Estuaries in a Changing Climate

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Abstract:

Estuaries are highly dynamic physical and ecological systems and are regularly subject to extreme fluctuations in water levels, salinity, heat and other natural forces. How the ecosystem responds to these fluctuations helps to define the estuary's natural resilience. Potential changes in these natural forces, beyond the existing variability, may push the estuarine system beyond its current resilience.

Existing methods to assess the impact of climate change across an estuary are highly simplified or lack site specific detail. This paper summarises three (3) approaches to assess the potential impact of climate change in estuaries.

The first method is a state-wide approach where the vulnerability of estuaries to changes in physical forcing factors is assessed against geomorphic classifications. The second method is an estuary specific approach comparing predicted climate change variables (under various climate change scenarios) against variance in real, historical observations. This method statistically assesses the potential vulnerability of a forcing factor (e.g. sea level, heat, rainfall, etc), as predicted by downscaled climate models, to a selected estuary. The first two methods identify which of the forcing factors are potentially changing with climate change are likely to influence an estuaries resilience and where future resources should be targeted.

The third method uses deterministic modelling to assess specific impacts over spatial and temporal scales. As an example, two estuary types under varied sea level and catchment processes from climate change are modelled. The results highlight shifts in salinity structure at key locations due to varied hydrology and sea level rise. In combination, these approaches highlight the importance of assessing existing variability in estuaries against future variability.

Introduction:

Linking the fluctuating river with the dynamic coastline, estuaries are dynamic systems constantly adjusting to change. Future changes in the climate, however, have the potential to alter estuarine systems beyond their current variability. Understanding these potential implications to a local estuary can be difficult without detailed scientific analysis and process understanding.

Estuarine environments are intrinsically linked to, and affected by, climate operating over a range of temporal and spatial scales. An estuary's local and regional climate affects its functioning, distribution, dimensions, and form (Glamore et al., 2016). Indeed, estuaries are rarely in a steady state, even under current climatic regimes, and are thereby, particularly threatened by climate change. Precipitation patterns, freshwater runoff, temperature, evaporation, radiation and wind along with numerous additional forcing factors all influence the geophysical and biophysical nature of estuarine landforms, habitats, and ecosystems (Boesch et al., 2000).

There are limited techniques to assess the impact of climate change across an estuary. Prevailing methods are highly simplified, lack site specific detail and often do not take into consideration the existing variability already inherent in many estuaries. This paper summarises three (3) new approaches to assess the potential impact of climate change in estuaries across NSW.

The first method is a state-wide approach where the vulnerability of estuaries to changes in physical forcing factors is assessed against geomorphic classifications. This method results in indicative risk factors that may be vulnerable to climate change based on a detailed review of forcing functions across estuaries in NSW.

The second method is an estuary specific approach comparing predicted climate change variables (under various climate change scenarios) against variances in historical observations. This method statistically assesses the potential vulnerability of a forcing factor (e.g. sea level, heat, rainfall, etc), as predicted by downscaled climate models, to a selected estuary. This approach then identifies which of the forcing factors is likely to be stretched outside the natural range of variability and where future resources should be targeted.

The third method uses deterministic hydrodynamic modelling to assess site specific impacts over spatial and temporal scales. The results of this approach can be used to forecast shifts in salinity structure at key locations due to varied upland hydrology and sea level rise. In combination, these approaches highlight the importance of assessing existing variability in estuaries against future variability.

