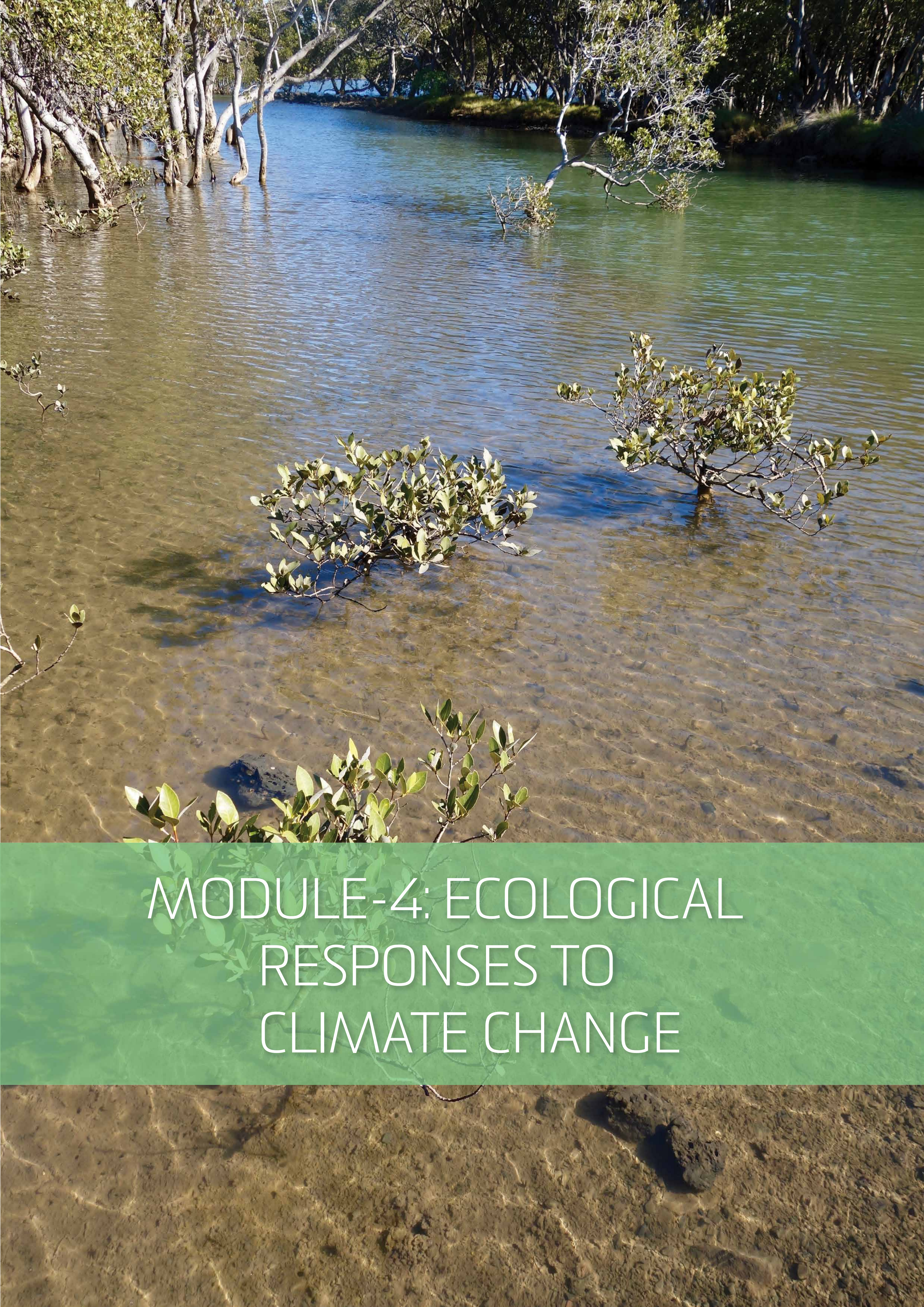

MODULE-4: ECOLOGICAL RESPONSES TO CLIMATE CHANGE

"Because mangroves store greater amounts of carbon per area than any other terrestrial ecosystem, conservation of mangrove forests on a global scale represents a potentially meaningful strategy for mitigating atmospheric greenhouse-gas emissions."[60]

Mangroves in the Hunter River wetlands, NSW; photo: Valentin Heimhuber, 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 the project partners based on their extensive knowledge and experience in the field of estuaries and climate change with advice from the scientific community. The guide has been published as a series of modules. Each module is a stand-alone document addressing an important aspect of 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
4. **Ecological responses (this module)**
5. Developmental stressors
6. Application of the framework
7. Review of ecological thresholds
8. Knowledge gaps and research needs

Summary of Module-4

Module-3 focused on how the physical estuarine environment has changed and is likely to change, as a result of climate change. The next step is to understand how these changes will likely affect ecological estuarine communities. This module begins by providing an overview of the ecological significance of estuaries in NSW and their most relevant ecological communities. This is followed by a summary of ecological responses to climate change stressors that were established in Module-3. Further, an estimation of the level of exposure (based on geomorphology) and sensitivity (based on the intrinsic characteristics of key species) of estuarine communities to climate change stressors is provided. Finally, a qualitative framework for assessing the vulnerability (based on exposure vs. sensitivity) of estuarine communities to climate change is presented.

Questions addressed by Module-4

1. Which ecological estuarine communities are found in NSW estuaries?
2. How might estuarine organisms respond to environmental stressors due to climate change?
3. How does the type of estuary influence the level of exposure to climate change stressors and which communities are most sensitive?
4. What is the likely climate change impact on NSW estuarine species?

Cover photo

Mangroves in the Hunter River wetlands, Newcastle, NSW, Photo: Valentin Heimhuber, WRL, UNSW.

Authors

Gabriel Dominguez, Melanie Bishop, Valentin Heimhuber, William Glamore, Peter Scanes

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Peer review

Module-4 has been peer-reviewed by Dr. Nathan Waltham (TropWATER, James Cook University) and Dr. Melissa Wartman (Blue Carbon Lab, Deakin University).

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 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

Estuaries support a diversity of species that vary in their environmental tolerances and in their ecological interactions. The definition of “environmental tolerance” may vary among evolutionary biologists, biologists or ecologists, yet in this guide, we simplify the definition as the range of environmental conditions under which a species is able to live and reproduce. It is also important to distinguish between acute and chronic environmental tolerances. Acute tolerance refers to the critical or lethal physiological thresholds reached after short-term exposure to extreme adverse conditions, while, chronic tolerance is defined by the thresholds reached after long-term exposure to sub-optimal conditions.

This module provides an overview of key New South Wales (NSW) estuarine habitats and their ecological significance, including the ways in which climate change may directly or indirectly modify their characteristic species. It provides an overview of the types of ecological and physical data that is required to model these effects and discusses how geomorphology influences the exposure of estuarine communities to climate change. Based on the existing literature, the sensitivity of key species to changes in the physical environment (i.e. temperature, salinity, oxygen) is summarized and integrated into a qualitative framework for assessing the vulnerability (exposure x sensitivity) of key ecological groups to relevant climatic stressors.

This module provides the knowledge base and assessment method used in Module-6, which is a practical application of the *Framework for Assessment* presented in Module-1. It demonstrates how climate change impacts to estuarine ecosystems can be assessed using climate models projections in conjunction with physical estuary models and biological data. In Module-7, a detailed synthesis of existing literature either directly or indirectly relevant to climate change impacts to estuarine species and ecological communities in NSW is provided.

1.1 Ecological significance of estuaries

Estuaries are among the most productive ecosystems on earth, providing a host of ecosystem services, of value to humans. Their habitats can serve as spawning, nursery and feeding grounds for commercially and recreationally fished species; sequester and store carbon; trap pollutants and improve water quality; stabilize shorelines and protect them from erosion and inundation.[1] For example, in NSW, estuaries account for about 30% of the Marine Estate’s total commercial wild harvest landings,[2] with about 127 different species of fish, shellfish, crabs and prawns commercially fished.[3]

Aquatic primary producers can be important sources of organic matter (through their production of dead plant material) which is a source of energy and nutrients to microbes, invertebrates and the food webs that depend on these. Organic material that is not remobilized in food webs may be buried by sedimentation and stored in waterlogged sediments for millennia, serving as a carbon store (blue carbon). Shellfish play an important role as water filters, removing particles from the water column, improving general water quality and depositing organic material into adjacent sediments.[4]

Unvegetated flats are important abiogenic habitats that dominate estuarine intertidal and subtidal zones. These sedimentary systems depend on organic matter resources from adjacent biogenic habitats. This organic matter fuels productive sediment-dwelling invertebrate communities that oxygenate sediments and are an important food resource for commercially important fish and macroinvertebrates.

