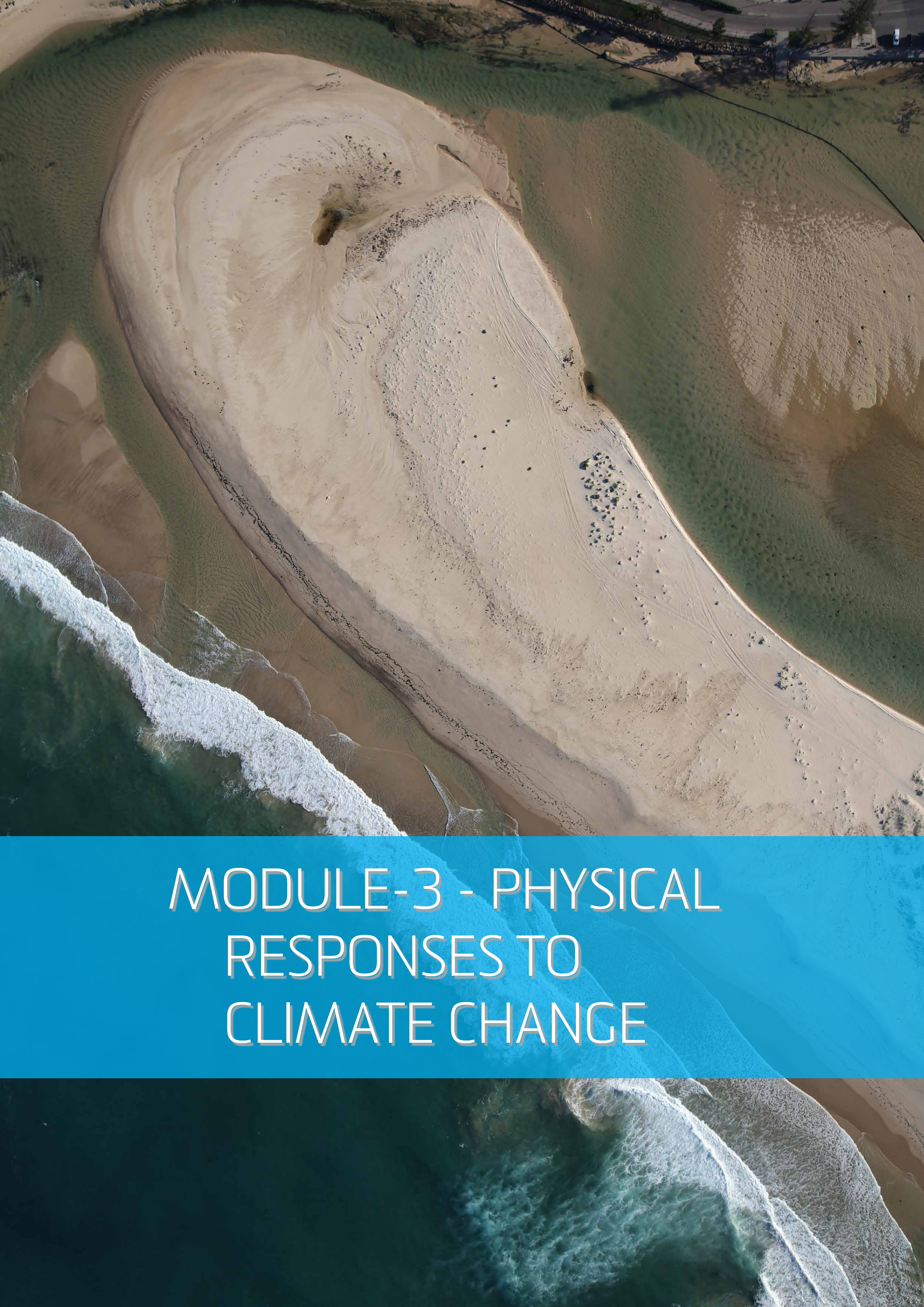
MODULE-3 - PHYSICAL RESPONSES TO CLIMATE CHANGE



All aerial photos in this module were taken during drone surveys at Narrabean Lagoon, Cockrone Lagoon and the entrance of Lake Tuggerah (cover photo), New South Wales, by Chris Drummond; Water Research Laboratory - University of New South Wales.

Drone view of Narrabean Lagoon, Sydney, Northern Beaches, NSW; Photo: Chris Drummond, WRL, UNSW

MODULE OUTLINE

Preface

This guide is the result of five years of research and close collaboration between project partners. The guidelines and information reproduced in this guide have been agreed by all project partners based on their extensive knowledge and experience in the field of estuaries and climate change with advice from the scientific community. This guide has been published as a series of modules. Each module is a stand-alone document addressing an important aspect of assessing climate change risks in estuaries. The following modules are available in the series (titles are abbreviated here):

1. Introduction
2. Changes in climate
3. **Physical responses (this module)**
4. Ecological responses
5. Managing local stressors
6. Application of the framework
7. Review of ecological thresholds
8. Knowledge gaps and research needs

Summary of Module-3

Estuaries are highly dynamic and complex systems. Each estuary will have a unique physical response to future climatic changes, depending on its geomorphological regime and hydrological setting. A summary of physical estuarine processes and their relationship with the surrounding climate was provided in Module-1. Module-2 illustrated how changes in the climate and ocean system can be estimated and prioritized based on their relevance for estuaries. This module covers the physical responses of estuaries to these projected changes in the climate. To estimate this response requires some form of modeling. Provided in this module is an overview of available modeling approaches and their respective data requirements. This module concludes with a summary of the strength and direction of key physical climate change impacts for different types of estuaries in NSW.

Questions addressed by Module-3

1. What are the likely responses of physical estuarine processes to projected climate change?
2. What modeling tools and datasets are available to determine physical responses to climate change?
3. What are the key physical changes within estuaries that are likely to occur in response to projected climate change?

This report should be referenced as

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Peer review

Module-3 has been peer-reviewed by Dr. Peter Coad (Hornsby Shire Council) and Michelle Fletcher (New South Wales Office of Environment and Heritage).

Disclaimer

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Tip for readers

The modules in this series are designed to be read as double page booklets. To benefit from the many double page-sized figures and illustrations, it is recommended to read the modules in double page view, which is possible with most pdf readers. The first page is the booklet cover and should be in single page view.

1 Introduction

Module-1 introduced the physical and ecological functioning of estuaries together with the likely impacts of climate change and presented the conceptual framework for assessing impacts. Module-2 reviewed and summarised the changes in climate drivers that estuaries are, or will likely, be facing. To estimate how estuarine ecosystems will respond to those climatic changes (Module-4), it is necessary to first understand the impacts of climate change on the physical estuarine environment, which is the focus of this module.

Figure 1 shows a conceptual diagram of the content of this module and its linkages with the other modules. In Section 2 of this module, the impacts of projected changes in climate on physical estuarine processes are reviewed and summarized. Estimating physical responses of estuaries to changes in climate conditions requires some form of modeling, which can be conceptual, statistical, numerical or physical (Figure 1). Models can help strengthen our understanding of processes occurring in estuaries as well as the relationship between the external (i.e. rainfall, ocean temperature) and internal processes (estuarine mixing and water quality). The external processes are the boundary conditions or forcing of the estuary model. Once a model is developed to simulate estuarine processes, based on observed conditions, it can be used to simulate possible future scenarios via climate projection forcing data. Available modeling approaches that can be used for this assessment are briefly summarized in Figure 1 and discussed in Section 3 of this module. For many applications, it is sufficient to understand the general trend and magnitude of physical changes resulting from climate change and a summary of likely physical changes in different types of estuaries is provided in Section 4.

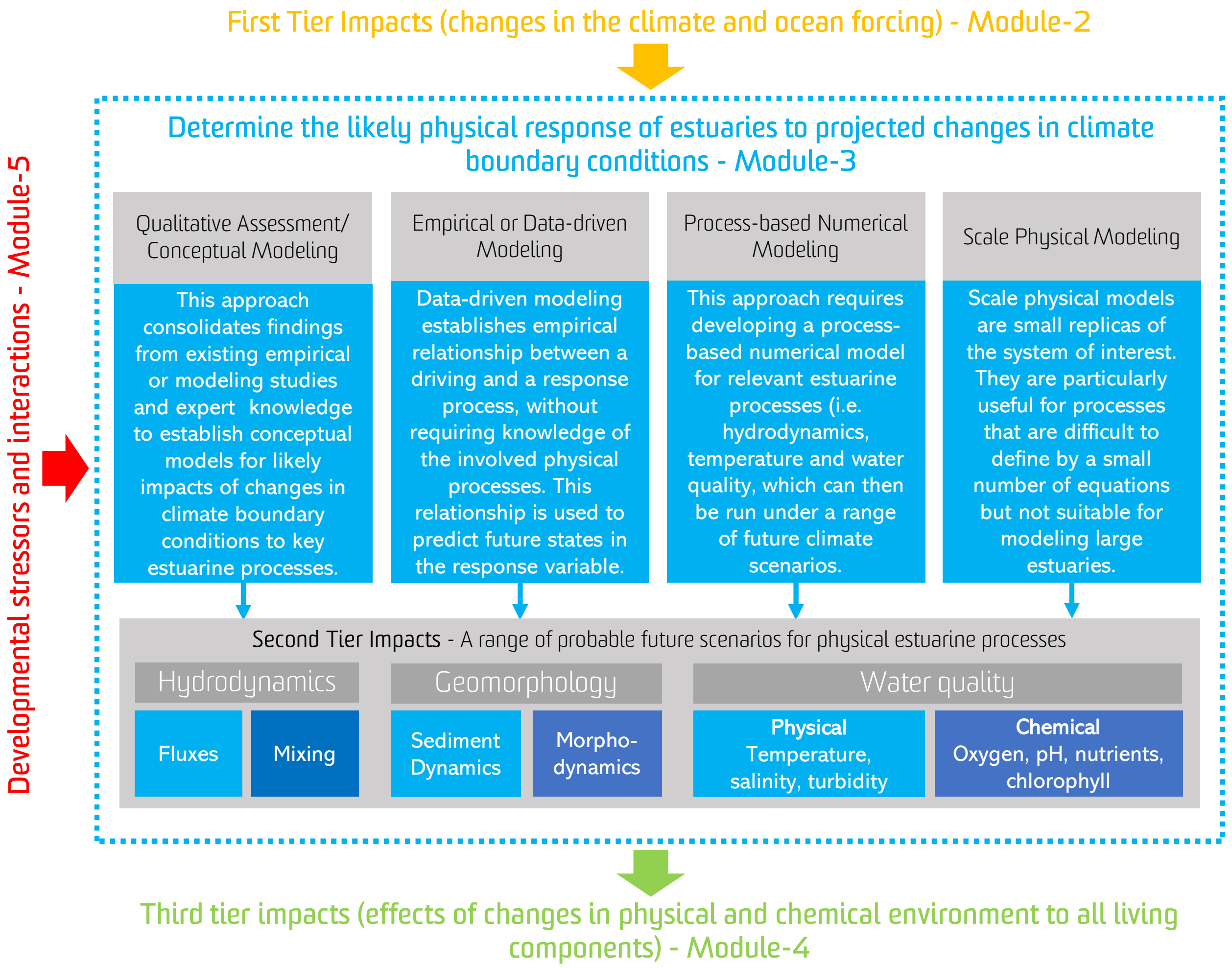


Fig 1: Conceptual flowchart illustrating the scope of this module and its role in the overall climate change risk assessment.

2 Review of physical responses to changes in climate drivers

Estuaries are rarely in steady state, even under natural climatic regimes, but climate change may push many physical processes beyond the boundaries of natural variability. Water temperature, salinity, acidity, dissolved oxygen, turbidity, sediment loads, nutrients, chlorophyll and hydrodynamics (i.e. water levels, flows and hydroperiods) are key variables that define the physical estuarine environment.[1] Module-2 established that changes in rainfall and runoff, ocean and air temperature, sea levels, oceanic acidity and winds and storms are the main climatic changes affecting estuaries. This section provides a review and summary of the direct and indirect physical and chemical responses of estuaries to changes in these climate drivers.

> Estuaries are rarely in steady state, even under natural climatic regimes, but climate change may push many physical processes beyond the boundaries of natural variability.

2.1 Parameters that define the physico-chemical environment

Physical estuarine processes can largely be categorized into either hydrodynamic, geomorphological or water quality processes (see Framework for Assessment provided in Module-1). Hydrodynamic processes include tides, mixing, residence times and freshwater flows, which, together with geomorphological processes were explained in detail in Module-1. The physical and chemical parameters that are commonly used as indicators for water quality in estuaries were introduced in Module-1 and are explained below with additional detail as they are critical in assessing estuarine responses to climate change.

The New South Wales (NSW) Monitoring, Evaluation and Reporting (MER) program[1] is an estuarine water quality and ecological monitoring program that was initiated in 2007 by the NSW Government. The MER program provides quality-controlled continuous data (2007 onwards) on a range of important water quality parameters for the majority of NSW estuaries and hence, can provide valuable baseline data for the assessment of climate change impacts to estuaries. Available sources of data and website links are provided in Section 3.2.

2.1.1 Physical water quality parameters

Temperature:

Temperature is a critical factor that influences most chemical and biological processes in an estuary. Increased temperature decreases the level of oxygen that can be dissolved in the water column. Water temperature also influences the rate of plant photosynthesis, the metabolic rates of aquatic organisms, and the sensitivity of organisms to toxic wastes, parasites, diseases, and other stresses.[2]

Salinity:

Salinity is a measure of the amount of salts dissolved in water. Salinity levels influence the type of species that can live in an estuary and influences physical and chemical processes such as flocculation and the amount of dissolved oxygen (DO) in the water column. In clean water, salinity approximately equals the concentration of total dissolved solids (TDS), which are the sum of particles that are smaller than 2 microns (i.e. electrolytes and dissolved organic matter).[3]

Turbidity and total suspended solids:

Turbidity is a measure of water clarity, that is, the ability of water to transmit light, and is influenced by the level of suspended material in the water column. The amount of suspended material in water is measured as the concentration of total suspended solids (TSS), which is the concentration of all particles larger than 2 microns.[4] In estuaries, TSS mostly consists of fine sediment, silt, sand, plankton and algae. Elevated TSS and turbidity levels occur naturally through erosion, storm runoff, and the input of plant material on a seasonal basis. Turbidity can also be indicative of degraded water quality if elevated levels are caused by excessive erosion, upland development, organic material due to nutrient enrichment, or uncontrolled discharges from sewage treatment plants or industrial facilities.[4]

2.1.2 Chemical water quality parameters

Oxygen:

Two oxygen parameters commonly monitored in waterbodies are dissolved oxygen (DO) and biological oxygen demand (BOD). DO is the level of oxygen in the water column in molecular form that is available to support estuarine ecology. The DO level is controlled by mixing at the air/water interface, temperature and salinity, the level of photosynthesis, and decomposition of organic material. Generally, DO levels greater than 4 mg/l indicates an adequate supply of dissolved oxygen to support marine species growth and activity, while levels from 1-3 mg/l indicate hypoxic conditions, which are detrimental to marine life. DO below 1 mg/l indicate anoxia, a condition in which no life that requires oxygen can be supported. BOD measures the amount of oxygen that organisms would require in decomposing the organic material in the water column and in chemical oxidation of inorganic matter (and is indicative of pollution levels). For instance, unpolluted water has a BOD of less than 5 mg/l, while raw domestic sewage has a BOD of 150 to 300 mg/l.[5]

Nutrients:

Nitrogen and phosphorus (in combination commonly called nutrients) influence estuarine water quality as they have significant direct or indirect impacts on plant growth, oxygen concentrations, water clarity, and sedimentation rates. They influence both the overall biological productivity of the estuary and the decline of the estuarine water quality through eutrophication, a process where high nutrient concentrations cause excessive growth of plants and algae in waterbodies.[1] Nitrogen (N) is essential in protein and DNA synthesis in organisms and photosynthesis in plants. Phosphorus (P) is critical to many metabolic processes. The ratio between N and P has significant effects on species succession and abundance of organisms in estuarine environments.[6] A low N:P ratio, for example, will allow species with lower N requirement to prosper and may facilitate agal blooming.

Primary nitrogen species of interest in the estuarine environment include nitrate (NO_3), nitrite (NO_2), and ammonia and ammonium (NH_3 and NH_4).[1] Nutrient concentrations are typically reported in mg/l of total nitrogen and total phosphorus. Even though nutrients themselves are not a threat to marine life, they can contribute to problems such as excessive plant and algae growth, low DO, and eutrophication. Excessive nutrients can also trigger and sustain toxic algae blooms. However, these adverse effects are dependent on other factors in addition to nutrient levels.

pH and Alkalinity:

The pH of water is a measure of the concentration of hydrogen ions (H^+) and indicates how acidic or basic it is. A pH level of 1 to 7 indicates degrees of an acidic solution, while a level of 7 to 14 indicates degrees of a basic solution (with 14 being extremely basic).[7] Alkalinity is a measure of water's capacity to neutralize acids and is influenced by the presence of alkaline compounds in the water such as bicarbonates, carbonates, and hydroxides. Alkalinity is reported as mg/l of calcium carbonate ($CaCO_3$) and oceanic water naturally has a high level of alkalinity,[8] providing estuaries with a high degree of tidal flushing improved acid buffering capacity. Most aquatic plants and animals are adapted to a specific range of pH and alkalinity. Significant variations outside of this range can be detrimental. In addition, pH and alkalinity influence the estuarine carbon cycle, which involves the movement of carbon from the atmosphere into waterbodies and plant/animal tissue.

Chlorophyll-a:

Chlorophyll-a is a green pigment found in phytoplankton (small microscopic marine algae found in waterbodies), the first trophic level in the primary production cycle. The amount of chlorophyll-a in the water column is indicative of the biomass of phytoplankton, which can indicate nutrient levels (or excess nutrients if the chlorophyll-a values are elevated). The presence of excessive nutrients and plant growth can potentially decrease DO levels and increase turbidity.[9]

Further reading:

Water quality parameters:

https://www.fondriest.com/environmental-measurements/parameters/water-quality

Water quality of New South Wales estuaries:

NSW Monitoring, Evaluation and Reporting program and estuarine water quality data:[1]

2.2 Responses to increases in temperature

Module-2 established there is high confidence that both air and ocean temperatures along the NSW coastline have already increased and are likely to increase by another 2°C (on average) by 2070. Both terrestrial and oceanic heat extremes are likely to become more frequent and intense, with increases in the temperature baseline outside of the historical variability range becoming more likely. Estimating the response of estuaries to these changes requires a thorough understanding of the importance of water temperature as well as the heat energy budget of estuaries.