Assessing the impact of climate change to an estuary requires an understanding of how the estuary presently functions – the interconnection of different processes, tolerance thresholds and limits to resilience – and predicted regional climate change. For all assessment methods presented within this paper a similar framework has been established as per Figure 1. This process is recommended to ensure that a robust approach is undertaken to link the local process understanding with the local priorities. A brief description these steps are detailed below.
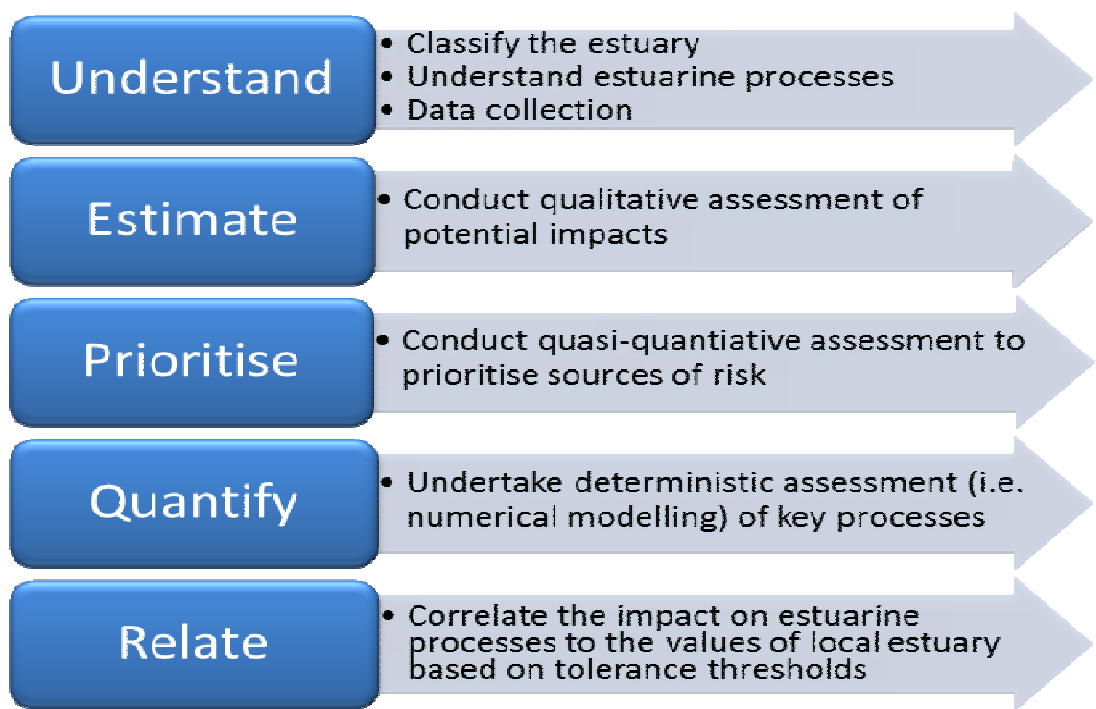

Understand
- Classify the estuary
- Understand estuarine processes
- Data collection

Estimate
- Conduct qualitative assessment of potential impacts

Prioritise
- Conduct quasi-quantiative assessment to prioritise sources of risk

Quantify
- Undertake deterministic assessment (i.e. numerical modelling) of key processes

Relate
- Correlate the impact on estuarine processes to the values of local estuary based on tolerance thresholds

Figure 1. Assessing Estuarine Vulnerability to Climate Change

Understand: Understanding the processes that are unique to a particular estuary is critical in determining the potential impact of climate change. Estuarine classifications can be helpful to highlight the key processes in an estuary. Different regions may utilise different classification systems; however, derivation of the dominant processes is common across systems.

Field data are required to quantify the state of the estuary. Data is critical in understanding how the estuary functions and the natural variability of processes and ecosystems. Importantly, data provides a baseline from which to compare future climate change predictions.

Estimate: Based on an understanding of an estuary and the observed response and sensitivity of an estuary to change, the potential impacts due to climate change can be estimated. A qualitative assessment enables targeted identification of potential impacts. An example of a qualitative assessment is provided in Table 1.

Prioritise: Quantitative assessment prioritises sources of risk to estuaries through comparing regional climate and water-level data to predicted climate change at a catchment scale. This should be undertaken on a seasonal and annual basis, but may be limited by the temporal resolution of climate change predictions. Key to the prioritisation methodology is the comparison of the natural variability of present-day climate and water levels against the change as predicted by climate models. Processes that are predicted to deviate the furthest from present-day variability may pose the greatest risk within an estuary.

Quantify: Estuarine processes identified to be most at risk due to climate change can be investigated in detail through further assessments. A common deterministic assessment involves numerical representation of an estuary under present-day conditions and simulation of the estuary under climate change. This stage of the assessment focuses on particular processes of interest, such as saline dynamics, to quantify the specific magnitude of change.