Intertidal environment in Patonga Creek, Central Coast, NSW; photo: Valentin Heimhuber, WRL , UNSW

2 KEY ESTUARINE HABITATS IN NSW

2.1 Seagrass meadows

Seagrass meadows are flowering plants adapted to live fully submerged in the sea, acting as engineering species influencing deeply the physicochemical characteristic of the coastal waters.[5] In NSW, seagrass meadows are formed by three dominant species *Posidonia australis* (strapweed), *Zostera muelleri* (eelgrass) and/or *Halophila ovalis* (paddle weed). *Posidonia australis* is an endemic species (Figure 1), found in 20 NSW estuaries between Wallis Lake and Twofold Bay while Zostera muelleri and Halophila ovalis are more broadly distributed across the east Pacific and the Indian Oceans. Aquatic plants from the genus *Ruppia* (*R. polycarpa* and *R. megacarpa*), although not considered seagrasses, also contribute to the structure of NSW seagrass meadows. Seagrass meadows are typically on sedimentary substrates, at shallow subtidal elevations of low- to moderate-energy coastlines with low turbidity, and on intertidal shorelines. Minimum water depth is determined mainly by tide and wave energy, and maximum depth by light availability.

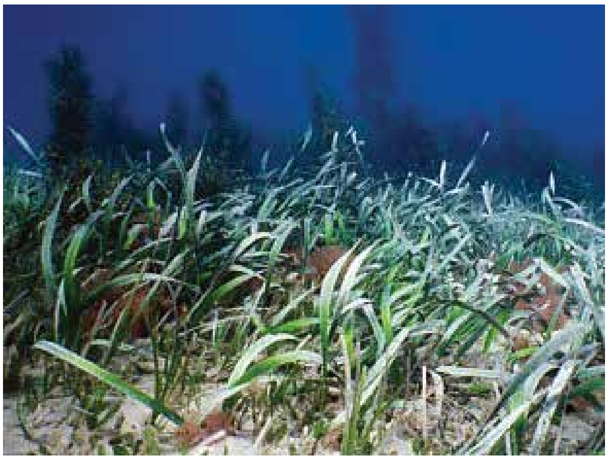


Figure 1. P. australis seagrass meadow in NSW (Photo: David Harasti)

2.2 Mangroves

Mangroves are woody plants that grow in the interface between land and sea in tropical and sub-tropical latitudes and, are considered one of the world's most productive ecosystems.[6] Mangrove forests in NSW are dominated by two species *Avicennia marina* (grey mangrove) and *Aegiceras corniculatum* (river mangrove), although in the north of the state other species such as the tropical red mangrove *Rhizophora stylosa* (red mangrove) may also be found.[7] Mangroves are present in the intertidal zones of many NSW estuaries (Figure 2). Rainfall and sediment supply from rivers and currents promote mangrove establishment and persistence, while waves and large tidal currents can erode mangrove substrates.

Figure 2. Mangroves in the Hunter River estuary, NSW (Photo: Valentin Heimhuber, WRL, UNSW)

2.3 Saltmarsh

ıarsh refers to intertidal vegetated communities dominated by herbaceous and low woody plants that are adapted to high soil salinity and occasional inundation.[8] In NSW, key endemic species comprising saltmarshes include: *Juncus kraussii* (sea rush), *Sarcocornia quinqueflora* (samphire), *Sporobolus virginicus* (sand couch) and *Baumea juncea* (blue twig-rush), with the invasive species *Juncus acutus* (spiny rush) now a major component of communities at many sites. Saltmarshes typically occur higher on the shore than mangroves and may not be inundated every tidal cycle (Figure 3).

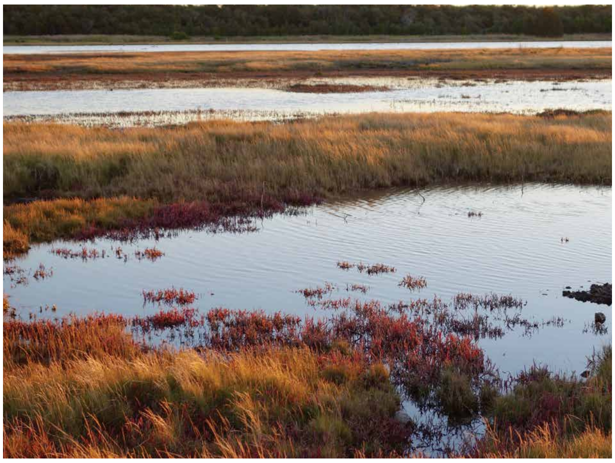


Figure 3. Saltmarshes in the Hunter River estuary, NSW (Photo: Valentin Heimhuber, WRL, UNSW)

2.4 Shellfish ecosystems

Shellfish ecosystems are dense aggregations of oysters or mussels, forming reefs (high vertical profile structures) or beds (lower profile structures with little variation in relief from their surrounds).[9] In NSW, reefs may be formed of monocultures or mixtures of the native *Saccostrea glomerata* (Sydney rock oyster) (Figure 4), the native *Ostrea agasi* (flat oyster) and the introduced *Cassostrea gigas* (Pacific oyster). However, with 90% of Australian oyster reefs lost since European settlement, today these species are more commonly found as beds on rocky substrates or amongst mangrove roots. Additionally, less common species like *Isognomon epphippium* (leaf oyster), *Xenostrobus seuris* (little brown mussel) may also form beds.

Figure 4. Rock Oyster (S. glomerata) reef in the Hunter river, NSW (Photo: Kylie Russell)

2.5 Intertidal unvegetated flats

Intertidal unvegetated flats refer mainly to mudflats and sandflats. Mudflats are sedimentary habitats, lacking conspicuous plants, which occur along sheltered shorelines where wave action is low and there is a supply of fine estuarine sediments and/or marine animal debris.[10] Sandflats are comprised of coarser particles than mudflats. These typically occur in higher energy environments where there is a supply of sediments (Figure 5). These habitats support commercially important invertebrate species like *Scylla serrata* (mud crab), *Portunus pelagicus* (blue swim crab), *Donax deltoids* (pipis), as well as several species of fish and shorebirds which use them as feeding grounds and resting areas during overseas migrations.

Figure 5. Sandflat near Ettalong, NSW (Photo: Valentin Heimhuber, WRL, UNSW)

2.6 Subtidal sediments

Subtidal sediments are sedimentary habitats, lacking conspicuous plants, which are permanently submerged. These may vary in grain size from muddy to sandy, depending on local hydrodynamic conditions and sources of sediment. These habitats are the dominant bottom substrata of estuaries.

2.7 Intertidal rocky shores

Intertidal rocky shores are typically located between the high and low water mark of exposed coast lines and some NSW estuaries. The hard substratum provides an attachment point for seaweeds and sessile invertebrates that provide food and habitat to small mobile invertebrates and fish that can utilize rocky shores at high tide (Figure 6). The ecology is strongly shaped by the gradient of increasing desiccation stress with elevation.

Figure 6. Rocky shore near Saltwater Creek, NSW (Photo: Valentin Heimhuber, WRL, UNSW)

2.8 Subtidal rocky reefs

Subtidal rocky reefs are permanently submerged rocky environments. These habitats are more common along the open coast than in estuaries. Nevertheless, these habitats can underpin high levels of fisheries productivity. Kelp (large brown algae) can colonize these environments providing food and refuge for several macroinvertebrates and fish species. The two dominant kelp species in NSW are *Ecklonia radiata* (common kelp) and *Phyllospora comosa* (crayweed) (Figure 7).

Figure 7. Rocky reef cover in Kelp, Sydney Harbour, NSW (Photo: John Tumbull)

2.9 Pelagic zones

Pelagic zones are estuarine waters away from bottom habitats and shorelines. These have a larger contribution to habitat area in large estuaries of deep maximum depth, than small, shallow estuaries where all waters are proximate to bottom habitat or shoreline. These ecosystems are dominated by fish and jellyfish, the former of which may be an important food source of seabirds.