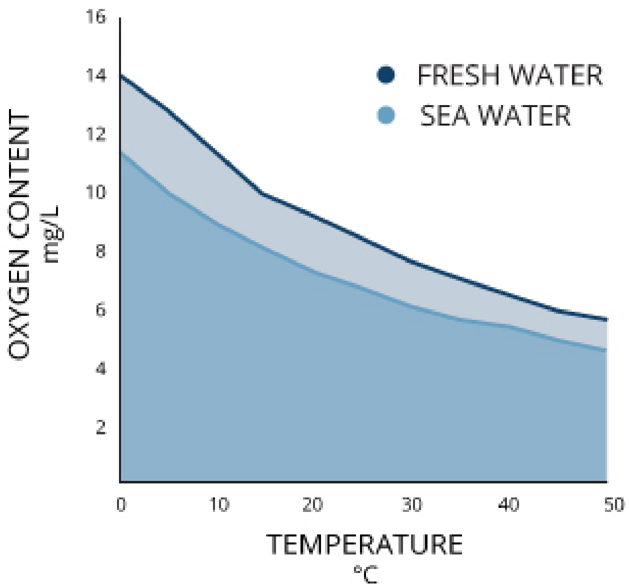


Fig. 2: Maximum dissolved oxygen content depending on temperature and salinity of water. Source: Fondriest Environmental (2014) [5]

Water temperature is a critical parameter in estuaries as it directly affects physical properties such as density and conductivity as well as the rate of most chemical reactions and biological processes. With increasing temperature, the solubility of oxygen and carbon dioxide decreases (Figure 2), while the oxygen respiration of bacteria increases.[5] As a result, the likelihood of harmfully-low oxygen levels (i.e. hypoxic and anoxic conditions) increases when average and extreme temperatures in estuaries rise in response to climate change. Details on the ecological effects of these changes are discussed in Module-4.

2.2.1 Heat budget and temperature dynamics within estuaries

To understand how estuarine water temperatures will respond to climate change, it is necessary to first understand the heat budget of an estuary. A schematic overview of the heat energy budget of an estuary, including all of the significant incoming and outgoing energy fluxes, is shown in Figure 3.[10] The fluxes shown represent the inputs and outputs of heat energy from the waterbody. Similar to a balance sheet, the heat content of the waterbody is equal to the sum of all incoming energy fluxes minus all outgoing energy fluxes.

As can be seen in Figure 3, water temperatures within an estuary are controlled by a large number of processes including the temperature/volume of water inputs from rivers (Q_v), rains (Q_p) and the adjacent ocean (Q_v), solar heating (R_n), atmospheric temperature (H), and evaporation (LE). Changes or fluctuations in any of these fluxes affect the total heat energy content of the estuarine waterbody (Q_x). In reality, water temperature is highly variable within estuaries across space and time due to localised effects and the influence of horizontal and vertical stratification.[11–13]

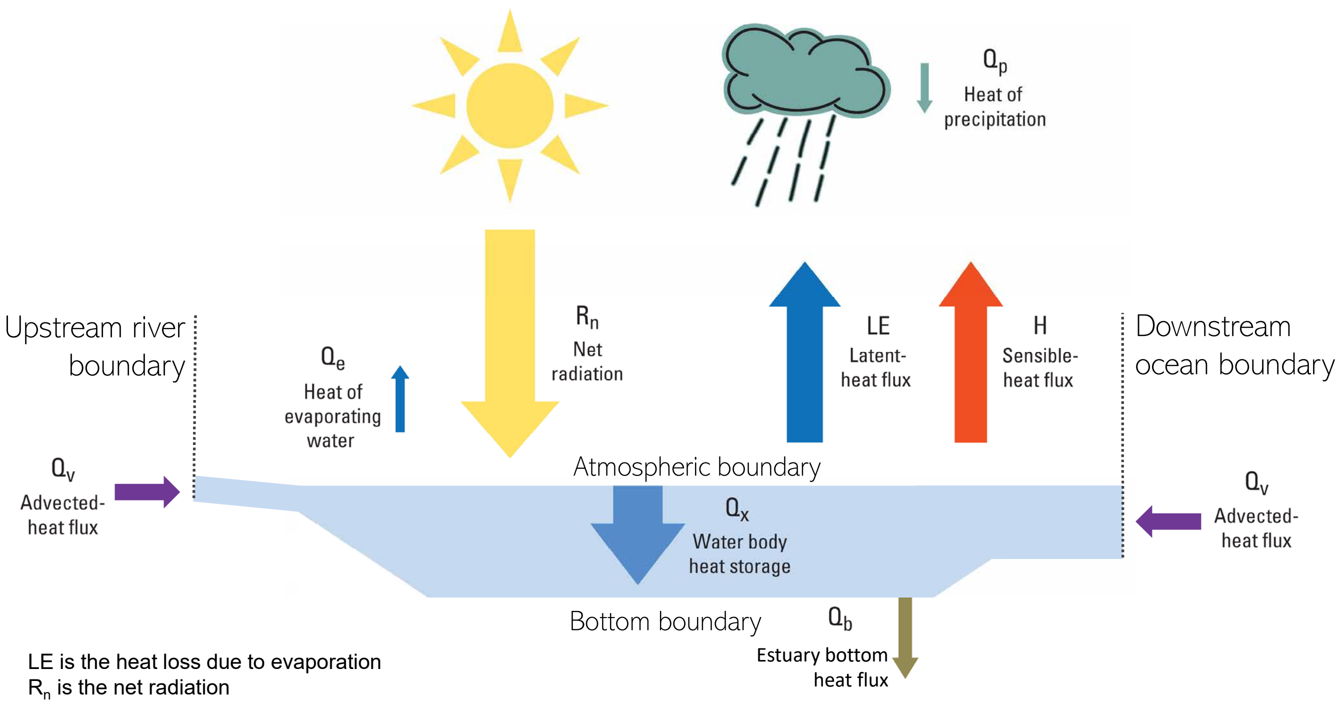
Estuaries often exhibit complex temperature dynamics. The transport and distribution of heat within estuaries is the result of advection, the transport of heat as the result of movement of water, and convection, the movement of heat from warm to cold areas via diffusion.[14–16] Advective heat transport in an estuary is largely driven by mixing, which is controlled by wind, freshwater inflows, tides and density gradients. In addition, the heat exchange at the open water surface plays a significant role in the overall heat budget of estuaries and is controlled by a number of physical processes such as the sensible heat flux (heat conveyed from water to adjacent air), the latent heat flux (heat lost due to evaporation) and the heat that is received and emitted through long and shortwave radiation.[16]

All of the above-mentioned heat energy fluxes depend on the particular geomorphic, hydrological and hydrodynamic regime of individual estuaries and the response to increased temperatures also depends on possible changes in the overall water balance (i.e. changes in rainfall and freshwater flow regimes).[12,17]

Together with the net radiation (R_n), advective heat inputs from the rivers/ocean (Q_v) and rainfall (Q_p) are the main sources of heat energy for estuaries.[12,18,19] The remaining terms are typically net exports of heat energy from the system. As with most waterbodies, water temperatures in estuaries vary seasonally and, to a lesser extent, between night and day. Due to the lower sun angle and shorter sunshine durations, R_n is significantly lower in winter compared to summer as is the temperature of rivers, rainfalls and the ocean. This creates a distinct seasonal pattern in the temperature of estuaries as can be seen in the daily temperature data measured near Raymond Terrace in the Hunter River estuary since 2013 (Figure 4).

Typical for waterbodies, the diurnal (i.e. daily) variation of surface water temperature is small compared to the fluctuations observed over nearby dry land areas. This is because i) some of the incoming solar radiation penetrates the water surface and is transferred to deeper layers, ii) water has a much higher heat storage capacity than dry soil and iii) there is unlimited water supply for evaporation, which limits surface warming during the day through the latent heat flux.[10] Waterbodies, such as estuaries, act as heat storages that absorb much of the incoming solar radiation during the day and release a portion back into the atmosphere throughout the night, without undergoing substantial temperature variations at the water surface. This is also the reason why oceans typically exhibit limited temperature variations at daily time scales and provide warmer and less variable climate conditions to coastal areas as compared to inland areas.

$$Qx = Rn + Qv + Qp - LE - H - Qe - Qb$$



LE is the heat loss due to evaporation
R_n is the net radiation
Q_v is the heat energy in and out of the system through in and outflows of water at the river and ocean boundaries
Q_b is the energy exchange between the water body and the bottom sediments.
H is the heat convected (i.e. transported) between the water surface and adjacent air.
Q_x is the energy stored in the water body.
Q_e is the heat energy exported from the water body through the evaporated water
Q_p is the input of heat energy through precipitation

Fig. 3: Heat energy budget of an estuary. Adapted from Stannard et al. (2013)[9]

Some of the concepts explained above can be illustrated using a real world example. Figure 4 (the blue line with grey boundaries) shows an estimate of the average water temperature over a 5-year period in the Hunter River estuary at each day of the year. This is also known as the seasonal component of the temperature time series. In addition to this regular seasonal component, estuary water temperatures fluctuate at daily, weekly and monthly time scales due to changes in weather and various energy budget inputs.

For instance, during a coastal storm, the net radiation might be close to zero or negative for several days due to the lack of sunlight (e.g. when rainfall and large volumes of freshwater inflows dominate the energy balance). During droughts and heatwaves, on the other hand, freshwater inflows are likely to be warmer than usual, and the sensible heat flux can be negative during the day (due to the hot air temperatures near the water surface) and close to zero at night. Such conditions favour the occurrence of extreme surface water temperatures in estuaries.

Since evaporation typically increases with water surface and air temperature, heatwave conditions would likely coincide with the highest observed levels of evaporation and corresponding latent heat flux. High evaporation rates can lead to increased salinity, reduced stratification and an increase in the mixed layer depth. A study by Ridd and Stieglitz (2002)[20] determined that rapid salinity increases in estuaries in arid parts of Australia were largely the result of evaporative distilling. For estuaries in more humid settings, the effects of evaporation on salinity might be expected to be less important than in arid settings because of the relatively high precipitation and stream flow and the associated diluting effects of these inputs.[21] Both increased temperatures and decreased densities in the upper layers might reduce the vertical convection in the estuary sufficiently to prevent oxygenation of the bottom waters, which can further increase the likelihood of low dissolved oxygen conditions (i.e. hypoxic) in the near-bottom waters.[22] Extreme heat and low oxygen conditions can have significant adverse impacts to estuarine ecological communities, which are discussed in Module-4.

In summary, the heat budget involves multiple fluxes, which are highly dependent on the geomorphic type and hydrological regime of estuaries. Depending on the type of estuary, the heat budget can be dominated either by freshwater inflows, the ocean or the surface heat budget with many estuaries experiencing a unique and variable combination of these fluxes. While ocean temperatures can sometimes change rapidly by a few degrees within a single day, due to upwelling of cooler water from deeper areas or movements in large currents such as the Eastern Australian Current, ocean temperatures are usually very stable at daily and weekly time scales.[8]

Consequently, areas in estuaries that are close to the entrance and undergo tidal flushing typically have more stable water temperatures, with a narrow annual temperature range similar to that of the open ocean. These areas typically get less cold in winter and less warm in summer, as compared to the upstream end of estuaries, where the amount and temperature of freshwater inflows

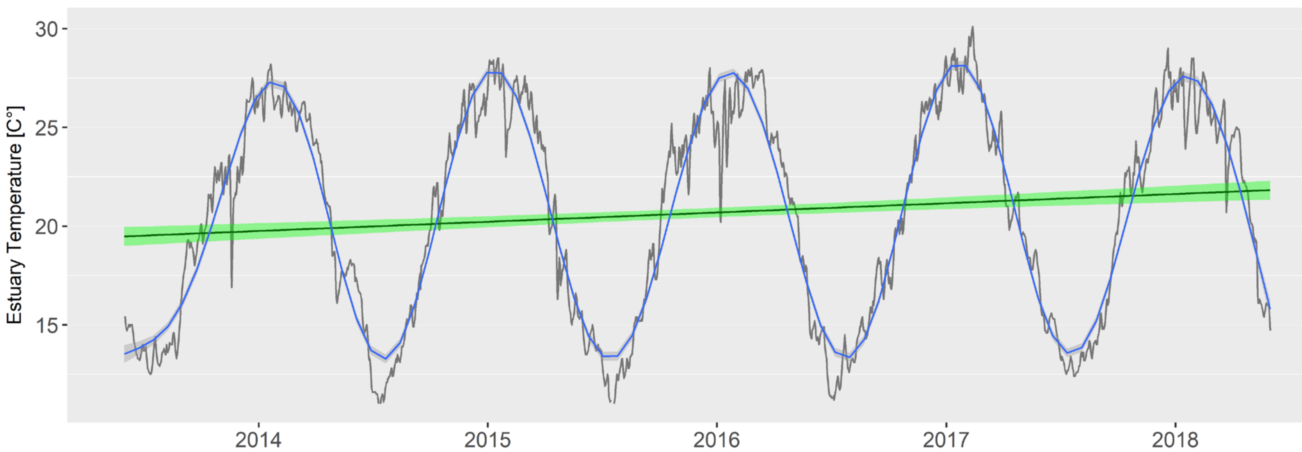


Fig. 4: Near surface water temperature time series measured at Raymond Terrace along with a seasonal component (blue) and a linear trend (green). Over the 5-year period, there was a linear trend of 0.457°C/year increase with p<5%. Source: https://realtimedata.waternsw.com.au/

and the surface heat budget have a more pronounced effect. In these upstream areas, the buffering effect of the ocean becomes less pronounced and, as with salinity, estuaries exhibit a wider range of temperatures throughout the seasons and in response to weather conditions. ICOLLs in particular, exhibit unique temperature dynamics since they can be largely driven by the ocean exchange during openings, while the surface heat exchange dominates the heat budget when the system is not connected to the ocean. More information on the likely effects of climate change-driven temperature increases on estuaries depending on their geomorphic type is provided in Section-4 of this module.

2.2.2 Impacts of climate change on the estuary heat budget

Climate change is likely to affect most of the estuarine heat energy inputs discussed above (Section 2.2.1). Increases in atmospheric greenhouse gases drive climate change by increasing the longwave radiation reflected from the atmosphere back towards the land surface, causing an increase in the average global net radiation (R_n). As detailed in Module-2, average and extreme air (H) and ocean temperatures (Q_v) have increased throughout the 20th century and are projected to continue to increase throughout this century. As a result of the warmer atmosphere, the average temperature of rainfall (Q_p) and freshwater inflows (Q_v) also increases (see Module-2). Each estuary will exhibit a unique response to these changes depending on its geomorphic and hydrological regime. These ongoing increases in the heat forcing will push estuarine water temperatures outside the historic variability range more frequently.

Figure 4 illustrates the nature of the likely temperature response of estuaries. Over the 5-year period, average temperatures increased by 0.457°C per year (see green linear trend line). Large deviations from the seasonal component (blue line), such as the period in early 2017 where temperatures reached nearly 30°C, are usually referred to as anomalies (and heatwaves are commonly defined as positive temperature anomalies that last for a certain number of days). The consistent increase in the average temperature was accompanied by increases in the minimum and maximum temperature of each year, suggesting a tendency of more frequent and extreme positive temperature anomalies occurring at any time of the year.

Temperature records in estuaries are often not long enough to derive statistically meaningful trends. In comparison, reliable longer-term records usually exist for air and sea surface temperature and, to a lesser extent, for significant coastal rivers. Due to limited in-situ data, understanding the existing temperature dynamics of estuaries and the likely response to increases in heat forcing requires modeling. Available models and data sets are presented in Section-3 of this module. A summary of important physico-chemical impacts from the projected increases in water temperature is given in Table 1.

Table 1: Summary of physical responses to increases in estuarine water temperatures

Climate change impact	Physical responses in estuaries
Estuarine water temperatures are rising in response to increases in oceanic, atmospheric and riverine temperature forcing, making the occurrence of previously unobserved temperature levels and estuarine heatwaves more and more likely.	Changes to all temperature dependent chemical and biological processes, primary productivity and nutrient cycles Changes to stratification and salinity (if evaporation increases); increasing likelihood of hypersalinity Decreases in the solubility of oxygen, which favour the occurrence of low dissolved oxygen condition (i.e. hypoxic) Decreases in solubility of carbon dioxide, which can alter the acidity of water

Drone view of a bridge crossing the Tuggerah Lake estuary entrance channel, The Entrance, NSW; Photo: Chris Drummond, WRL, UNSW

2.3 Responses to changes in rainfall and runoff

As noted in Module-2, projections of future rainfall changes are of low confidence, but indicate that the frequency, intensity and distribution of rainfall is changing due to climate change. Future changes along the New South Wales coastline are likely to be increases in the frequency and magnitude of extreme rainfall, the growing length of dry spells and a shift in the seasonality, with more rainfall during summer and autumn and less rainfall during winter and spring.[23] Even though there are no significant changes projected for the total annual rainfall sums (both increases and decreases are possible), these changes in the rainfall regime can have significant effects on the amount, timing and pattern of freshwater inflows to estuaries.

While local rainfall across an estuary can be an important component of the water budget, especially in humid and tropical areas, rainfall mainly influences estuaries by controlling the amount of freshwater inflow from the upstream catchments. The generation of runoff from rainfall as well as its transfer and routing through rivers are affected by both meteorological forces, surrounding landuse and the local physical properties of the catchment. As such, runoff generation varies over time (i.e. season, year) and space (i.e. from catchment to catchment). Factors that affect the freshwater inflows to estuaries in addition to rainfall include catchment storages (surface storage, soil moisture storage, groundwater storage, vegetation, snow and ice) as well as evaporation and transpiration rates which are driven by temperature and solar radiation.[24]

> Changes in the amount, timing and properties of runoff can result from both anthropogenic influences and climate change.

Changes in the amount, timing and properties of runoff can result from both anthropogenic influences and climate change. Changes in human population and water demand, land use, flow abstraction and diversion, and physical impediments such as dams and detention basins all affect the amount and timing of freshwater flows. Climate controls the pattern of seasonal flows, timing and frequency of extreme flows, magnitude of low/intermittent flow as well as instances of no-flow events.[25]

Both changes in average and extreme (i.e. floods) runoff can significantly affect the ecohydrological functioning of estuaries. Chiew et al. (1997)[26] investigated the impacts of climate change on long-term runoff conditions in Australian catchments and found that changes in rainfall are most commonly amplified in runoff, with the amplification factor being higher in drier catchments. Littleboy et al. (2015)[27] investigated the likely future changes in surface runoff across New South Wales using the NARCliM projections as input to a rainfall runoff model. This study found that the average annual runoff will likely increase along the NSW coast with increases of 0–20 mm/year (proportion of rainfall over the catchment that contributes to runoff) projected for the near future and increases up to 80 mm/year for the far future at some locations.[27] Due to the low confidence associated with projections of future rainfall, however, these findings should be interpreted with care.