Relate: Once climate change impacts to estuarine processes have been quantified, impacts to dependent processes can be assessed. This involves understanding tolerance thresholds and limits to resilience of particular processes, ecosystems, and species.

Method 1: Using Estuarine Geomorphic Variability as an Indicator of Climate Change Vulnerability

The sensitivity of a particular estuary to climate change is significantly influenced by the geomorphic and hydrological regime (or classification) of the estuary. For example, an intermittently closed and open lake or lagoon (ICOLL) system with a small catchment may be highly sensitive to increases in temperature and evaporation and less sensitive to changes in ocean acidity or sea-level rise. However, an estuary that is dominated by tidal hydrodynamics may be significantly impacted by sea-level rise. The exact extent of that change is still largely unknown and requires detailed scientific analysis.

This method focuses on assessing the natural inherent variability in estuaries in NSW and uses broad geomorphic characteristics to determine if the proposed change in climate will be within the natural background variability. With this method the exact impact of a specific change is difficult to quantify, however, based on our understanding of existing processes and the response of various estuarine processes to present-day stressors, the risk of climate change to estuaries can be estimated. This risk factor can then be used to focus further investigations.

A summary of potential impacts for each estuary type is provided in Table 1 (as per Glamore et al., 2016). This table provides a comparison between estuarine types (as adopted by NSW) for south-eastern Australia and climate variables, and the expected risk based on climate change predictions. Note that the climate variables selected include mean sea level, rainfall, surface heat budget, ocean acidity and wind are based on the predictions from the global circulation models, our current best available tool for forecasting change in climate. Each one of these climate variables has then been assessed against it's resulting influence on (i) hydrodynamics and mixing, (ii) sediments and geomorphology and (iii) water quality interactions. Obviously any changes to these forcing factors will influence the ecological function of the estuary. The influence of that change being represented by 3 risk factors namely low, moderate and high.

These risks are defined as:

Low: A process within an estuary is not likely to be influenced by a change in a particular climate variable or the change is within the natural variability.

Moderate: A process may be influenced by a climate variable; however, the climate variable is not the only controlling factor.

High: Change in a particular climate variable will have a significant direct impact on an estuarine process. The estuarine process is directly dependent on this climate variable

The qualitative assessment outlined in Table 1 helps to identify the potential impacts and estuarine sensitivities relative to each other. While this assists in focusing adaptation strategies and estuarine management policies, it does not quantify the impact of a specific change in a local process (eg. rainfall or temperature) to the specific response of a key estuarine process. To identify these specific impacts a more detailed and site specific methodology is presented below.

Table 1. An Assessment of Climate Change Vulnerability versus Estuary Type (for Physical Variables Predicted by Climate Change Models)

Climate variables	Estuary type			
	Oceanic embayment	Tide-dominated estuary	Wave- dominated estuary	ICOLL
Mean sea levels				
Hydrodynamics and mixing	MODERATE	MODERATE	MODERATE	HIGH
Sediments and geomorphology	MODERATE	HIGH	MODERATE	MODERATE
Water quality interactions	MODERATE	MODERATE	MODERATE	MODERATE
Rainfall				
Hydrodynamics and mixing	LOW	LOW	MODERATE	HIGH
Sediments and geomorphology	LOW	LOW	MODERATE	MODERATE
Water quality interactions	LOW	LOW	HIGH	MODERATE
Surface heat budget				
Hydrodynamics and mixing	LOW	LOW	MODERATE	MODERATE
Sediments and geomorphology	LOW	LOW	MODERATE	HIGH
Water quality interactions	LOW	LOW	MODERATE	HIGH
Ocean acidity				
Hydrodynamics and mixing	LOW	LOW	LOW	LOW
Sediments and geomorphology	LOW	LOW	LOW	LOW
Water quality interactions	LOW	LOW	LOW	LOW
Wind				
Hydrodynamics and mixing	MODERATE	MODERATE	HIGH	HIGH
Sediments and geomorphology	MODERATE	LOW	HIGH	HIGH
Water quality interactions	LOW	LOW	MODERATE	MODERATE

*As per Glamore et al., 2016.

