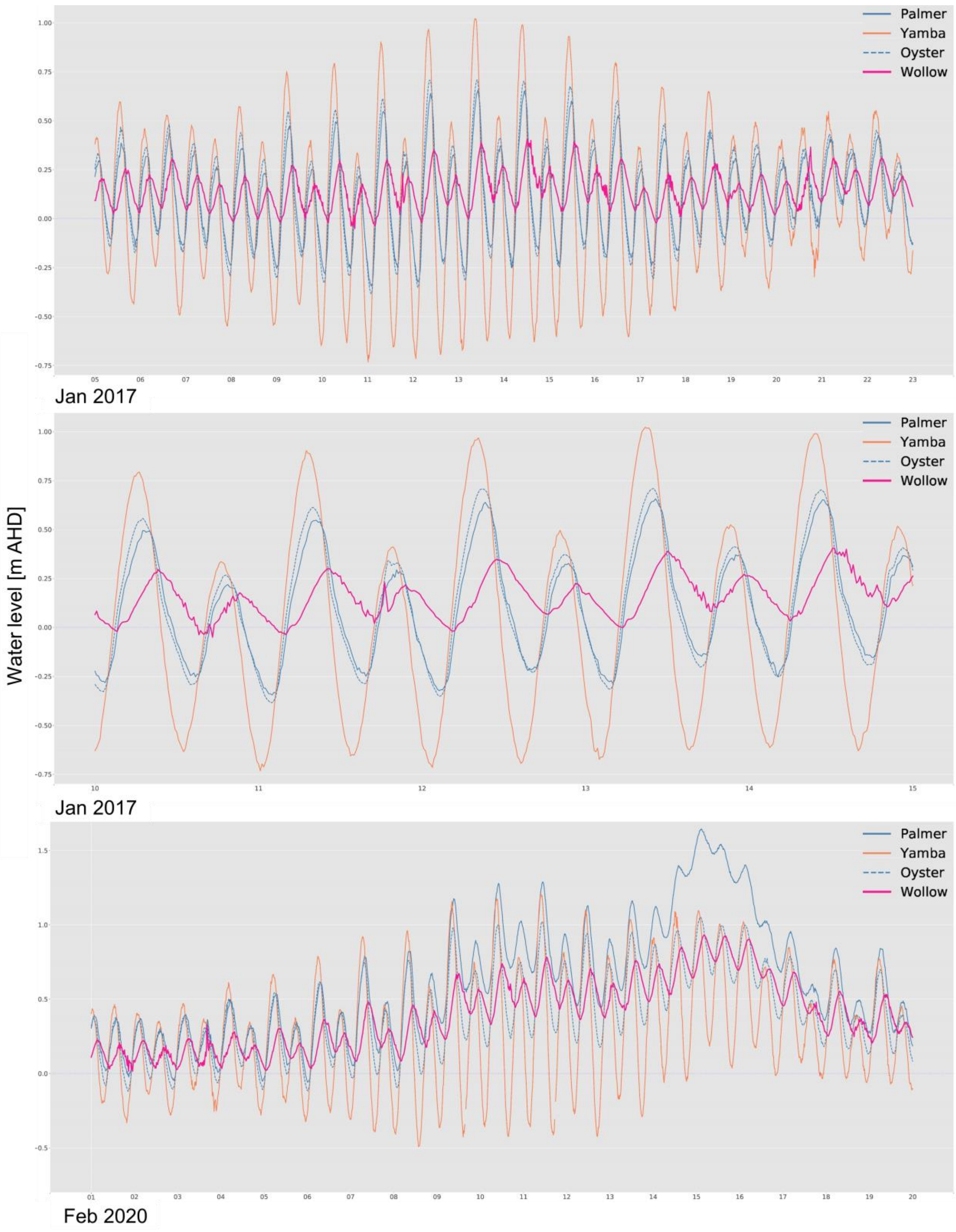


Figure 21: Tidal water levels from four permanent tide gauges in and around Lake Wooloweyah (Manly Hydraulics Laboratory) shown for the month of January 2017 (top panel), a 5-day period in January 2017 (middle panel) and during a flooding event in the Clarence River in February 2020 (bottom panel). See Figure 5 for location of gauges.

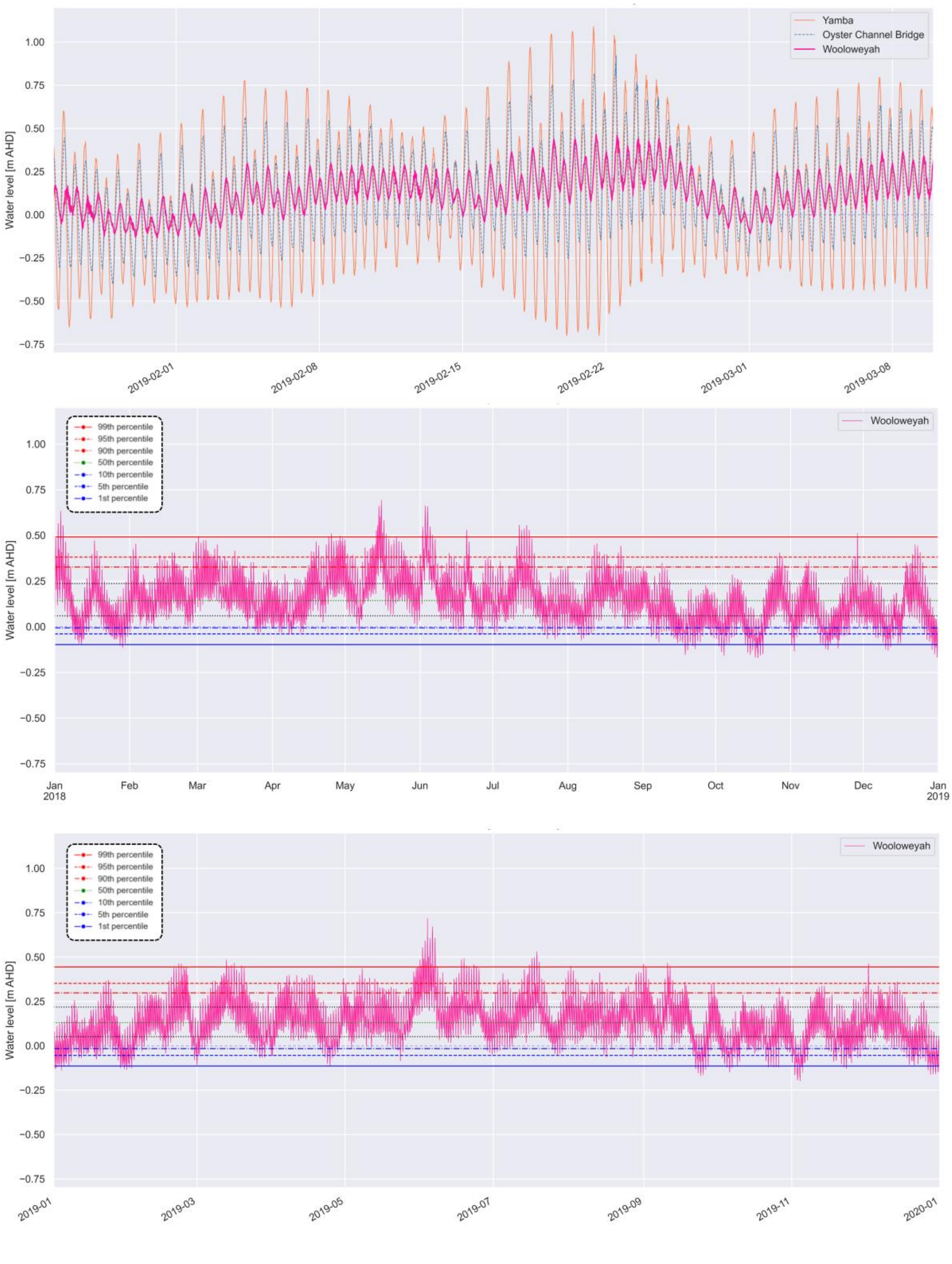


Figure 22: Tidal water levels from three permanent tide gauges in and around Lake Wooloweyah (Manly Hydraulics Laboratory) shown for February-March 2019 (top panel) and tide water levels inside Lake Wooloweyah for the full year of 2018 (central panel) and 2019 (bottom panel), along with key percentiles. See Figure 5 for location of gauges.

