Estuaries

and climate change

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School of Civil and Environmental Engineering

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National Climate Change Adaptation Research Facility
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This document has been prepared by the Water Research Laboratory of the School of Civil and Environmental engineering at UNSW Australia for the National Climate Change Adaptation Research Facility (NCCARF). The document is designed to support stakeholders in understanding the influence of climate change on Australian estuaries.

This document should be cited as:
Glamore, W. C., D. S. Rayner, and P. F. Rahman, 2016: Estuaries and climate change. Technical Monograph prepared for the National Climate Change Adaptation Research Facility. Water Research Laboratory of the School of Civil and Environmental Engineering, UNSW.

Preamble

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

This document provides an overview of Australian estuaries and describes how estuarine processes are at risk through future changes in the climate. The information presented highlights the variability of environmental conditions across the continent and describes important classifications and key physical processes in various estuary types. Potential threats to estuaries resulting from future climate change are examined. The document concludes with a discussion of how to assess potential climate change impacts at a local estuary, both in terms of physical changes and potential broader impacts on ecological processes.

The science and conclusions presented are based on widely accepted climate change documents. These include recent publications of the Intergovernmental Panel on Climate Change, the Commonwealth Scientific and Industrial Research Organisation, the Bureau of Meteorology, Geoscience Australia's Online Coastal Information (OzCoasts) and other recent scholarly peer-reviewed publications. Further sources of information are provided at the end of this document.

What is an estuary?

Estuaries are partially enclosed coastal water bodies where fresh waters from upland catchments mix with oceanic waters. Estuaries can either be permanently or intermittently connected to the ocean. They are often influenced by tides and are protected from the full force of ocean waves, winds and storms by surrounding land forms such as headlands, beach sand dunes and coastal floodplains.

Why are estuaries important?

Estuaries support unique communities of plants and animals specially adapted for life at the ocean's margin. As a result, estuaries are home to some of the most dynamic and diverse environments in Australia. Many different habitats are found in and around estuaries, including shallow open waters, freshwater and saltwater marshes, swamps, sandy beaches, mudflats and sand flats, rocky shores, oyster reefs, mangrove forests, river deltas, tidal pools and seagrass beds. The vegetation and plant life that live underwater and on the fringes of our estuaries provide unique habitats that sustain significant aquatic and terrestrial species.

Estuaries are important feeding, spawning and nursery grounds for many animals. Over 70% of coastal fish species in south-eastern Australia move through estuaries to complete their life cycle (Copeland and Pollard 1996). Animals such as crabs also rely on estuarine water to complete their life cycles, while others, such as migratory shore birds, visit estuaries to feed and roost.

Estuaries are a vital part of everyday life for over 80% of Australia's population who live within 50 km of the coastline. The fisheries and aquaculture industries, both recreational and commercial, ecotourism and port facilities provide additional human values from estuaries and contribute significant annual revenue to national, regional and local economies. Our coastal cities and towns on estuarine foreshores use these waterways for disposal of stormwater run-off and wastewater treatment plant discharges.

What does an estuary look like?

Australia has thousands of estuarine systems (Short and Woodroffe 2009). They range in shape and size, from large open embayments to drowned river valleys, tidal deltas and small coastal lagoon systems. The shape of an estuary is determined by a large number of factors such as geology, sea-level history, climate, topography, tectonic setting, sediment supply, tidal currents, wave action, biota and human activity. The physical characteristics of an estuary are the dominant cause of ecological patterns at large scales, with differences between estuaries arising from long-term effects of various dynamic processes. Estuaries in Australia can be grouped into three main types described below as well as many sub-classifications (Figure 1).

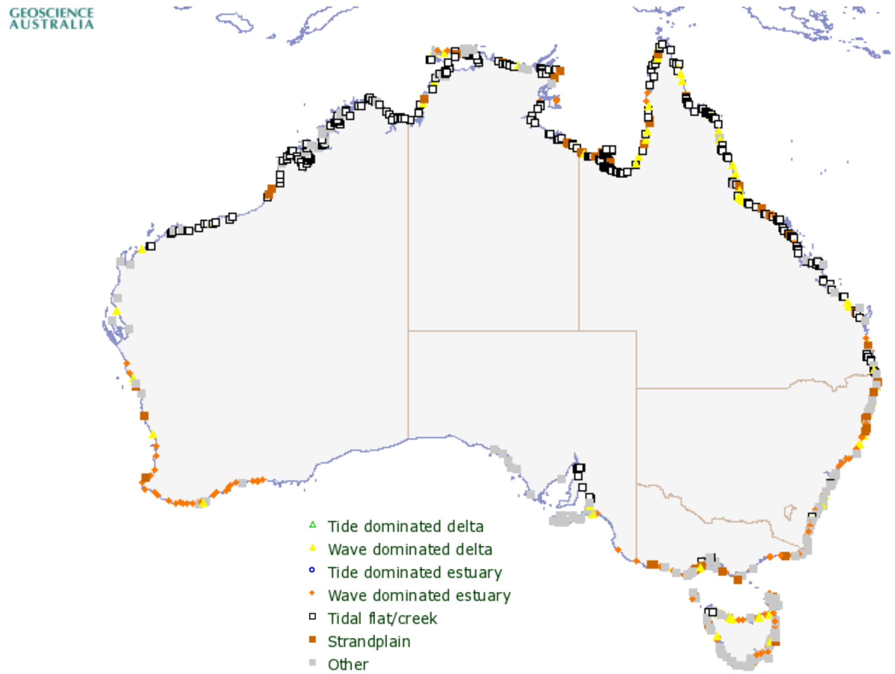

Figure 1: Common estuary types throughout Australia.
Source: © OzCoasts (Geoscience Australia) 2008.

Open embayment estuaries are semi-enclosed systems characterised by marine waters with limited freshwater inflows. The relative influence of waves and tides on embayments is variable, with differences in the orientation, configuration and water depth affecting the penetration of waves and salinity gradients. Strongly indented embayments support more sheltered environments. The influence of waves and tides is generally reduced with distance from the entrance of the embayment. This is mostly due to friction from the seabed and localised landform features such as headlands or offshore islands, which may also form a protective barrier and limit wave penetration into the embayment.

Tide-dominated estuaries generally consist of a landward-tapering funnel-shaped valley, bounded by various intertidal sedimentary environments such as intertidal flats, mangroves, saltmarshes and salt flats. Tide-dominated estuaries have large, often deep entrances, with tidal ranges similar to the open ocean. Tide-dominated estuaries are distinguished by relatively high tidal energy at the mouth (compared to wave energy, which is generally dissipated by tidal sand banks). Tide-dominated estuaries evolve by infilling river valleys with terrestrial and marine-derived sediments and are characterised by a translation of geomorphic and sedimentary environments in a seaward direction. Vegetation associated with mangrove, saltmarsh and salt flat environments plays a major role in determining estuarine form during the early stages of evolution because of their capacity to trap fine sediment. These habitats typically support both transient and permanent marine species.

Wave-dominated estuaries have tidal inlets that are constricted by wave-deposited beach sand that forms barriers and flood tide deltas at the entrances. The resulting entrances are commonly smaller than those in tide-dominated estuaries. The tidal ranges within the estuary basins are generally considerably less, in the order of 5–10% of the ocean tide, and tidal currents are negligible. Local wind waves and wind-induced water movements are the dominant sediment transport mechanisms and the estuaries are predominantly influenced by river discharge. The unpredictability of rainfall in parts of Australia means the opening behaviour of these estuaries may be intermittent and the salinity regime highly variable. There are different types of wave-dominated estuaries, such as barrier estuaries, barrier lagoons and inter-barrier estuaries. Intermittently closed and open lakes and lagoons (ICOLLs) are a subset of wave dominated estuaries that occur where wave energy is high and the catchment is relatively small. The mouths of these estuaries are often blocked by beach sand for extended periods due to small run-off volumes or upstream river discharges. These estuaries can be non-tidal for long periods but can naturally open to the ocean following heavy rainfall or be mechanically opened to reduce upstream water levels.