Over 70% of coastal fish species in NSW use estuaries at some stage of their lives,[11] many of which are valued by commercially and recreationally important fishing industries. Among the most important of these, in terms of landings are: *Mugil cephalus* (sea mullet), *Girella tricuspidata* (luderick), *Acanthopagrus australis* (yellowfin bream), *Platycephalus fuscus* (dusky flathead), *Sillago ciliata* (sand whiting) and *Gerres subfasciatus* (silverbiddy).[12] *Anguila sp.* (eels) trapping is also economically significant. Generally, eel species spend their early life stages in the open ocean and migrate to estuaries and freshwater as adults.[12]

There is a high level of connectivity and interdependence among estuarine habitats, and the ecological health of estuaries is therefore dependent on maintaining diverse and connected mosaics of habitats (Figure 8).[13] Many species of fish and invertebrates migrate among estuarine habitats at time-scales of tidal cycles to years. For example, fish and prawns may forage in intertidal habitats such as mangroves and saltmarshes at high tide but retreat to subtidal unvegetated habitats when the tide falls.

While some species are estuarine residents (“true estuarine” species), completing their entire life cycle within the estuary, others are temporary species that use the estuary only for one life stage or as feeding grounds. Several species of economically important fish spawn in surf zones near estuarine entrances and return to estuaries following spawning.

2.10 Coastal freshwater ecosystems

This module is primarily focused on extant (currently living) estuarine communities, but also considers coastal freshwater communities situated just upstream of estuarine environments, because these may be modified by saltwater intrusion due to sea-level rise. These environments support a large number of semi-aquatic grasses and sedges (e.g. *Paspalum distichum* (water couch), *Leersia hexandra* (swamp rice-grass), *Lepironia articulata*) as well as fully submerged macrophytes (e.g. *Azolla filiculoides var. rubra, Ceratophyllum demersum* (hornwort), *Hydrilla verticillata* (water thyme), *Lemna spp.* (duckweeds), *Nymphaea gigantea* (giant waterlily)). These ecosystems serve as habitat for birds, amphibians, reptiles, mammals and fish, some of which are considered threatened,[14] and are important filters of pollutants and sources of water for human activities.

2.11 Species groups

Predicting climate change impacts on estuarine ecosystems is complex due to their varying exposure and sensitivity to environmental stressors, and the complexity of ecological interactions that may buffer or exacerbate impacts. In this module, the following groups of species are highlighted in our assessments of sensitivity and impacts:

- Foundation species
  Structurally complex species that underpin biogenic habitats.
- Dominant taxa
  Species that are found in high numbers or occupy large areas.
- Economically important species
  Commercially important species.
- Endangered species
  Endemic species of high extinction risk.
- Exotic/Invasive species
  Introduced species which potentially could replace endemic species changing the original community structure.

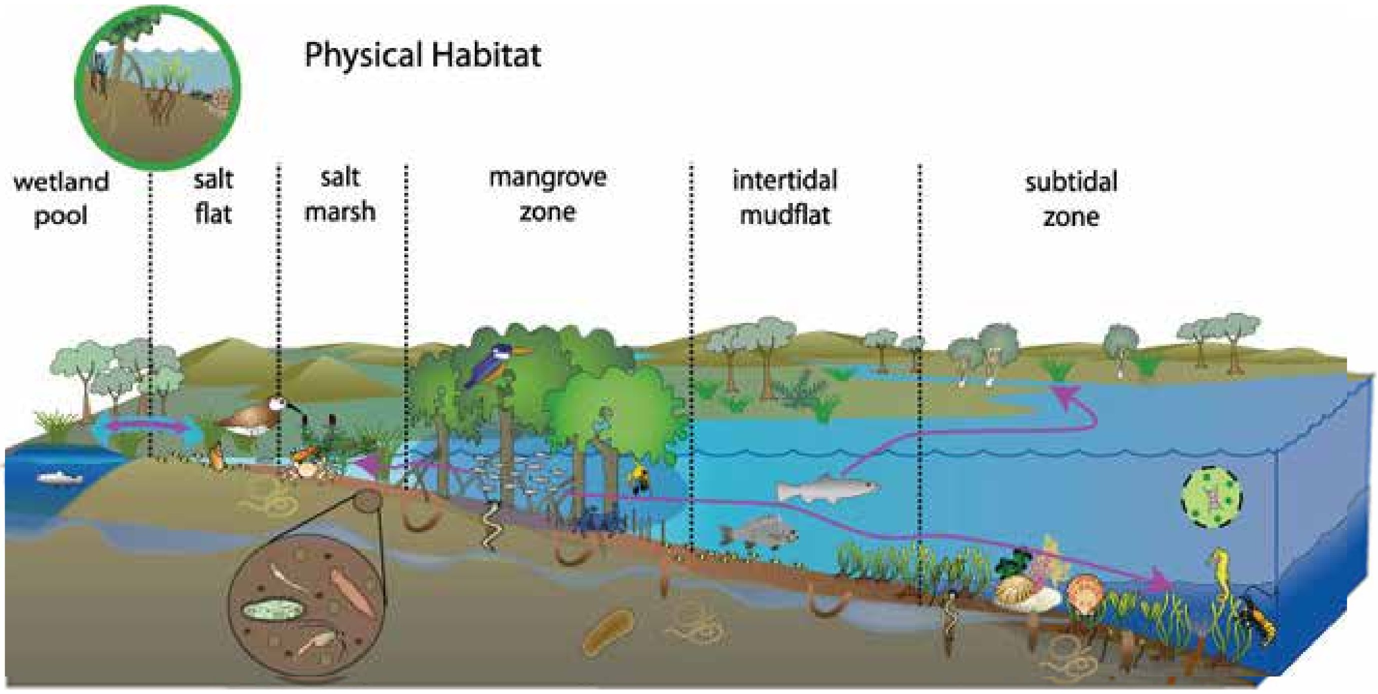


Figure 8. The spatial distribution of key physical habitats in estuaries. Source: OzCoast[13]

Intertidal rocky shore environment in Sydney Harbour, NSW; photo: Valentin Heimhuber, WRL , UNSW

3 ENVIRONMENTAL STRESSORS AND ECOLOGICAL RESPONSES

An environmental variable acts as a stressor if it produces conditions outside the optimal zone (Figure 9)[15] for organisms or ecosystem processes. Global climate change is predicted to modify a number of environmental variables that are important in shaping the distribution, abundance, and function of estuarine species as well as the communities and ecosystems where they reside. In particular, water and air temperature, salinity, acidity, dissolved oxygen and sea-level are each expected to change over the next 50 to 100 years, either as a direct or indirect effect of global climate change. The impact of these climate change related stressors on estuarine ecological communities will depend on the magnitude of environmental change, the global change in average conditions (e.g. change in global temperature, sea level rise) and the increase in extreme local events (e.g. storms, heat-waves). The cumulative effect of both average conditions and extreme events may notably increase the potential impact of climate stressors such as the likely increases in estuarine water temperatures (Figure 9). Although, the impact of increasing extreme events has not been well studied, extreme events will likely impact natural environments, reducing their resilience to environmental stressors.[16]

The vulnerability of ecological estuarine communities is also affected by the level of exposure to different stressors, as well as behavioural, physiological and ecological characteristics of the species that comprise them. Stressors may alter the physiology, morphology and behaviour of species, their distribution and abundance, as well as biological interactions. These stressors may act on the reproductive success, early life-history stages (e.g. larvae, juveniles) and/or adults. Figure 9 illustrates that species performance declines when water temperatures rise above certain thresholds (a) and that the early and late live stages of fish species have narrower thermal windows compared to the juvenile and adult stages (b).