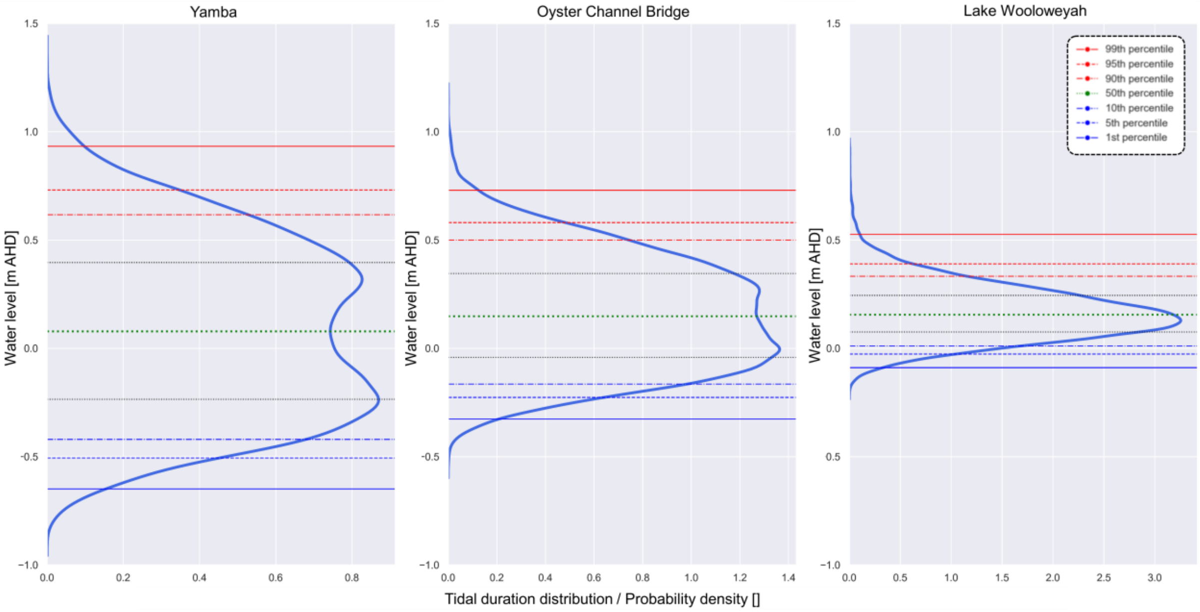


Figure 23: Tidal duration distributions, key upper and lower end percentiles, and median of water levels from three tide gauges in and around Lake Wooloweyah for the period from January 2016 to February 2020.

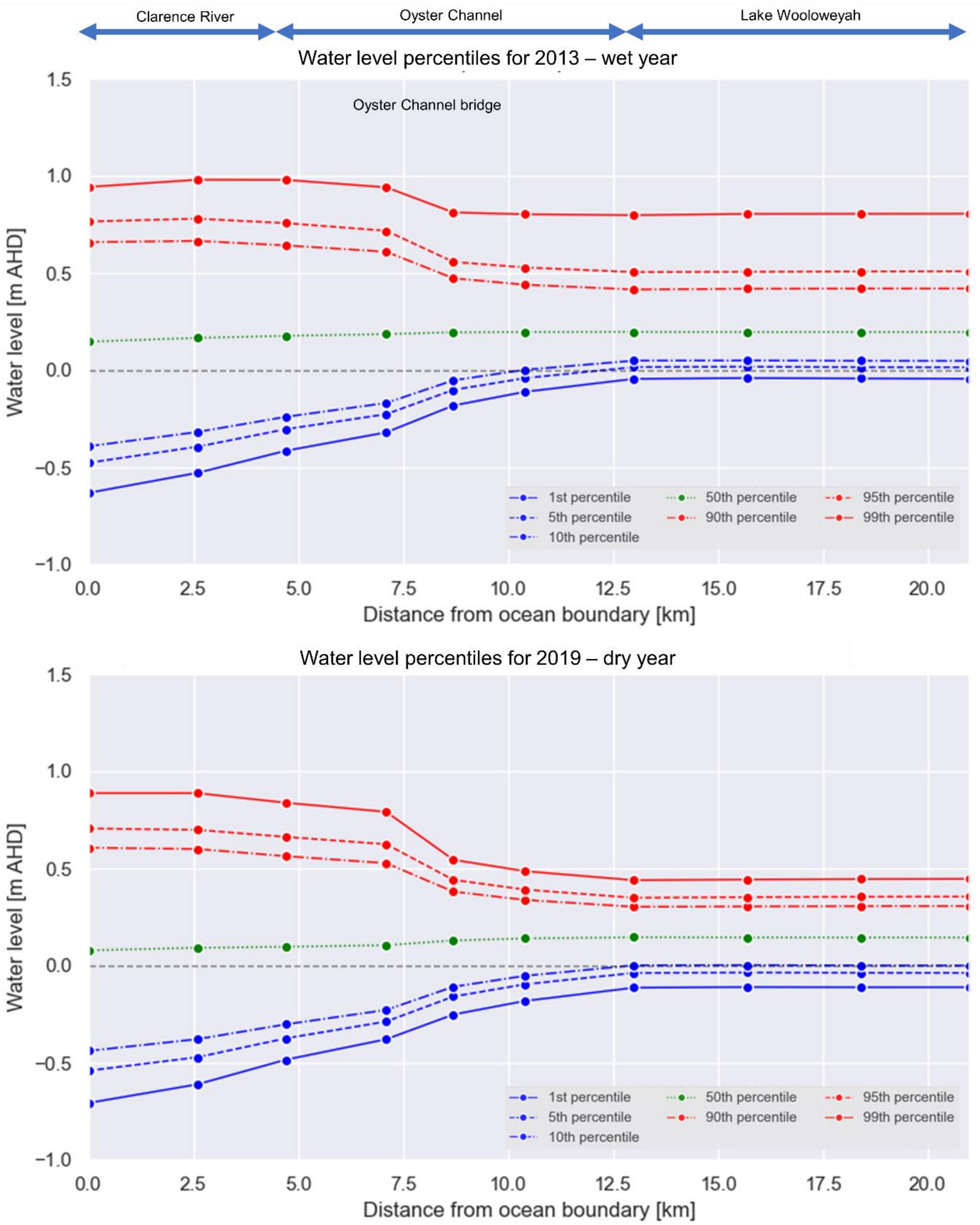


Figure 24: Water level percentiles plotted along Clarence River Estuary through Oyster Channel and into Lake Wooloweyah for the wet and dry year hydrodynamic model runs.

Vegetation linkages

Figure 25 shows the results of the vegetation elevation survey, grouped into four clusters. It can be seen clearly that the vertical layering of vegetation follows the attenuating trend of the tidal regime from the mouth of the Clarence River estuary into Lake Wooloweyah. Especially for mangroves, the vertical habitable range decreases dramatically into the lake. It is also clear that there is a substantial degree of vertical overlap across the different surveyed vegetation groups, even though the points were measured in relatively close proximity to each other for the four clusters. Based on the vertical distribution of surveyed GPS points within each vegetation group within each cluster, we inferred the vertical habitable ranges for mangroves and saltmarsh, which are shown as stacked barplots in Figure 25. Although not explicitly surveyed, we assumed tidal flats below the habitable range of mangroves, and coastal upland forest above the saltmarsh range. In some locations, freshwater wetlands and backswamps would follow uphill of saltmarshes.

The habitable ranges were inferred from the survey point groups as follows:

- The mangrove habitable envelope is from the 25th percentile of the mangrove lower-end points to the median of the mangrove to saltmarsh interface points.
- It is extended as low as the bottom whisker of the mangrove lower-end points, which represents the 5th percentile (see dashed black box).
- The saltmarsh habitable vertical envelope is from the median of the mangrove/saltmarsh interface points to the median of the saltmarsh/coastal upland forest interface points. It further extends to the upper end (top whisker) of either the saltmarsh or the saltmarsh/coastal upland forest interface points, whichever is higher.
- In the Lake Wooloweyah flood tide delta group, we were not able to survey any saltmarsh/upland vegetation interface points. Based on an examination of the DEM and mapped saltmarsh areas and taking into consideration the upper limit for saltmarsh in Micalo Channel, we set the upper limit to 0.45m AHD (see dashed black box).

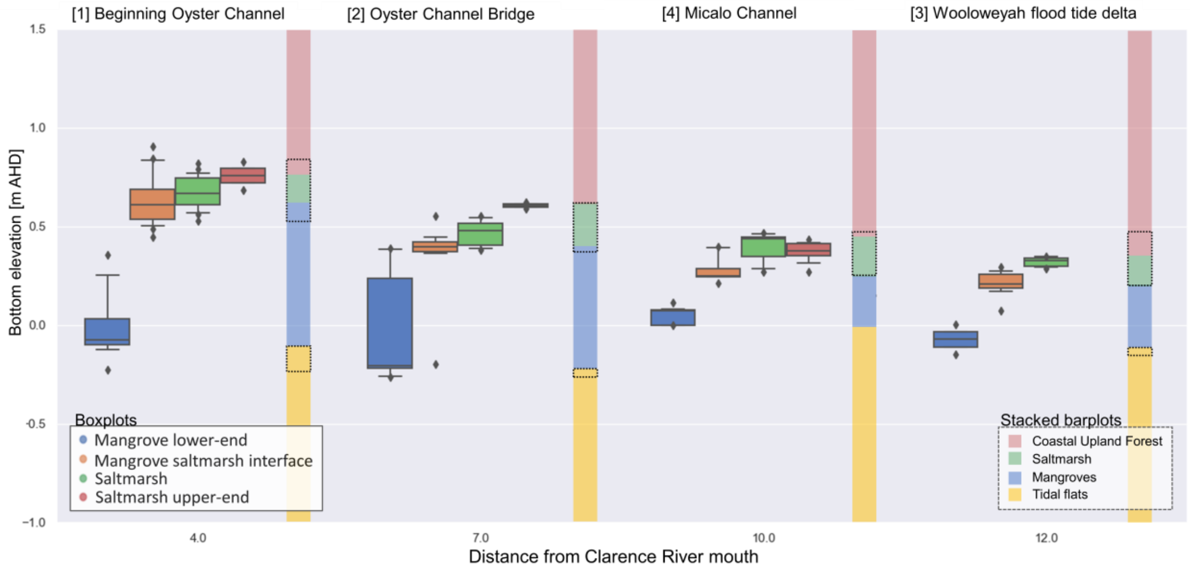


Figure 25: Result of the vegetation elevation survey shown in the form of boxplots, based on a clustering of all survey points into four groups. The stacked bar plots show the habitable vertical ranges inferred from the boxplots at each location. Location of the clusters are shown in Figure 10.