Different environments within an estuary

Australia's estuaries are as varied as the climate, ranging from large unregulated rivers flowing into expansive tidal deltas in the tropical north to small coastal lagoon systems in the country's southeast. The wide variety of estuarine systems, within a range of climatic conditions and geological settings, contributes to the formation of diverse environments that harbour habitats and species making up the unique biodiversity of Australia's coastline. Different estuarine environments, supporting different ecosystems, occur due to differences in tidal action, waves and freshwater flow. Some of these environments are listed below (and see Figure 2):

- continental shelves
- barriers
- central basins
- flood and ebb tidal deltas
- channels
- rocky reefs
- fluvial deltas
- intertidal flats
- mangroves
- saltmarshes
- salt flats (salt pans)
- tidal sand banks

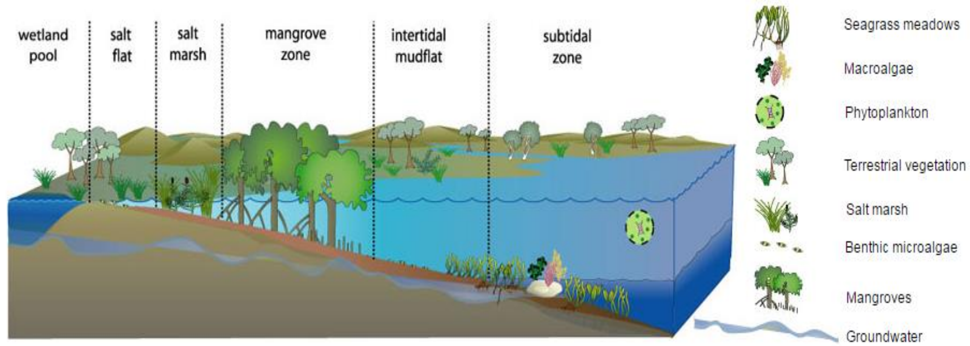

Figure 2: Estuarine intertidal environments.
Source: © OzCoasts (Geoscience Australia) 2008.

Natural climate of estuaries

Like the climate, estuaries are rarely in a steady state, even under existing weather patterns. In general, an estuary mirrors the physical characteristics of the region, including the underlying geology and subsequent geomorphology, and the long-term driving forces such as climate. Shifts in the climate beyond the historical natural patterns (as may happen due to climate change) will be subsequently reflected in the estuary.

Climate affects the functioning, distribution and geomorphology of estuarine systems. Estuarine environments are intrinsically linked to, and affected by, climate factors operating over a range of temporal (sub-daily, daily, annual, decadal, century and millennial) and spatial (sub-catchment, catchment, regional, continental and global) scales. Precipitation patterns and freshwater run-off, temperature, evaporation, radiation and wind, along with numerous additional forcing factors, all influence the geophysical and biological nature of estuarine landforms, habitats and ecosystems.

Imbalances between annual rainfall and heat (temperature and evaporation) can result in climatic extremes, particularly in areas with strong rainfall seasonality, such as Australia's north (Figure 3). This can dramatically alter the hydrology and salinity throughout an estuary as freshwater inflows influence the tidal processes. Estuaries in different areas of Australia are exposed to different rainfall trends, with areas such as north Queensland experiencing monsoonal rainfall during summer months, with reduced winter rainfall. Tasmania, on the other hand, experiences less seasonality and receives regular year-round rainfall. Other areas, such as the arid coastline of Western Australia, are dominated by evaporative processes.

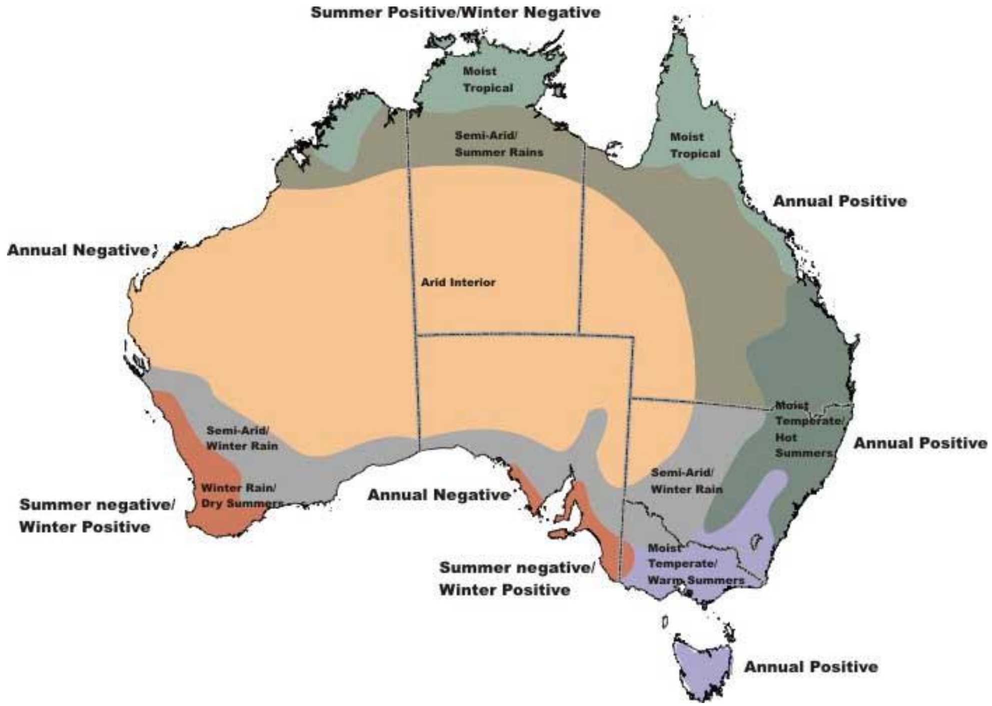

Figure 3: Seasonality of annual rainfall, with evaporation resulting in a negative balance. Source: © OzCoasts (Geoscience Australia) 2008.

Estuarine processes

Estuaries are dynamic systems with cycles and processes operating at a range of spatial and temporal scales. Physical estuarine processes, the primary focus of this document, can be explained by examining hydrodynamic (water movement) and mixing processes, geomorphology processes, and water quality processes (see summary box).

The hydrodynamic processes present in an estuary (see Figure 4) significantly influence the biological processes present. Hydrodynamic processes include tides, inflow, wind and wave action, and water density variations. Geomorphological processes are influenced through variations in catchment run-off, the ingress of marine sediments, and changes within the estuarine river channel. Water quality processes are typically driven by catchment run-off processes (e.g. changing water quality resulting from changes in land use) and in-estuary processes, including the biological processes. While individual events, such as a large flood, a spring tide, or a change in entrance condition might determine the short-term characteristics of an estuary, the longer term composition is a mixture of various forces operating over multiple spatial scales (catchment-wide and regional climate) and temporal scales (years, decades and centuries).

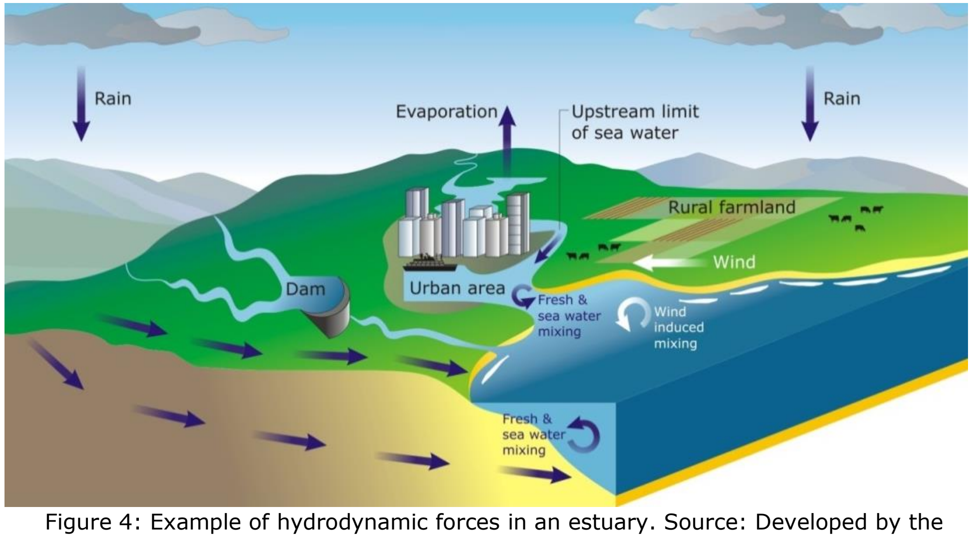

Figure 4: Example of hydrodynamic forces in an estuary. Source: Developed by the author.