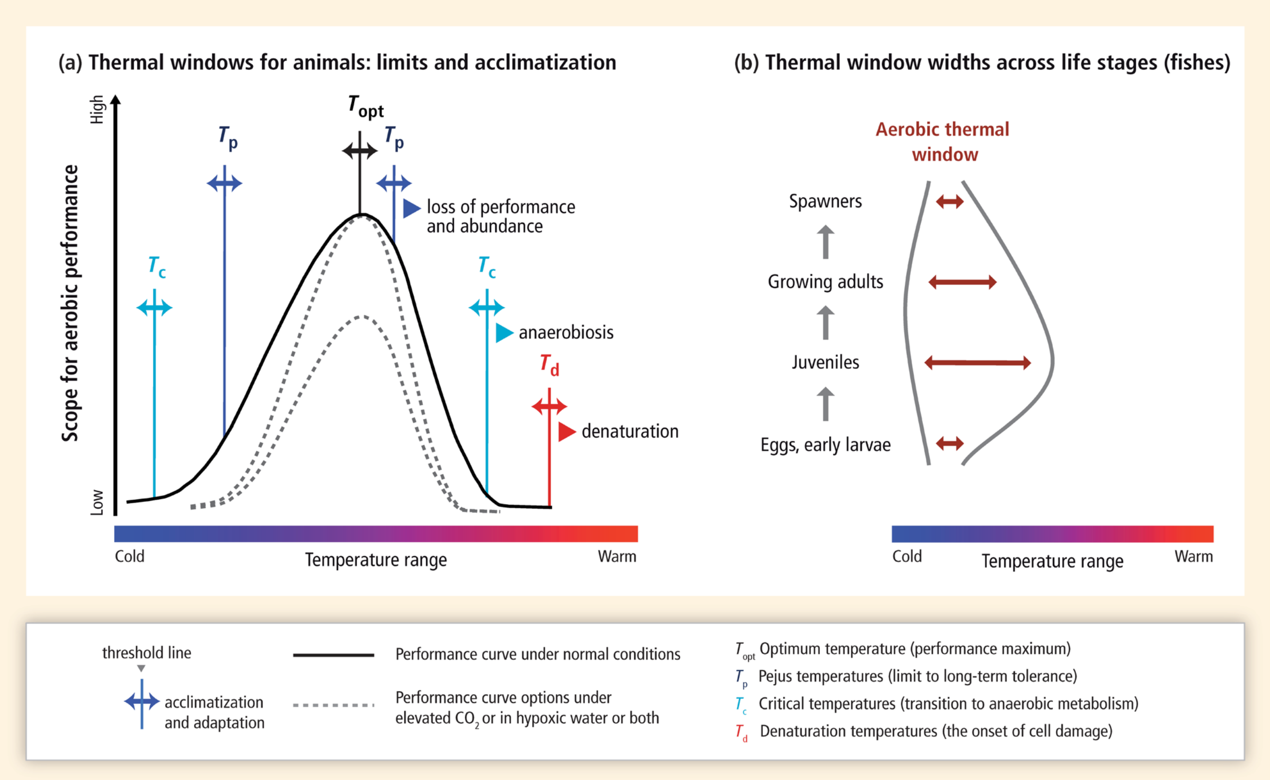


Figure 9. Ecological niches of species, with respect to environmental stressors. Source: Pörtner et al. (2015)[61]

In the sections below, both the direct and indirect influences of climate change on the five environmental variables listed above are discussed. These changes are then highlighted to consider how they may impact estuarine ecosystems. Finally, the variation of these effects within key NSW estuarine types and the ecological communities they support is explored.

3.1 Temperature

How will it be influenced by climate change?

Climate warming has been predicted to increase mean air and water temperatures, thereby increasing the severity of heat-wave events.

What do changes mean for estuarine species?

Temperature is a key determinant of chemical reaction rates, and therefore affects many physiological processes in organisms, ranging from rates of respiration to degradation of proteins. The key demographic processes of populations of marine organisms (reproduction, growth rates and death rates) are directly affected by temperature. Whereas elevating temperatures above a thermal minimum (CT_{min}) may initially enhance the performance of organisms, above the thermal optimum (T_0), performance decreases to the thermal maxima (CT_{max}), at which performance is zero (i.e. death) (see Figure 10). Thermal performance curves vary among species, populations (i.e. there can be latitudinal variation in thermal tolerance) and with life-history stage.

Climate change may push temperatures above the thermal optimum of species, resulting initially in reduced performance and death. Organisms may exhibit some ability to adapt to warming, through behavioural changes (e.g. seeking shelter in cooler microhabitats), acclimation (within individuals), and evolutionary adaptation (across generations). However, even for high mobile species like estuarine fish behavioral responses to thermal changes may require a significant increasing in energetic cost and their adaptive capacity will depend on several other environmental variables.[17] Where adaptation is not possible, organism must migrate or else face local extinction, both of which will result in shifting species ranges.

Temperature may also affect the timing of reproduction and of life-history transitions. Where changes in temperature differentially effect the timing of recruitment of predators and their prey, food shortages may occur. Temperature may also influence predator-prey interactions by influencing metabolic rates, and hence energy (food) demands, and by producing mis-matches in the distributions of predators and their prey. Poleward range expansions in species may result in novel combinations of species contributing to ecological communities, altering how species interact in positive (e.g. facilitation) and negative (e.g. competition, predation) ways (Figure 11). Additionally, sub-lethal temperature stress can render organisms more susceptible to pathogens and disease-causing parasites.

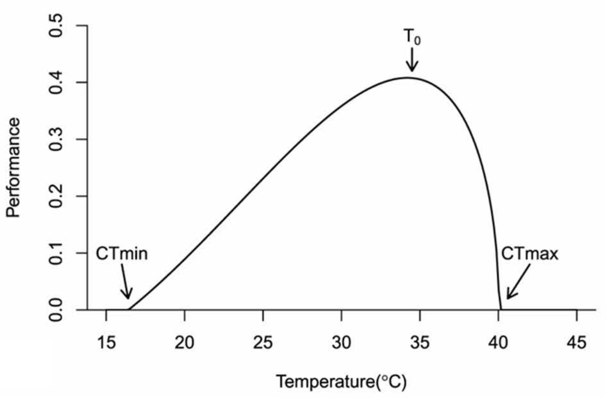


Figure 10. A typical thermal performance curve. Performance rises slowly from the critical thermal minimum (CT_{min}) to a thermal optimum (T_o), declining sharply to the critical thermal maximum (CT_{max})

3.2 pCO_2 and acidity

How will it be influenced by climate change?

The oceans absorb a third to a half of the CO_2 emitted to the atmosphere. When CO_2 is absorbed by seawater, chemical reactions occur that reduce seawater pH (acidification), carbonate ion concentration, and saturation states of biologically important calcium carbonate minerals.[18]

What do changes mean for estuarine species?

As compared to the ecological and physiological effects of changes in temperature or salinity, the effects on estuarine ecosystems of increasing pCO_2 are poorly understood. For plants and seaweeds, increased concentrations of pCO_2 in the air and water is expected to enhance growth rates and biomass production by increasing photosynthesis which, at the same time, will help to reduce pCO_2 (Figure 11). For calcifying species, such as coralline algae, oysters, and cockles, however, negative effects may be seen as a consequence of reductions in the concentration of carbonates in the water for structure building and as a result of dissolution of existing materials. Reductions in the size and strength of shells and other defensive structures can make organisms more vulnerable to predation.

Acidification may also have a negative impact on fertility and larval development. In general, however, marine organisms have very efficient mechanisms to maintain their internal acid-base balances. Nevertheless, greater energy allocation to maintaining pH balance under altered pCO_2 conditions could eventually negatively impact other vital functions. Furthermore, phytoplankton communities could be dramatically affected, with a recent study predicting profound structural changes due to oceanic acidification and pCO_2 increase.[19] Since phytoplankton communities are the base of the estuarine trophic chain, such changes may produce a substantial impact in all estuarine communities.

Most research on ocean acidification has come from full-marine waters where pCO_2 and pH has historically been very stable.[20] By contrast, the more constrained water bodies of estuaries may exhibit strong natural diurnal fluctuations in pCO_2, and hence pH, reflecting shifting balances between respiration, that produces CO_2, and photosynthesis, that consumes it, as the availability of sunlight varies.