Method 2: Assessing Natural Versus Predicted Variance as an Indicator of Climate Change Resilience

This methodology proposes that climate change impacts within estuaries can be assessed by comparing present day climate variability for a site (or region) against associated climate change predications. The risk of impact due to changes in climate drivers can then be ranked with respect to the predicted deviation outside the observed natural variability. Underpinning this assessment is that the further the predicted data is from the observed data, the greater the vulnerability of the system to climate change.

For this method, natural variability was described as one standard deviation, or variance, from the long-term (i.e. 20 year) average. Standard deviation is often utilised to describe variability of a range of measures including vegetation (Oindo and Skidmore, 2002), fisheries (Pepin and Myers, 1991) and climate (Rutllant and Fuenzalida, 1991) data, and as a trigger for defining change (May and MacArthur, 1972).

To undertake this method a statistical comparison of regional climate predictions with local climate observations is required. Local data can be obtained from selected areas and climate change data can be obtained in NSW from the NARCLIM dataset. Assessments for this method can be made across monthly, seasonal or annual periods depending on the availability of the climate prediction data. Indeed, if the climate change data is sufficiently robust, extreme events (e.g. temperature extremes per year) can also be assessed.

Once analysed, potential impacts within estuaries can be defined as per the categories below:

Low: High certainty that the future average has not moved outside the present day variability (within 1 standard deviation).

Moderate: Somewhat certainty that the future average has not moved beyond 1 standard deviation from the present day average but some model predictions fall outside.

Major: Some certainty that the predicted average has moved outside 1 standard deviation of present day average data but some model predictions remain with present day variability (1 standard deviation).

Severe: High certainty that the future average has moved outside of 2 standard deviations from the present day average conditions but some model predictions remain within the present day variability.

Extreme: High certainty that the range of model predictions of future climate have moved beyond 2 standard deviations from the present day average conditions.

The defined categories are visual depicted in Figure 2. It is worth noting that the range of the modelled prediction plots (as shown as box plots in Figure 2) is representative of the range of the model ensemble data predicted from the various climate change models. As such, a larger range suggests that the various models run have a higher degree of uncertainty.
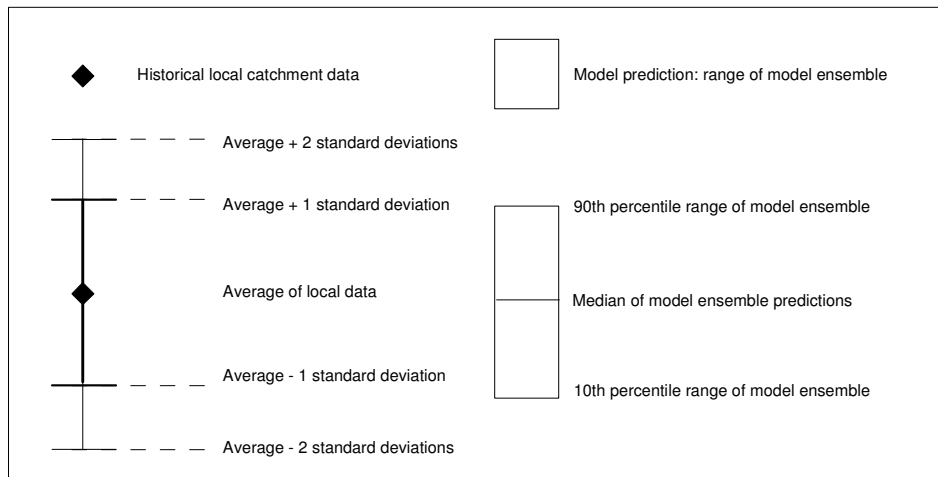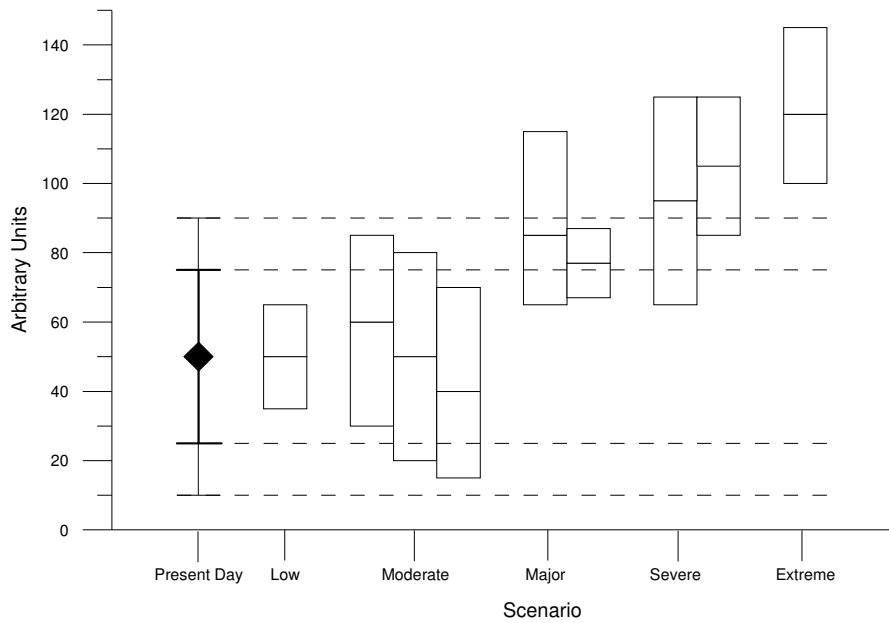
Figure 2. Assessment categories defined against an arbitrary unity (e.g. rainfall, sea levels, temperature, etc) to depict risk of vulnerability to climate change.