Summary of estuarine processes

Hydrodynamic (and mixing) processes

Tides are driven by the gravitational attraction of the moon and the sun, which causes regular periodic movement of waters.
Gravitational forces can affect estuarine water circulation due to gravity acting on the density differences in the estuary.
Coriolis forces caused by the rotation of the Earth about its axis may affect large estuaries. Inward and outward currents displace leftward (in the Southern hemisphere) of their direction of flow.
Freshwater flow can come from rainfall run-off on the estuarine catchments, less any infiltration. Run-off volumes can be amplified (e.g. via urbanisation) or reduced (e.g. via detention basins) by anthropogenic influences.
Waves can be generated offshore or internally and affect shores, marginal shoals or shallow estuaries. Waves redistribute eroded material offshore/onshore throughout an estuary.
Wind forces can significantly modify circulations and turbulent mixing in wider environments. Strong winds may cause storm surges in surface waters that can induce large flow volumes. Wind also impacts on the level of stratification and mixing within the estuary. Large open, shallow estuaries are more influenced by wind energy than are deep, narrow estuaries.

Geomorphological processes

Catchment sediments are derived via catchment erosion, biological activity and/or aeolian (e.g. wind-borne) transport.
Marine sediments are delivered from the continental shelf in front of the estuary. The sediments are transported due to the inequalities in tidal currents (ebb versus flood tide) to supply sediment on various timescales.

Water quality processes

Temperature 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.
Salinity is the amount of salts dissolved in water. It controls 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.
Turbidity is a measure of water clarity, that is, the ability of water to transmit light. Turbidity is influenced by the level of suspended material in the water column.
Oxygen, measured as dissolved oxygen, affects estuaries. DO is the level of oxygen that is available to support estuarine ecology. Biological oxygen demand (BOD) is a measure of the amount of oxygen that organisms would require to decompose the organic material in an estuary and is indicative of pollution levels.
Nutrients, in particular nitrogen and phosphorus, are key water quality parameters in estuaries, as they have significant direct or indirect impacts on plant growth, oxygen concentrations, water clarity and sedimentation rates.
Acidity/alkalinity are important to ecosystem health because most aquatic plants and animals are adapted to a specific range of pH and alkalinity. Sharp variations outside of this range can be detrimental.

Ecological processes are linked with these physical processes, often through complex feedback loops, which are still being understood. Generally, the biotic composition of an estuary is determined through a hierarchy of processes, with the higher order processes influencing the lower stages. In this way, estuarine ecology such as floral distribution, faunal species richness and fisheries production are directly influenced by the estuary's physical and chemical characteristics, which are, in turn, controlled by geological setting, entrance conditions, evolutionary history and regional climate. Figure 5 provides a simplified hierarchical diagram demonstrating how climate processes might influence estuarine processes. In reality, the feedback process is more complex.

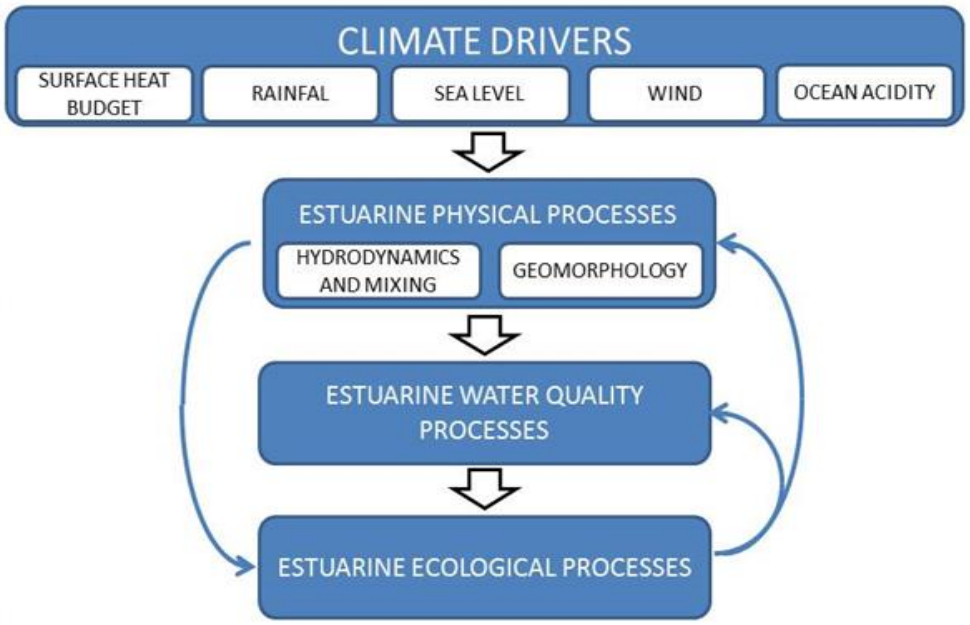

Figure 5: Simplified dependence of estuary processes. Source: Developed by the author.

Mixing processes within estuaries

Mixing processes, such as flow circulation and mixing dynamics, influence nutrients, salinity, contaminants and sediment transport within an estuary over various spatial and temporal scales. Mixing can be caused by a variety of factors such as winds and tides; however, mixing between freshwater inflows and oceanic salinity can be important in defining the structural and functional characteristics of estuaries. The key components of this process are provided below.

Saline waters from the ocean, with higher densities, can penetrate an estuary to produce salinity/density gradients. This 'salt wedge' effect, shown in Figure 6, can induce currents and influence mixing conditions and circulation patterns in an estuary. These dynamics are often important to estuarine processes.

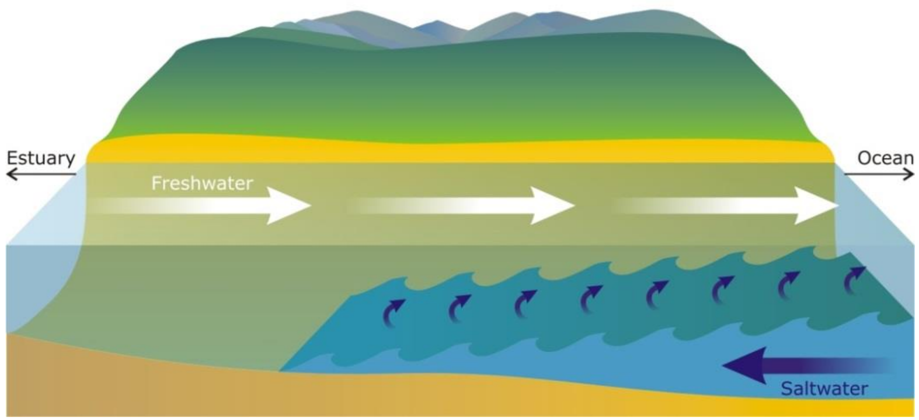

Figure 6: The formation of a salt wedge in an estuary due to the mixing of freshwater inflows and oceanic salt water. As the oceanic water is denser, it can intrude into the estuary as a wedge, depending on mixing conditions. Source: Developed by the author.

A salt wedge is sensitive to changes in upland catchment flows and the sea level. For example, an elevated sea level can cause saline water to migrate further upstream, potentially influencing the availability of water suitable for agricultural and industrial uses (Figure 7). This can occur periodically, due to elevated water levels from coastal storms, or permanently, due to climate change.