Figure 26 shows the habitable ranges for mangrove and saltmarsh communities overlaid on the water level percentiles plotted along Clarence River Estuary through Oyster Channel and into Lake Wooloweyah. The habitable ranges exhibit a pronounced relationship with the percentile based tidal planes. The upper end of the saltmarsh range appears to trace the level of the 99th percentile in a dry year without substantial flooding in the estuary. The vertical range appears to remain roughly stable at around 20-30cm from there to the lower end of the saltmarsh envelopes, which roughly corresponds to the 90th percentile for the two survey clusters outside of Lake Wooloweyah. Inside the lake, the saltmarsh extends further down than the 90th percentile, which could be due to the overall much narrower tidal enveloped of the lake. The narrow tidal envelope (i.e., small tidal range) might work in the favour of saltmarsh, which, according to Rodríguez et al. (2017), is constraint at its lower margins by inundation higher than the height of grasses during spring tide conditions. For mangroves, the upper end of the envelope roughly corresponds to the 90th percentile, while the lower end (see dashed black boxes) appears to be driven by the mean sea level (i.e., hydroperiod = 0.5) and the height of the propagules, which need to have access to oxygen at least half of the time on average (Rodríguez et al., 2017). This is demonstrated by the lower margin of the mangrove envelopes extending roughly to 20-30cm below the mean sea level in all clusters.

Figure 27 provides a more detailed breakdown of this analysis for all four cluster groups based on the tidal duration distribution plots inferred from the hydrodynamic model results. These results largely confirm the above observations, with the main uncertainty remaining the lower end of the mangrove elevation envelope, which, for instance, differs slightly between the Micalo Channel and the flood tide delta group. Nevertheless, the above model of mean sea level minus the height of propagules roughly holds for all four groups.

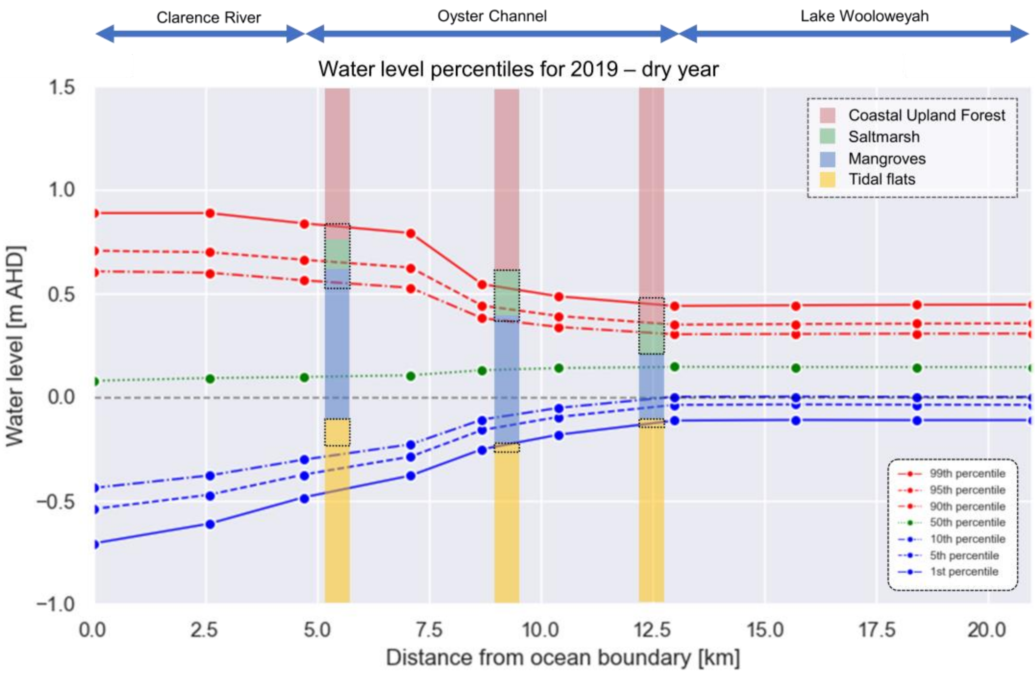


Figure 26: Habitable elevation ranges (stacked bar plots) for three locations (Micalo is excluded here) overlaid on the water level percentiles plotted along Clarence River Estuary through Oyster Channel and into Lake Wooloweyah for the dry year hydrodynamic model run.

Importantly, these results and in particular Figure 26 demonstrate that the vegetation elevation survey around the Lake Wooloweyah flood tide delta is strongly representative for the entire lake, since the tidal percentile planes are static across this part of the estuary (i.e., see tidal planes between km 12.5 and km 20). This means that the habitable ranges inferred from these survey points can be extrapolated to other low-lying lands surrounding Lake Wooloweyah, which, for example, could not be done for the habitable ranges inferred from the Oyster Channel bridge point group.

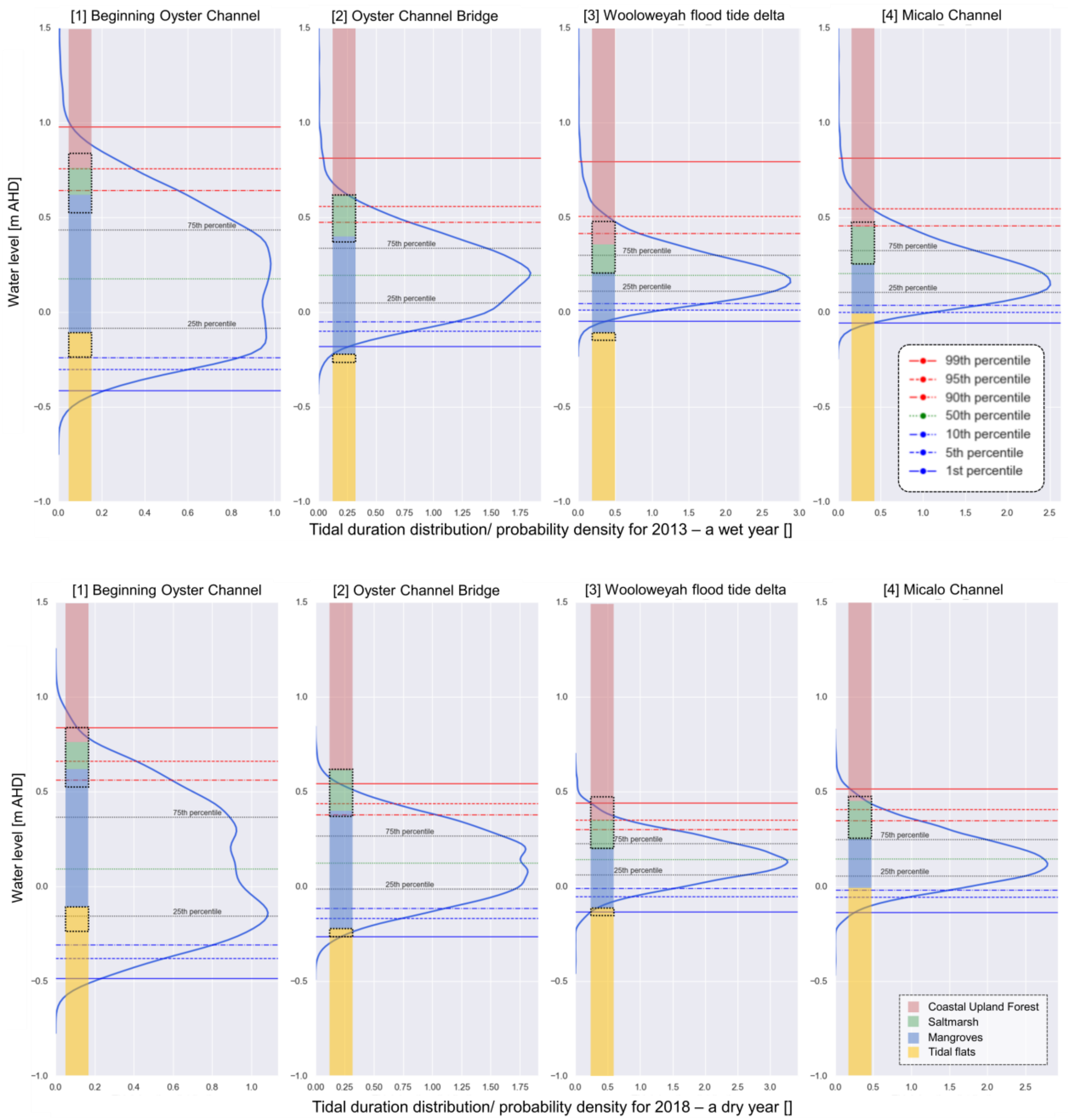


Figure 27: Habitable elevation ranges (stacked bar plots) for the four survey point clusters overlaid on tidal duration distribution plots obtained at the location of the clusters from the hydrodynamic model runs for a wet and dry year.

Based on the above results, the following three scenarios were considered for modeling the intertidal habitat creation potential:

- Scenario 1, conservative or low-end outcome: For this scenario, we used the lower end of the habitable vertical ranges for mangrove (-0.15 to 0.15 m AHD) and saltmarsh (0.15 - 0.3m AHD) communities as inferred from the vegetation surveys and used the DEM as provided.
- Scenario 2, intermediate outcome: For this scenario, we used the upper end of the habitable vertical ranges for mangrove (-0.15 to 0.2 m AHD) and saltmarsh (0.2 - 0.45m AHD) communities as inferred from the vegetation surveys and used the DEM without any vertical adjustment.
- Scenario 3, high-end outcome: For this scenario, we used the same habitable vertical ranges as in scenario 2 and used the DEM with a vertical adjustment of -15cm, to account for the previously calculated vertical offset between surveyed bottom elevation and DEM bottom elevation.