As a case study, this methodology was applied in the Hunter River estuary for a range of climate change parameters (Table 2). These results indicate that depending on a range of Regional Climate Predictions (RCP), the potential vulnerability of that parameter in the future can be determined. For instance, for the RCP 2.6 (2030), the method results suggest that there will be major shifts in the temperature and extreme shifts in the water levels. However, the results also indicate that there will be a low potential impact in the acidity, rainfall and wind patterns. This assessment helps to identify and prioritise which variables will be of particular concern into the future and where resources should be dedicated.

Table 2. Summary of Prioritised Potential Impacts Posed by Climate Change to the Hunter River Estuary

Parameter	RCP2.6, 2030	RCP4.5, 2030	RCP8.5, 2030	RCP2.6, 2090	RCP4.5, 2090	RCP8.5, 2090
Temperature	Major	Severe	Severe	Severe	Extreme	Extreme
Evaporation	Moderate	Moderate	Moderate	Moderate	Major	Severe
Acidity	Low	Moderate	Low	Low	Moderate	Moderate
Rainfall	Low	Low	Low	Low	Low	Low
Water Levels	Extreme	Extreme	Extreme	Extreme	Extreme	Extreme
Wind	Low	Low	Low	Low	Low	Low

Method 3: Climate Change Assessment of Estuarine Locations Using Deterministic Methods

The final method is based on deterministic numerical modelling of estuarine processes to compare the response of an estuary variable (flow, tidal prism, salinity, etc) under varied climate change conditions. For this method, detailed numerical models of estuarine processes are required. Each model requires significant local data for calibration and verification of existing processes. Once the model has been shown to accurately reflect these processes, then climate change scenarios can be undertaken to simulate future changes. By simulating individual changes to an estuary, such as changes to sea level rise or catchment inflows, then the estuary response can be assessed for that variable.