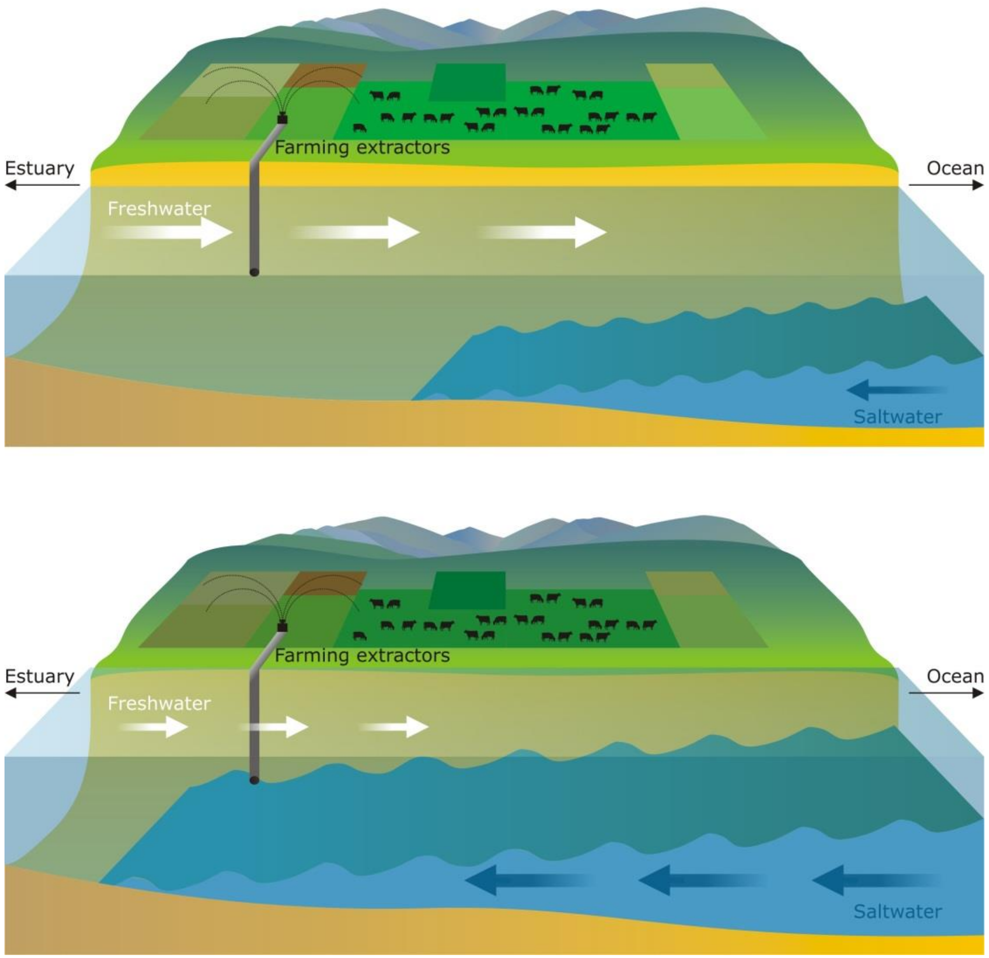

Figure 7: The penetration of the salt wedge further upstream due to elevated sea levels can limit the availability of freshwater available for agricultural use. Source: Developed by the author.

Estuarine systems can be dominated by episodic, short-lived freshwater inflows during storms that flush salt water out of the estuarine system either partially or completely (Figure 8). Persistent changes in catchment inflows and sea levels can lead to different areas of the estuary transitioning from a highly stratified salt wedge, to a partially mixed estuary, to a vertically homogeneous estuary. These changes may impact both freshwater and marine organisms, which are highly sensitive to salinity thresholds and will respond to altered salinity gradients.

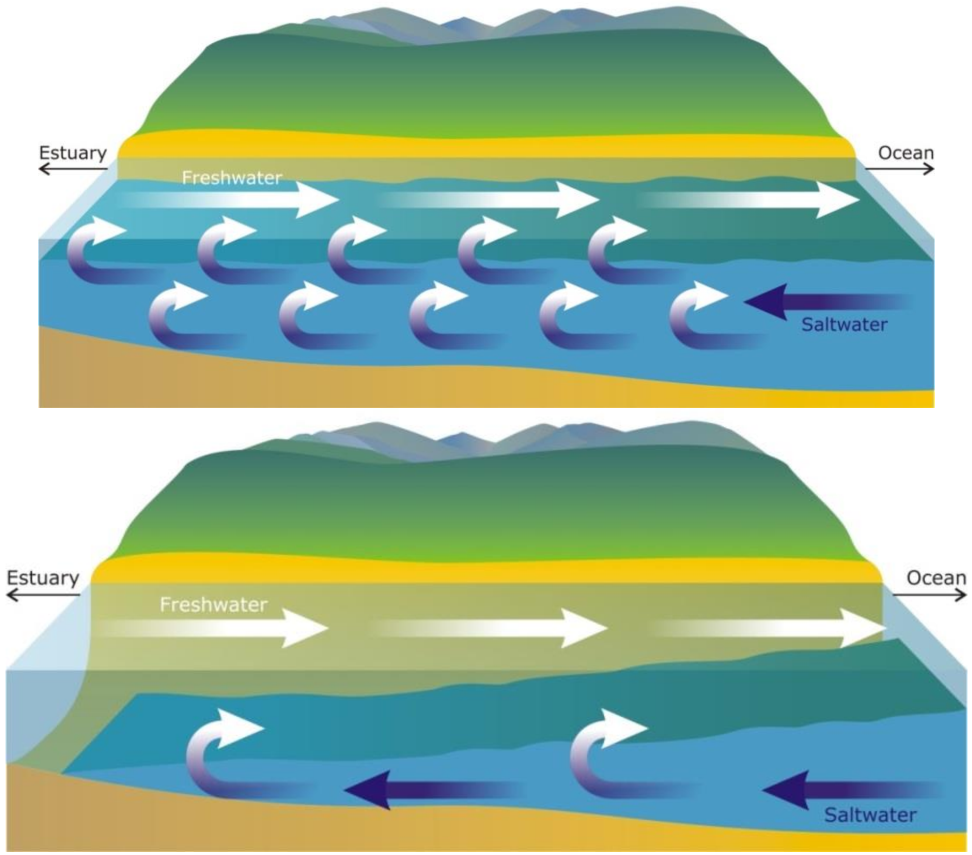

Figure 8: Freshwater from catchment storm events can lead to flushing of the salt wedge in the estuary. Source: Developed by the author.

Natural change/variation in estuaries

Estuarine processes are constantly altered by events of varying frequency and magnitude. Estuaries experience frequent disturbances, ranging from short-term tidal water-level changes, or inflows from rainfall bursts, to longer term climatic changes such as those due to the El Niño Southern Oscillation. Infrequent events such as large floods (Figure 9) or coastal storm surge alter an estuary's geomorphology, for example opening or closing an ocean entrance or creating a new channel connection. These infrequent events may occur over a large spatial area that may cover multiple estuaries.

Figure 9: Infrequent events such as flooding can temporarily alter estuarine conditions.
Source: Top photo courtesy Isabelle Ghetti; bottom photo courtesy Taree City Council.

Coastal flora and ecosystems have evolved physiological, morphological and reproductive strategies to cope with the impacts of these sorts of natural disturbances. Plants are often able to handle moderate increases in single stressors (such as increased salinity, water logging, anoxia or toxins); however, when they are subjected to multiple stressors, ecosystems such as coastal wetlands have been shown to be significantly impacted.

Disturbance and change in estuaries often occurs in response to anthropogenic actions. Activities such as land clearing for development, dredging, irrigation, agriculture or the training of an ocean entrance with break walls can permanently alter an estuary (Figure 10). Such activities have historically led to significant impacts on estuarine systems, including loss of biodiversity and change in the ecological state. These changes can significantly influence the natural variability and/or resilience of an estuarine system to withstand threats or pressures.

Figure 10: Human impacts and development can alter estuarine long-term processes.
These images depict Cooks River near Sydney airport, 1943 and 2016.
Source: Images courtesy of NearMap Australia.

Estuaries under a changing climate

Climate affects the functioning, distribution and geomorphology of coastal and estuarine systems. Estuarine environments are intrinsically linked to, and affected by, the climate operating over a range of temporal and spatial scales. Precipitation patterns and freshwater run-off, sea surface temperatures, evaporation, wind and solar radiation, along with numerous additional forcing factors all influence and shape the geophysical and biological nature of estuarine landforms, habitats and ecosystems (Figure 11).

Key climate processes that are likely to influence estuaries under climate change include:

- sea-level rise
- rainfall
- surface heat budget (i.e. temperature, evaporation, solar radiation)
- wind
- ocean acidification.