Optimised habitat via optimised hydrology

This section presents the results of the rehabilitation scenario modelling. As previously noted, all outcomes are based on the hydrological rehabilitation potential and do not consider factors such as current land use or land ownership. Maps of the intertidal vegetation outcomes for the low and high-end scenarios are provided in Figure 28 and Figure 29 respectively and a summary of all vegetation outcomes broken down by into the four rehabilitation areas is provided in Table 1.

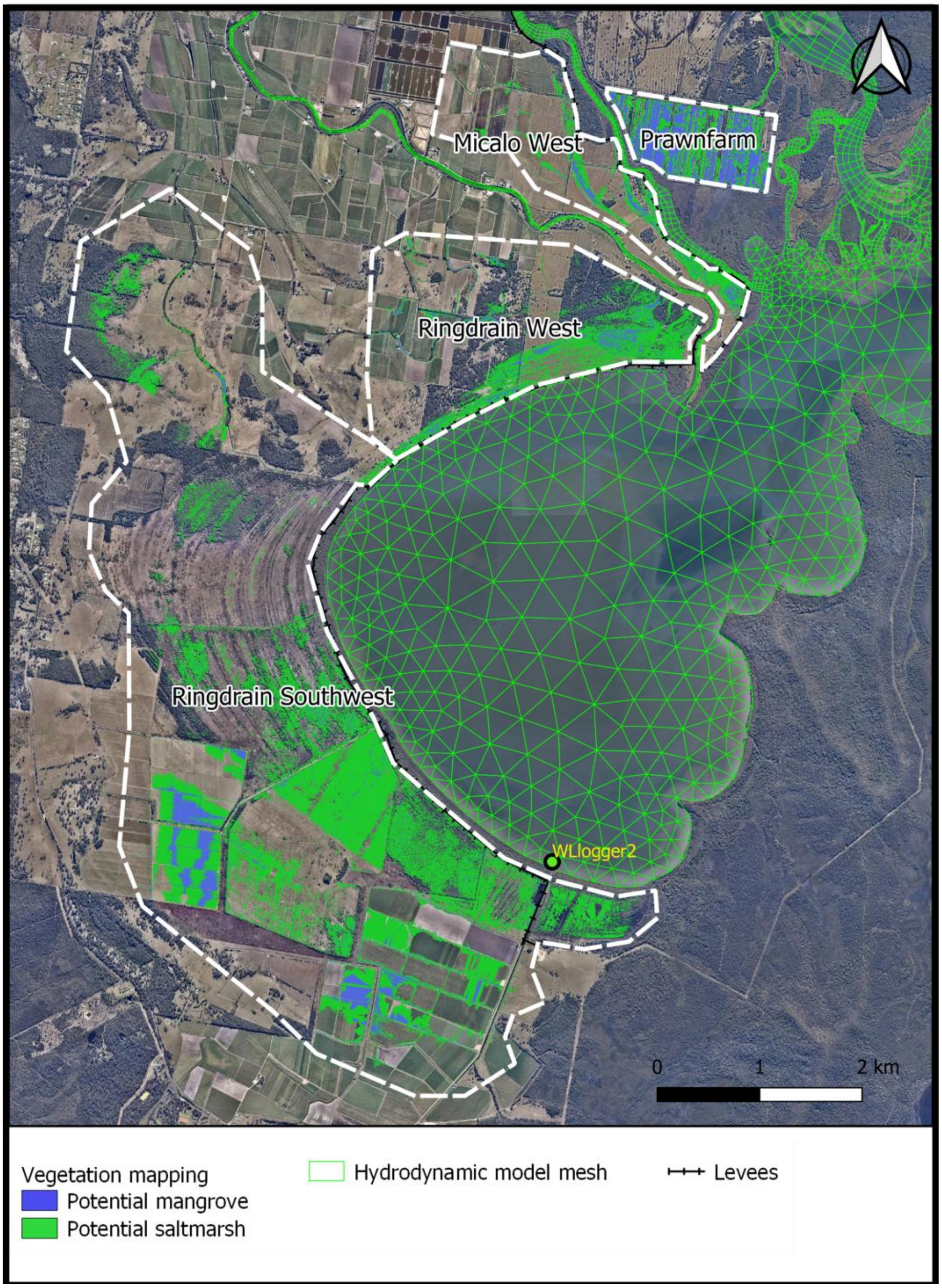


Figure 28: Low-end scenario outcome of the potential estuarine habitat area that could be rehabilitated through modification of hydrology within the Lake Wooloweyah system. The areas that could be rehabilitated are separated into four separate hydrological systems.

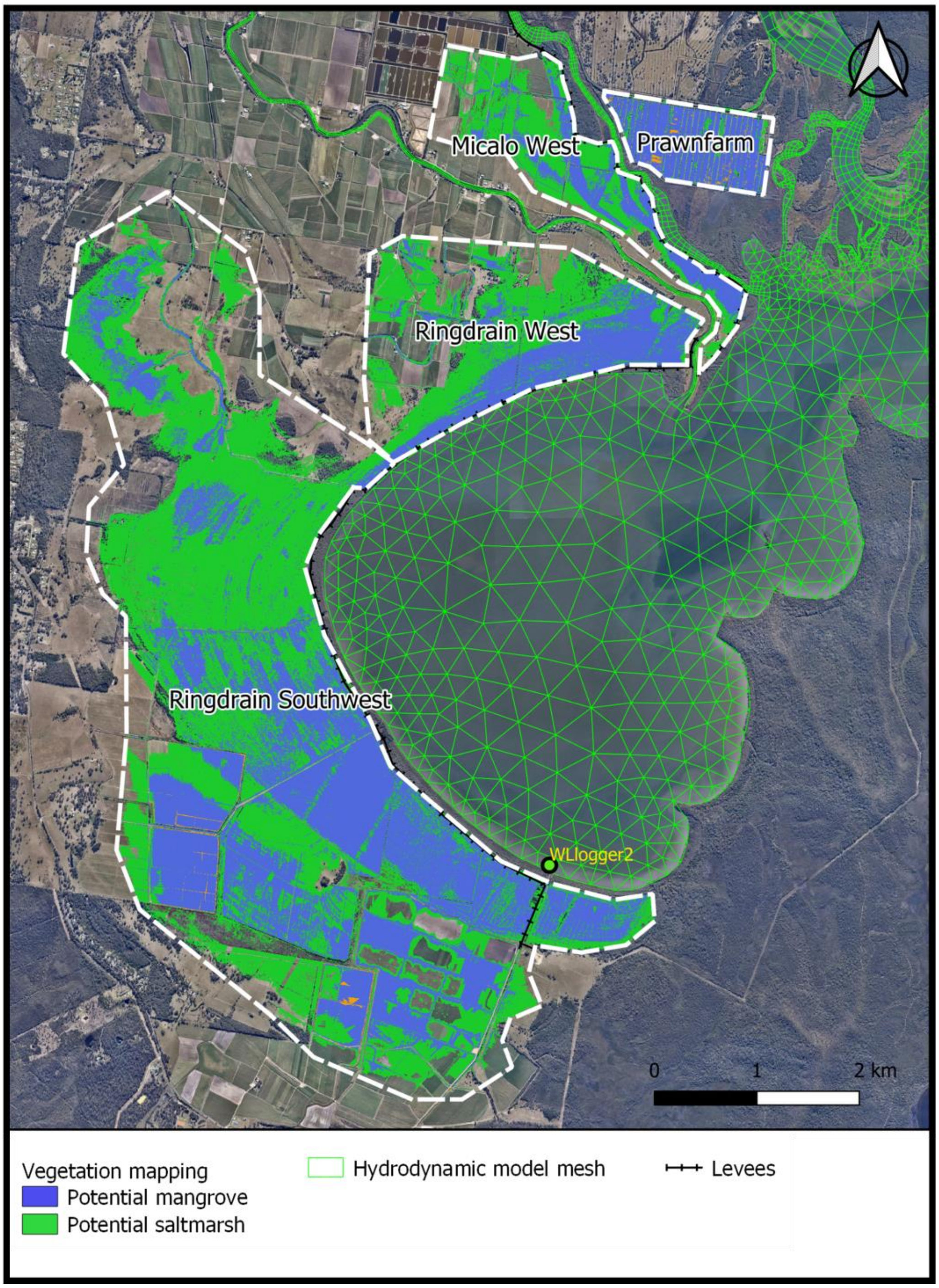


Figure 29: High-end scenario outcome of the potential estuarine habitat area that could be rehabilitated through modification of hydrology within the Lake Wooloweyah system. The areas that could be rehabilitated are separated into four separate hydrological systems.

Our results indicate that large areas of possibly up to 2000 ha of currently drained lands around Lake Wooloweyah are hydrologically suitable for creating intertidal saltmarsh and mangrove habitats (Table 1). For the prawn farm, all three scenarios lead to an increase of about 80-90 hectares in the combined mangrove and saltmarsh area, indicating that this area is highly suitable for intertidal habitat creation (predominantly mangroves) under current tidal conditions.

Table 1: Summary of low, intermediate, and high range of the modelled estuarine habitat rehabilitation potential in hectares, separated into different hydrological zones within Lake Wooloweyah.