For floods, it is likely that the projected increases in the intensity of extreme rainfalls will manifest in more severe floods.[28] Comprehensive guidance for estimating catchment flood characteristics in Australia is provided by the Australian Rainfall and Runoff (ARR) guideline, available through the dedicated website (http://arr.ga.gov.au/). The ARR also provides data and software tools for easy estimation of design floods in catchments in Australia in a form readily accessible to practitioners.[29] To account for climate change in catchment flooding, the ARR recommends applying a multiplication factor of 5% per 1°C atmospheric warming to the design rainfalls (i.e. 1 in 100-year rainfall event), which are used to estimate the design floods. Importantly, the already observed increases in extreme rainfall do not always manifest in more floods, due to the altered antecedent conditions before the onset of the heavy rainfall.[24]

Due to the low confidence associated with future projections of rainfall (see Module-2), the naturally-high interannual and decadal variability in rainfalls in South-East Australia[23] and the unique response of each catchment, it is recommended that a detailed hydrological study is conducted for an estuary catchment as part of the climate change risk assessment. The available modeling approaches are discussed in Section-3 of this module. Detailed guidance on flood risk analysis and management in NSW is provided in the Office of Environment and Heritage's Floodplain Development Manual.

Rainfall predominantly drives estuarine processes via freshwater inputs (i.e. runoff from the catchment) but groundwater storages and direct rainfall over the estuary can also be significant contributions. The latter is particularly important for areas with high precipitation. Depending on the type and hydrological setting of an estuary, groundwater discharge can be a significant component of the water balance and affect a range of water quality processes and biota.[30] Freshwater inflows influence estuarine processes such as hydrodynamics (e.g. circulation patterns), mixing (e.g. salinity gradients), sediment dynamics (e.g. entrance conditions, geomorphology, pool and riffle habitats), water quality (e.g. salinity, turbidity, DO, BOD and nutrients), and ecological processes (e.g. productivity, algal response, aquatic vegetation distribution, food web etc.). The potential effects of changes in rainfall on runoff on these estuarine processes are presented below.

2.3.1 Effects on hydrodynamics and mixing

Freshwater inflows affect the estuarine circulation patterns in the horizontal and vertical dimension. Depending on the strength of the river flow, freshwater can penetrate throughout or only within a limited distance into the estuary. The mixing of freshwater with seawater is the main process that determines salinity patterns in estuaries. As the effectiveness of mixing is directly determined by the comparative magnitude of both waters,[31] changes in either flux will influence the salinity conditions.

Large river discharges (i.e. during flood events) can temporarily displace the tidal mixing zone from the estuary. In comparison, very low flows in combination with high evaporation can result in hypersaline conditions or cause density gradients. Such conditions favour salinity intrusion upstream into the freshwater zone. The resulting temporary increase or decrease in salinity can have adverse effects on the ecological communities (see Module-4).

> Large river discharges during floods can temporarily displace the tidal mixing zone from the estuary.

The extent of these effects depends on the type of the estuary and the quality of the freshwater inflows. An extreme example occurs in some estuaries in Western Australia, which are influenced by hypersaline conditions arising from seawater intrusion, evaporation and saline runoff from the catchment.[32] A study by Davies and Kalish (1994)[33] showed a clear relationship between river flow and the location of a salt wedge in the estuary on the Derwent River in Tasmania, where flows of 75 m^3/s were needed to displace the salt wedge from its reference position. They also found a negative relationship between salinity and DO, with periodic high flows being required to maintain adequate DO levels. Estuaries on the northern and eastern coast of Australia can also undergo distinct phases of salinity, with a dry phase followed by a flood flow that can expel salt water from the estuary.[34] This saline structure can be highly variable as a result of the high interannual variability of rainfall.[35]

Brisbane Water estuary and surrounding catchment, Central Coast, NSW; Photo: Valentin Heimhuber, WRL, UNSW

2.3.2 Effects on sediment dynamics

Runoff is typically the main supply of terrestrial sediment to estuaries. As such, future changes in sediment supply to estuaries largely depend on the catchment rainfall and runoff processes and the land use type in the catchment. Locally, more intense rainfall episodes have the potential to alter flood regimes and cause extensive catchment erosion. These episodes, and their impacts, are further exacerbated with land clearing and catchment development.[36] Consequently, intense runoff often causes rapid accumulation of bed sediment as it mobilises more suspended sediments and pollutants into estuaries. The long-term accumulation of sediment on the benthic layer can form barriers to flow and navigation with consequences to the tidal hydraulics and ecology. This can result in extended water residence times which may result in nutrient over-enrichment and favour toxic algal blooms.[37,38]

> The geomorphic and hydrological variability of estuaries across Australia and the uncertainty of the overarching impact of rainfall to various types of estuaries means it is difficult to predict impacts on a broad scale.

The geomorphic and hydrological variability of estuaries across Australia and the uncertainty of the overarching impact of rainfall to various types of estuaries means it is difficult to predict impacts on a broad scale. Eyre (1998)39 classified Australian estuaries according to their hydrology and reported that 68% of Australian estuaries fall in the "Wet and Dry Tropical/ Subtropical Category", which are dominated by episodic short-lived large freshwater inputs during summer with limited inflow during winter. Large episodic freshwater flows significantly affect the transport, retention, and transformation of material from catchments to estuaries and are likely to become more common with the onset of climate change. Dry periods favour antecedent accumulation of sediments, salts and pollutants in the catchment, particularly during prolonged droughts with drying vegetation.[40] Drier soils can impact on the quality of the sediment and nutrients delivered to the catchment. For further information, Römkens et al. (2002)[41] provides a good summary of erosion under different rainfall intensities, surface roughness, and soil water regimes.

On the other hand, despite the increased runoff intensity, sediment inputs to estuaries can also be reduced due to sediment trapping in dams constructed along the rivers.[42] Such impoundments and river regulations change the flow regimes in rivers, such that the intermittently periodic flushing of estuarine sediments in large floods may be reduced.

2.3.3 Water quality

In addition to changes in freshwater inflow and sediment dynamics, runoff from developed catchments may convey contaminants in various forms (physical, chemical, microbiological), which can impact estuarine water quality.[43] Pollutant characteristics vary according to catchment land uses with contaminant loadings generally being higher in urban runoff than in rural areas although rural agricultural areas can have very high pollutant loads.[26] While sediment and litter are the most obvious physical pollutants, chemical pollutants may comprise inorganic and organic compounds including oil, metals, pesticides, nutrients and their transformation products.

Stormwater pollution is typically a consecutive process of build-up and wash-off. Pollutants accumulate during dry spells, and are mobilized and transported during the rainfall and runoff process, with higher rainfall intensities leading to increased mobilization.[44,45] Field and laboratory experiments by Vase and Chiew (2003)[45] showed that pollutant wash-off is transport limiting, meaning the energy of both rainfall and runoff are significant in generating pollutant wash-off.[45] This suggests that there is a strong relationship between climate change impacts on rainfall (i.e. increasing extreme rainfall intensities and dry spell length) and pollutant loadings in stormwater runoff to estuaries (through increasing build-up and wash-off).

Turbidity, DO and pH (see Section 2.1) are variables that are often impacted by sediments and pollutants conveyed by freshwater inputs.[43] Increased turbidity concentration limit available light in the water column, which can have secondary impacts to estuarine ecology, including plankton and submerged aquatic vegetation (see Module-4). Nutrient enrichment in estuarine areas that are poorly flushed can lead to eutrophication and cause oxygen depletion and toxin accumulation. These interrelated processes indicate how the biological community in estuaries can be impacted by changes within the physical environment in response to freshwater inputs.

One impact that has received considerable attention in NSW is sulfuric acid runoff following oxidation of sulfides in previously anaerobic sediment containing iron sulfides, commonly known as acid sulfate soils. The resulting acid plumes typically occur in response to heavy rainfall events after prolonged dry periods,[46] both of which may increase due to climate change.[23] Further details are discussed in Section 2.5.

2.3.4 Summary of impacts of changes in rainfall and runoff

Table 2 provides a summary of the key changes in rainfall and runoff along with the most relevant physical responses of estuaries to these changes. In summary, increases in freshwater input can have both beneficial and detrimental impacts on estuaries. Runoff can aid soil accretion and increase the nutrient concentrations, which influences primary production. Negative impacts can include the delivery of excessive nutrients and sediments, which can lead to algal blooms and low oxygen conditions in bottom or benthic waters. Pierson et al. (2002)[34] summarizes the likely consequences to estuaries based on the dominant changes in the freshwater flow regime as follows:

Shift towards low magnitude runoff

Decreases in runoff can reduce inflows to estuaries and result in reduced vertical mixing and protracted water retention time, particularly in deep sections within the upper-middle estuary. This can lead to elevated salinity and decreased DO, which may adversely affect sensitive flora and fauna. Subsequent water-quality deterioration may occur due to collapsed bank materials and dying riparian plants. Reduced flows can further limit the transport of eggs and larvae, reduce the longitudinal connectivity between the upstream river and estuarine system and aggrevate pollution problems.

Shift towards middle and high magnitude runoff

Increased runoff can reduce water quality through higher sediment inputs from catchments and banks, and through reduced tidal exchange flushing. High flows in estuaries can also cause substrate turnover by the flushing of fine sediments and organic materials that may reduce inputs of nutrients, limiting the deposition/attachment sites for eggs and larvae and lowering reproductive success.

Shifts across all runoff magnitudes

Shifts across runoff magnitudes can affect the variability of inflows and flow velocities in estuaries, which can disrupt the salinity structure. Changes in velocity fields can affect the availability of important physical habitat features.

Table 2: Summary of impacts of changes in rainfall and runoff on physical estuarine processes

Climate change impact	Physical responses in estuaries
Rainfall is projected (low confidence) to undergo further increases in the magnitude and frequency of extremes and the duration of dry spells, along with a shift in the seasonality, with more rainfall during summer and autumn and less rainfall during winter and spring. These changes in the rainfall regime can lead to large changes in freshwater inflows to estuaries. Projections of future freshwater flows are of low confidence but indicate increases of up to 80 mm in annual surface runoff along the NSW coastline in the far future.	Changes in local density currents, circulation patterns and mixing Changes in salinity regimes, stratification, water balances and water quality Changes in the transformations of nitrogen and phosphorus which occur within areas of high turbidity (resulting from catchment sediments delivered from runoff) Changes in sediment dynamics and erosion Changes in nutrient loads, leading to changes in water quality Changes in flushing and residence times, particularly for intermittently open estuaries

2.4 Responses to sea level rise

Module-2 illustrated that the mean sea level along the NSW coastline has risen approximately 10 cm since 1900 and there has been an acceleration in the rate of rise since 1990. Under the business as usual emission scenario RCP 8.5, there is *high confidence* that sea levels will rise by another 45 [31-59] cm by 2070 and by 78 [54-106] cm by 2100 (relative to the 1996 mean sea level).[47] Historic trends around Sydney and Perth indicate that extreme sea levels have increased slightly faster than mean sea levels during the last century.[48] However, end-of-century projections for the driving processes behind sea level extremes are of *low confidence* and indicate only minor changes in the average storm and wave climate.[49] Details on these projections are given in Module-2 and the corresponding summary table of recent historic and future changes in the NSW coastal climate.

Estuarine hydrodynamics and mixing are controlled by a unique combination of wave, tide and river energy. The steadily accelerating rise in the mean sea level will cause a shift in this balance.[50] Since estuarine hydrodynamics directly influence geomorphological processes (and most other physical processes), these changes will have wide-reaching impacts on estuary ecosystems. As such, quantifying the internal responses of estuaries to sea level rise requires a detailed understanding of the complex tidal dynamics (i.e. water levels, flow velocities and hydroperiods) of estuaries under present day conditions. Once a thorough understanding of the system's hydrodynamics is established, the impacts of sea level rise can be estimated, which typically requires some form of modeling. Since the majority of estuaries in NSW are separated from the open ocean through confined entrances and barriers, the projected changes in open ocean mean sea levels cannot be applied directly within estuaries. This is because each estuary has a unique internal response to sea level rise, which depends on its geomorphological setting and hydrological regime.[51–54]

Sea level rise is anticipated to impact low-lying coastal areas as a result of inundation, thereby increasing bank erosion and reducing drainage efficiency.[55–57] Mean sea level rise will amplify factors that contribute to coastal flooding and have disproportionate impacts on coastal regions. This has prompted considerable focus by all levels of government to better understand these impacts to coastal regions.[58] As discussed in Module-2, sea level rise leads to an increase in both average and extreme sea levels, even if the forcing factors causing extreme sea levels (i.e. coastal storms) remain unchanged in response to climate change. Increases in the average water level can lead to significant changes in the water level and mixing dynamics of estuaries. Increases in extreme water levels may proliferate coastal flooding and erosion in and around

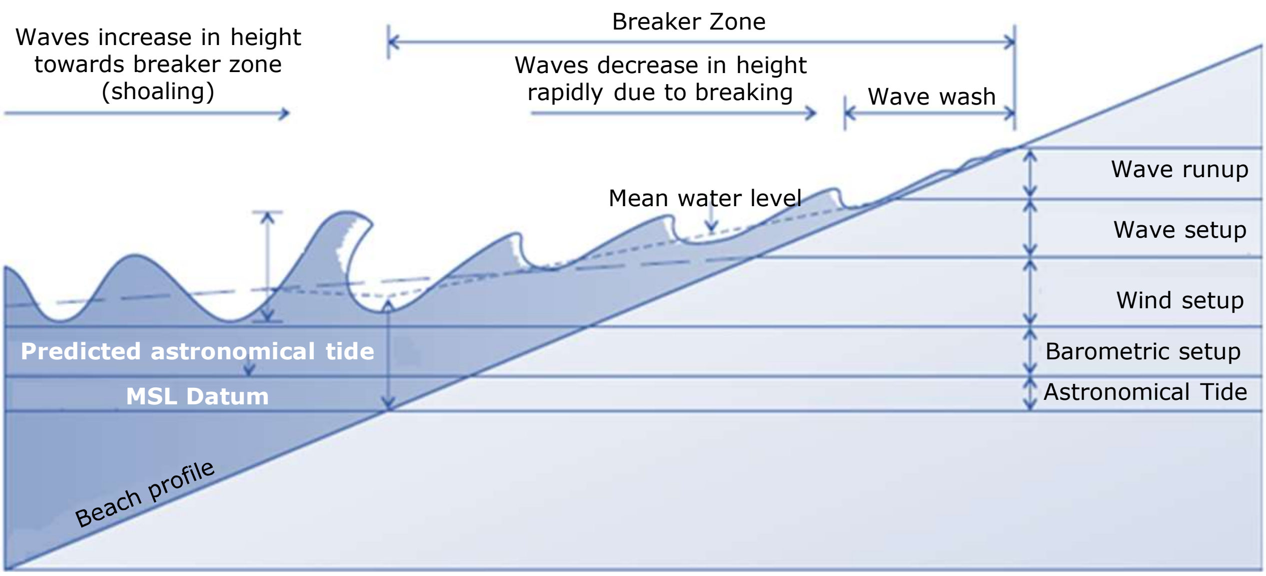


Figure 5: Components of elevated water levels during a storm event (after NSW Government, 1990)

estuaries. The multitude of direct and indirect internal physical responses of estuaries to sea level rise are reviewed in the following sections.

2.4.1 Future sea levels at the open coast

Due to the limited effect of sea level rise on the tidal dynamics at the open coast, adding the projected sea level increases to the present-day oceanic tidal planes is considered a reasonable approximation. This approximation generally also applies to large oceanic embayments. However, prediction of extreme water levels at the open coast, which are the main driver of estuarine inundation, is complex as a number of other factors need to be considered.

In NSW, extreme water levels are typically the result of storm surges caused by east coast lows.[59] Storm surge (also referred to as storm tide, storm set-up, wind set-up, storm-induced rise, or storm rise) is the temporary rise in water levels along a coastline as a result of reduced atmospheric pressure (i.e. barometric set-up) and is often accompanied by strong onshore winds blowing across a large fetch of open water (i.e. wind set-up)[60] (Figure 5). In NSW, traditional definitions of storm surge exclude wave setup and wave runup, with storm surge comprising predominantly barometric and wind set-up, plus other components described below. Low atmospheric pressure has a broad-scale influence on coastal water levels, while wind set-up is more severe in shallow coastal waters and semi-enclosed bays.[61]

Storm surge duration can vary from hours to days, depending on the severity of the event, with typical values along the NSW coast provided in Table 3. Importantly, the values provided in Table 3 are based on historic observations. Uncertain, yet possible, changes in the frequency and force of coastal storms due to climate change may affect future extreme values.

To date, the majority of existing coastal inundation studies have used static “bathtub” approaches, where sea level rise projections are added to existing estimates of coastal extreme sea levels to derive an inundation extent.[49] Whilst these approaches provide useful guidance for areas most vulnerable to coastal inundation from sea level rise, they do not capture the processes that influence inundation during extreme events. To better assess these attributes, the various components that contribute to the overall expected extreme water level should be considered. Figure 6 provides an illustration of the components that contribute to extreme water levels in NSW without accounting for climate change. In addition to these factors, geomorphic factors such as land subsidence, dredging, biological sediment deposition, sand mining, beach erosion and nourishment should be considered as they may have an impact on wave set-up and run-up dynamics at a local scale.

2.4.2 Future sea levels in estuaries

Average conditions

Compared to the open coastline, estimating future water levels in estuaries is subject to additional related effects of catchment runoff, internal hydrodynamics and geomorphological responses. Mean water levels are a determining factor for the physical estuarine environment

Table 3: Elevated water level components due to storm events without accounting for climate change (after NSW Government, 1990)[60]

Component	Typical Range (m)	Additional Comments
Barometric set-up	0.1 – 0.4	Barometric set-up can cause a 0.1 m increase in water level for every 10 hPa drop below 1013 hPa (i.e. average atmospheric pressure). Storm surge (the combination of barometric and wind set-up) can raise coastal water levels in NSW by up to 0.5 m[62]
Wind set-up	0.1 - 0.2	
Wave set-up	0.7 - 1.5	Measurements from open coast beaches in NSW suggest that a wave set-up of up to 1.5 m can be expected at the shoreline during serve storms (Nielsen, 2010)[63] in (SMEC, 2013)[64]
Wave run-up	3.0 - 6.0	Design levels for wave run-up on open coast beaches in NSW exposed to waves may be up to 10 m AHD[65]

and are primarily controlled by sea levels and tides, with rainfall and runoff typically only having a negligible influence (with the exception of very high flows during river floods).[25] Consequently, the propagation of tidal fluctuations upstream within estuaries is the determining factor for present day and future mean water levels.