Climate change predictions vary significantly depending on future carbon emissions over the coming century. The predicted change to

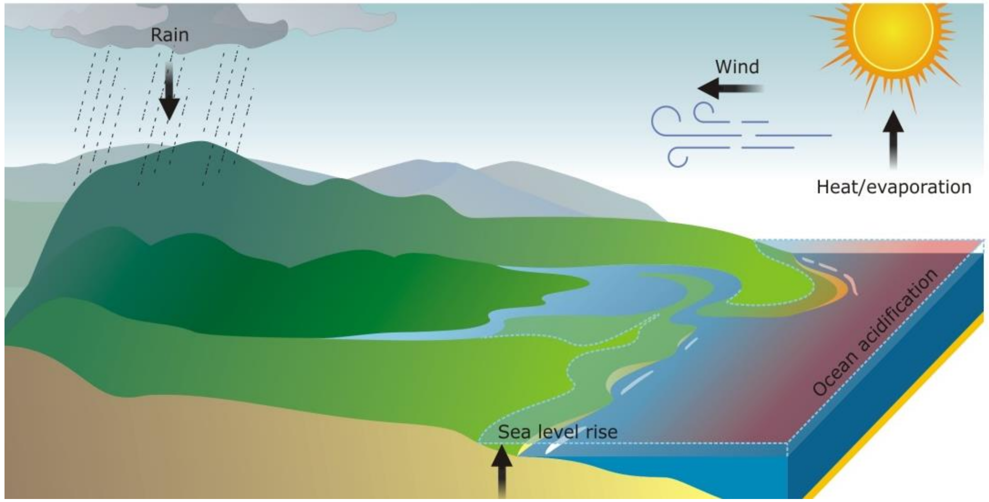

Figure 11: Physical climate change drivers impacting estuaries. Source: Developed by the author.

Australia's climate is likely to vary in severity across the country. Some areas may experience increases in rainfall, whereas other areas may become drier. Wind fields may differ depending on latitude, the influence of seasonal storm events or global circulation patterns. Ocean acidification is likely to impact some estuaries and not others, due to the sensitivity of different ecologies to acidification. However, all climate change predictions project an increase in average temperatures and increases to mean sea levels for the entire Australian coastline.

The magnitude of possible change in an estuary depends on its geographic location and on future carbon emissions. Climatic processes impact the physical, chemical and ecological processes of estuaries in different ways. Importantly, the future impacts from these processes will not be equally distributed, and the relative impacts will depend on the extent to which these climate drivers vary at regional and catchment scales and on the adaptability of the various estuarine environments and components to these changes.

Direct versus indirect impacts

Many estuarine processes are interconnected, with various linkages and feedback loops between ecological and physical processes. The impact of climate change can occur directly and indirectly.

For example:

- The direct impact of sea-level rise could lead to an increase in tidal volume flowing through an estuary entrance.
- An indirect impact of sea-level rise could be changes to seagrass habitat due to increased current speeds and sediment movement throughout the estuary.

The responses of an estuary to climate changes will be determined by the sensitivity of different estuaries to different processes. The sensitivity of a particular estuary largely depends on the geomorphic and hydrological regime of the estuary. For example, an intermittently open and closed lagoon system with a small catchment will be sensitive to increases in temperature and evaporation, but less sensitive to changes in ocean acidity or sea-level rise. However, an estuary that is dominated by tidal hydrodynamics is likely to be impacted by processes such as sea-level rise and catchment inflows.

Impacts of sea-level rise

Changes to mean sea levels are expected to play a dominant role in many estuarine environments. This is because, with the exception of extreme flood events, rainfall and run-off have a limited influence on the depth of an estuary, which is controlled primarily by ocean water levels, the tidal prism and regional geology.

Sea-level rise will not be uniform in space and time. Regional variations in sea level can result from climate and oceanic processes, including changes in winds and air pressure, local topography, freshwater fluxes, offshore currents, and geological processes such as tectonic displacement, land subsidence or isostatic rebound.

Sea-level rise will impact estuaries in variable ways. Significant threats include the increased vulnerability of shorelines and floodplains, resulting in elevated water levels during extreme storms, coastal flooding, and permanent submergence. In these circumstances, built infrastructure may be potentially at risk, including drainage pathways, abutments, and adjoining roadways. Undeveloped shorelines may be equally vulnerable, with potential significant ecological implications.

The resultant changes to tidal hydrodynamics from sea-level rise are likely to influence the water quality and mixing processes of estuaries. This may be particularly apparent in mature channelised estuaries that have an efficient and permanent connection to the ocean. Sea-level rise will likely propagate tides and saline water further upstream, resulting in an increase in the extent of saltwater intrusion. Increased salinity may impact inland soils, freshwater and groundwater resources and nutrient retention. This may lead to the progressive drowning of intertidal environments and freshwater habitats and increase the rate of landward displacement of estuarine shorelines. Changes in tidal prism and tidal velocities will also increase the susceptibility of river banks to erosion and influence water quality and geomorphology.

If estuaries are already dynamic, then why does sea-level rise matter?

Changes to mean sea level can lead to:

- increased coastal erosion
- increased inundation of coastal wetlands, floodplains, estuaries and low-lying areas
- reduced drainage and prolonged inundation of low-lying coastal areas (Figure 12)
- landward displacement of shorelines, estuaries, wetlands and salt marshes
- intrusion of salt water further upstream into estuaries and groundwater systems
- changed overall salinity and temperature density distribution within the estuary
- increased threat to existing coastal and infrastructure through increased potential for inundation
- changed aquatic vegetation distribution through changed inundation levels
- displaced coastal property boundaries
- accelerated changes to ecosystem habitat distribution and land use
- altered estuarine tidal range and circulation patterns
- altered sediment transport regimes within the estuary
- changes to nutrient dynamics within sediments and the adjoining floodplain.

Processes driving regional sea level

Global mean sea level is influenced by the thermal expansion of the oceans due to higher temperatures, melting of polar ice caps and glaciers, and/or changes in freshwater storage.
Astronomical tides are caused by the gravitational attraction between the sun, moon and the rotating Earth, which generates forces on the ocean surface to make sea levels fluctuate daily.
Storm surge is the temporary rise in water levels along a coastline due to reduced atmospheric pressure and is often accompanied by strong onshore winds blowing across a large fetch of open water (i.e. wind set-up).
Wave set-up refers to the shoaling process that causes waves to decrease in speed and wave length with increasing wave height until they ultimately break.
Wave run-up occurs when breaking waves surge up the beach face.
Seasonal temperature can affect heat exchange between the ocean surface and the atmosphere, changing the density of the ocean and resulting in sea-level variations. The change in ocean density leading to change in sea level is known as the Steric Effect.
Coastal-trapped waves are caused by remote meteorological disturbances and can travel along continental shelves freely in the absence of wind effects.
Oceanic processes:

- Inter-decadal Pacific Oscillation
- El Niño Southern Oscillation (ENSO)
- Indian Ocean Dipole (IOD)
- Southern Annular Mode (SAM), also known as the Antarctic Oscillation (AAO)

Source: McInnes et al. (2016).

Impacts of changing rainfall

Rainfall depends on temperature and the supply of moisture through winds and surface evaporation. While future changes to rainfall are not directly influenced by rising greenhouse gases (the key driver of emissions scenarios), a warmer atmosphere can hold more water and induce heavier precipitation. Changes in precipitation can also be caused by winds (circulation), which are in turn impacted by temperature variation on a global scale.

Catchment run-off from rainfall events is influenced by soil moisture, catchment characteristics (such as infiltration, slope, roughness, soil characteristics and landform) and land use. Changes to run-off can also result from anthropogenic influences, such as changes in human activity, land use, water demand, water consumption and diversion, and physical impediments such as dams and detention basins. Direct and indirect anthropogenic factors both influence catchment inputs into estuaries at varying degrees depending on regional climate change and existing and future catchment development.

How will changes to future rainfall impact estuaries?

Changes to rainfall can:

- influence freshwater inflows
- increase flood frequency
- change salinity regimes (including stratification and circulation patterns)
- change water balances and water quality (i.e. changes to the transformations of nitrogen and phosphorus, which occur within areas of high turbidity from catchment-derived sediments)
- alter sedimentation and erosion rates
- alter nutrient loads, leading to changes in water quality
- change flushing and residence times, particularly for intermittently open estuaries
- impact ecology through altered water quality (nutrient delivery and sediments) and changes to the frequency and magnitude of freshwater flows.