	Rehabilitation option	Mudflats	Mangrove	Saltmarsh
Low-end range	Ringdrain West	0	13.1	80.8
	Ringdrain Southwest	1.9	51.8	429.1
	Prawnfarm	0	38.9	33.3
	Micalo West	0	7.2	31.9
	Sum	**2**	**111**	**575.1**
Intermediate range	Ringdrain West	0	35	164
	Ringdrain Southwest	1.9	141.7	911.7
	Prawnfarm	0	51	31.8
	Micalo West	0	15.8	100.8
	Sum	**2**	**243.6**	**1208.3**
High-end range	Ringdrain West	0	128.6	182.8
	Ringdrain Southwest	5.7	672.4	908.5
	Prawnfarm	2.3	75.4	10.6
	Micalo West	0.2	61.2	115.5
	Sum	**8.2**	**937.7**	**1217.4**

Potential return on investment

The per hectare value of seagrasses was highest relative to other habitat types, while mangroves had the lowest value. The distribution of possible seagrass values was very broad, however, suggesting a lot of uncertainty around this value attribution (Fig. 30). Historical catch data suggest a progressive loss of value in the habitats associated with a decline in total landings of school prawn (Fig. 31). Since the 1980s, the decline in value across habitats is approximately 50%. Across the four habitat types, saltmarshes had the highest total value for landings (~\$250,000 $AUD.yr^{-1}$) while mangroves have the lowest landed value of the 'traditional' estuarine habitats. Sugar cane had the lowest value among the habitats measured, with uncertainty that overlapped with 0, suggesting a negligible value. The broader values of these habitats are approximately five times higher as per Taylor et al. (2018).

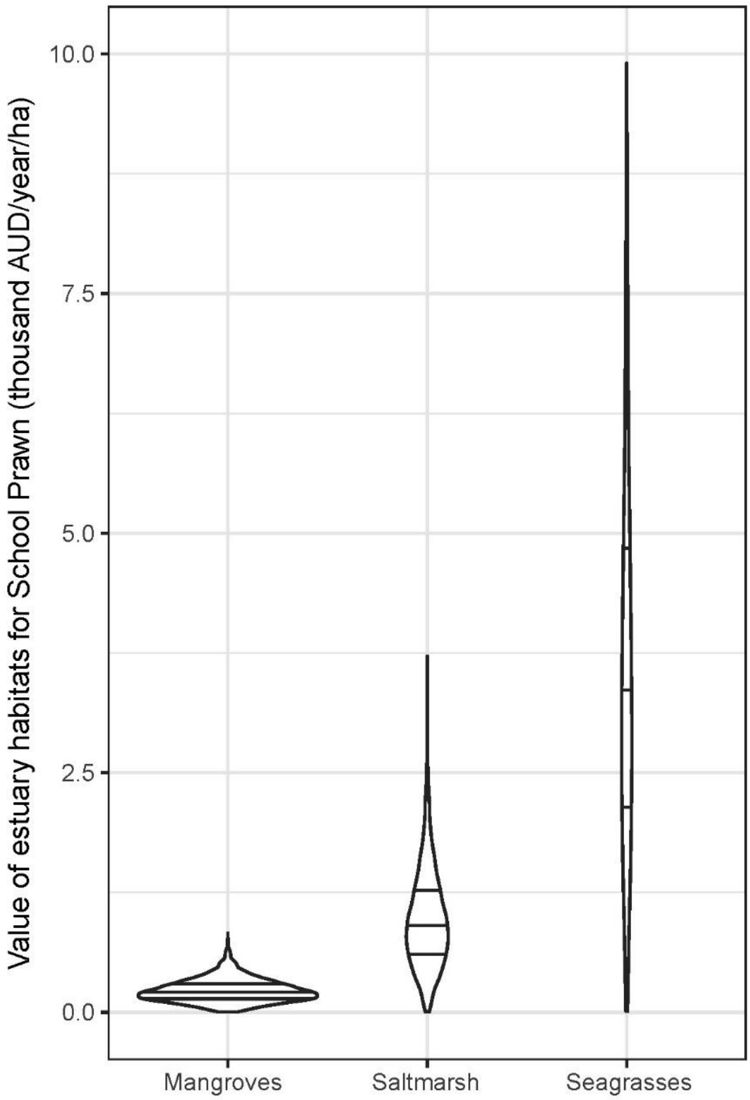


Figure 30: Violin plots of per area value of estuarine habitats for the School Prawn fishery, as inferred from Bayesian stable isotope mixing models and a Monte-Carlo Markov Chain framework. These plots highlight the distribution of the data, with the 'width' of the violins relating to the density of data in that area. Horizontal bars represent 25, 50 and 75% quantiles for data distribution. The most likely 'true' value of the habitats is likely to be where the violin is widest, and a 'thin' violin implies greater uncertainty with where the 'true' value sits.

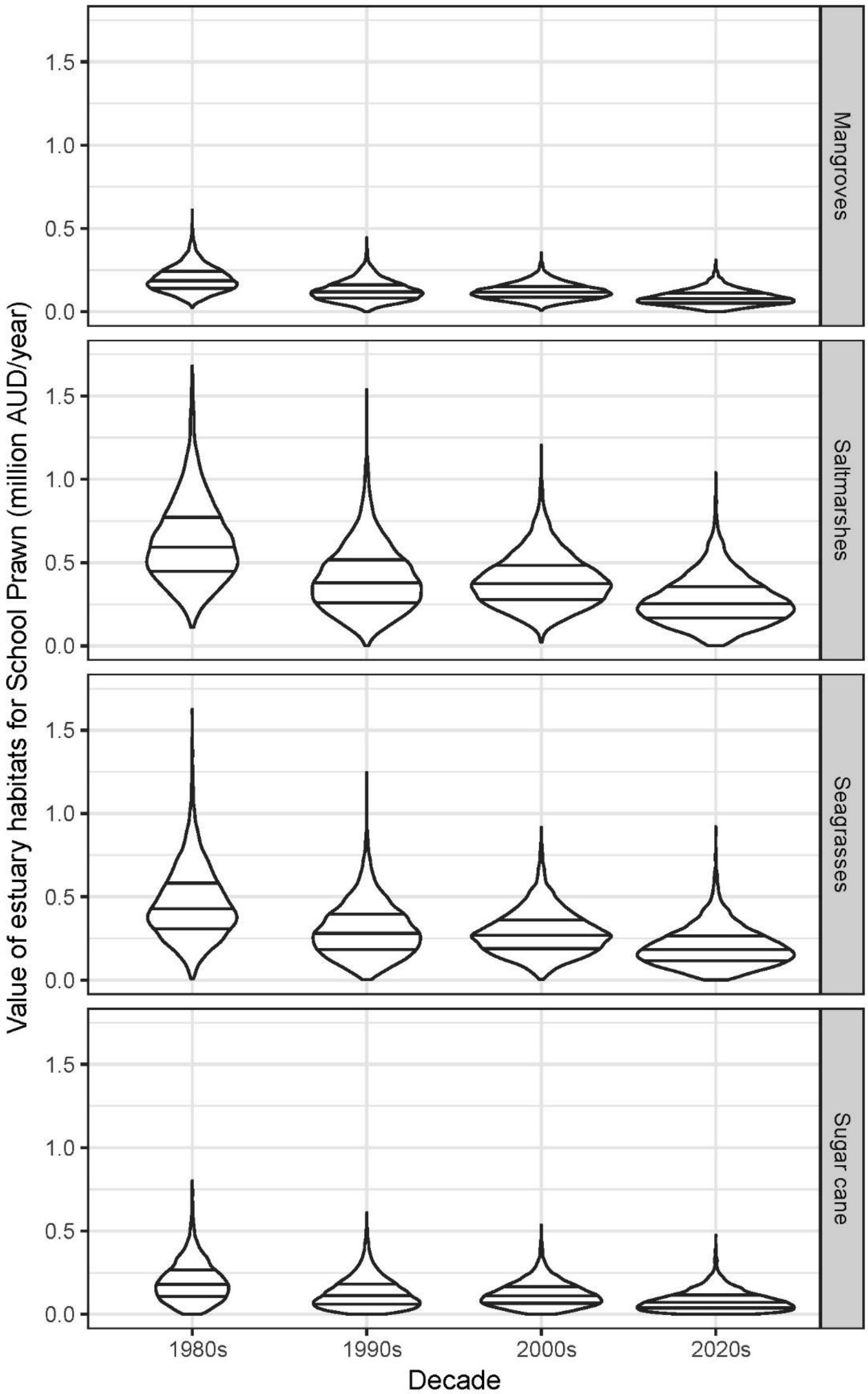


Figure 31: Violin plots of estimates of change in landed value of estuarine habitats over time for the Lake Wooloweyah school prawn fishery. Horizontal bars indicate 25, 50 and 75% quantiles. The most likely 'true' value of habitats is likely to be where the violin plots are widest (most simulations result in those values).

Given the area of estuarine habitat that could be rehabilitated through modifications of hydrological infrastructure and assuming the mean of per hectare value of estuarine habitat remains constant, the projected range of wider benefits to the school prawn fishery within Lake Wooloweyah could extend to over \$7.2 million AUD.yr^{-1} (Table 2). In contrast, focusing on habitat health/quality only returns the total value to that at the peak of fisheries landings (in the 1980s) showed that the extended value of seagrasses was highest and could extend to \$49,900 AUD.ha^{-1}.yr^{-1}, followed by saltmarshes at \$13,200 AUD.ha^{-1}.yr^{-1}.

Table 2: Range of possible value gained (in thousand AUD.yr^{-1}) to the prawn fishery in landings using a low to high range of rehabilitation scenarios.