The propagation of open ocean tidal fluctuations within estuaries differs greatly amongst different geomorphic types and sizes of estuaries. This section focuses on the response of estuarine hydrodynamics and tidal dynamics to sea level rise. The reader is referred to Section 2.3 of this Module and the ARR (http://arr.ga.gov.au/) to gain a further understanding of catchment floods and the impacts of climate change. In addition to the shape and size of the entrance, the length, width and depth of an estuary affects the propagation of tides between the entrance and the up-stream tidal limit.[66] Roy et al. (2001)[67] denotes three main estuarine geomorphic types and their influence on tidal behaviour including tide dominated drowned river valley estuaries, wave dominated barrier estuaries and ICOLLs. In general, tide dominated estuaries have a tidal range that is similar to the adjacent ocean, while wave dominated estuaries exhibit significant tidal attenuation (e.g. the high tide water level is lower and the low tide level is higher than the adjacent ocean water levels).

Hanslow et al. (2018)[68] further extended this concept using an extensive record of continuous water level measurements from a large number of locations in different estuaries in NSW. Based on these measurements, the study was able to establish tidal planes for five geomorphic estuarine types that reflect the water level between the upstream and downstream end of estuaries during the peak of the High High Water Solstice Springs (HHWSS) tide (Figure 7). These HHWSS estuary tidal planes are indicative of the highest water level that can occur in an estuary in a given year purely as the result of astronomical tides (i.e. without storm surge, wave run up and river flooding). The HHWSS used in this analysis was roughly consistent with “king tides” and slightly lower than the Highest Astronomical Tide (HAT).[68]

It can be seen that drowned river valleys can amplify open ocean water levels due to the funnelling effect and unobstructed entrances. All other connected estuary types show significant attenuation of the HHWSS open ocean water levels, with differences at the entrance of over 0.5 m possible in tidal lakes, as seen in Figure 7.[68] This shows that using a static ‘bathtub’ type of approach (i.e. where water levels are raised uniformly across the entire tidal pool of the estuary using GIS methods) to estimate the impacts of sea level rise in estuaries can lead to significant over- or underestimation of the maximum water levels. The bathtub method, therefore, is not recommended to be used for assessing the risk of estuarine tidal inundation in NSW. A superior approach is to use the tidal planes as the HHWSS baseline, which can then be shifted up by the projected increases in mean sea level over the planning horizon. However, ultimately, only a physically-based numerical model can reliably simulate the impacts of sea level rise on estuarine flooding, since this is the only approach that can account for hydraulic structures, the volume of water, flow velocities, energy losses and friction.

Extremes

Assessment of future extreme water levels in estuaries requires consideration of both river floods and storm surges. The former is driven by regionally varied changes in rainfall and evaporation regimes (hydroclimatic intensity, timing, dry spells), changes in the rainfall and runoff properties of catchments, changes in catchment land use and water management (i.e. storage and diversion of flows), and the conveyance of catchment runoff through the upland river systems and floodplains (Figure 8). Since climate change will likely have regionally varied impacts to these forcing factors, individual estuaries along the NSW coast (within close proximity to one another) might experience significantly different changes in the magnitude and frequency of extreme water levels. Therefore, it is important that the selected assessment approach can capture the hydrological characteristics of individual estuaries and their tributary catchments.

Fig. 6: Determining extreme water levels at the open coast

Manipulating estuarine tidal planes is an efficient method to estimate the impacts of sea level rise to average water levels within estuaries. However, both the tidal plane and bathtub approaches use geographic information systems (GIS) for mapping inundated areas by overlaying the tidal planes with a digital elevation model, which is problematic when assessing the impacts of extreme sea levels. The main problem with GIS-based models is their inability to account for important aspects of estuarine hydrodynamics such as the bathymetry and corresponding volume of water or the hydraulic characteristics of flow channels, which are critical factors that influence water levels and residence times in estuaries. GIS-based methods also do not readily account for the effect of levees, which are in place across estuaries in NSW and other parts of the world.

Accounting for the effects of flood protection infrastructure requires detailed information of all levees in combination with an inundation model that can properly account for such flow barriers. In addition, the most extreme water levels in estuaries (i.e. the once in 5-, 25- and 100-year floods) can be substantially higher than the HHWSS tidal planes and are the result of either large river floods, extreme sea levels or a combination of these two processes. Extreme sea levels at the open coast comprise of the various factors shown in Figures 5 and 6 and, due to the likely presence of significant wind and pressure forcing during a storm surge event, the corresponding peak water level throughout the estuary may deviate from the shape and magnitude of the HHWSS tidal plane.

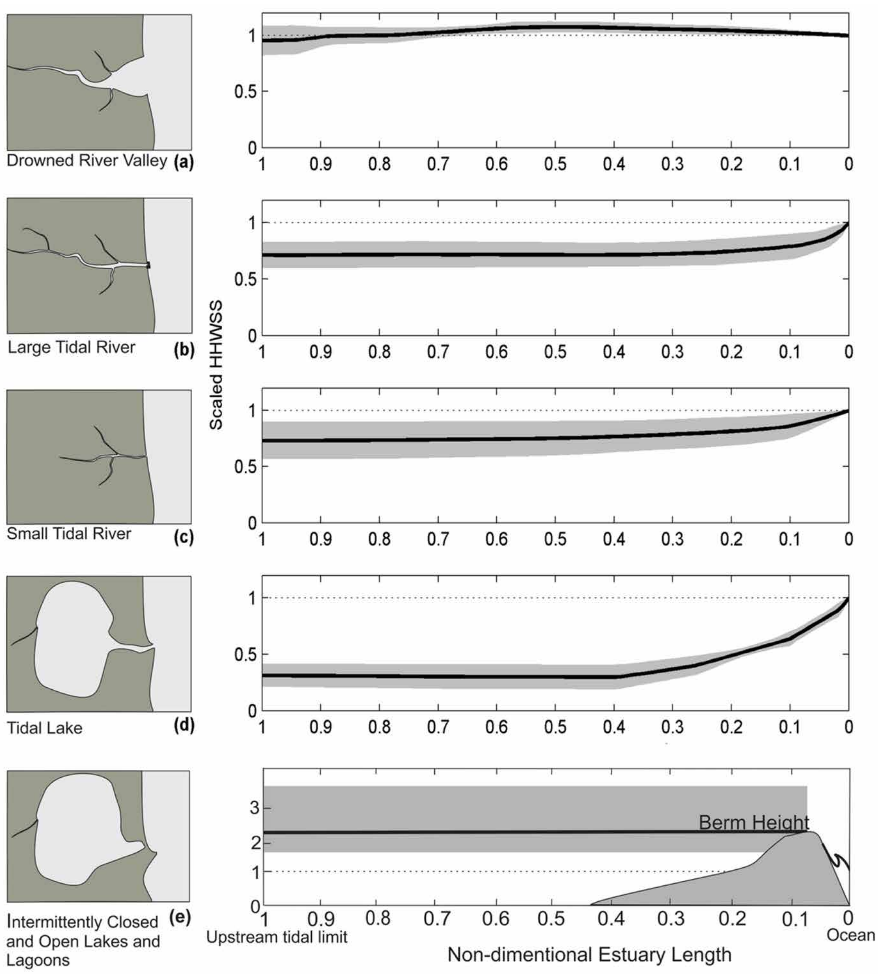


Figure 7: High High Water Solstice Springs (HHWSS) tidal plane for different types of estuaries found in NSW. The tidal planes show the approximate water level between the upstream and downstream end of estuaries relative to the HHWSS (1m in the open ocean), which are derived from an extensive record of continuous water level measurements within many NSW estuaries. The grey envelopes show the upper and lower boundaries within the measured water level data for each estuary type. Source: Hanslow et al. (2018)[68]

2.4.3 Accounting for joint probability in estuarine flooding

In the context of coastal flooding, joint probability describes the probability that two extreme events (e.g. extreme runoff and extreme ocean water level) may occur at the same time. Despite the fact that east coast lows have the potential to simultaneously trigger storm surges and catchment flooding, there are few recorded instances of large catchment flooding coinciding with extreme sea levels along the NSW coast. This may be because the NSW coastal database contains approximately 20 years of continuous water level data, which is not adequate to capture a statistically significant number of major floods. Smith et al. (2013)[66] state that it would be unwise to dismiss the possibility of elevated water levels and catchment runoff events coinciding. They propose that uncertainty in this "joint occurrence" can be addressed through sensitivity analysis, which involves simulating a range of model scenarios to examine upper and lower outcomes.

Two comprehensive joint probability analysis have been conducted for flooding along the NSW Coast. Shand et al. (2012)[69] completed an investigation of the joint occurrence of large waves and elevated ocean water levels along the NSW coast. They concluded that there was a relatively high dependence for wave height and tidal residual in NSW. For designs where both tidal residuals (anomaly) and wave height are of interest, their occurrence cannot be assumed to be independent (and therefore joint probability of extreme events should be considered). Westra (2012)[70] investigated the joint probability of extreme rainfall and elevated ocean levels for three locations along the East Australian coastline (Sydney, Brisbane and Mackay) and found that:

- There is a statistically significant dependence between extreme rainfall and storm surge;
- Dependence could be observed over distances of at least several hundred kilometres at each of the three tide gauge locations, although it weakens with distance; and
- The dependence between rainfall and storm tide is heavily influenced by storm burst duration, with relatively small levels of dependence for short durations (particularly sub-hourly durations) which increases gradually for longer durations.

2.4.4 A framework for assessing extreme water levels at the ocean boundary

The interaction of catchment flooding and coastal processes is an important consideration in determining flood risk in coastal waterways. The above work (Section 2.4.3) highlights that while much is known about sea levels and the propagation of ocean tides into estuaries, the response of estuaries to extreme events is less well understood. In particular, the physical process of storm surge propagation and wave set-up in estuaries as well as the interactions with river flooding during extreme events remains poorly quantified.

Smith et al. (2013)[66] consolidated all relevant available information on flooding in NSW estuaries. Although this study did not account for impacts due to climate change

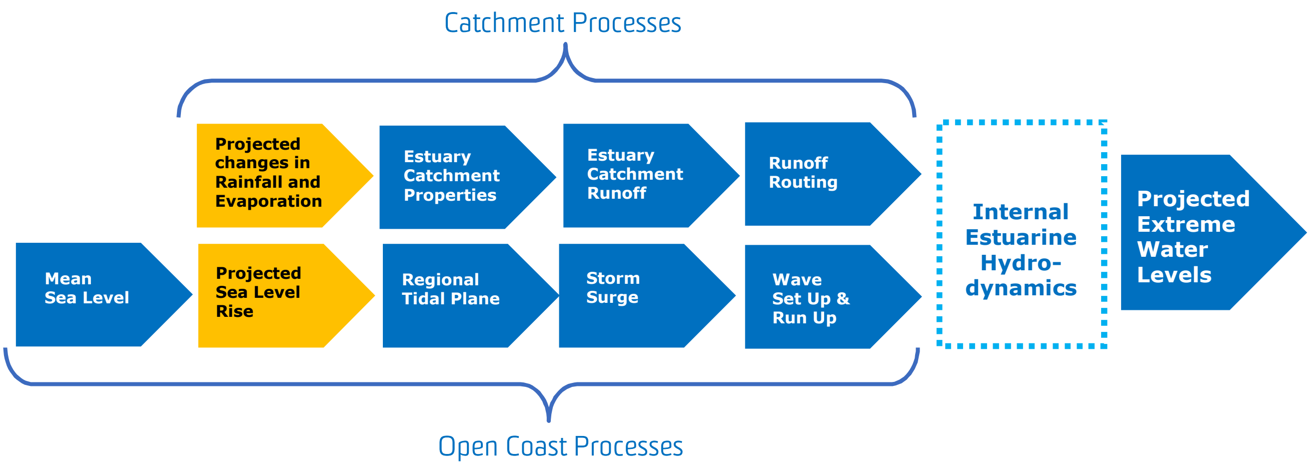


Fig. 8: Determining extreme water levels in estuaries

directly, the authors presented a pragmatic approach for the combination of ocean-driven and catchment-driven flooding mechanisms. They highlighted that wave set-up can play a significant role in estuarine flooding and should be factored into the ocean boundary water levels for flood studies in NSW. The authors developed a structured approach to joint catchment and ocean flooding and proposed a selection criterion for setting ocean boundaries based on the different NSW estuary classifications of Roy et al. (2001).[67] Here, we updated this approach by also factoring in the compounding impacts of sea level rise (Figure 9). Presently, there is limited guidance for estimating flood risk along the Australian coastline for dependant events. The NSW Office of Environment and Heritage (OEH) has developed formal guidance for assessing the coincidence of coastal and catchment flooding in NSW under the Floodplain Management Program.[71]

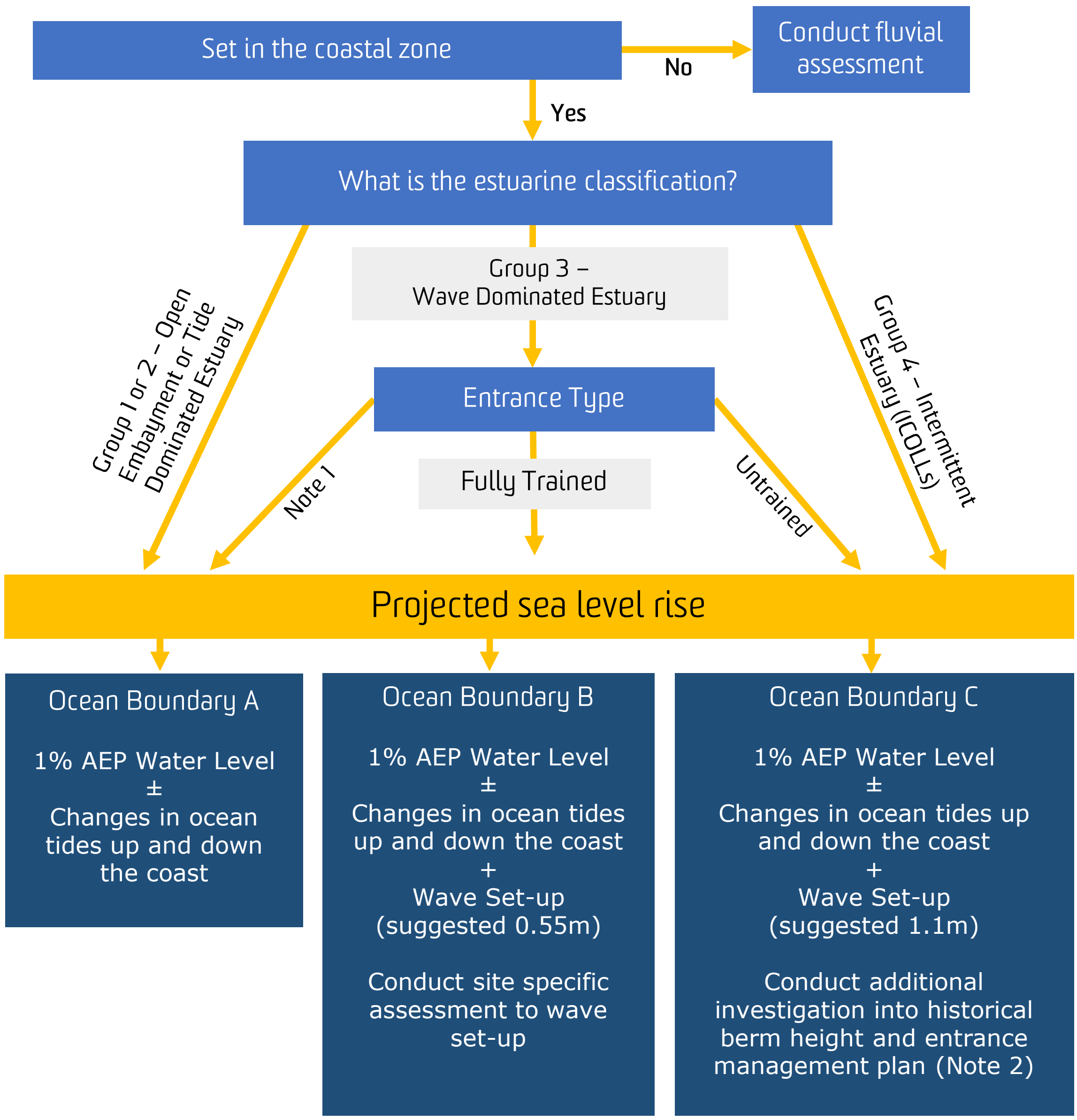


Fig. 9: Estimating an ocean boundary for flood risk assessment in estuaries. Based on Smith et al. (2013)[65]
Note: 1. Wave dominated estuaries that are ports and harbours or drain into bays.
2. Berm Height will control the water level when the entrance is closed.

2.4.5 Impacts of increased water levels in estuaries

Sea level rise is likely to cause impacts within estuaries and the communities living around them. As previously discussed, the tidal influence in estuaries can be variable in its propagation (either amplified or diminished) depending on the estuary's bathymetry, shape, length and bed friction.[72] As the estuarine environment is well-adapted to variable sea levels due to changing tides, the expected impacts associated with sea level rise are thereby a result of the increase in the baseline sea level rather than the sea level rise itself. In the face of the projected (with high confidence) accelerating increases in both mean and extreme sea levels faced by estuaries, there are a number of obvious impacts that can be reliably established from the scientific literature and physical principles. The potential impact of rising estuarine water levels include, but are not limited to, a landward movement or drowning of intertidal habitats, shoreline recession and erosion, increasing probability of coastal flooding and decreasing drainage capabilities of low-lying areas (Figure 10). The following sections provide an overview of the processes to be considered when initially assessing the impacts of sea level rise in estuaries.