Rainfall predominantly controls freshwater flows into an estuary by means of surface run-off and groundwater recharge. Variations in rainfall patterns are likely to have a far-reaching impact on estuarine systems, as freshwater flow is a large source of physical variability in estuaries. Rainfall run-off processes control the pattern of seasonal flows, timing of extreme flow, frequency of extreme flow, magnitude of low/intermittent flow and instances of no-flow events.

Impacts of increasing temperature

Atmospheric and oceanic processes work together on a variety of time scales to control both air and surface ocean temperature. Annual average temperatures in Australia are expected to rise in parallel with global average temperatures; however, there is likely to be significant regional variation, particularly near the coast. Even though the regional surface heat budget is predominantly determined by global climate patterns, it may be influenced by local, regional, and human activities. For example, the heat island effect results from trapped heat due to land clearing and the presence of urban areas.

The surface heat budget may affect estuarine processes primarily through hydrodynamics and mixing and through water quality impacts. Hydrodynamic processes are influenced through changes in catchment evapotranspiration and soil moisture. As with most climate change stressors, temperature and radiation interact with other stressors such as rainfall to influence run-off, further complicating the ability to predict the total impact of climate change within estuaries. While the surface heat budget can be predicted at daily timescales, it is less predictable for inter-decadal and centennial scale fluctuations.

In what ways will a warmer climate impact estuaries?

Higher than average temperatures can:

- increase evaporation from water bodies
- lower soil moisture, which can affect catchment run-off, water balances and sediment loads to the estuary
- impact on biological processes and primary productivity
- change biogeochemical processes and the degradation of toxic chemicals
- lead to changes in stratification and salinity
- promote hypoxic conditions (low DO)
- reduce soil moisture that can alter dissolved organic carbon
- alter photosynthesis of submerged plants
- increase the risk of disease and parasitism which can alter species distribution, mortality rates and reproduction of estuarine organisms.

Impacts of changing wind

Changes to wind fields can impact estuaries via a number of processes at a range of spatial and temporal scales. Changes to wind may impact the viability of wave climates, coastal storms, soil moisture and evaporation. Features such as oceanic fronts and upwelling and downwelling zones will be strongly influenced by wind variations. Changes in wind direction can also influence hydrodynamic flows and littoral sediment transport that are sensitive to changes in the wave climate. Wind-induced flows can also provide ingress and egress of fish and invertebrates that use estuaries for nursery habitats. Strong winds can also elevate fire risks, which can have secondary effects on estuaries through changes to nutrient and sediment delivery and run-off conditions.

In what ways will changes to future wind patterns impact estuaries?

Changes to wind conditions can:

- alter circulation and mixing
- impact coastal erosion and accretion and aeolian sediment delivery
- impact coastal flooding due to storm surge and cyclones
- lead to secondary implications due to increased fire hazards and subsequent sediment and nutrient influxes
- alter coastal/estuarine wind set up.
- Wind induced exchange flows can provide ingress and egress of fish and invertebrates that use estuaries for nursery habitats.

Impacts of changing acidity

Altered acidity will impact estuaries in two potential ways. First, anthropogenic changes to catchment run-off volume/quality facilitate conditions that support acidification and changes to pH due to additional nutrients. Second, there will be an increase in the level of oceanic acidity.

Acidity of estuarine waters is critical to the survival of most aquatic flora and fauna; however, the tolerance to acidity is variable. For example, some species have tolerance thresholds if the pH level drops under 5.0, whereas other species may be a risk if the pH level rises above 9.0. Although such extreme changes are unlikely due to climate change, the change in acidity may impact the ability of estuarine waters to resist, or 'buffer', changes in acidity.

What are the impacts of increased acidity?

Changes to estuarine acidity can:

- alter metal solubility and estuarine water chemistry
- impact the rate of flocculation, with indirect impacts on mixing, sediment dynamics and water quality
- impact calcium carbonate–dependent species such as oysters and shellfish
- alter estuarine ecological productivity and mortality.

Ecological impacts from estuarine acidification can affect the environmental, recreational and commercial value of estuaries. Generally, estuaries are exposed to fast changes in acidity in comparison to open ocean environments. Large flood events flush rainwater (pH ~5) into estuaries and can result in episodic acidification, such as leachate from acid sulphate soils, to produce low pH events (pH <5). The variability of estuarine acidity is generally greater than that of the open ocean due to episodic flushing events.

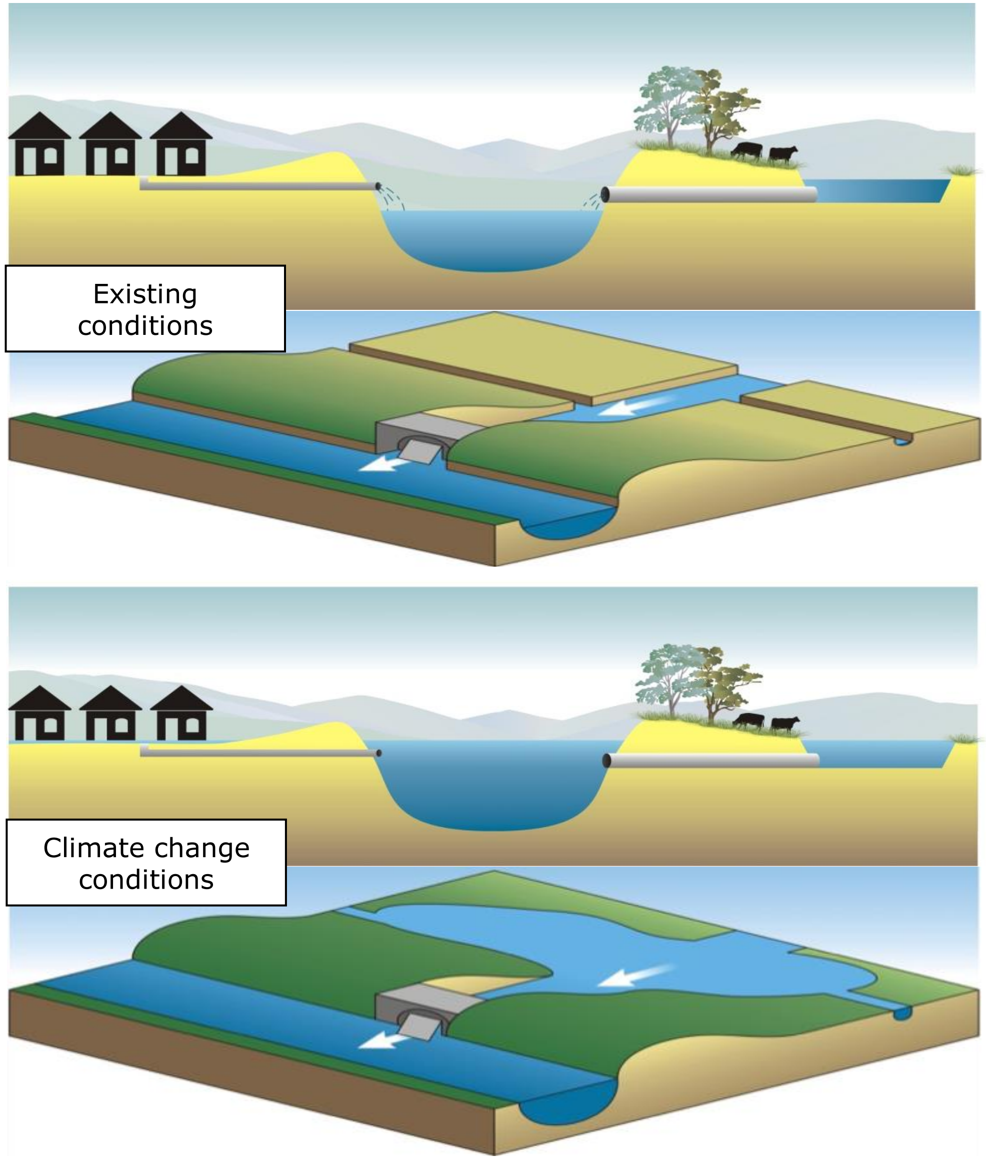

Figure 12: Increased estuarine levels will cause higher low tide elevations, resulting in reduced drainage and prolonged inundation of low-lying coastal areas, impacting agricultural, urban and natural coastal systems. Source: Developed by the author.