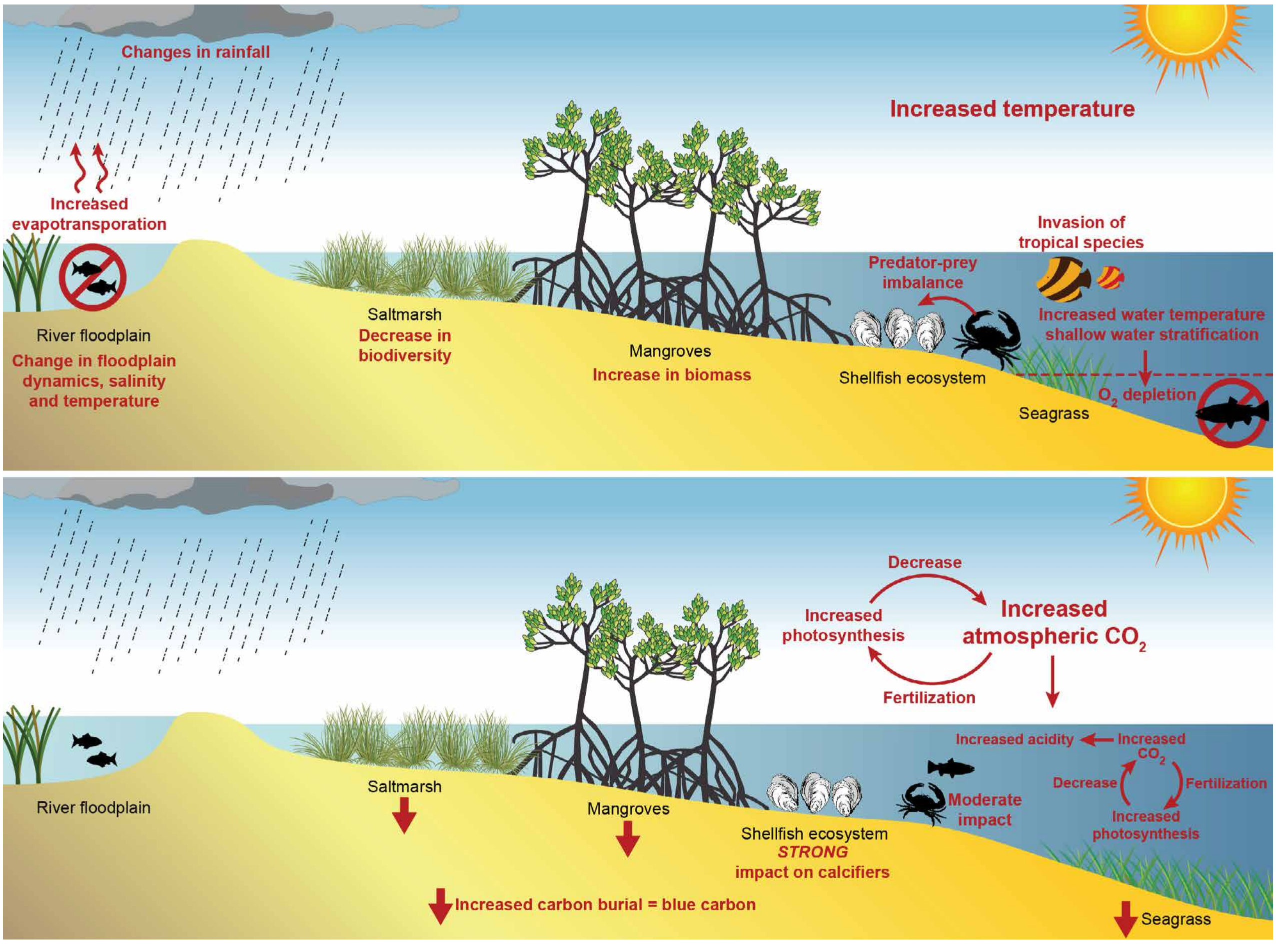


Figure 11: Key impacts of increased temperatures and increased atmospheric CO_2 on estuarine environments. Impacts of increased temperature include increased evapotranspiration and salinity, decrease in saltmarsh biodiversity and increased stratification. Impacts of increased CO_2 include increased acidity of estuarine waters, increased photosynthesis rates and increase in blue carbon storage.

e fluctuations may be larger in magnitude than the long-term changes predicted to occur as a result of pCO_2 induced ocean acidification. Importantly, many estuaries in NSW are impacted by acid sulfate soils, which may be far more significant in reducing pH than changing pCO_2 concentrations. Sulfide rich soils occurred naturally near to estuarine areas, sulfide minerals can react with oxygen to produce sulfuric acid which is drained into adjacent water bodies causing acidification.[21] As a result, estuarine organisms may be better equipped to adapt to changing pCO_2 and acidification than their open ocean counterparts, although it is also possible that they may be more likely to reach tipping points if the system is already under stress. Additional research is required in NSW to better understand the linkages between acid sulfate soils and climate related shifts in pH.

3.3 Dissolved oxygen

How will it be influenced by climate change?

Global climate change may influence dissolved oxygen concentrations in estuarine waters via two main pathways (Figure 11). First, warming reduces the solubility of oxygen in water. Second, changes in wind and rainfall patterns may alter water column stratification, affecting dissolved oxygen in bottom-waters. Particularly where reduced mixing is coupled with nutrient enrichment, microbial ration may lead to depletion of oxygen in bottom waters.

What do changes mean for estuarine species?

Oxygen is critical to aquatic organisms that breathe. Aquatic organisms vary in the minimum concentration of oxygen that they can tolerate. In general, photosynthetic organisms, can tolerate lower levels of oxygen than animals. Dissolve oxygen in seawater varies depending mainly on temperature and salinity levels and ranges from about 4 to 9 ppm in different regions. Also, extreme daily changes in oxygen levels have been observed in wetlands during day-night cycles at different depths.[22] It is important to assess these variability especiall when lethal oxygen tresholds are extremely variable among aquatic species. Early life-history stages may be particularly susceptible to low oxygen, as well as sessile life-history stages that are unable to migrate to avoid low oxygen concentrations.

3.4 Salinity

How will it be influenced by climate change?

Salinity gradients and variations in estuaries are influenced by tides, waves and currents that determine the extent of mixing of marine and freshwater, and by the timing and magnitude of freshwater flows. Climate change may influence salinity by influencing rainfall, rates of evaporative water loss, wave-climate and currents, as well as sea-levels.

What do changes mean for estuarine species?

Longitudinal gradients and tidal variations in salinity are a defining feature of estuarine ecosystems, and they underpin spatial patterns of variation in biodiversity. Within an estuary, salinity tends to be most stable at the mouth, where the strong tidal influence and mixing maintains salinities close to those of the ocean, and at the upper tidal limit, where the weak tidal and strong freshwater influence maintain low salinities. In the mid-reaches, salinity can vary markedly from high to low tide.

Organisms display marked variation among species and life-history stages in the range of salinities they can tolerate. Some species, termed stenohaline, can tolerate only narrow ranges of salinity and are found in either marine or fresh waters. Other ‘euryhaline’ species can tolerate wider variations in salinity, by osmoregulation - controlling their internal balance of salt-water. In many estuarine species (especially plants and fish) early stages of life require low to medium salinity conditions, even if as adults they are highly resistant to high salinity. In estuaries, the number of stenohaline marine species at the mouth and stenohaline freshwater species in the upper reaches typically exceeds the number of euryhaline species in the mid reaches.[23]

Changes in salinity will shift the distributions of stenohaline species, and negatively impact the fitness of euryhaline species. Osmoregulation is energetically costly, and where the requirement for this is very high, it can negatively impact fertility, growth rates and resilience to other stressors. Depending on the intensity and duration of the environmental stress, it may be categorised as a chronic or acute stressor. Chronic stressors exert constant pressure over extended periods of time, changing mean conditions. Acute stressors exert short-term pressure and affect the extremes of the environmental gradient rather than the mean. Although, in general the environmental factors listed above act as chronic stressors, they also can increase the frequency and/or strength of environmental events which act as acute stressors (e.g. storms, floods).

3.5 Sea-levels

How will it be influenced by climate change?

Sea levels are rising as a consequence of thermal expansion of seawater with rising temperatures and melting of ice-caps and glaciers.

What do changes mean for estuarine species?

Intertidal organisms as well as aquatic plants and seaweeds that require light to photosynthesise will be particularly susceptible to the effects of sea-level rise (Figure 12). Light is rapidly attenuated as it travels through water, and its availability often limits the maximum depth to which aquatic primary producers can extend. Even small changes in water depth may lead to large changes in the distribution of aquatic primary producers, particularly when coupled with declining water quality from coastal development. While some intertidal and light-dependent organisms may be able to migrate landward in response to rising sea-levels, this is dependent on the availability of suitable habitat, the pace at which they can migrate and the pace of sea-level rise.

Coastal development can constrain landward migration, squeezing out intertidal habitats and photosynthesizers (Figure 12). Some habitats, such as mangroves and oyster reefs, may be able to respond to sea-level rise by accreting vertically.[24,25] For mangroves, this occurs via the trapping and retention of sediment and will depend on sediment supply. While mangroves may exhibit some capacity to counter moderate sea-level rise with vertical accretion and inland migration, this may be at the expense of other habitats, such as saltmarsh, which have lower capacity to do so and will be encroached upon.[26,27] Vertical accretion and surface elevation are key uncertainties in climate change risk assessments. These processes are difficult to quantify because they depend on the species assessed plus the geomorphology, sedimentation rates and hydrodynamics of each specific site (Module-6 and 7 provide additional information on this topic).