2.4.5.1 Increased coastal inundation and reduced drainage

One of the most significant threats to estuaries will be the steadily increasing vulnerability of shorelines and floodplains to inundation and erosion. This is due to an accelerating increase in the baseline water level that will

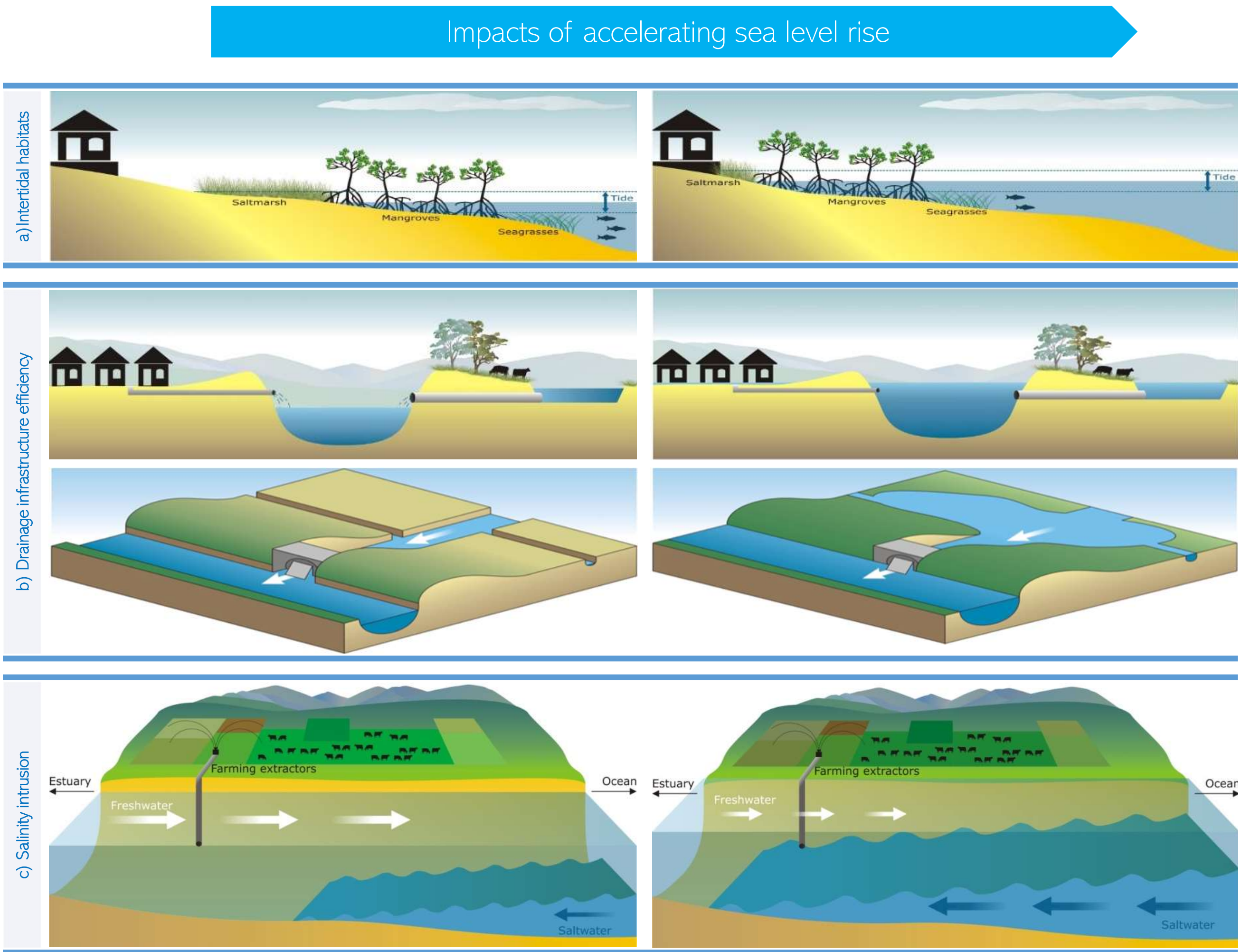


Fig. 10: Conceptual diagrams showing the impacts of sea level rise on a) intertidal vegetation communities b) drainage efficiency and coastal flooding and c) salinity intrusion

increase the magnitude and frequency of extreme water levels. As discussed in Section 2.4.2, estimating future inundation in and around estuaries requires accurate estimation of extreme water levels at the river (floods) and ocean (storm surges) boundary. Once future extreme water levels are established for these boundaries (see Module-2), inundation modeling is required to determine the extent, depth and duration of inundation in and around an estuary. The available modeling approaches are discussed in Section-3.

Coupled with this increased risk of coastal inundation, an increase in the low tide water levels throughout the estuary can significantly decrease the efficiency of existing agricultural and urban drainage infrastructure. Stormwater in urban areas around estuaries is mostly discharged via outfalls along estuarine banks. Elevated water levels in the estuary can change the tail water conditions at these outlets (Figure 10b) and thus, impact existing urban drainage networks.[73] In many instances, tide gates have been installed to restrict water from entering drained areas altogether, while during low tide, accumulated water from the drainage network is released into the estuary through opening of the gate (hydrostatic head). Since the minimum water level on the estuary side of the gate is rising with the rising mean sea levels, the functioning of this drainage scheme might be increasingly impeded. As such an upgrade of the infrastructure (i.e. pumps) may eventually be necessary to restore the same level of drainage currently in place.

2.4.5.2 Changes in salinity and mixing

Before assessing the impacts of sea level rise on estuarine salinity, it is useful to understand the physical principles that drive estuarine salinity. Salinity is typically considered as the main structuring factor of the physical and ecological estuarine environment (see Module-1). Estuary ecosystems are uniquely aligned with the salinity gradient along the estuary, with freshwater species dominating in the upstream areas and marine species inhabiting areas near the entrance, where salinity ranges are similar to the open ocean.

Due to the higher density of salt water compared to fresh water, salinity intrusion in an estuary commonly occurs in the shape of a salt wedge. Therefore, sea level rise will cause an increase in salt water intrusion by pushing the salt water wedge further upstream in the estuary, independent of the existing salinity and mixing regime (Figure 10c). This typically leads to a reduction in the size of the freshwater habitat (i.e. squeezing) and available freshwater extraction. The upstream excursion of tidal waters will increase the extent of saltwater intrusion upon freshwater resources, and impacts landuses such as agriculture.

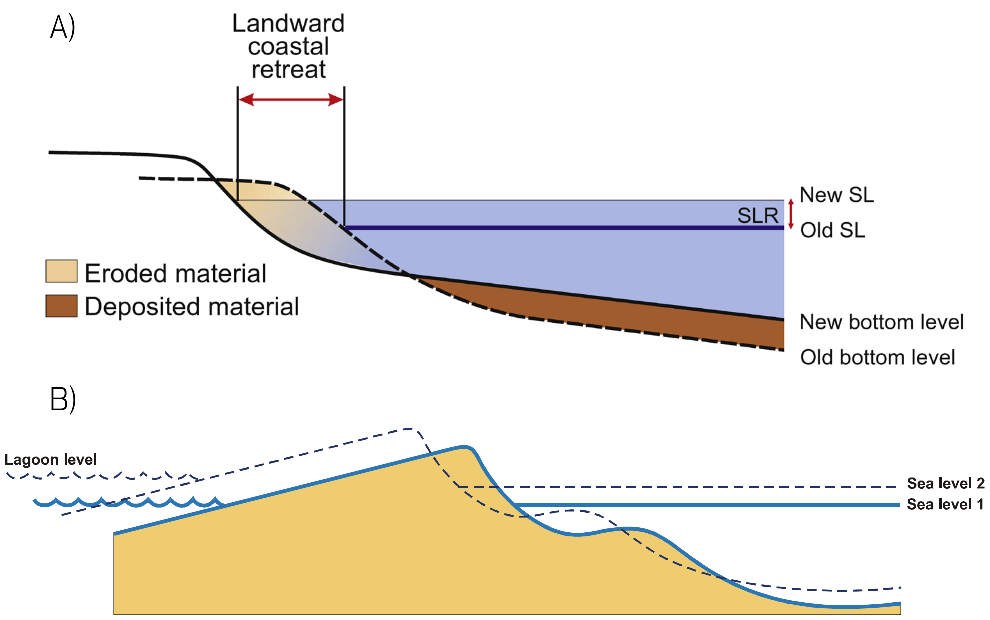


Fig. 11: Conceptual models of sea level rise impacts at the coast illustrating A) the Bruun rule of beach profile response to sea level rise where upper areas are eroded and deposited at the near shore with a thickness similar to the increase in mean sea level. Source: (FitzGerald et al., 2008)[74] and B) the response of ICOLL berms to SLR showing landward retreat and increased berm height as proposed by Hanslow et al. (2000).[135] SL = sea level; SLR = sea level rise

2.4.5.3 Geomorphological impacts

One of the most significant and widespread geomorphological impacts of sea level rise is likely to be the erosion and migration of sandy shorelines in and around estuaries. In response to the elevated sea level baseline, the shoreline as well as ICOLL berms may migrate landwards to maintain its position within the energy gradient (Figure 11).[74,75] The shoreline erosion model shown in Figure 11-A is a highly simplified response model for open coast sandy shores based on the Bruun rule and in reality, shoreline responses are likely to be far more complex.[75] Erosion due to sea level rise will also occur along the river channel banks in the upstream sections of estuaries, which might result in river channels becoming wider and shallower.[76] Pethick et al. (1993)[76] also suggest that the estuaries might migrate landward slowly in response to rising se levels, largely due to the redistribution of sediment.

When detailing the geomorphological response of estuaries, the entrances are often where the most significant changes are expected, with the mouth and the sand barrier being the priority reconstitution area. With changes in tidal prism, mean water level and entrance hydrodynamics, it is likely that the shapes and areas of sandbars will change. The resultant implications for the entrances, however, is very site-specific, particularly when the effects of climate change are combined with longshore sediment transport at adjacent beaches. For wave-dominated estuaries, accelerating sea level rise tends to cause both the sandbar and the mouth to migrate landwards (i.e. erode), and when this occurs simultaneously, the entrance may become more expansive.[76,77] For ICOLLs in NSW, this evolution can vary depending on the position of the entrance relative to the coastal compartment (e.g. at the northern vs the southern end of a beach). Changes in the rotation of beaches due to a potential southward shift in the average wave direction would cause ICOLL entrances at the northern end of beaches to become more susceptible to closure, and entrances at the southern end of beaches to become more open.[77] However, historic trends and future projections in the NSW wave climate are driven by decadal climate variability (i.e. ENSO) and are of low confidence (see Table 1 in Module-2). Hence, the future state of ICOLLs entrances in NSW should be considered highly uncertain.

Another major concern with sea level rise in estuaries is the potential drowning of intertidal wetlands. As illustrated in Figure 10a, these communities consist of largely salt marsh ecosystems in the high intertidal zone and mangroves in the medium and low intertidal zones, while seagrasses typically grow in shallow subtidal areas. Each of these communities has particular requirements for the average depth and length of inundation throughout the tidal cycles in estuaries (see Module-4). These systems, which are sometimes referred to as intertidal vegetation communities, have the ability to build, extend and elevate the sedimentary base on which they grow,[78,79] a process known as accretion. The details of this process are

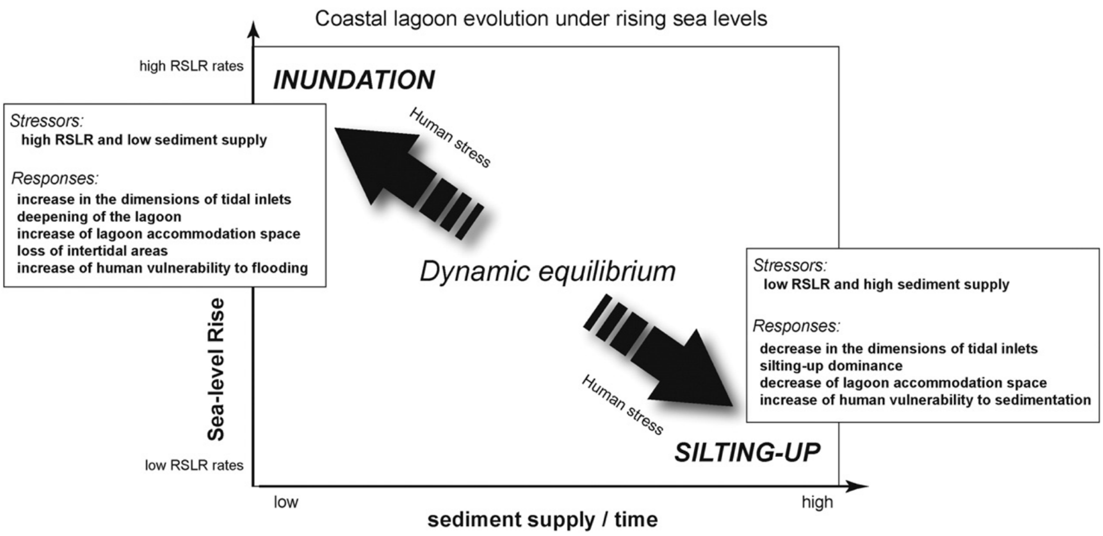


Fig. 12: Conceptual model of coastal lagoon evolution as a balance between relative sea level rise (RSLR) and sediment supply, leading either to inundation or silting-up. Source: Carrasco et al. (2016)[80]

discussed in Module-4 of this guide, but since accreation within intertidal wetlands can significantly alter estuarine landforms and thereby, many physical processes, the key aspects are discussed briefly here.

In general, the rate of accretion is highly dependent on the amount and particle size distribution of sediment that is available over time and space. The sediment dynamics of a particular estuary control the vertical accretion rate and, if this rate is significantly slower than the rate of sea level rise, drowning of the system is likely. As shown in Figure 10, however, estuarine vegetation communities also have the ability to migrate horizontally towards higher elevations, where their inundation depth and duration requirements are fulfilled relative to the increased sea level baseline. A global study that included estuary sites in Australia, found that due to horizontal migration potential, intertidal wetlands have the potential to maintain and even expand their extent in the face of accelerating sea level rise if horizontal migration space is available and provided.[80] This study estimated that the loss in the presently available global coastal wetland area by 2100 will be between 0-30%, if no further accommodation space is provided. Increases of up to 60% are possible if 37% of the theoretically suitable accommodation space and sediment supply is actively made available.[80] The critical balance between sea level rise and the amount of sediment available over time is illustrated in Figure 12.[81]

High rates of sea level rise in combination with low sediment supply over time favour the inundation of intertidal wetlands. In contrast, low rates of sea level rise and high sediment loads favour the built-up of sediment and the accretion of intertidal wetlands.[81,82]

It is important to mention that accretion of intertidal wetlands is a complex process that varies across space and time. Hence, assessing the future response of these systems to sea level rise is subject to a high level of uncertainty. Rogers et al. (2013a, 2013b)[82,83] investigated the accretion dynamics of an intertidal wetland in the Hunter River estuary in NSW, Australia, over a ten-year period. They found that the sediment bed elevation responds to both long-term climate variability and short-term weather events with both accretion and erosion occurring over the analysis period. A comprehensive study undertaken for US pacific coast intertidal wetlands found that SLR (upper-end scenarios) could cause up to 83% of marshes to convert into unvegetated habitats (i.e. mud flats) by 2110.[84] In NSW, where most estuaries (particularly in the central and southern parts of the coast) have comparatively low sediment supply levels, inundation may also be the dominant response across the intertidal vegetation zones.[85] Table 4 provides a summary of the most relevant physical responses of estuaries to projected sea level rise.

Table 4: Summary of impacts of sea level rise on physical estuarine processes

Climate change impact	Physical responses in estuaries
Mean sea levels along the NSW coastline have increased by approximately 10cm from pre-industrial levels and are likely to rise at accelarating rates by up to 80cm by the end of the century. Each estuary has a unique tidal propagation but generally, increases in open ocean mean and extreme sea levels will cause similar increases within estuaries.	Increased coastal erosion & increased risk to coastal housing and infrastructure Changes to tidal ranges, circulation patterns and mixing Changes in erosion, transport and deposition of sediments altering the geomorphology and bathymetry of the system Increased inundation/drowning and reduced drainage of coastal wetlands, floodplains and other low lying areas Landward migration of shorelines & intertidal wetlands if terrain is suitable (i.e. no obstructions & steep slopes) Changes in the abundance and distribution of sub- and intertidal vegetation communities Reduction in freshwater habitat size through increased salinity intrusion into estuaries, floodplains and groundwater systems

2.5 Responses to oceanic acidification

Climate change will impact acidity levels in estuaries in two ways. First, changes in the rainfall regimes can potentially facilitate high-acidity conditions such as during heatwaves, dry periods and floods. Second, the projected steady increase in oceanic acidity will manifest in an increase of the acidity baseline with the level of estuarine exposure depending on the oceanic influence. Global average ocean pH levels have decreased by approximately -0.1 pH units from the pre-industrial pH levels of 8.17, equalling an increase of 26% in hydrogen ions (H^+).[8] Under the business as usual RCP8.5 scenario, further decreases of 0.42 pH units in the global average ocean pH are likely by 2100, which is equivalent to an increase of almost 110% in hydrogen ions.[8]

The risk of acidification in estuarine waters may be offset by the acid buffering capacity, which is directly proportional to the volume of buffering agents within the system.[46] Bicarbonate and carbonate are two major acid buffering agents inherent in sea water and introduced to estuarine water through tidal exchange.[46,86] As such, estuarine buffering capacity also depends on the hydrodynamic regime of the estuary, which controls the input of acids and buffering agents from the open ocean.[86]

2.5.1 Acidity dynamics in estuaries

There are few high-quality ocean acidification time series data sets that exceed five years in the coastal zone.[87–89] Available data sets exhibit considerable differences compared to open ocean stations illustrating that anthropogenic ocean acidification can be lessened or enhanced by processes such as primary production, respiration and calcification.[90,91] A comprehensive summary of the impacts of oceanic acidification can be found in Gattuso and Hansson (2011).[92]

The estuarine water pH is critical to the survival of most aquatic plants and animals.[93] The typical pH levels in freshwater bodies and estuaries range between 6.5 and 8.5 (Figure 13). The oceanic zones of estuaries typically have pH levels similar to the open ocean (>8), with acidity increasing in the upstream direction approaching the pH levels of the freshwater inflows. Due to their dynamic nature and multitude of different water inflows (i.e. urban, catchment, floodplain, agriculture), the majority of estuaries exhibit a high level of variability in acidity conditions in space and time and this typically involves occasional extreme acidity events. Most plant and animal species are sensitive to changes in acidity and have trouble surviving pH levels of under 5.0 or above 9.0. Ecological impacts from estuarine acidification can affect the environmental, recreational and commercial value of

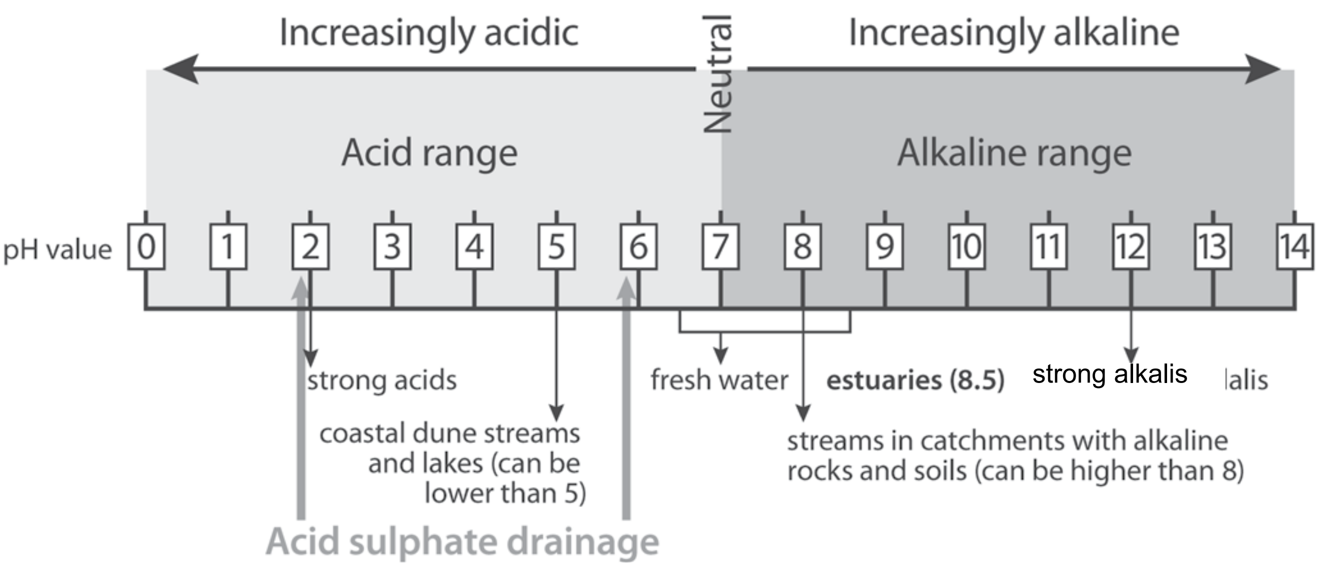


Fig. 13: Overview of typical pH ranges of waterbodies and acid sulphate drainage. Source: (Waterwatch Australia Steering Committee, 2004)[92]