	Rehabilitation option	Mangrove value gained	Saltmarsh value gained	Total value gained
Low-end range	Ringdrain West	17	463	481
	Ringdrain Southwest	69	2461	2530
	Prawnfarm	52	191	243
	Micalo West	10	183	193
	Sum	**148**	**3298**	**3446**
Intermediate range	Ringdrain West	47	940	987
	Ringdrain Southwest	189	5228	5417
	Prawnfarm	68	182	250
	Micalo West	21	578	599
	Sum	**324**	**6929**	**7253**
High-end range	Ringdrain West	171	1048	1219
	Ringdrain Southwest	895	5210	6105
	Prawnfarm	100	61	161
	Micalo West	81	662	744
	Sum	**1248**	**6981**	**8229**

Discussion

Hydrological modelling suggests rehabilitation of estuarine habitats through tidal restoration could result in a return on investment to the broader community of over $7 million AUD.yr[1]. While these sorts of rehabilitation projects can be costly (e.g. estimated at ~$3 million AUD plus ongoing monitoring and management in Harrison et al. (2019)), the estimate here is conservative and excludes other valuable commercial species that are caught within the estuary. In addition, as in Taylor et al. (2018), the valuation here excludes other value that may be drawn from these habitats including social value (Martin et al., 2020) or value from other services such as blue carbon (Davis et al., 2015) that may provide comparable or higher value than that drawn from fisheries landings. We suggest that, even though rehabilitation can be costly, an assessment of the cost of rehabilitation at the zones identified in Lake Wooloweyah would be of benefit to the fishing industry and the local economy. These results suggest that ecologically-based habitat-fishery linkages can be combined with hydrological modelling to identify the broad benefit that estuarine habitat rehabilitation could have for stakeholders.

Valuations suggest that the value of estuarine habitats has declined by approximately half since the 1980s, reflecting a decline in the landings of school prawn in the Clarence system. Historical data suggest that the areal extent of estuarine habitats identified as important for school prawn diet (saltmarshes and mangroves) has declined by > 60% since the 1940s. The peak of the school prawn fishery occurred in the 1980s, however, and no estuarine habitat extent data exist for that period until the 1990s, when the fishery landings and habitat extents had already declined significantly. This makes it difficult to place a causal link between the decline in estuarine habitat coverage and the decline in fishery landings/value. However, given the importance to the diets of school prawns of the two habitats that have declined the most in that time (saltmarshes and seagrasses), it is likely that a loss in carrying capacity of the Lake Wooloweyah ecosystem would have occurred with the loss of these habitats. A decline in prawn landings would be expected from such a change in the productivity of an ecosystem.

Habitat 'quality' is a factor that likely has implications for the productivity and by association valuation. Estuarine habitats can be degraded without a reduction in areal extent, which would presumably result in a loss of ecosystem services including productivity for the school prawn food web. This compounds the complexity of the fishery-habitat link, as the different species of estuarine primary producers (especially saltmarshes) may be more or less abundant in different parts of the habitat. The 'value' of every hectare of estuary habitat is therefore likely to be variable depending on the health of any given area. In this project we considered the hypothetical scenario that all the loss of value in the prawn fishery from the 1980s is a result of habitat degradation rather than loss of habitat. Habitat degradation of seagrasses, saltmarshes and mangroves is common in settled estuaries and can be the result of cattle grazing, and the accumulation of pollutants or debris (Di Bella et al., 2014, Tonjes et al., 2018). In the hypothetical case explored here, the value of seagrasses was very high (~$50,000 AUD.ha^{-1}.yr^{-1}), however, the cost of rehabilitating seagrass habitats would be unlikely to provide a good cost-benefit given the restricted areal extent of seagrasses in the current system (~50 ha) and the unreliability of rehabilitating seagrasses on a larger scale (Tanner et al., 2014, Tan et al., 2020). Our modelling approach is less effective at modelling potential seagrass rehabilitation area than saltmarshes and mangroves, as seagrass habitat is dependent on other factors such as water clarity that are difficult to model (though this may be possible in the future (Pearson et al., 2021)). While quantifying the health of a given extent of estuarine saltmarsh should be valued, health is more difficult to quantify than areal extent and therefore may make it difficult to set rehabilitation targets for success.

The hydrodynamic modeling and sub-sequent eco-hydrological outcome assessment identified a very large potential for intertidal wetland creation via modification of drainage works around Lake Wooloweyah, ranging from 700 ha for the low-end to over 2000 ha for the high-end scenario. Even though the differences in the upper limit of the habitable ranges of saltmarsh and mangroves across the three scenarios were only 5 and 15cm respectively (between the low and intermediate scenarios), we found large differences between the low-end and high-end scenario in terms of achievable gains in mangrove and saltmarsh areas.

Interestingly, even the conservative estimates for hydrologically feasible intertidal wetland gains are very high in comparison to the total area of these communities that was present in this part of the system in the 1940s. These findings are interesting since in 1940s, the Taloumbi Ring Drain and drainage system hadn't been built yet. Instead, a natural levee along the edges of Lake Wooloweyah limited the tidal exchange between the lake and the adjacent wetlands, more so along the western shoreline and less so in the southern part of the system (Foley and White, 2007). Foley and White (2007) argue that back then, most of the western part of the Taloumbi areas were predominantly freshwater wetlands, especially during the wet season, while the southern parts were brackish or saline, featuring extensive saltmarshes.

Our findings on the potential for intertidal habitat creation are in contrast with these historical observations. One of the reasons for this is that we did not consider upstream freshwater inflows and local rainfall into the areas considered for rehabilitation. These freshwater inflows are significant for the hydrology of these former wetland areas but do vary in significance through wet and dry (i.e., drought) cycles. In a natural system, freshwater inputs during wet periods can maintain predominantly freshwater wetlands and corresponding vegetation communities. These freshwater wetlands are constraint at the lower end by infrequent tidal inundation during spring tides or estuarine flooding, during which saline conditions are pushed further up the system. As our vertical vegetation envelope analysis demonstrated, our intertidal habitat predictions are well within the surveyed 'dry-year' tidal inundation regime of Lake Wooloweyah. Therefore, we believe that if tidal reintroduction works are designed without significant hydraulic constraints (i.e., with sufficiently large openings and feed channels), then the achievable intertidal wetland area would be very close to our predictions.

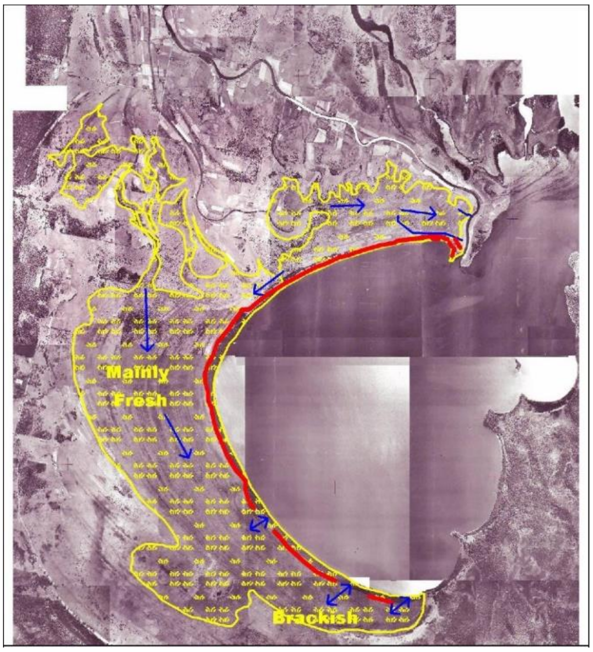


Figure 32: Assumed hydrological functioning of the Taloumbi Ring Drain floodplain wetlands in the 1940s (source: Foley and White (2007)).

Another important factor to consider here is that the extensive network of drains throughout the former freshwater wetland areas has now created an entirely different baseline condition for wetland establishment, and former wetland species have largely been replaced with agricultural land uses such as sugercane and grazing. This 'altered baseline' condition makes the assessment of fresh vs. saline wetland establishment difficult. In any case, any on-ground restoration works in this area should carefully factor in these freshwater inflows in the wetland design process.

Another reason for the large potential for intertidal wetland rehabilitation that we found could be that the tidal regime of Lake Wooloweyah could have changed between 1940 and now due to expansion of the Clarence River entrance training works (entrance training and dredging leads to increases in the tidal range of estuaries) and increases in the global and local mean sea level of about 19cm between 1900 and 2010.

Given the lake's very narrow tidal regime, an increase of this magnitude can certainly have wide-reaching impacts. Although future sea level rise was not explicitly factored into our analysis, it is therefore critical to consider its implications here, since any changes in the mean sea level will have wide ranging impacts on intertidal vegetation communities and the surrounding drainage systems. By and large, further increases in mean sea level will decrease the efficiency of existing drainage systems and push existing intertidal vegetation communities and upland freshwater wetlands towards higher areas on the existing floodplains, until 'hard boundaries' such as roads, housing or steep natural slopes are reached. Since both the tidal and habitable vertical ranges in the lake are very narrow, even minor increases in the mean sea level will have widespread impacts on both drainage and ecosystems around the lake.

To illustrate, Figure 33 shows the current habitable ranges of vegetation communities overlaid on the tidal duration distribution at the location of the four survey point clusters provided in Figure 10. The water level data shown is from a 2013 wet year model run, where 67cm of end of century sea level rise were added to the tidal boundary. These results show that in particular for Lake Wooloweyah, the tidal regime corresponding to end of century sea level rise will be almost entirely incompatible with the current habitable ranges of intertidal vegetation communities, unless these keep pace with rising sea levels via vertical accretion.