Future extreme events in estuaries

The state of an estuary is often determined by extreme events. That is, statistically rare events, be they rainfall, ocean swells, or drought periods, can generate conditions that alter the ecological and geomorphic equilibrium of an estuary. This section briefly discusses these events under a changing climate, but also notes that the prediction of these future extreme events is generally considered less reliable than the prediction of long-term trends.

Recent analysis by the Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organisation (CSIRO) of future climate models found that the average rainfall in southern Australia is projected to decrease compared with the climate of 1980 to 1999. Despite the decreases in average rainfall, the frequency and intensity of extreme daily rainfall is projected to increase for most regions. The change in rainfall magnitude and distribution is more difficult to predict because of the interactions with complex regional climate systems. For example, rainfall intensity can increase whilst the number of rain days can decrease, with no change in the average annual total. There have been similar trends found in other climate change modelling outputs, whereby a trend in rainfall (increases or decreases) is predicted, but the magnitude of the change cannot be reliably simulated. Nonetheless, an increase or decrease in rainfall event frequency has the potential to impact estuarine physical states including geomorphology, mixing and sediment loads. Correspondingly, this may impact water quality and other ecological processes.

Compound effects of climate change to estuaries

Climate change might compound the stresses experienced by estuarine ecosystems. For example, as water temperatures increase, there may be shifts in the distribution of some plants and animals and possible loss of those species that cannot move to more suitable temperature conditions. A decrease in annual average rainfall, punctuated with more intense events, may mean that larger volumes of poor quality stormwater are delivered to estuarine environments. Both of these impacts can compound and may lead to detrimental impacts on estuarine ecological communities.

Determining sea-level impacts

In an unrestricted marine environment or open coastline, there are various components that must be considered to accurately calculate sea levels (Figure 13). These complex calculations must include both commonly predictable occurrences, such as tides and mean sea level, and event-driven occurrences, such as storm surges, which are related to short-term weather patterns (e.g. wind, waves and atmospheric pressure). To date, most inundation studies have used static 'bathtub' approaches, where sea-level rise projections are added to existing estimates of sea level and topography to determine inundation extents. While these approaches provide first-pass guidance for areas vulnerable to coastal inundation, they do not capture all of the processes that might influence the resulting water-level rise and subsequent influences on hydrodynamics, land elevations and inundation.

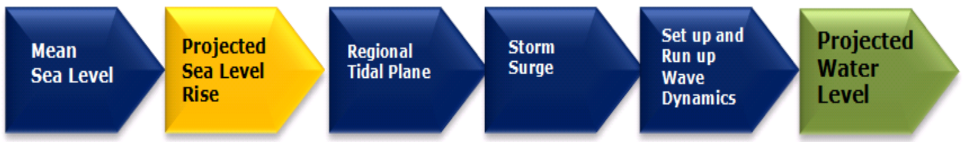

Figure 13: Components of water levels for the open coast. Source: Developed by the author.

Determining the impact on estuarine water levels (Figure 12) is even more complex, as it consists of additional uncertainty related to catchment run-off (Figure 14). Accurate estuarine hydrodynamic studies require numerous datasets including bathymetry, local rainfall, catchment losses, run-off properties and land-use distributions. This information is required to predict total run-off volumes (freshwater inflows) to estuaries, which are then combined with sea-level forces to characterise hydrodynamics on individual estuaries. These complexities mean that individual estuaries, even within close proximity, can be subjected to different hydrodynamic impacts from similar climate change conditions.

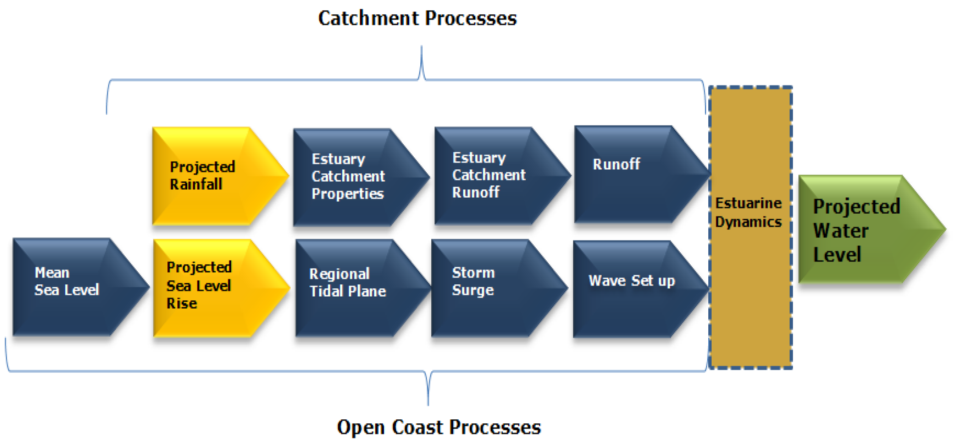

Figure 14: Components of water levels in estuaries. Source: Developed by the author.

The bathtub method also fails to represent how the estuary will actually respond under changing climatic forces. In contrast, local hydrodynamic models can provide detailed predictions of changes to phenomena, such as amplification and dampening of tides as they propagate though the estuary. These models can also incorporate the direct connectivity of wetlands and floodplain backchannels, and allow for assessments of water quality functions such as salinity gradients. However, this deterministic modelling approach requires sophisticated computer programs that rely on local datasets of bathymetry and topography, discharge volumes, and various catchment parameters. Also, even the most sophisticated numerical models have limited ability to simulate the dynamic geomorphic responses within the estuary or other second-order processes, such as groundwater dynamics or ecosystem responses.

Climate change impact assessment

As detailed above, the exact impact of changing climate drivers on Australian estuaries is difficult to quantify. However, based on our understanding of existing processes and the response of various estuarine processes to present-day stressors, the risk of climate change to estuaries can be estimated.

Assessment of the impact of climate change on an estuary requires an understanding of how the estuary presently functions – the interconnection of different processes, tolerance thresholds and limits to resilience – and predicted regional climate change. An assessment methodology for assessing the impacts of climate change on estuaries is presented in Figure 15.

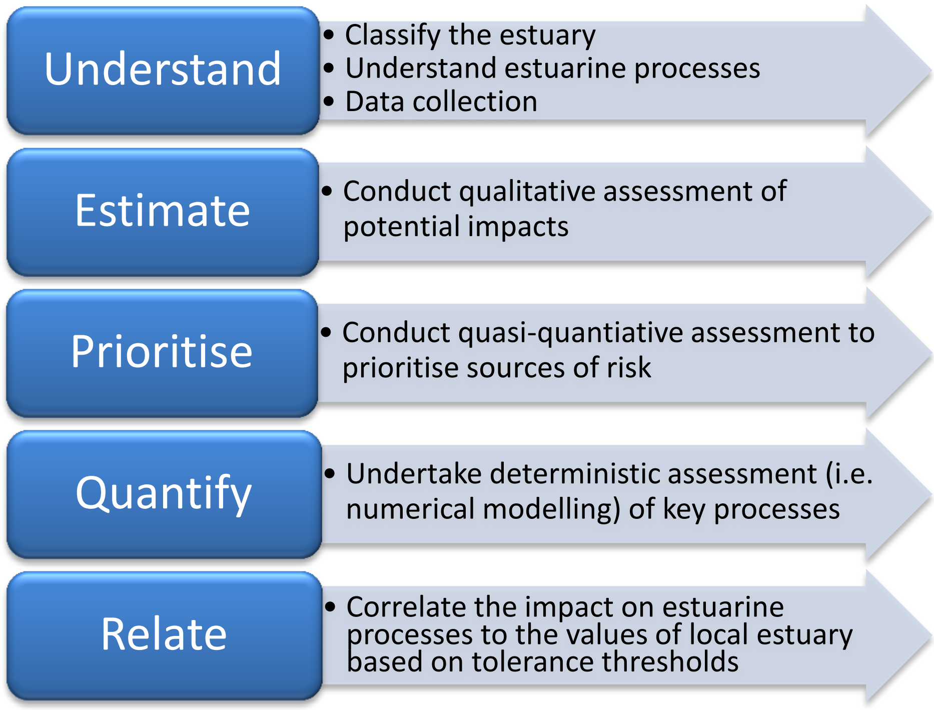

Figure 15: A methodology for assessment of climate change impacts on estuaries, increasing in detail and complexity. Source: Developed by the author.