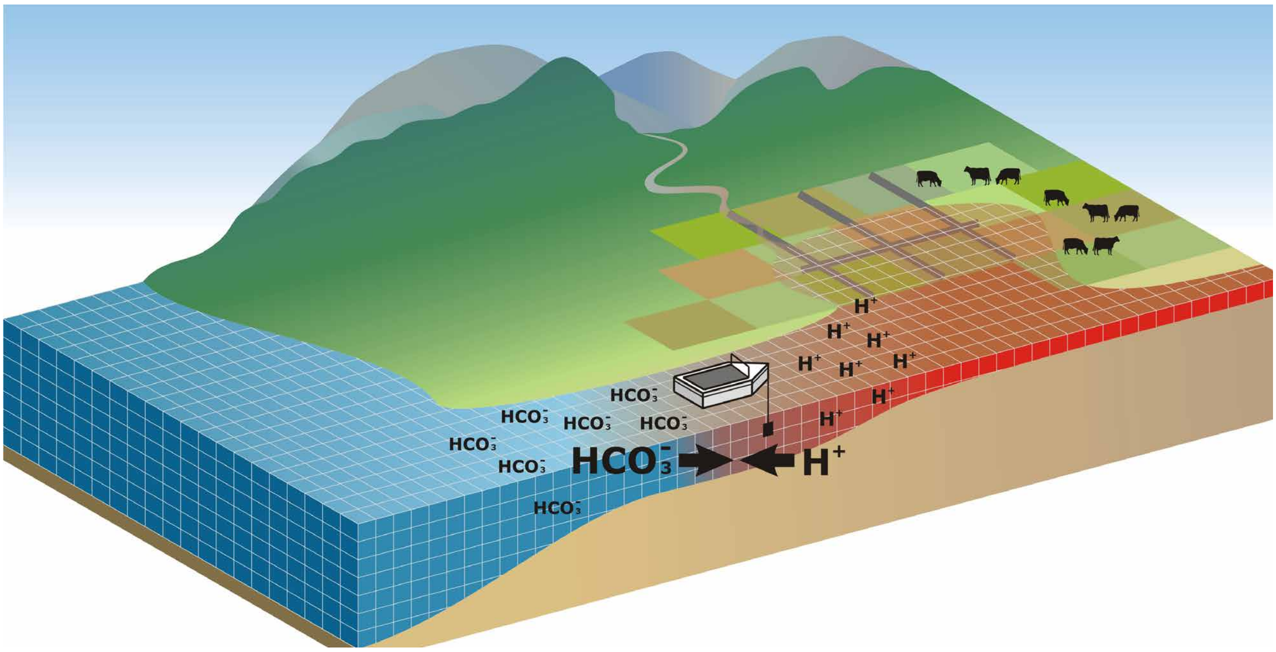


Figure 14: Conceptual diagram illustrating the buffering of an acid plume in the mixing zone of an estuary. Source: Ruprecht et al. (2017)[101]

estuaries[94] and these impacts are explained in detail in Module-4. Changes in acidity also have secondary impacts on other chemical processes in estuaries. For instance, small shifts in pH can affect the solubility of metals such as iron and copper, allowing toxic metals to be resuspended into the water column from the bottom sediments.

Mass mortalities of fish and other gilled organisms in response to the release of acidic plumes have been recorded in Australian estuaries when prolonged dry periods were followed by heavy rainfall.[95,96] These occurrences have been related to stream acidification, caused by drainage from oxidised sulfidic sediments.[94,96–99] Figure 14 illustrates the propagation and buffering of an acid plume in an estuary caused by acidic runoff from drained agricultural land during periods of flooding.[100,101] Such episodic extreme acidification of estuaries (i.e. pH<5) is common in NSW and is caused by the oxidation of sulfidic floodplain sediments.[100] Sulfidic sediments have been found in most estuarine lowlands and coastal embayments along the eastern[102] and northern Australian coasts, as well as in parts of Western Australia, South Australia and Victoria.[94] Whilst estuarine acidification can occur naturally,[95] regional anthropogenic impacts such as landform modification, in particular drainage of intertidal zones and floodplains, has exacerbated the problem significantly.[102–105] The steadily increasing levels of oceanic acidity resulting from climate change might lower the buffering capacity in the brackish-marine parts of the estuary, which could potentially increase the duration and severity of acid plumes and the corresponding impacts to estuary ecosytems. A summary of physical impacts of oceanic acidification on estuaries is provided in Table 5.

Table 5: Summary of impacts of oceanic acidification on physical estuarine processes

Climate change impact	Physical responses in estuaries
Oceanic pH is steadily decreasing and projected to drop 0.42 pH units by 2100, producing an increased acidity baseline for estuaries.	Higher acidity baseline can proliferate localized extreme acidity events following heavy rains Changes in solubility of metals and estuarine water chemistry Impacts on flocculation, with indirectly impacts on mixing, sediment dynamics and water quality

"Exposure to sea level rise is particularly high around tidal lake systems, where reduced tidal ranges have allowed development to occur in relative proximity to present sea level, and around larger coastal rivers, which feature extensive low-lying plains exposed to potential inundation"[67]

Drone view of dredging in the Lake Tuggerah estuary entrance channel, The Entrance, NSW; Photo: Chris Drummond, WRL, UNSW

2.6 Responses to changes in winds and storms

As shown in Module-2 (Table 1), NARCliM projections suggest a likely decrease in the number of East Coast Lows in winter and potential increases in summer near the NSW coastline.[106] In line with these projections, the global climate model (GCM) ensemble used in Climate Change Australia suggests that there will be a decrease in the average near-surface wind speed of possibly up to 5% in autumn and up to 10% in winter, with increases of a similar range in spring and summer by 2090 (10^{th} percentile of ensemble change based on RCP8.5 – see Module-2 for details).[107] Projections for extreme winds also indicates that only minor changes are anticipated, with the median of the ensemble changes being slightly negative (i.e. between 0-5%).[107] There are also only minor differences expected in the wave climate of the NSW coastline[108] with future projections indicating small decreases in the average significant wave height, accompanied by potential increases in the magnitude of extreme wave events.[109]

While tropical cyclones are projected to occur less often, they are expected to become more intense and to reach further south in the future.[107] In general, the ability of climate models to accurately reproduce the number, magnitude and location of East Coast Lows is limited[106] and, as such, these projections are rated to be of low confidence (see Module-2). In summary, the changes projected for the average and extreme winds along the New South Wales coastline are small compared to the historic variability and subject to a high level of uncertainty.[106]

Wind has a complex relationship with estuarine processes. While wind does affect estuaries directly through wind-induced mixing and redistribution of sediments through wind transport, its primary impacts are indirect by driving the wave climate and storm surges. The indirect impacts of winds on estuaries through extreme wave and storm events have been discussed in Section 2.4 (Responses to sea level rise) of this module as they are the driving force behind extreme sea levels (i.e. storm surges).[49] Therefore, this section is focused on the direct impacts of potential changes in the wind climate.

Estuaries can be affected in several ways by long-term changes in the regional wind climate. Changes in wind climate may cause changes in the wave climate and storm surges,[109] near shore oceanic processes such as upwelling and downwelling[8] as well as soil moisture and evapotranspiration and, thereby, also the rainfall runoff process in estuarine catchments.[24,110,111] The level of wind-induced mixing in an estuary depends on the wind intensity and its distribution over the water surface area.[112] The effect of wind on estuarine mixing depends on the water depth and the distance over which the wind acts upon the waterbody, which is called the wind fetch. The effect of wind-induced mixing is generally higher in shallow areas within estuaries. An understanding of the mechanisms of wind is important as it also controls riverbank and beach erosion. A summary of the direct physical impacts of potential changes in wind forcing is shown in Table 6.

Table 6: Summary of impacts of changes in wind climate on physical estuarine processes

Climate change impact	Physical responses in estuaries
Relatively small changes are projected for the average and extreme winds and waves along the New South Wales coastline, but these projections are of low confidence. Winds have direct (mixing and aeolian sediment transport) and indirect (driving waves and wind setup) impacts to estuaries.	Changes in mixing and circulation Changes in erosion and accretion of beach berms and other sandy formations due to changes in wave climate and aeolian transport Changes in the magnitude and frequency of storm surges Changes in estuarine wind setup Changes in evapotranspiration and soil moisture affecting the rainfall runoff process in coastal catchments

3 Modeling physical responses to climate change

Estuaries are complex systems and it is necessary to understand how they currently function before assessing how they will likely be influenced by climate change. Modeling helps develop our present understanding of a natural system, which we can then use to infer future changes. Using real-world examples, this section introduces available modeling techniques and the required data sets.

A model is only as good as the data and assumptions on which it is built and generally, a model is more likely to accurately reproduce the real-world system if high-quality observational data is available. There are generally four types of models to be used in modeling estuaries; (1) conceptual models, (2) scale physical models, (3) empirical models and (4) numerical models (see Figure 1). These are discussed in the following sections.

> Once a model is built with enough skill to adequately reproduce present day conditions, it can be used for projecting future changes, such as the likely impacts of climate change on physical estuarine processes.

3.1 Types of models

3.1.1 Conceptual models

According to Mylopoulos and Zicari (1995) *"conceptual modeling is the activity of formally describing some aspects of the physical and social world around us for the purposes of understanding and communication."*[113] A conceptual model typically identifies the major processes within the system of interest and how different processes might interact with one another. In the context of estuaries and climate change, the primary aim of this type of model is usually to identify and illustrate significant processes, their drivers, and the broad outputs that are expected. As such, conceptual models are different from the other three types of models discussed in this section as they do not simulate or model a process, rather they conceptualise and represent it in an illustrative way. Nevertheless, developing a conceptual model requires thorough understanding of how a system works and they are commonly used to generate the basis for more sophisticated process-based models.[114]

Conceptual models vary considerably in their design and complexity and can range from 3-dimensional process illustrations to simple arrow diagrams or rating tables. A commonly-used form of conceptual models are conceptual diagrams, which, according to OzCoasts, are *"concise and visually-stimulating illustrations that use symbols or drawings to depict the important features, processes and management challenges in a particular environment, such as coastal waterways. This is accomplished using the most current knowledge or understanding of that particular environment and is presented in a way that is easy to understand."*[115] Figure 10 of this module is an example of a conceptual diagram, illustrating key impacts of sea level rise on intertidal wetlands, drainage infrastructure and salinity intrusion in estuaries.

3.1.2 Scale physical models

Scale physical models are built as small replicas of the system that is being modelled. They are particularly useful for processes that cannot be modelled easily or accurately using existing formulas or numerical modeling tools. They also allow a visualisation of the processes simulated. Physical models are often used to model a limited area of the system of interest due to space and cost limitations. These experiments can simulate physical impacts reliably and can save money in the long-term, especially when used to guide the design process of coastal infrastructure. A typical case for using physical scale models is the testing of waves and storm surge impacts on planned coastal protection infrastructure under different climate change and sea level rise scenarios.

Fig. 15: Example wave flume testing setups at the University of New South Wales - Water Research Laboratory showing A) a wave deflector and back beach washout zone with overtopping collection trays and B) a wave flume model of storm surge impacts on island reef coastlines under different climate change and sea level rise scenarios.

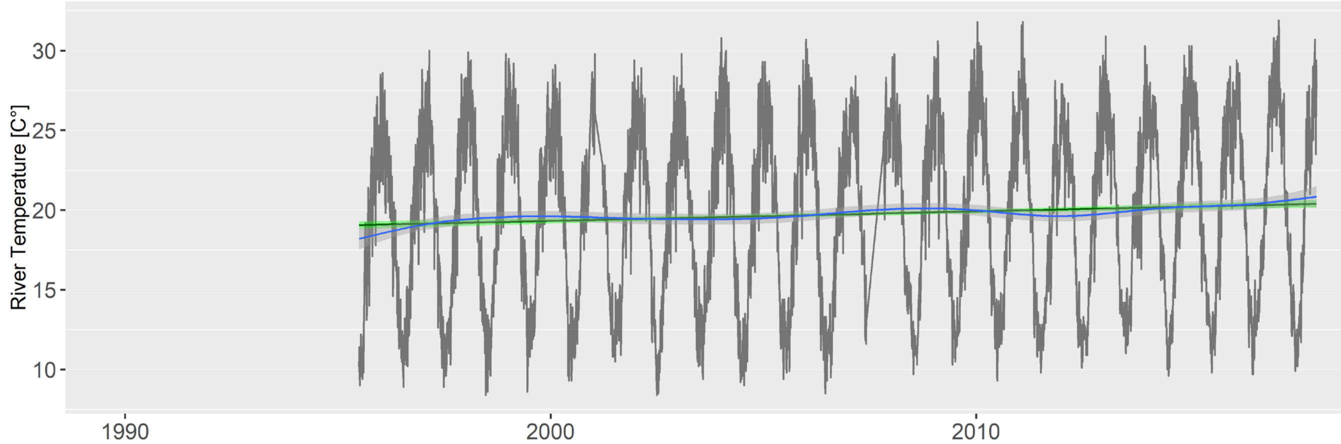
A recent example is the study of Cox and Pearce (2015),[116] which tested the effectiveness of different seawall structures and designs in coping with present and future extreme wave events, using wave flume testing at the Water Research Laboratory of the University of New South Wales (Figure 15-A). This experiment determined an effective combination of the coastal protection measures to manage the projected sea level rise and wave climate. Another suitable application of physical models is the assessment of impacts from extreme cyclone-driven storm surge water levels on island reef coastlines, and understanding how these extremes might shift with climate change as done by Blacka et al. (2013)[117] (Figure 15-B). In this example, the physical modeling was undertaken to provide a robust dataset to calibrate and validate the empirical models that were then applied along a larger stretch of impacted coastline.

3.1.3 Empirical modeling

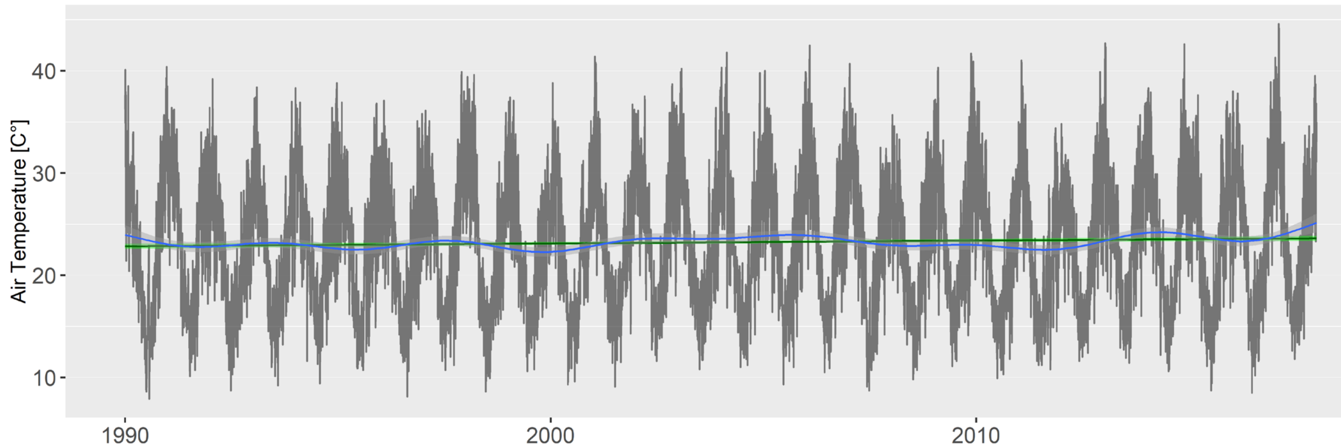
According to Abrahart et al. (2009),[118] empirical modeling *"is based on analyzing the data about a system, in particular finding connections between the system state variables (input, internal and output variables) without explicit knowledge of the physical behavior of the system."* In comparison to numerical modeling, empirical modeling uses mathematical equations that are not derived from physical processes but rather from analysis of observed data.[118] Due to recent advances in computational techniques and machine learning, empirical modeling has become increasingly powerful and with the inclusion of recent novel machine learning techniques, it is commonly called data-driven modeling. Data-driven modeling is particularly suitable for studying and quantifying processes for which observational data exists and where physically-based modeling is not feasible or limited. In such cases, observational data exists for both the process or variable of interest, commonly called the response variable, as well as a set of variables that are thought to drive the response variable, commonly called the driver or explanatory variables. Specific examples of empirical models range from simple linear regression over established empirical equations to more complex machine learning techniques such as random forests or neural networks.[118] A number of real-world examples are discussed in the following sections.