An example of applying the third method is shown in Figures 3 – 5. In this example, numerical hydrodynamic models were developed and calibrated/verified for the Hunter River estuary, a mature tide dominated estuary, and for Lake Cathie/Innes, a managed ICOL. For each system alternative sea level rise and rainfall/runoff scenarios were simulated as well as combined sea level rise/inflow scenarios to reflect climate change. In the results presented, spatial variant water level and salinity concentrations were extracted from the final model outputs (over an annual cycle) and plotted to compare climate change scenarios versus existing conditions. Long-term salinity exceedance plots were generated to highlight the shifts in conditions under various forcing conditions.
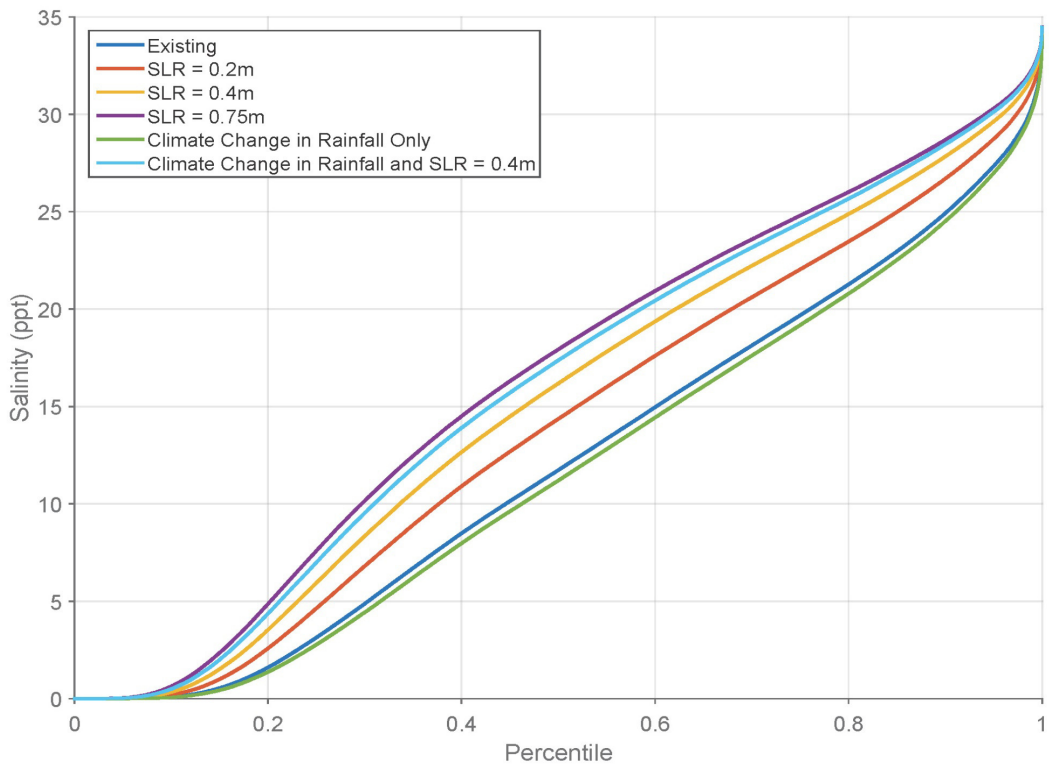
Ramsar Wetland (12 km upstream of entrance)