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

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

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

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

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

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

Example: Qualitative estimate of impacts on different estuary types

The sensitivity of a particular estuary to climate change largely depends on the geomorphic and hydrological regime (or classification) of the estuary. 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 may be significantly impacted by sea-level rise. The exact extent of that change is still largely unknown and requires detailed scientific analysis.

A summary of potential impacts for each main estuary type is provided in Table 1. This table provides a comparison between estuarine types (as adopted in New South Wales) for south-eastern Australia and climate variables, and the expected risk based on climate change predictions. This qualitative assessment helps to identify the potential impacts and estuarine sensitivities relative to each other. While this assists in focusing adaptation strategies and estuarine management policies, it does not quantify the impact of a specific change in rainfall or temperature on the specific response of a key estuarine process.

For Table 1, an assessment is provided with three levels of identified risk. These risks are defined as:

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

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

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

Table 1: Example of a qualitative assessment to estimate potential vulnerability of estuarine processes to climate drivers (south-eastern Australia).

	Estuary type			
Climate variables	**Oceanic embayments**	**Tide-dominated estuaries**	**Wave- dominated estuaries**	**Intermittently closed and open systems**
Mean sea levels				
Hydrodynamics and mixing	MODERATE	MODERATE	MODERATE	HIGH
Sediments and geomorphology	MODERATE	HIGH	MODERATE	MODERATE
Water quality interactions	MODERATE	MODERATE	MODERATE	MODERATE
Rainfall				
Hydrodynamics and mixing	LOW	LOW	MODERATE	HIGH
Sediments and geomorphology	LOW	LOW	MODERATE	MODERATE
Water quality interactions	LOW	LOW	HIGH	MODERATE
Surface heat budget				
Hydrodynamics and mixing	LOW	LOW	MODERATE	MODERATE
Sediments and geomorphology	LOW	LOW	MODERATE	HIGH
Water quality interactions	LOW	LOW	MODERATE	HIGH
Ocean acidity				
Hydrodynamics and mixing	LOW	LOW	LOW	LOW
Sediments and geomorphology	LOW	LOW	LOW	LOW
Water quality interactions	LOW	LOW	LOW	LOW
Wind				
Hydrodynamics and mixing	MODERATE	MODERATE	HIGH	HIGH
Sediments and geomorphology	MODERATE	LOW	HIGH	HIGH
Water quality interactions	LOW	LOW	MODERATE	MODERATE

What does this mean for the local estuary?

As each estuary is different, the potential impact of a changing climate will be different in every estuary across Australia. Understanding how the local estuary currently functions, including the physical and ecological components over various temporal and spatial scales, is the most important requirement for determining how it may respond to future climate changes.

The potential impacts from climate change include effects on every aspect of estuarine form and function. A list of example impacts on different areas of an estuary is given below.

Underwater

- Changes in light penetration
- Altered scour and mobilisation of bed sediments
- Changes to temperature and salinity stratification of enclosed waters
- Impacts on benthic ecology
- Impacts on fish habitat
- Impacts on primary production (at the base of the food web)
- Changes to processes influencing bivalves and filter feeders (e.g. oysters)
- Changes to scour around wharfs, bridge pylons and breakwaters
- Potential shifts in salinity gradients and freshwater tidal pools

Riverbanks

- Increased erosion to river and estuary banks
- Loss of riparian vegetation
- Increased sediment transport
- Altered groundwater dynamics

Wetlands/intertidal

- Inundation of intertidal habitats, including mangroves, saltmarsh, mudflats, sand banks, rocky shorelines (Figure 16), potentially leading to coastal squeeze
- Changes to connectivity of intertidal areas
- Altered heat exposure regimes

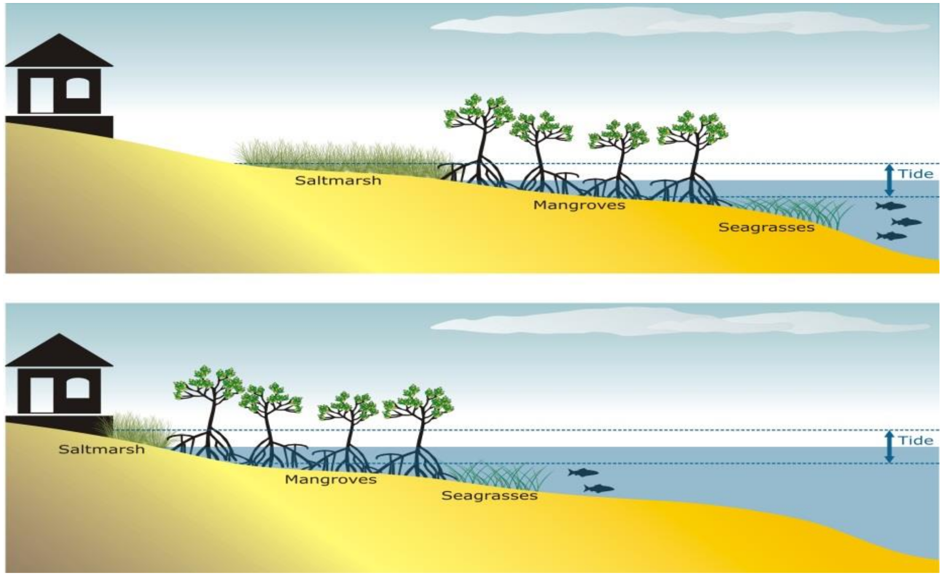

Figure 16: Potential impacts on intertidal habitats due to coastal squeeze. Source: Developed by the author.

Floodplain – rural

- Reduced drainage and increasingly prolonged inundation of low-lying floodplain area due to higher tidal levels
- Increased frequency of saline inundation due to overtopping of drainage structures and levee banks
- Changes in upper tidal limit impacting current freshwater extractions
- Impacts on port and shipping infrastructure, including commercial and recreational aspects

Floodplain – urban

- Impacts on shoreline infrastructure
- Reduced drainage of connected infrastructure
- Increased saline inundation
- Increased flood levels

Floodplain – natural

- Saline inundation of freshwater areas
- Changes in soil moisture and sediment transport
- Impacts from aeolian sand transport

Monitoring estuaries under a changing climate

The long-term monitoring of climate variables and key estuarine processes is critical. Estuaries are dynamic environments that are constantly undergoing change. The majority of estuarine processes are interdependent, with physical processes connected to water quality processes, which are connected to ecological processes. The climate and the geological setting of the estuary govern all physical, chemical and biological processes. The natural variability of the climate over days, months, seasons, years and decades results in a natural range of estuarine processes. Understanding these natural patterns, linkages and interactions through monitoring and assessment is vital to determining the potential impact of a changing climate.

Importantly, climate change impacts on estuaries may only become apparent after change has started to occur. Long-term comprehensive monitoring is required to determine background processes, potential tolerance thresholds and limits to resilience. Strategic and long-term monitoring programs are encouraged to ensure existing processes are understood and potential pressures/threats recognised.

Comprehensive monitoring programs can be used to develop estuary-wide adaptation strategies. These strategies should ensure that, where feasible, key functions are maintained. Moreover, an adaptation strategy derived from comprehensive monitoring data can detail how different estuarine components or specific areas may be threatened by climate change over time (for example at periods of 15, 30, 50, 75 and 100 years into the future). A careful analysis of these temporal scales will ensure the best allocation of existing and future resources.

Resources and further information

National
National Climate Change Adaptation Research Facility
http://www.nccarf.edu.au

Climate Change in Australia
http://www.climatechangeinaustralia.gov.au

Victoria
Climate Change and Victoria http://www.climatechange.vic.gov.au

New South Wales
Adapt NSW http://www.climatechange.environment.nsw.gov.au

Queensland
Queensland Government Climate Change
http://www.qld.gov.au/environment/climate/climate-change

Northern Territory
Local Government Association of Northern Territory: Climate change risk assessment and adaptation
http://www.lgant.asn.au/policy-programs/sustainability-environment/climate-change-risk-assessment-and-adaptation

Western Australia
Department of Environmental Regulation
http://www.der.wa.gov.au/your-environment/climate-change

South Australia
Department of Environment, Water and Natural Resources
http://www.environment.sa.gov.au

Tasmania
Tasmanian Climate Change Office
http://www.dpac.tas.gov.au/divisions/climatechange

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