Qiu and Wan (2013)[119] developed an operational data-driven time series model of salinity in key locations within the Caloosahatchee River estuary, USA, (response variable) that used the salinity level at the same location from the day before, rainfall, total inflow and tidal flows as driver variables. This model is able to predict salinity levels at key locations within the estuary and could outperform a 3-dimensional numerical model. Wang and Xu (2008)[120] used linear regression to establish an empirical relationship between salinity measured at different locations and different points in time within Lake Pontchartrain, an estuarine lake in the USA, and pixel reflectance values of optical satellite images from the Landsat satellite. The pixel reflectance values could successfully reproduce the salinity levels and this relationship could be applied to recreate surface salinity

A) Monthly time series (grey), linear (green) and smooth (blue) trend of water temperature in the Hunter River at Greta. Linear trend was 0.059 °C/year and statistically significant (i.e. p < 5%)



B) Monthly time series (grey), linear (green) and smooth (blue) trend of air temperature in the Hunter River catchment. Linear trend was 0.028 °C/year and statistically significant (i.e. p < 5%)



C) Monthly time series (grey), linear (green) and smooth (blue) trend of flow in the Hunter River at Greta. Linear trend was -0.404 cubic-meter/year statistically significant (i.e. p < 5%)

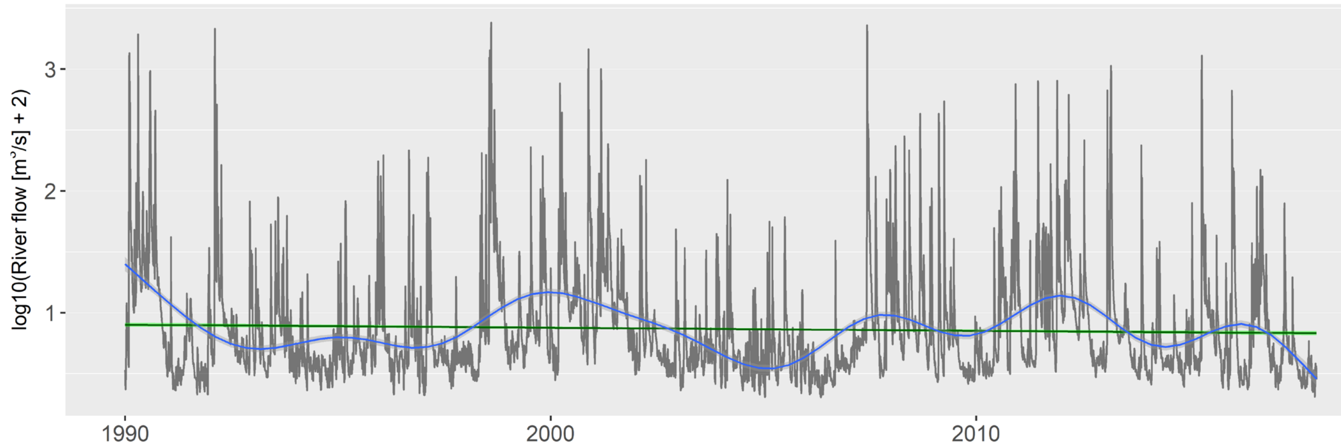


Fig. 16: From top to bottom: A) Observed time series of river temperature at the Greta station in the Hunter River, NSW (source: https://realtimedata.waternsw.com.au/); B) time series of air temperature in the geographical centre of the Hunter River catchment (source: SILO) and C) log10 transformed time series of river flow at the Greta station (source: https://realtimedata.waternsw.com.au/). Green lines are linear trends (least square regression), blue lines are long-term smooth trends generated using the GAM technique.

concentrations across the entire lake for the full period of the satellite operation (i.e. 1987-present).[120] Both of these studies illustrate that data-driven modeling can be a cost-effective approach for monitoring and predicting salinity dynamics in estuaries, even when observational datasets cover relatively short periods. However, it is important to consider that these models provide very limited information about the underlying processes as well as the relationship between cause and effect.

To illustrate the usefulness of data-driven modeling for assessing climate change impacts in estuaries, the water temperature in the Hunter River estuary in NSW is shown as an example. As shown in Module-2, the water temperature at the Greta gauge in the Hunter River upstream of the estuary's tidal limit exhibited a positive linear trend of 0.028°C per year over the available data period (1996-2018). Independent of whether this observed trend is driven by climate change or natural long-term climate variability, it may be useful to understand how river temperatures will likely change over the course of this century and beyond.

Since global climate models do not provide future projections of river temperature, it is necessary to first establish an empirical relationship between river temperature and variables for which future projections exist. This relationship can then be used to generate future projections for water temperature in the river. In this example, air temperature in the Hunter River catchment is used as an explanatory variable. In addition, the flow in the river might also have an influence on the river temperature and this can be applied as an additional explanatory variable. Future levels of river flow could be inferred from climate projections by using rainfall runoff modeling.

Figure 16 shows time series of observed temperature and flow in the Hunter river at the Greta gauge along with air temperature in the Hunter River catchment. Initially, it is evident that river and air temperature exhibit a very similar pattern over time, showing a pronounced seasonality. Both of these series had a slight increasing trend over the data period. In contrast, the logarithmically transformed river flow series had a slight decreasing trend and exhibited a very different dynamic over time. A simple way of testing whether the behaviour of the explanatory variables can explain the behaviour of the river temperature, as the response variable, is to fit a linear regression model between the response and each of the explanatory variables. Since there are several lags in the catchment rainfall runoff process such as the time that it takes for flows to reach the Greta gauge, we will first calculate monthly averages for all variables before fitting a linear regression model. Figure 17 shows the results of the linear regression (i.e. regression line and equation) on top of scatterplots between the variables of interest.

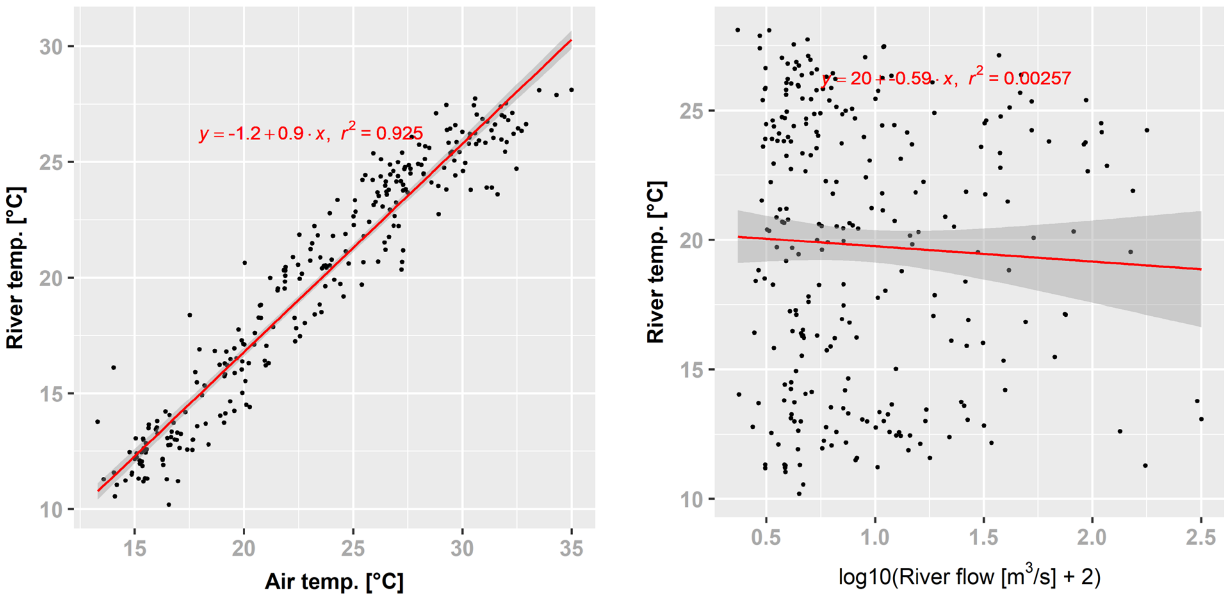


Fig. 17: Scatterplots of river temperature against catchment air temperature (left panel) and river temperature against log transformed river flow (right panel). Red lines show the linear regression model that was fit to the data with grey areas indicating the 95% confidence intervals of the model fit.

Even without modeling, the scatterplots (each dot shows the average in both variables for a specific month within the data period) illustrate that there is a pronounced positive linear relationship between river temperature and air temperature in the catchment. In contrast, the relationship between river temperature and river flow is poorly pronounced and negative. The coefficient of determination (r^2), is a measure for how much of the variability in the response variable is explained by the explanatory variable, with 1 meaning that 100% of the variability is explained and 0 meaning that none of the variability is explained. The model using air temperature as an explanatory variable had an r^2 of 0.93, indicating that average monthly air temperature in the catchment is a good predictor for average monthly river temperature, while river flow is a poor predictor, with an r^2 close to 0.[121]

It is important to understand that even a perfect $r^2=1$ doesn't suggest that catchment air temperature drives river temperature through physical mechanisms. This is why correlation doesn't imply causation.[121] Therefore, it is important to consider the physical processes taking place in the system and to assess whether they can explain the empirical relationships reflected in the data, which is arguably the case in this example.

Using the monthly average air temperature in the catchment, the monthly average river temperature at the Greta gauge location can be obtained via the following equation as obtained from the linear regression model:

River Temperature = -1.2 + 0.9 * Air Temperature

For the month with the hottest observed average air temperature in the catchment (data point furthest to the right in Figure 17, left panel), which was 35°C, our linear regression model would yield an average monthly river temperature of 30.3°C. The actual average river temperature for that same month, however, was only 28°C. The reason for this discrepancy is that our model is not a perfect fit (i.e. $r^2=1$) and as is often the case, does not represent the relationship in the upper and lower extremes very well. Nevertheless, there is a lack of alternative approaches and the model could be applied to generate a first pass estimation of future changes in river temperature. When doing this, it needs to be assumed that the relationship between catchmen air and river temperature is linear, even for very high temperatures that haven't been observed yet and were thus not used in the fitting of the model. If there is doubt that this assumption is not valid for the variable of interest, a process-based physical model would be a more appropriate choice.

For the Hunter River catchment, the NARCliM model ensemble projects an increase in the hottest monthly average air temperature of the year of +1.9[1.6, 2.3]°C (median[10^{th}, 90^{th}] percentile change) by 2070 (for the Hunter River catchment). Adding the possible upper-end increase of 2.3°C to the observed present day maximum monthly average air temperature of 35°C would yield a maximum monthly average river temperature of 32.37°C by 2070, which may have significant ecological ramifications.

3.1.4 Numerical modeling

Engineers Australia (2012)[122] defines numerical models as *"sets of equations representing a subset of the physical processes being solved by computers throughout a grid or network on an iterative basis".* Depending on its governing equations, a numerical model can be one-, two- or three-dimensional (1D, 2D, or 3D), which is also reflected in the dimensions of the model grid built on a particular coordinate system (e.g. cartesian coordinates or curvilinear coordinates). The governing equations of these models are invariably a form of the Navier-Stokes equations for the flow of viscous fluids supplemented by physical equations for water temperature, salinity, turbulent energy and with appropriate source and sink terms.[123]

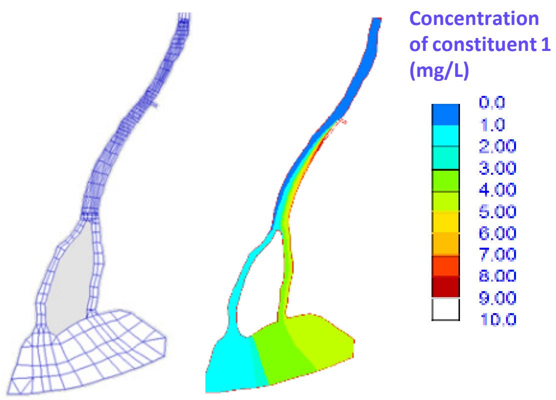


Figure 18: Two-dimensional unstructured numerical model grid of an estuary and model output showing the concentration of a constituent across the system.

1D models consider spatial change over a single coordinate only, usually the direction of flow. As such, the model's variables are averaged over the other two directions.[124] 2D models are suitable for modeling estuaries that are well mixed vertically (i.e. when stratification is not an important issue).[16] They exist in 2D depth-averaged models and 2D width-averaged models. 3D models are the best in representing the relation between the components of velocity, pressure and the concentration of a water constituent (i.e. salinity) at any point (x,y,z) in an estuary, especially when the waterbody is vertically stratified (e.g. due to heat, salinity, and suspended sediments). However, 3D models are computationally costly and there is often limited data to calibrate this type of model appropriately.

The hydrodynamic model grid is a network of grid cells or elements that define the spatial domain (i.e. the geometry of the estuary). Model grids can be structured or unstructured depending on the method used to solve the governing equation, which is either the finite-difference (for structured) or the finite-element (for unstructured) method. The latter is more flexible as it allows the model grid to be adapted to any desired shape and resolution.[123] An example of an unstructured 2D modeling grid, and the concentration of a water quality parameter obtained by this model, is shown in Figure 18. In addition to the model grid, initial and boundary conditions are needed by a numerical model to start and complete a simulation. Boundary conditions refer to the exchange of water and energy at the boundaries of the domain (i.e. river, ocean and atmospheric boundary).

The use of hydrodynamic modeling for assessing the impacts of climate change on estuarine processes includes the study of effects on hydrodynamics, water quality (e.g. salinity, nutrients, phytoplankton and zooplankton), water temperature (heat transport) and sediment transport. Some examples of advanced numerical modeling packages suitable for estuarine studies include ECOM, NCOM, FVCOM, EFDC, POM, MIKE 3, TRIM, CH3D, CE-QUAL-ICM, WASP, RCA, DELFT3D, TUFLOW and RMA.

A recent study used the SCHISM hydrodynamic model to analyse the tidal response of multiple estuaries to sea level rise in different types of estuaries in the Chesapeake Bay estuarine system on the US east coast by Du et al., (2017)[125]. The simulated changes in the estuarine water levels are shown in Figure 19.

In Module-6, the hydrodynamic (RMA2) and water quality (RMA11) model from the RMA suite of models[126,127] are applied to study the impacts of climate change on the

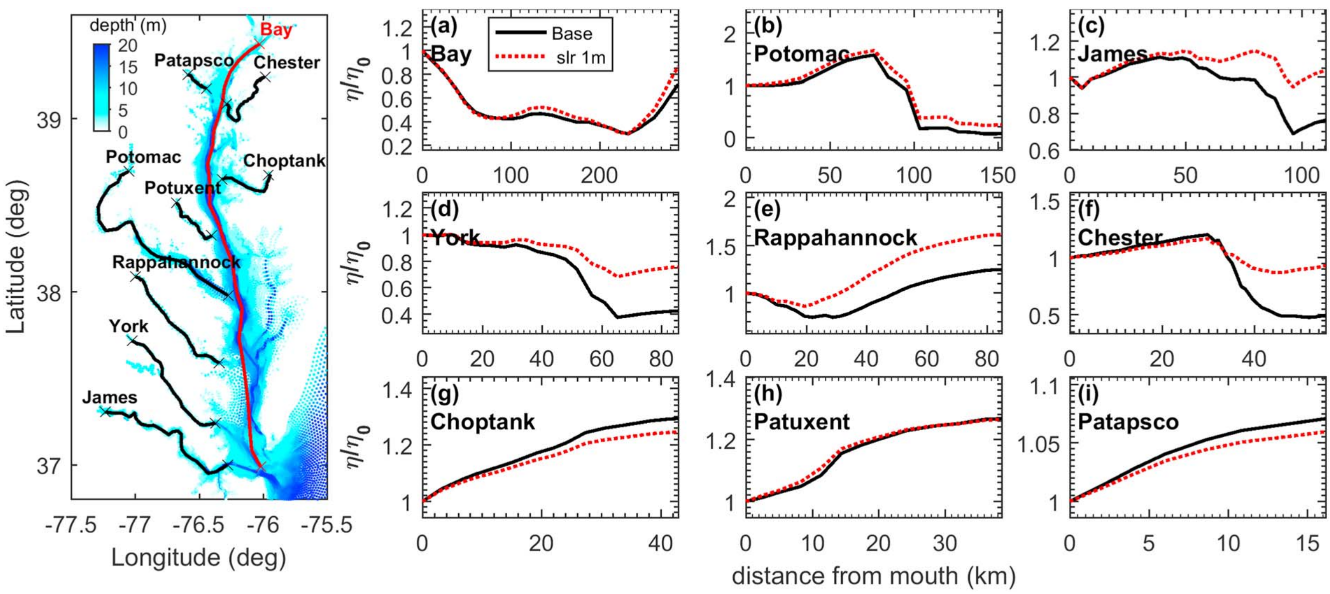


Fig. 19: The tidal response to SLR in multiple estuaries. Locations of the realistic channels are shown in the left panel, where the coloured dot is the depth of the nodes of the unstructured grid. The tidal range (η) along the channel is normalized by the tidal range at the mouth of each estuary. (Source: Du et al., 2018)[123]

Hunter River estuary in Newcastle, NSW, as a case study. This study looks at the impacts of increasing sea levels, sea surface temperature, river water temperature, and varying freshwater flows on estuarine hydrodynamics and a range of water quality parameters for a near future (2025-2035) and far future (2065-2075) scenario. The hydrodynamic simulation results for salinity levels between the estuary mouth and upstream tidal are shown in Figure 20.

It can be seen that the model is able to provide a quantitative prediction of the changes to the salinity conditions in the estuary both on the spatial and temporal domain for different climate change scenarios. These projected changes in salinity and other water quality parameters resulting from climate change form the basis of the ecological impact assessment, undertaken in Module-6.

In general, numerical models are a robust method for obtaining predictions on the changing environmental conditions in estuaries due to climate change. However, like any model, numerical models have drawbacks. The principal limitation lies in the parameterization of numerical models, which is often limited by a lack of sufficient in-situ data. Accurate parameterization is particularly difficult for models related to water quality and sediments, where providers are often overoptimistic when it comes to the reliability of predictions, due to the lack of sufficient data for validation.[122]

Further reading:

Jakeman, A.J., Letcher, R.A., Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environ. Model. Softw. 21, 602–614. doi:10.1016/j.envsoft.2006.01.004

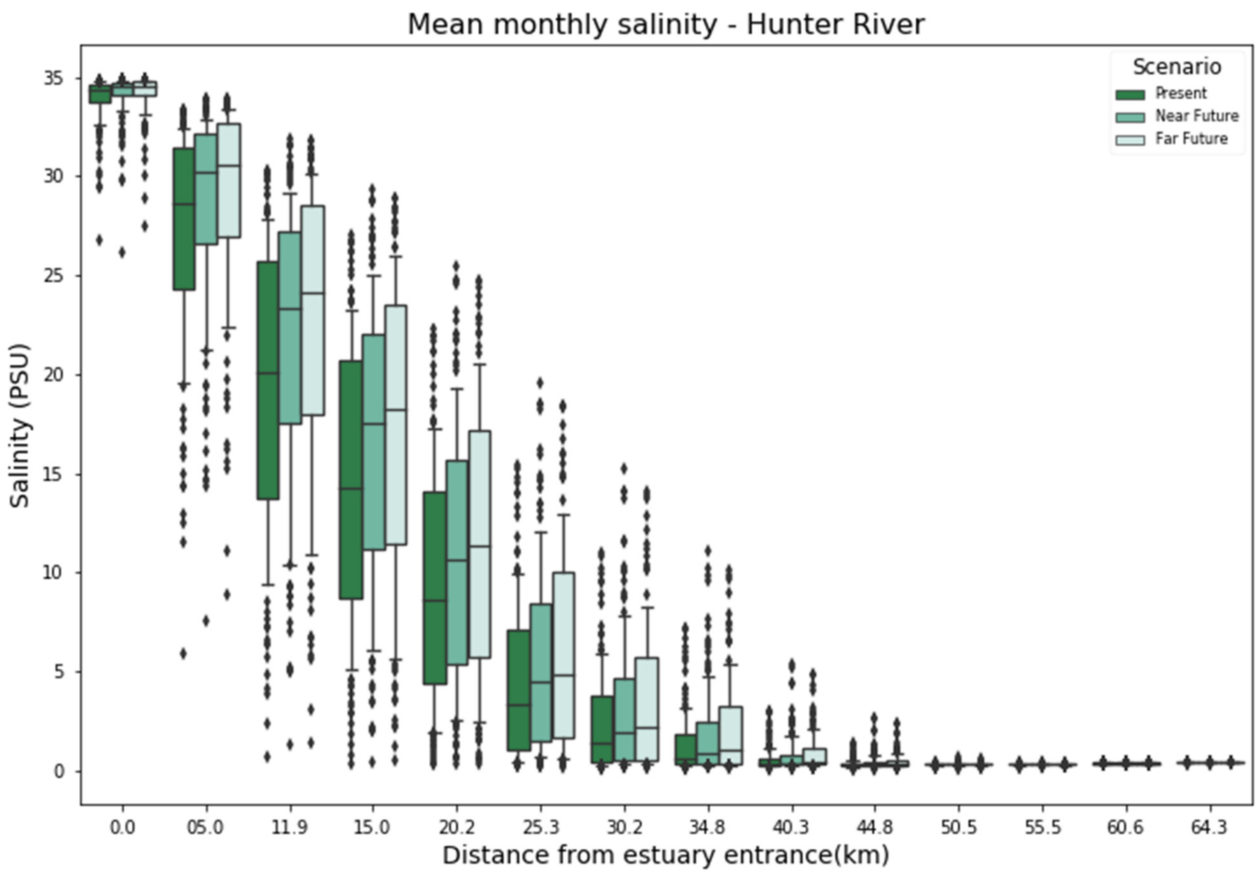


Fig. 20: Example of hydrodynamic modeling results of a present day (2010, dark green), near future (2030, 0.2m sea level rise, medium green) and far future (2070, 0.5m sea level rise, light green) scenario, shown as boxplots of average monthly salinity levels along the Hunter River Estuary in New South Wales, Australia.