Figure 3. Salinity Exceedance Percentiles for Existing and Climate Change Scenarios at the Hunter River Ramsar Wetland Site (note SLR = sea level rise).
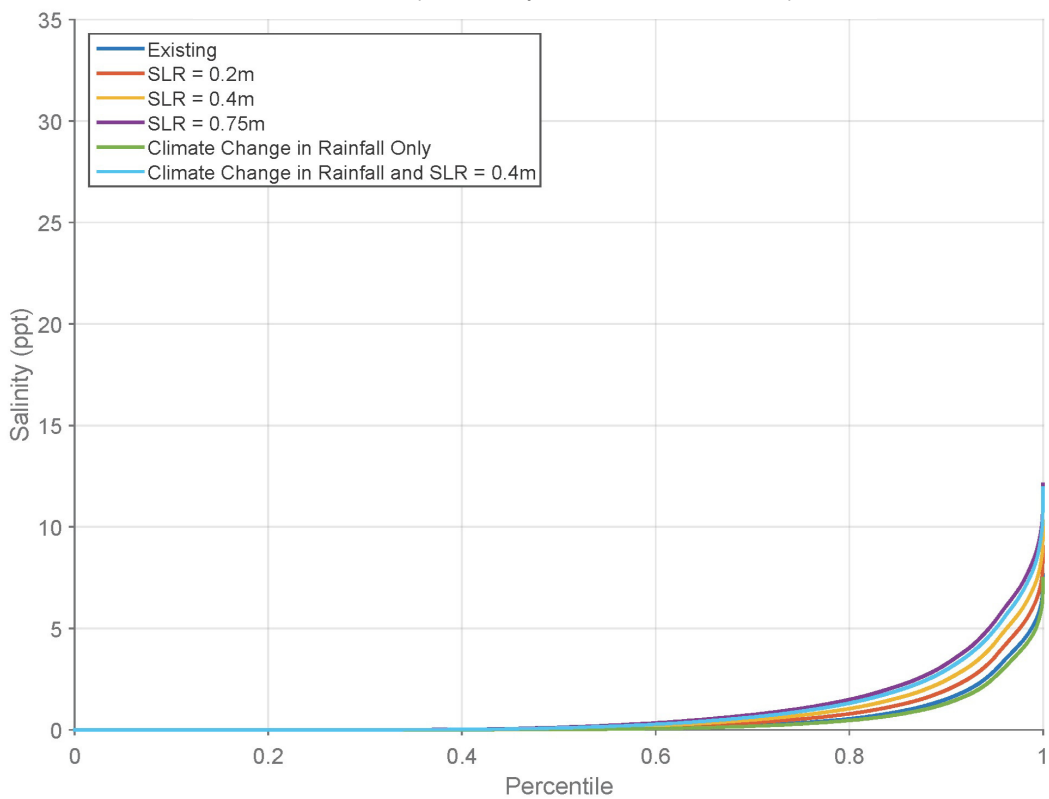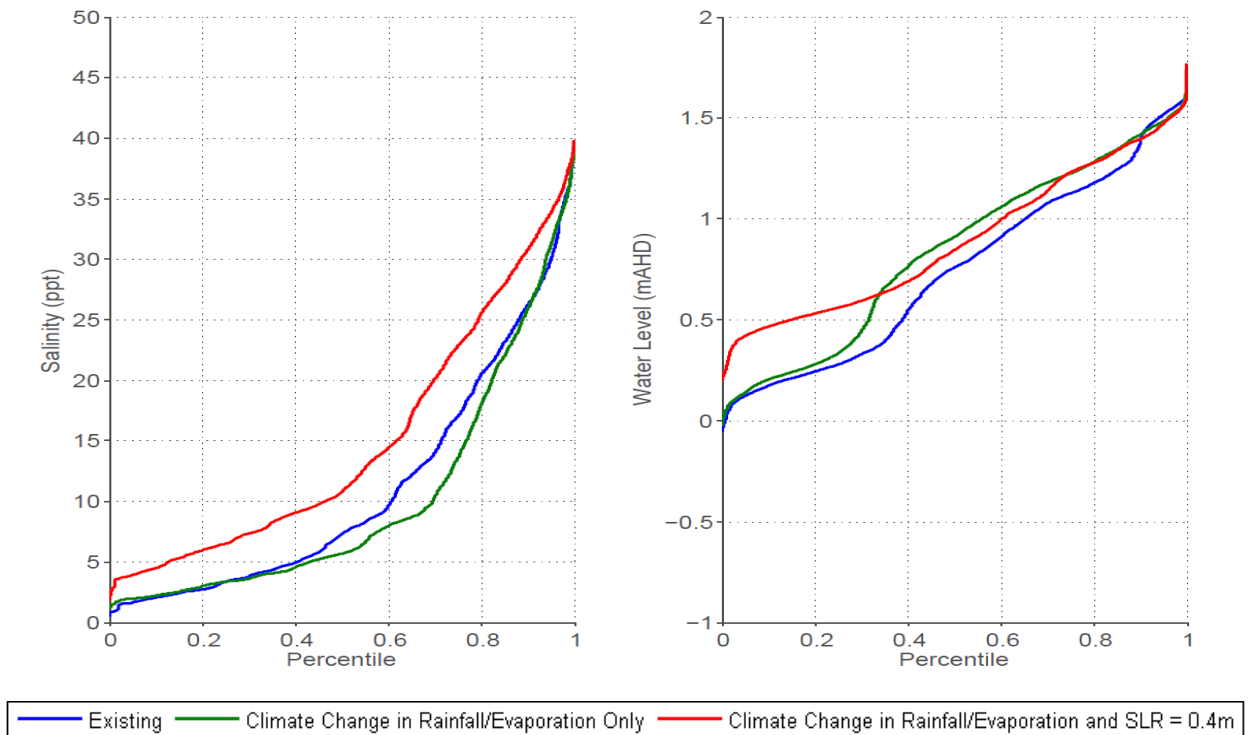
Tidal Pool (40 km upstream of entrance)