Another important consequence of sea-level rise is saltwater intrusion. Saltwater may be pushed further upstream into estuaries and into coastal aquifers resulting in the salinization of previously freshwater ecosystems (Figure 12). Also, saltwater intrusion into groundwater tables, which is already a problem in many areas due to overextraction, is expected to increase parallel with sea-level rise.[31] Loss of freshwater habitats may negatively impact on estuarine and marine species that are dependent on these habitats for certain stages of their life-history. Such saltwater intrusion may also shift the distribution or areas of brackish estuarine waters and dependent species.

Finally, sea-level rise may enhance the susceptibility of estuarine shoreline communities to erosional events during periods of storm surge and several other secondary processes which may result in habitat loss.

Intertidal environment in Patonga Creek, Central Coast, NSW ; photo: Valentin Heimhuber, WRL , UNSW

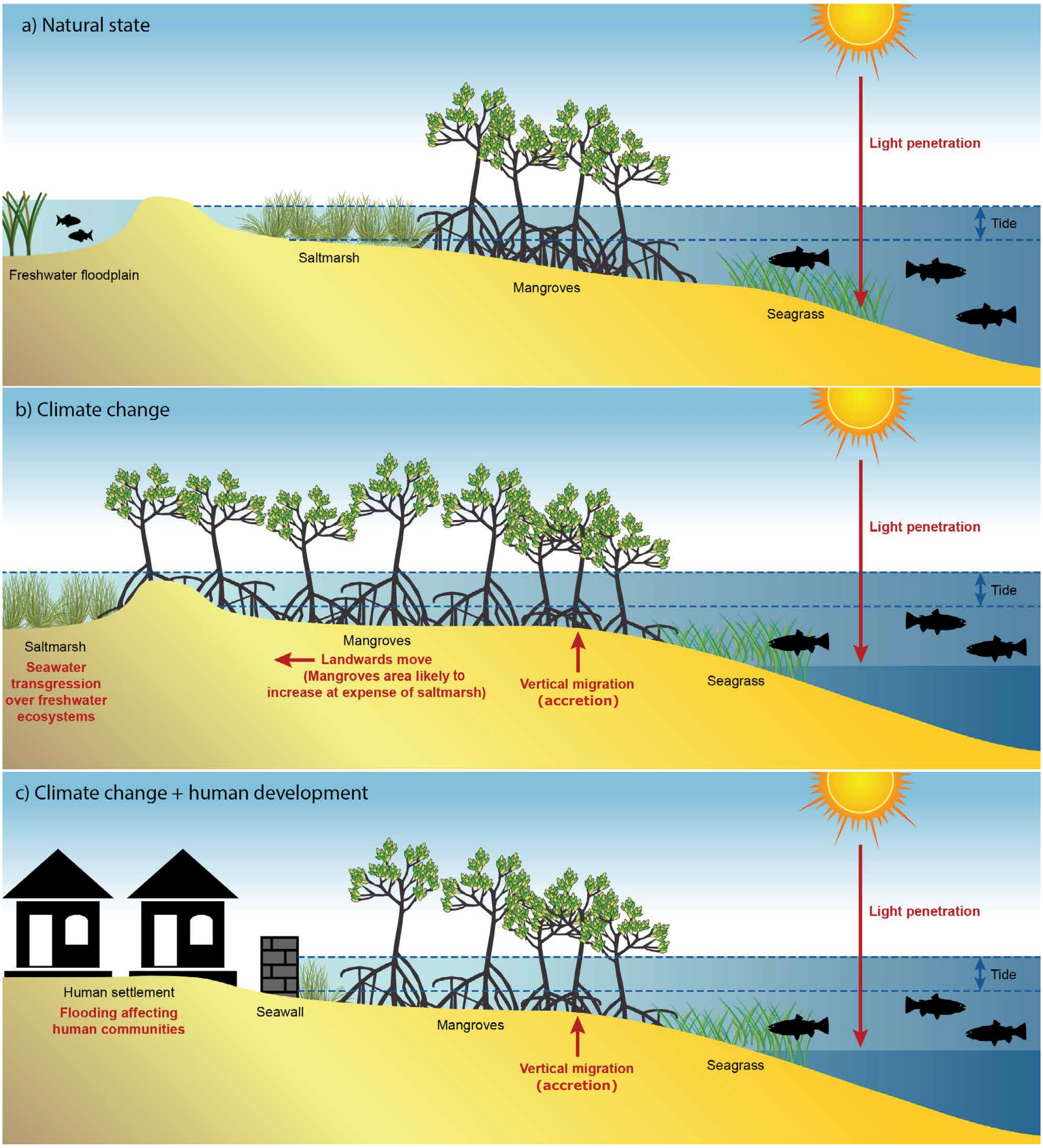


Figure 12. Impacts of sea level rise on estuarine vegetation:

a) Natural estuarine and floodplain vegetation under present day sea levels

b) Key impacts of projected sea level rise without human development including the landward migration of intertidal vegetation and seagrass, vertical accretion and the expansion of mangroves at the expense of saltmarsh

c) Key impacts of projected sea level rise with human development & coastal armour including the squeezing of intertidal vegetation communities and the expansion of mangroves at the expense of saltmarsh

Satlmarsh in the Hunter River wetlands near Newcastle, NSW; photo: Valentin Heimhuber, WRL , UNSW

4 SOURCES AND TYPES OF DATA

Predicting the ecological responses of NSW estuaries to climate change requires understanding of (1) how environmental variables that shape ecological communities will respond to climate change (i.e. water temperature, dissolved oxygen, acitiy, water levels; see Module-3 for detailed information) and (2) how ecological communities will respond to changes in these variables. Below, we discuss different sources of climatic and ecological data and the limitations and strengths associated with using these different data types. Detailed information on how to apply these data to model different climate change scenarios in estuaries is covered in Modules-3 and 6 of this guide.

4.1 Ecological data

Ecological data may be sourced from observational studies that document correlative relationships among environmental and ecological variables, often through ecological field surveys that span large geographic areas or multiple time periods, or manipulative studies that explicitly test how varying one or more environmental variable(s) influences ecological variables.

Observational studies:

These studies can be useful in documenting the range of environmental conditions that an organism can persist and function. Nevertheless, because they document correlative relationships only, and not cause and effect, the absence of organisms from particular environments cannot necessarily be used to infer that the environment is unsuitable: barriers to larval/propagule supply, or ecological interactions such as predation and competition that limit survival may also contribute to the absence of species.

In contrast to manipulative experiments, which may, for logistical reasons, only be able to test causal responses of organisms to a few levels of an environmental factor, the large amounts of data generated by observational studies can be useful for identifying possible environmental thresholds beyond which organismal performance or survival is compromised. The advantage of observational over experimental studies is that, when conducted in the field, they possess an element of environmental realism that may be difficult to replicate in experiments, the latter of which are often plagued by experimental artefacts. For example, the relationships between environmental and ecological variables that are observed in the field may have been generated over many years, and reflect evolutionary as well as ecological and physiological processes.

A good example of an observational study applied to determine ecological thresholds is the study of Dasgupta et al. (2017)[29] In that study the salinity tolerances of several mangroves species were determined based on their geographic limits distribution along an extensive estuarine area (Bangladesh Sundarbans) correlated with *in situ* measures of water salinities. That study was undertaken for one year and its results provided strong evidence of seasonal changes in salinities, the effect of these changes in the local mangrove community and a baseline for prediction of sea level rise impact in this area. However, it cannot quantify accurately the influence of other variables (different to salinity) in the mangroves species distribution, as interspecific competition or sedimentation rates. This study is a typical example of the advantages and disadvantages of using observational data on ecological threshold.

Manipulative experimental studies:

In a manipulative study the researcher applies experimental treatments to a system (in this case an organism, population, community or ecosystem) to determine their effect on variables of interest (e.g. growth, survival, reproductive output, physiology, behaviour, etc.). Manipulative experiments have an advantage over observational studies in that they are able to demonstrate cause and effect.

In contrast to observation studies, manipulative studies often compare ecological responses across a relatively small number of environmental conditions. For example, manipulative studies designed around climate change scenarios often treat environmental change as a categorical variable, thereby limiting their capacity to identify the specific threshold values above/below which organisms can no longer survive or function. Further, because the number of categories is limited, experimental studies often struggle to identify non-linearities in relationships. For this reason, it is important not to extrapolate data beyond the range of conditions examined (e.g. if the survival rate of a species is higher at 30°C than at 10°C, it does not necessarily mean that at 20°C survival rates will be intermediate between the two values).

'Ramping' experiments gradually increase an environmental variable to identify tipping points beyond which organisms can no longer survive or function. Although these can be helpful in identifying potential environmental thresholds, their results need to be interpreted with caution where they do not allow adequate time for organisms to acclimate before increasing environmental stress.