This analysis illustrates that any rise in the mean sea level will work in the favour of tidal reintroduction-based wetland rehabilitation. For instance, with a sea level rise of only 15cm, the high-end rehabilitation outcome (Figure 29) would quickly become the 'low end' outcome at the point in time in the future where this level of sea level rise is reached. In the context of this analysis, it is therefore critical to consider that the Clarence River estuary and Lake Wooloweyah are already experiencing accelerating sea level rise that is shifting the baseline conditions in the favour of intertidal wetland rehabilitation. The currently drained floodplains around Lake Wooloweyah would therefore benefit from adaptive management, where upland migration corridors are identified and established.

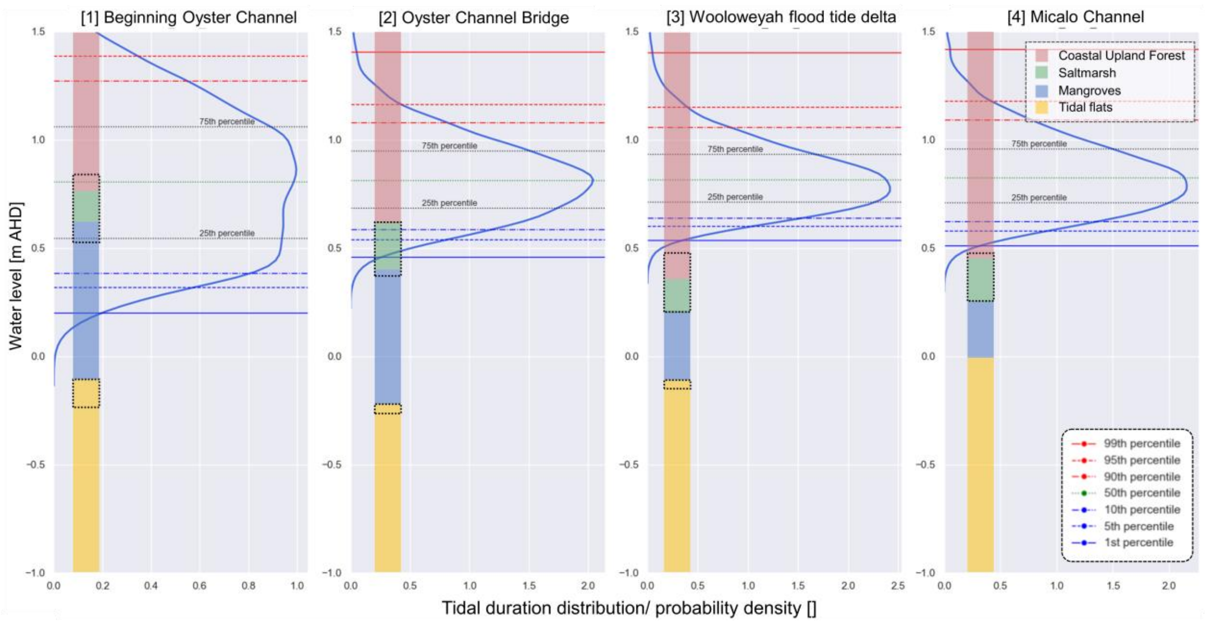


Figure 33: Habitable elevation ranges (stacked barplots) inferred from the four survey point clusters overlaid on tidal duration distribution plots obtained at the location of the clusters from the hydrodynamic model runs for a wet year with 67cm of sea level rise added to the oceanic boundary condition of the model. (Note that the habitable ranges were not adjusted to account for the effects of vertical accretion).

Methodological considerations

Stable isotope ecology is one of the most powerful tools to track the movement of nutrients through food webs, however, food web complexity can make it difficult to pinpoint specific sources driving food web production (Parnell et al., 2010). While the incorporation of sulfur stable isotopes helps limit this and can, for example, eliminate some sources like fine benthic organic matter and sugar cane that would otherwise appear to be contributors without this isotope in the mixing model, some sources like saltmarsh succulents and mangroves could not be separated isotopically in this study. This can make it difficult to value habitats since the one isotopic 'source' is present across two habitats and the stable isotopes cannot separate them. The approach we used to separate their contribution/value in equal proportions is the most parsimonious, but one of these sources could be making all the contribution (and might thus provide all the value for the prawn fishery). If the source in question has little identified contribution (e.g. as in Raoult et al. (2018)) this does not create management issues, but for Lake Wooloweyah the mangrove and saltmarsh contribution was not negligible. A solution to this problem would be to use additional isotopic tracers that could separate saltmarsh succulents and mangroves. Fatty acid analysis is often used on its own or in conjunction with stable isotopes for food web studies (Meziane and Tsuchiya, 2000, Koussoroplis et al., 2011) and could assist with separating these sources.

The trophic link (the intermediate consumer feeding on the habitat that prawns feed on) is still unknown, which makes it difficult to validate the patterns observed. Euphausiid and mysid crustaceans are thought to play an important role in the diets of many estuarine species (Mees et al., 1993, Allen and Allen, 1981, Kaneko et al., 2016) and direct capture of these small organisms should be a priority within these systems to validate their role in the food web. We expect that 1) the stable isotope values of these small organisms will confirm their likely role in the food web and 2) that they will be present in greater densities in the habitat that is the dominant contributor to food webs. Very high mysid concentrations have been observed over seagrasses that were identified as a major contributor to prawn food webs in other NSW estuaries (Wallis Lake, Raoult pers. Comm.) and a comprehensive study characterising mysid concentrations across habitats could assist in correctly interpreting food web contributions and producing more accurate valuations of habitats.

The eco-hydrological assessment revealed that tidal reintroduction into currently drained low-lying land areas could achieve large gains in the current combined extent of saltmarsh and mangrove ecosystems. In general, we believe that our assessment is robust, since it is based on highly accurate RTK-GPS vegetation elevation survey data combined with a highly accurate hydrodynamic model of the entire Clarence River estuary. This analysis provided a very clear picture of the relationship between the tidal regime in different parts of the system and the corresponding intertidal vegetation community layering. The fact that the lake essentially behaves like a bathtub with a dramatically attenuated tide meant that we were able to extrapolate the eco-hydrological linkages established for the flood tide delta area across the entire lake system. This was done using a GIS-based bathtub modelling approach.

The 'bathtub' approach assumes that the tidal boundary condition as inferred here from the estuary scale hydrodynamic model can be extrapolated across the entire area considered for tidal reintroduction. This assumption is generally valid if the connection between the newly created tidal wetlands and the main estuarine waterbody is designed sufficiently large, which has previously been demonstrated in practice in Sadat-Noori et al. (2021).

The accuracy of this local-scale bathtub approach is strongly dependent on the accuracy with which the tidal boundary condition at the downstream end of the rehabilitation area can be predicted, as well as the accuracy of the bottom elevation data available for the same area. As previously demonstrated, the hydrodynamic model is able to reproduce the tide water levels in and around Lake Wooloweyah with a very high level of accuracy. Due to difficult site access and issues with private land ownership, however, it was not possible to survey the bottom elevation of the potential rehabilitation areas and instead, we used the best available LiDAR digital elevation model (DEM) as a surrogate. Uncertainties associated with the underlying bathtub method and the LiDAR DEM are partially addressed by modeling three different scenarios, which representative of the lower and upper range of these combined uncertainties.

The conservative estimate of gains in combined saltmarsh and mangrove area is around 700 ha, while the high-end estimate is over 2000 ha. These differences are partially due to the very narrow tidal range within Lake Wooloweyah as well as the large areas of flat, low-lying land behind the Taloumbi Ring Drain, where even a 10cm error in DEM bottom elevation can lead to large changes in the modeled vegetation outcomes. The 15cm DEM adjustment was the only difference between the intermediate and high-end scenario, with the habitable ranges being the same in both cases. This adjustment alone leads to a difference of around 700 ha in combined saltmarsh and mangrove areas, with the ratio of mangrove to saltmarsh area increasing substantially.

Implications

The findings from this work suggests that there is potential for significant value-adding in the form of fisheries contributions in Lake Wooloweyah. These would arise from the rehabilitation of estuarine habitats by modifying the hydrology of the system. The approach used here could be used in most other estuaries where commercial fisheries occur to inform management of estuarine habitats and therefore fishery productivity.

The Lake Wooloweyah and Clarence River prawn fishery would gain value through increased landings by rehabilitating saltmarsh, mangrove and seagrass communities. Seagrass rehabilitation, however, is complex and often costly, therefore, we recommend that any rehabilitation efforts focus on saltmarshes in the area. The per-year broader value or habitat rehabilitation to stakeholders is significant (>$7 million AUD.yr^{-1}), and since this is an underestimate of the value as it excludes other fishery species that occur in the area, we believe that the cost of this rehabilitation would rapidly be offset by benefits to the broader community.

Recommendations

Explicit cost-benefit analyses of rehabilitation projects for the areas identified in Lake Wooloweyah through hydrological models could help managers and the industry quantify the future benefit of these projects to commercial fisheries. Given the high value estimated from the potential rehabilitation area, this should be explored to determine whether there is a business case to rehabilitate an area with a particularly high cost/benefit ratio. Such approaches have been explored in previous studies that have examined the cost of rehabilitation through hydrological modification and management (Harris et al. 2017). Any such cost-benefit analyses would need to include explicit and fair compensation to land owners for any loss of land as a result of change in hydrology.