"Comparatively, our results show the potential future growth of exposure to inundation within estuaries to be a far greater problem in NSW than that of exposure to open coast erosion which while nevertheless significant, is an order of magnitude less than the results presented here."[67]

Drone view of the entrance barrier of the Lake Tuggerah estuary, The Entrance, NSW; Photo: Chris Drummond, WRL, UNSW

3.2 Sources of physical data

Sources of physical data need to be carefully chosen to ensure that they are applicable for use in a local-scale risk assessment and in associated models. Assessing the impacts of climate change in estuaries generally requires two types of data: a) observational (i.e. measured) data sets that capture the recent historic state, dynamics and evolution of estuaries and b) projections that provide a realistic set of future states for climate drivers.

As discussed in detail in Module-2, projections of future climate are generated by physically modeling the Earth's climate and ocean system under a range of socio-economic and greenhouse gas scenarios. Consequently, reliable projections of future changes only exist for boundary climate and ocean variables (see first-order impacts in the Framework for Assessment in Module-1) and the resulting physical changes within estuaries need to be inferred from these projections.

The NSW and ACT Regional Climate Modeling (NARCliM) project provides locally-relevant projections of future temperature, rainfall, wind and evaporation that are appropriate for regional climate change decision making in South-East Australia. Sources of future projections for other variables important for estuaries such as sea surface temperature, oceanic acidity and salinity are also provided and discussed in Module-2. Some important sources for present and historic data on important climate, estuary and ocean variables are summarized below.

Location, geomorphic type and key properties of estuaries in NSW

The NSW Office of Environment and Heritage hosts a database containing the location, geomorphic type, area and volume of all estuaries in NSW (http://www.environment.nsw.gov.au/topics/water/estuaries). A state-wide mapping of estuarine habitats for all NSW esutaries is provided by the NSW Department of Primary Industries (https://www.dpi.nsw.gov.au/content/research/areas/aquatic-ecosystems/estuarine-habitats-maps).

Water quality data for estuaries in NSW

Long-term monitoring programs, run by various agencies, are important sources of data that, depending on their start date and duration, can be used to track trajectories of environmental change. The Monitoring, Evaluation and Reporting (MER) estuarine monitoring program by the NSW Government provides in-situ data on many important estuarine water quality parameters for the majority of estuaries in NSW.[1] The data is available upon request from the NSW Office of Environment and Heritage. Parts of the dat are available online at the Sharing and Enabling Environmental Data portal of NSW government: (https://datasets.seed.nsw.gov.au/dataset/estuary-water-quality-data-compilation-soc-201034494).

Rainfall and streamflow

Real-time rainfall data of daily, weekly and monthly time steps as well as river height observations are available online at the website of the Australian Government Bureau of Meteorology (BOM) (http://www.bom.gov.au/nsw/flood/index.shtml). BOM also provides historical data of rainfall at many weather stations in the Climate Data Online page (http://www.bom.gov.au/climate/data/). Live rainfall data for coastal NSW is available online at (http://www.mhl.nsw.gov.au/data/realtime/Rainfall) provided by the Manly Hydraulics Laboratory (MHL). Data on historic and current levels of streamflow and water storage are accessible from the Water Data Online website of BOM (http://www.bom.gov.au/waterdata/) and the real-time data website of WaterNSW (https://realtimedata.waternsw.com.au/) This page contains data on quality and quantity of water in rivers, streams, groundwater and dams from monitoring stations across NSW that are managed by the NSW Department of Primary Industries (DPI) – Water and other NSW agencies including BOM, MHL, WaterNSW, the Murray Darling Basin Authority, State Emergency Services (SES) and the Border Rivers Commission (BRC). A typical monitoring site continuously measures the water conditions (most commonly flow, salinity and temperature) every 15 minutes.

Temperature

Long-term datasets and current air temperature from multiple meteorological stations in NSW are directly available from BOM through the Climate Data Online page and from satellite-based climate data (e.g. NOAA, MODIS).

For water temperature, data records across the water monitoring stations in NSW are available at the Water Data Online page of BOM and the Real-time Data page of WaterNSW. Coastal water temperatures are available from satellite climate data and regionally from the NSW-Integrated Marine Observing System (IMOS) (http://imos.org.au/nodes/nodes/nswimos/) which contains data from oceanographic buoys along the NSW coast. Water temperature data within estuaries are available only for limited locations from local government (e.g. https://www.mhlfit.net/users/HornsbyShireCouncil/) and scientific research institutions (e.g. DPI for a number of gauges in large estuarine rivers such as the time series shown in Figure 4 of this module, MHL and SIMS in Sydney Harbour or NSW DPI Fishery Centre in Port Stephens). Satellite measurements of sea surface temperature is available through the IMOS data (http://imos.org.au/facilities/srs/sstproducts/), which can be discovered and extracted through the Australian Ocean Data Network (AODN) portal (https://portal.aodn.org.au/).

In addition to these sources, there are several regional and global gridded datasets for land and sea surface temperature. The Australian Water Availability Project (http://www.csiro.au/awap/) and SILO (https://silo.longpaddock.qld.gov.au/) provide gridded time series data for many important climate variables including temperature, rainfall and soil moisture for the Australian continent at approximately 5x5km resolution. In addition, there are several global reanalysis datasets that provide gridded daily climate and ocean data including the NCEP/NCAR reanalysis data used in Module-2 (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html) or the MERRA-2 global data set (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/).

Salinity

In addition to the data from the MER program1, salinity data within estuaries can be provided from local government institutions or business units (e.g. MHL) depending on the availability of specific local projects. However, due to the dynamic nature of estuaries, salinity dynamics typically need to be modeled using a coupled hydrodynamic and salinity model as discussed in section 3.1.4 (Numerical models). Salinity measurements are often reported as electrical conductivity (EC), a measurement of the capacity of the water to transmit an electric current, which is directly influenced by the concentration and composition of dissolved salts in the water.[128]

A number of water monitoring stations in NSW provide recent hisytoric time series of EC, which can be accessed through the Water Data Online page from BOM and the WaterNSW real-time data portal, although typically for a shorter time span compared to streamflow and temperature records. Sites with salinity data available at the BOM website can be identified using The Environmental Information Explorer (http://www.bom.gov.au/jsp/eiexplorer/). Salinity data of selected estuaries can also be sourced from the Geoscience Australia (http://dbforms.ga.gov.au/pls/www/npm.mars.search) and through the publications of the MER program (https://www.environment.nsw.gov.au/soc/datainventory.htm#ecl).

Acidity

Data on future pCO_2 levels are available from the Intergovernmental Panel on Climate Change (IPCC). Data on current or past pCO_2 levels in NSW estuaries are limited to a few local studies (e.g. MER dataset;[1] Runcie and Byrne, 2018;[129] Maher and Eyre, 2012;[130] Maher et al. 2015;[131] Ruprecht et al 2018[101]). Water quality measurements available at the Water Data Online page of BOM and the WaterNSW real-time data portal also include pH at some monitoring stations.

Dissolved oxygen (DO)

The availability of data on DO is comparable to acidity. DO data are typically limited to local studies on water biochemistry but continuous DO data is available for selected rivers and estuaries from the MER datasets and the WaterNSW real time data portal (https://realtimedata.waternsw.com.au/). Predictions of future DO levels need to be modelled based on changes in water temperature, thermocline depth and nutrient inputs.

Sea-levels:

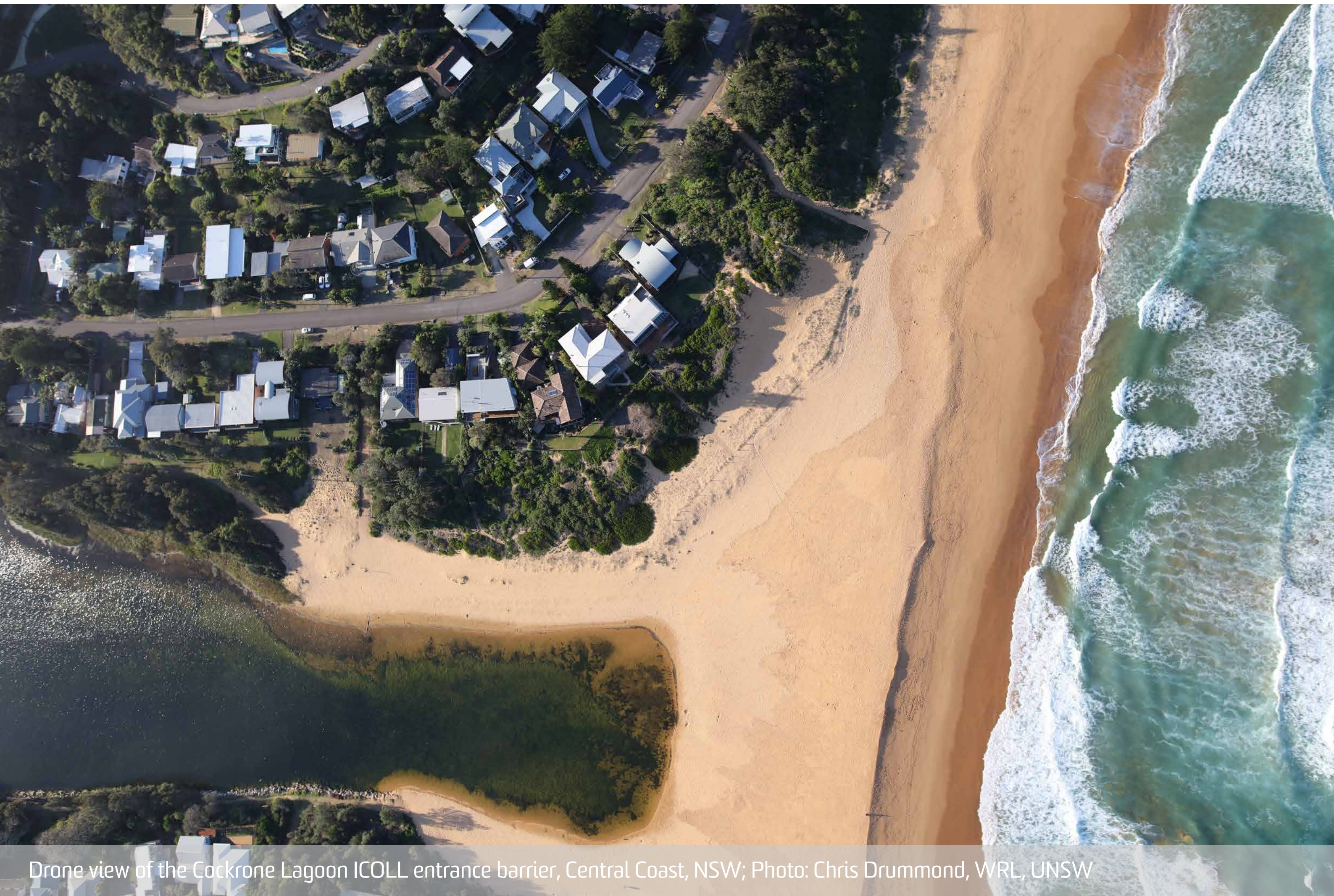
Projections of future sea-levels and rates of increase around the world based on four Representative Concentration Pathways (RCPs) are available from the Intergovernmental Panel on Climate Change (IPCC) and for Australia through selected reports.[47] Details of these projections are discussed in Module-2. Projected average sea level rise for the four RCPs up to 2100 for the open coastline in each coastal council in Australia is available online at CoastAdapt (https://coastadapt.com.au/sea-level-rise-information-all-australian-coastal-councils) with a baseline period from 1986 to 2005. This page also provides observed satellite data that can indicate the extent of present-day inter-annual variability of sea level rise in the location of interest. Such datasets, however, are useful for determining the future ocean boundary water levels for estuaries, whereas future water levels within estuaries require additional considerations (as discussed in Section 2.4 of this module).

Waves and tides:

Real-time wave conditions in NSW are measured by wave buoys, which provide robust data on wave height, wave direction and wave period at seven offshore locations along the NSW coast. This data is collected by the Manly Hydraulics Laboratory (MHL) through the NSW Coastal Data Network Program managed by the NSW Office of Environment and Heritage and can be accessed from the website (http://www.mhl.nsw.gov.au/data/realtime/wave/). Tidal charts are also provided by MHL in this page under the NSW Tide Charts tab (http://new.mhl.nsw.gov.au/data/realtime/oceantide/TideCharts) and available for most of the estuaries in NSW. A range of reports presenting data from these sites can be accessed from the MHL Publication Library (http://new.mhl.nsw.gov.au/services/publications/).

Sediment loads and turbidity:

Sediment loads and turbidity parameters (measured as secchi depth) are often used as a pressure and condition indicator and some data is provided in NSW through the MER program.[1] Prior to the beginning of the MER program, however, these data are rarely available as they have not been regularly monitored, except for certain, widely-studied, estuaries such as the Richmond river and estuaries in the Sydney region.[132–135]



Drone view of the Cockrone Lagoon ICOLL entrance barrier, Central Coast, NSW; Photo: Chris Drummond, WRL, UNSW

4 Summary of physical responses to climate change

The sensitivity of a particular estuary to climate change largely depends on its geomorphic and hydrological regime. For example, an intermittently closed and open lagoon 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 is likely to be significantly impacted by sea-level rise. The exact extent of these responses to climate change often remains poorly understood and requires a detailed and site-specific climate change risk assessment. Nevertheless, the direction and strength of the likely physical changes can be estimated based on existing knowledge and the corresponding scientific literature.

The findings of the literature review presented in Section-2 of this module is synthesized into a summary table (Table 7) of climate change impacts, which is structured by the type of estuary, the climate change driver and the affected processes. To avoid unnecessary complexity, the processes that define the physical estuarine environment have been grouped into the following three categories:

Hydrodynamic & mixing processes

This defines the movement of water throughout the estuary. It includes influences from the tides, gravitational forces, Coriolis, freshwater flows (catchment runoff), waves and wind.

Sediments and geomorphological processes

This describes the state and movement of sediments in the system. Sediments can be transported from the catchments or from marine sources through aeolian transport, wave, tidal or freshwater flows.

Water quality processes

Water quality is largely influenced by catchment runoff and the biological processes occurring within the estuary. Water quality is defined by temperature, salinity, turbidity, oxygen levels, nutrients and acidity.

The climate change drivers considered in the table are temperature and the surface heat budget, rainfall, sea level rise, oceanic acidity, wind and waves. The resulting summary of the likely strength of climate change impacts on estuarine processes for different types of estuaries is shown in Table 7. The table is based on the following three levels indicating the sensitivity of physical estuarine processes to possible changes in a climate driver (i.e. rainfall, temperature, sea levels).

Low

A process is not likely to be influenced by a change in the climate driver.

Moderate

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

High

Changes in the climate driver will have significant direct impacts on the estuarine process. The estuarine process is directly dependent on this climate driver.

For each climate driver, the table provides a rating of the sensitivity of an estuarine process to a potential significant change in this variable. Importantly, a high or medium rating does not imply that the climate driver is projected to undergo significant change in the course of this century in NSW (i.e. deviation outside of natural variability envelopes as discussed in Module-2). To estimate the likely level of change in the relevant climate drivers, it is recommended to carefully consult Module-2 and the summary table of climate change along the NSW coastline provided in it.

The qualitative assessment presented here is useful as a first pass assessment of climate change impacts in estuaries. It does not quantify the impact of the most likely change in a climate driver on a specific physical estuarine process. However, it can assist in developing adaptation strategies and to plan detailed climate change risk assessments.

Table 7: Qualitative rating of the sensitivity of broad physical estuarine processes to possible significant changes in climate drivers. A moderate or high level of sensitivity does not imply that the climate driver is projected to undergo significant change along the New South Wales coastline over the course of this century.

Climate Driver	Oceanic embayments	Tide dominated	Wave dominated	ICOLLs	Estuarine processes
Temperature & Heat Budget	Low	Low	Moderate	High	Hydrodynamics & mixing
	Low	Low	Moderate	Moderate	Sediments & geomorphology
	High	High	High	High	Water quality
Rainfall	Low	Low	Moderate	High	Hydrodynamics & mixing
	Low	Low	Moderate	Moderate	Sediments & geomorphology
	Low	Low	High	High	Water quality
Sea Levels	Moderate	Moderate	Moderate	High	Hydrodynamics & mixing
	Moderate	High	Moderate	Moderate	Sediments & geomorphology
	Moderate	Moderate	Moderate	Moderate	Water quality
Oceanic Acidity	Low	Low	Low	Low	Hydrodynamics & mixing
	Low	Low	Low	Low	Sediments & geomorphology
	High	High	Moderate	Moderate	Water quality
Storms, Winds and Waves	Moderate	Moderate	High	High	Hydrodynamics & mixing
	Moderate	Moderate	High	High	Sediments & geomorphology
	Low	Low	Moderate	Moderate	Water quality

Drone view of the the Tuggerah Lake estuary entrance channel, Central Coast, NSW; Photo: Chris Drummond, WRL, UNSW

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Back cover image

Drone view of the Belongil Creek estuary entrance, Byron Bay, NSW; Photo: Chris Drummond, WRL, UNSW