Climate change experiments will be most useful in investigating responses of organisms to extreme events such as heatwaves, or floods, which due to their sudden onset, often do not allow organisms time to acclimate, adapt or evolve. The interpretation of experiments aimed at assessing impacts of chronic stressors can be more problematic as, in this instance, organisms will have time to adapt and evolve, and experiments that do not account for these possibilities will give misleading results. Additionally, experiments examining responses of organisms to chronic stress need to be run for sufficient time so as to adequately address long-term effects. Whether a change in an environmental condition is lethal may depend on how long an organism is exposed to (e.g. Sydney rock oysters can close their valves for four weeks during flood events to avoid exposure to unfavourable salinities; however exposure to chronic changes in salinity may be challenging).

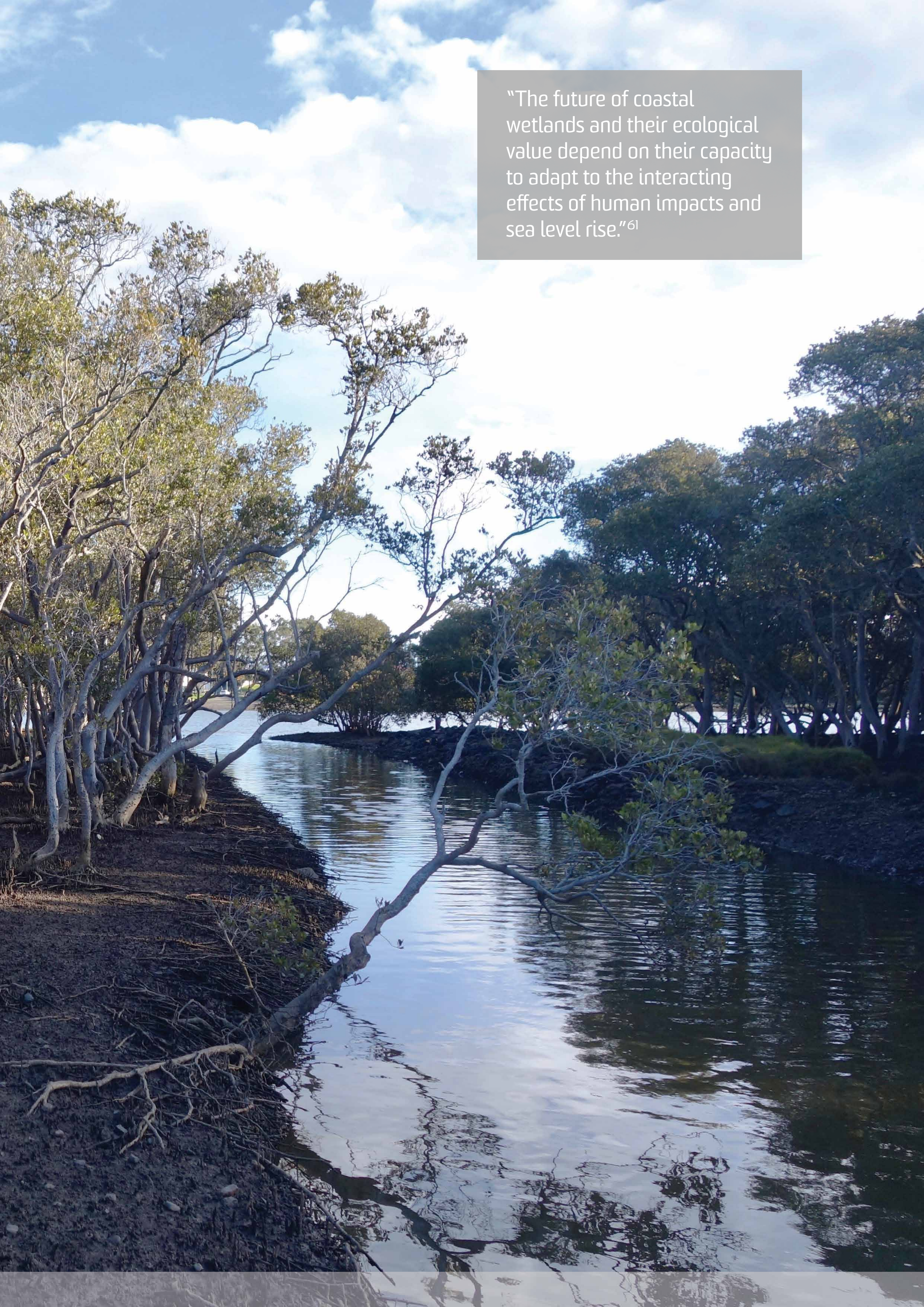
For example, Greenwood and Mcfarlane (2006)[30] undertook a manipulative experiment to determined salinity tolerance in the germination rates of the saltmarshes plant species *Phragmites australis*, *Juncus acutus* and *J. kraussii.* Seeds collected from Kooragang Island, NSW were exposed to salinities 0, 5, 10, 15, 20, 25, 30 PSU for 25 days. Germination rates in *Juncus* species decreased significantly at salinities between 15 and 20 PSU while in *P. australis* germination decreased markedly between 25 to 30 PSU. The results of this study are very useful to determined that *P. autralis* are more tolerant to high salinities than the *Juncus* species and that the results of this experiment are correlated only with salinity because the other variables were maintained constant for the three species.

However, the exact salinity threshold value cannot be assumed based on an approximation of 5 PSU range (salinities categories every 5 PSU). Also, differences among populations of the same species cannot be assessed, as seeds from the *Juncus* population that inhabit natural hypersaline environments may be more adapted to high salinities than those used in the experiment. Both, observational and manipulative studies have advantages and uncertainties that need to be taken into account when interpreting ecological data.

4.2 Physical data

Sources of physical data need to be carefully chosen to ensure that they are applicable to local-scale estuarine management. Modules-2 and 3 provide a detailed summary of climate change projections and physical estuarine data respectively and should be consulted here. The NSW and ACT Regional Climate Modelling (NARCliM) uses a combination of global climate models, downscaled by regional climate models, to produce high-resolution projection for future temperature, rainfall and wind that are appropriate to regional decision making in South-Eastern Australia. More detailed information about NARCliM climate projections is given in Module-2. Module-3 provides a detailed overview of available data on physical estuarine conditions (i.e. water temperature, river flow, dissolved oxygen, pH, water levels).

Mangroves in the Hunter River Wetlands during low tide, Necastle, NSW; photo: Valentin Heimhuber, WRL , UNSW



"The future of coastal wetlands and their ecological value depend on their capacity to adapt to the interacting effects of human impacts and sea level rise."[61]

5 QUALITATIVE ESTIMATION OF ECOLOGICAL IMPACTS

Estuarine ecosystems will likely display complex responses to climate change. The dominant habitats and species, the nature and severity of localized climatic changes, and the characteristics of the existing physico-chemical environment all influence the exposure of an estuary. Understanding the present condition of estuarine ecosystems and their existing sensitivity to environmental stressors can assist in estimating and quantifying impacts, using the framework shown in Figure 14.[31]