Figure 4. Salinity Exceedance Percentiles for Existing and Climate Change Scenarios in the Hunter River Tidal Pool (40 km upstream of the entrance)

Scenario	Change in Rainfall (%)				Change in Evapo-Transpiration (%)				SLR (m)
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	
1	-	-	-	-	-	-	-	-	-
2	+10.8	+20.6	-1.3	+7.2	+8.6	+11.7	+11.3	+7.0	-
3	+10.8	+20.6	-1.3	+7.2	+8.6	+11.7	+11.3	+7.0	+0.4

Figure 5. Salinity Exceedance Percentiles for Existing and Climate Change Scenarios at Lake Cathie/Innes under Varied Rainfall, Sea Level Rise and Evapo-Transpiration Scenarios.

The results depicted in Figures 3 and 4 indicate that salinity concentrations will increase under different climate change scenarios. Figure 3 highlights the potential changes in salinity at the Ramsar Wetland site located 12 kms upstream of the entrance. At this site the greatest change in salinity is predicted to occur during average conditions with 50 %ile salinity shifting from 12 ppt to 17 ppt with the addition of sea level rise and altered catchment inflows. Importantly, the results indicate that over an annual cycle the predicted changes in rainfall alone would likely reduce the salinity but when sea level rise is included salinity concentrations increase. Further seasonal modelling could be subsequently undertaken to investigate how these conditions would alter on a seasonal or monthly basis.

In contrast to the lower estuary Ramsar site, the upper estuary tidal pool (40 kms upstream of the entrance) responds quite differently under climate change scenarios. As per Figure 4, salinity concentrations under median conditions are largely unchanged, however, salinity concentrations during dry conditions are significantly altered. Of particular importance is the change at the 90 %ile where salinity concentrations are shown to increase from 1.5 ppt to 5 ppt. This is particularly relevant as the tidal pool is utilized for extraction most during these dry periods and elevated salinity conditions will limit irrigation.

Figure 5 shows the salinity and water level conditions at Lake Cathie/Innes under various climate change scenarios. As this system has a managed entrance (opening at 1.6 m AHD) tidal flushing only occurs after the system has been opened. Climate change results shown in Figure 5 indicate that salinity levels in the estuary significantly increase under elevated sea level conditions. In contrast to the Hunter River estuary, this is not due to the increased penetration of the sea (since the entrance mouth is closed) but instead is due to higher salinity concentrations when the entrance closes. In this scenario the total mass of salt is increased (compared to the existing conditions) when the system closes and thereby, freshwater inflows provide less overall dilution.

Importantly the results depicted in Figures 3 – 5 depict how a dynamic system responds under altered climate conditions. In contrast to traditional bucket model approaches, this method allows daily, monthly and/or seasonal variations to be tested and indicates how variables other than water depth (such as salinity) are likely to change. Further investigations are underway to assess the secondary impacts to nutrients, extreme events and related biota.

Summary

This paper presents three methods for assessing climate change in estuaries. The first method provides a broad risk-based assessment of estuaries in NSW versus geomorphic type. The second method examines proposed shifts in environmental forcing factors compared to existing conditions by comparing the natural variability versus the proposed variability. In this method the greatest vulnerability is associated with the greatest predicted change away from the existing conditions.

In the third method, detailed calibrated numerical hydrodynamic models are presented to highlight how individual parameters will likely change under different proposed climates. In this method individual parameters can be assessed dynamically over various spatial and temporal scales. Variations in water levels and salinity are highlighted for two different estuary types. Further research is underway to investigate the impact of extreme short term events using regional downscaled climate change predictions.

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