While the approach used here looked at potential value that could be gained from rehabilitation, the same approach could be used to forecast value that would be lost from events such as climate change. Sea level rise can be accurately modelled, and is expected to result in a net loss of estuarine systems caught in the coastal squeeze. Forecasting the loss in value could encourage rehabilitation of sites to mitigate those impacts on fisheries productivity.

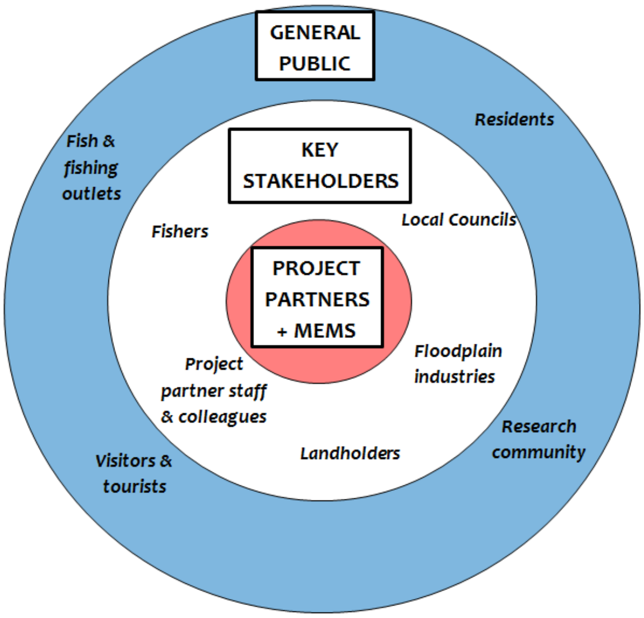
The project herein only looked at the Lake Wooloweyah component of the Clarence River estuary system, and commercial fisheries occur throughout the system. A Phase 2 component of the project that looks at the system more broadly would be relevant to stakeholders. The two systems (Lake Wooloweyah and the Clarence River) are connected hydrologically, so it is likely improvements through rehabilitation will have flow-on effects between the two systems and potentially for fisheries and ecosystems outside the estuary (for example, for eastern king prawns that depend on estuarine production for some or all their lives). A broader examination of the system would also include fisheries for species other than school prawn and provide a less conservative estimate of value that would only grow the business case for rehabilitation projects in this system.

Accurately separating the contributions of mangroves and saltmarsh succulents to the diets of prawns is difficult with stable isotopes, therefore we recommend ecological assessments that determine the trophic link between these habitats and prawn diets (e.g. through studies on zooplankton such as mysid shrimp, especially those that may monitor the movement of these organisms within and between habitats of interest) or the use of additional chemical tracers. Fatty acid profiles offer an avenue that could be integrated into the current methodology with Bayesian mixing models (Neubauer and Jensen, 2015), but alternatively other isotopes including oxygen (which separates according to temperature gradient (Vander Zanden et al., 2016)) could be useful in these sorts of systems. Every successive tracer added to these assessments will inevitably produce more robust results (Stock et al., 2018), and as of yet these assessments have not seen the optimal number of tracers used as sources from different habitats always have to be grouped at times. Since confidence in the outputs from these models is a key aspect of building business cases for rehabilitation projects, it would be worthwhile to explore the optimal number of tracers to produce results that can reliably separate the various sources that may overlap in mixing models.

The approached outlined herein only captures value to the fishery and as a result, always underestimates the value of estuarine habitats for the broader economy through additional co-benefits. We therefore recommend follow-on projects that account for additional co-benefits such as biodiversity (Baumgärtner, 2007), blue carbon (Macreadie et al., 2017), water quality improvement (Viscusi et al., 2008), etc. to value these habitats more comprehensively. A broader valuation of these habitats in addition to the fisheries value identified here would further increase the value of these habitats and could provide further incentives to rehabilitate these environments.

Extension and Adoption

The following diagram identifies and prioritises the project target audiences. The inner circle identifies the project partners and MEMS agency decision makers as the priority and the areas where the communication strategy initially concentrated its efforts. As the project continued, outcomes were communicated for the audiences identified in the outer circles with the direct assistance and programs of the project partners (including MEMS links). The diagram assisted in visualising the project's realm of influence and focus.



1. Land Management decision makers (largely government agencies, coordinated through MEMS)
2. Commercial and recreational fishing sectors
3. Commercial and recreational fisheries managers
4. Councils, landowners, conservation groups (for example Valley Watch) and individuals

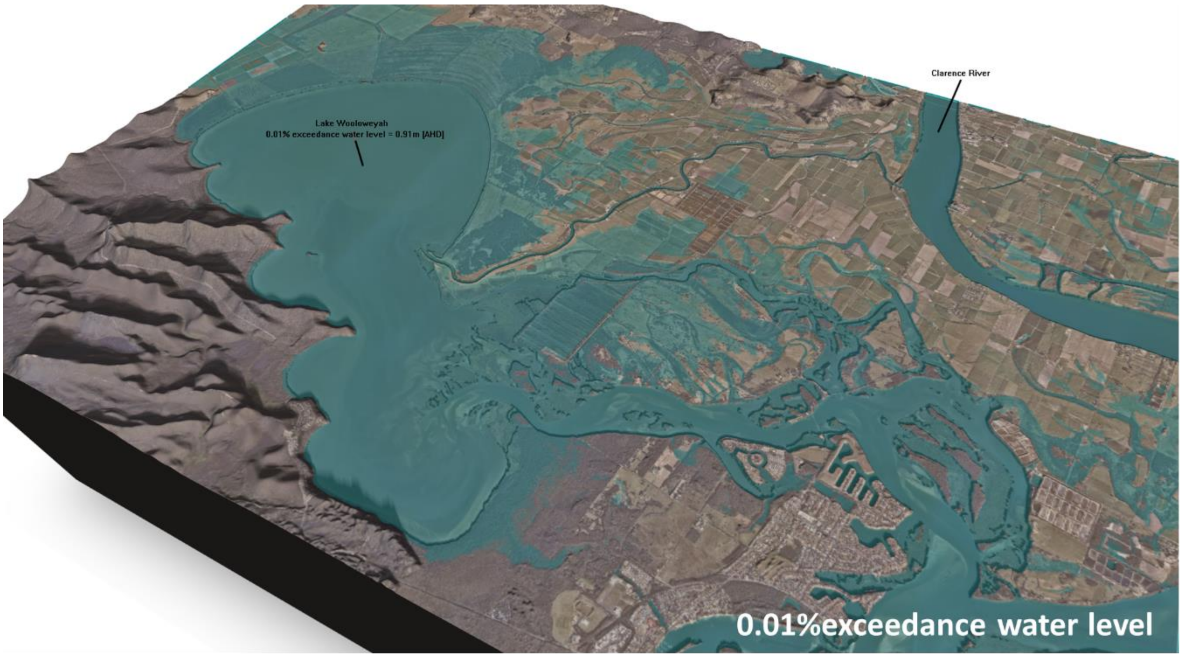
End-Users

- Commercial and recreational fisheries managers
- Commercial and recreational fishing sectors
- Coastal land/water management and planning bodies, including Local Land Services, National Parks and Clarence Valley Councils
- NSW Government, including portfolios associated with infrastructure, and regional development
- Fish Habitat managers such as National Parks and NSW Fisheries and advocates such as OzFish
- General public, including landowners, Lake Wooloweyah residents and recreational fishers

There were several key areas of communication for the project:

Communication Method	**Output/Timeframe**
Information letter	Email sent to key stakeholders outlining project objectives
Project updates	Progress reports submitted to FRDC in May 2020 and November 2020
MEMS Program Management updates	Regular contact with MEMS coordinator, Kylie Russell
Research papers	Three (3) manuscripts are in development: 1. Habitat-fishery linkages in Lake Wooloweyah 2. Hydrodynamic modelling dictates habitat repair 3. Fishery output scenarios for Lake Wooloweyah
Talking with the general community	Fieldwork trips in June 2020 and February 2021 also involved talking with local residents. There has been email contact with some residents that have heard about the project via word-of-mouth
Face-to-face with key stakeholder groups	Meeting with Clarence River Fisherman's Coop February 2020
Regional stakeholders' and managers' workshop	Meeting with Clarence River Fisherman's Coop January 2021. A regional workshop is planned for June 2021
Conference presentations	Planned for July 2021 – Australian Marine Sciences Association annual conference (Macquarie University)
Final Project Report	Submitted July 2021

Project materials developed



Snapshot of a 3-d rendered animation of water levels in and around Lake Wooloweyah for the 0.01% (0.91m AHD) tidal exceedance plane as calculated from the Lake Wooloweyah tide gauge. This animation was created as an initial illustration and outreach resource for the project that illustrates that large areas around the lake are physically suitable for tidal restoration. The animation can be accessed here. It is important to consider that although water levels are driven with data from the Wooloweyah gauge, it is still a simple bathtub GIS model that does not account for hydrodynamics, levees, or drainage infrastructure.

Appendices

- List of researchers and project staff (boat skippers, technicians, consultants)

    1. A/Prof Troy Gaston
    2. Prof William Glamore
    3. Dr Matt Taylor
    4. Dr Kylie Russel
    5. Dr Colin Creighton
    6. Dr Valentin Heimhuber
    7. Dr Vincent Raoult
    8. Finlay Johnson (PhD student)
    9. Harrison Smith (technician)
    10. Mark Bennet (PhD student)
    11. Tyrone Vance (skipper)

- Intellectual Property – N/A

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