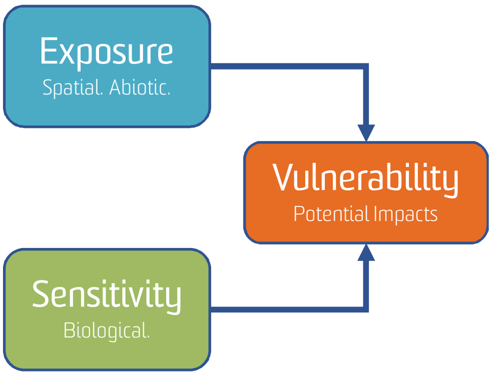
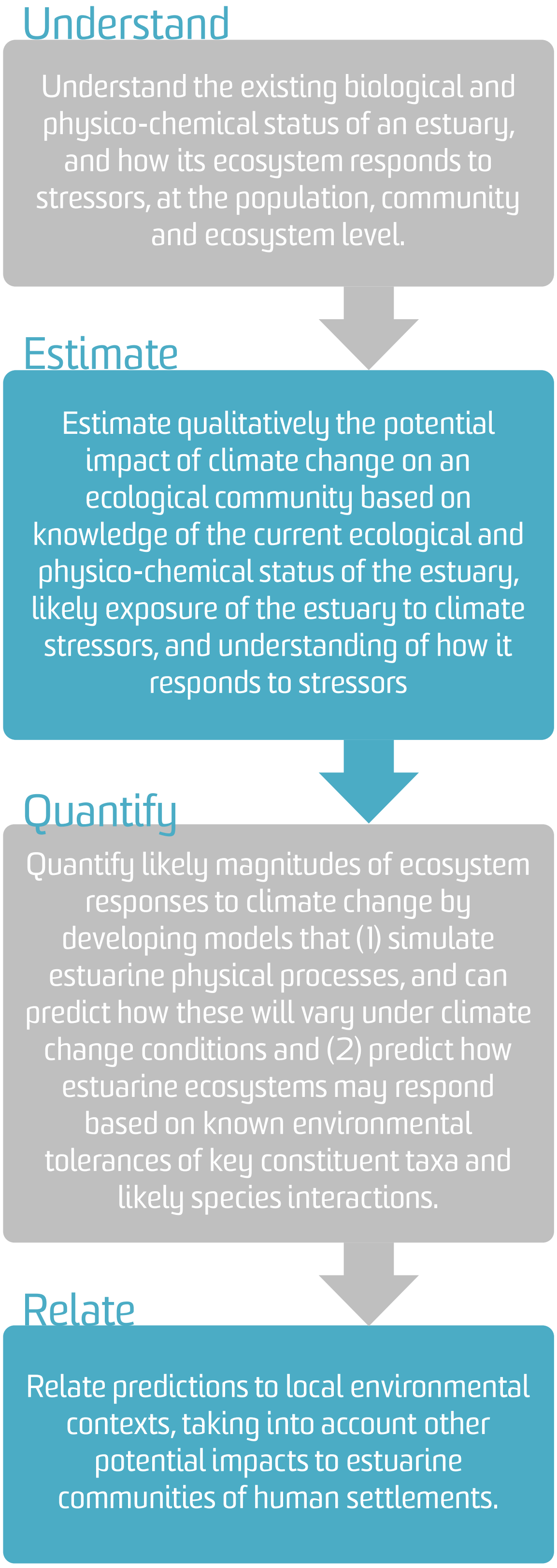


Figure 13. Vulnerability as a function of exposure and sensitivity

Determining the level of ecological risk is challenging since it depends on the type of ecological community, estuarine geomorphic classes and the existing level of local stressors (see Module-5). An important first step is to identify the relative vulnerability of estuarine communities to specific environmental stressors. Smit et al. (2000) define vulnerability as the degree of susceptibility of a system to be negatively impacted and it is composed by two main factors: exposure and sensitivity (Figure 13).[32] As shown in Module-3, the geomorphological and hydrodynamic regime of an estuary controls the extent to which the physical environment (i.e. water temperature, dissolved oxygen, pH, water levels, sediments) will change in response to changing climate drivers (i.e. rainfall, air temperature, sea levels, waves, oceanic acidity). The sensitivity of species in turn, is influenced by intrinsic characteristics like their individual physiological thresholds and ecological feedbacks.[33]



Understand

Understand the existing biological and physico-chemical status of an estuary, and how its ecosystem responds to stressors, at the population, community and ecosystem level.

Estimate

Estimate qualitatively the potential impact of climate change on an ecological community based on knowledge of the current ecological and physico-chemical status of the estuary, likely exposure of the estuary to climate stressors, and understanding of how it responds to stressors

Quantify

Quantify likely magnitudes of ecosystem responses to climate change by developing models that (1) simulate estuarine physical processes, and can predict how these will vary under climate change conditions and (2) predict how estuarine ecosystems may respond based on known environmental tolerances of key constituent taxa and likely species interactions.

Relate

Relate predictions to local environmental contexts, taking into account other potential impacts to estuarine communities of human settlements.

Figure 14. Framework for assessing climate change impacts on estuarine ecology

5.1 Exposure of estuarine communities to climate stressors by estuary type

Physico-chemical characteristics of estuaries may play an important role in determining whether their ecological communities will be impacted by climate stressors. This is because physico-chemical characteristics influence exposure to climatic changes, as well as traits of associated ecological communities, which in turn determines their sensitivity. In this guide, NSW estuaries are classified into four broad categories based on their geomorphology and their dominant physical estuarine processes (see Module-1). Here, we consider how the ecological communities of each estuarine type may be differentially affected by changes in climate-related stressors.

5.1.1 Open embayments

As a consequence of the relatively low input of freshwater into these estuaries, and the constant interchange of water with the thermally-buffered adjacent open coast, open embayments are unlikely to experience large changes in salinity under climate change. Additionally, because their waters tend to be well mixed by waves and tides, the probability of warming surface waters causing stratification and low dissolved oxygen concentrations developing in bottom waters is low. However, as tide and wave-dominated systems, their exposure to sea-level rise and coastal erosional events, caused by a combination of sea-level rise and altered wind and wave climates, will be high. Intertidal shoreline communities may be particularly sensitive to impacts of rising sea levels and erosion. Baseline acidity in seawater will increase notably in the next century (see Module-2), impacting on all types of estuaries. However, acidification impact will be less severe in open embayments where fluctuations in water pH are less marked and extreme low peaks will be less common than in more freshwater influenced estuaries. IPCC projected important increases in mean seawater temperature as well as in frequency and severity of heat waves (see Module-2). While open embayment estuaries are directly exposed to seawater heat waves, the effect of these extreme events may dissipate relatively faster than in more enclosed estuaries.

5.1.2 Tide-dominated

Tide-dominated estuaries are formed in river deltas by accumulation of terrestrial and marine derived sediments, and typically are characterized by large areas of mangroves. Of the five climate variables considered here, tide-dominated estuaries are most likely to be influenced by the effects of sea-level rise. In this type of estuary, the resilience of ecological communities to sea-level rise will be strongly influenced by sedimentation rates. Where sediment supply by rivers and tides is high, intertidal mangrove communities may be able to keep pace with sea-level rise by vertically accreting.[34]

These estuaries are highly influenced by riverine discharges, which create strong fluctuations in pH and salinity making ecological communities more exposed to potential extreme pH peaks due to the combined effect of seawater acidification, acidic soil runoff and riverine input. Increases in water temperature are likely going to have a strong impact in all estuarine systems. However, the large exchange with the open ocean in tide dominated estuaries may limit peak water temperatures during extreme thermal events when compared to more isolated systems like ICOLLs. Nevertheless, estuarine environments with large oceanic influence are adapted to narrow annual temperature ranges and consequently, the projected increases in sea surface temperature might induce significant levels of stress (see Module-3).

5.1.3 Wave-dominated

These estuaries are characterized by a sand barrier and constricted tidal inlet at their mouth. As a consequence, they are low-energy environments that are strongly shaped by freshwater flows. These conditions make wave-dominated estuaries more prone to extreme water temperatures and hypersalinity than open estuaries. Projected increases in the frequency and severity of drought and flood events in NSW may lead to more extreme fluctuations in salinity.[35] Although these estuaries are inhabited by true estuarine species that are adapted to variable salinity conditions, the fluctuations that may result from climate change could surpass the resilience of these organisms (see Module-1). Similarly, the strong influence of riverine and runoff inputs produces strong pH fluctuations, which in combination with a general reduction in seawater pH may amplify severe water acidification events. The semi-enclosed nature of these environments may also amplify temperature impacts. Estuarine heatwaves will dissipate slower in this environment and increased stratification could favour the occurrence of critically-low dissolved oxygen levels of bottom waters. The sand barrier provides some protection to the estuary from moderate sea-level rise, however under high sea level rise scenarios, these barriers may migrate landward, erode or disintegrate (see Module-3).[36]

5.1.4 Intermittently closed and open lakes and lagoons (ICOLLs)

These shallow estuaries, of typically small area, can remain disconnected from the ocean for long periods. During such periods, changes in freshwater inputs can produce marked changes in their salinity, and high air temperatures can considerably warm their shallow waters, in some instances leading to water column stratification. Consequently, they are the most susceptible of all estuarine types to changes in temperature, salinity, pH and dissolved oxygen. As compared to permanently open systems, ICOLLs can experience extended periods with little to no tidal influence, but sea-level rise and altered wave climates may still impact these systems by altering the timing and duration of sand-bar formation, which leads to entrance closure.

The species that persist within these highly dynamic systems can typically withstand large fluctuations in temperature, salinity and inundation.[37] Therefore, it is unclear to which extent climate change will modify the structure of ecological communities supported by ICOLLs, since they have already been subjected to a strong environmental filter. However, if the frequency and severity of low oxygen events increases due to a combination of stratification and high nutrient inputs from the surrounding catchment, large mortality events may result. Due to their relatively small area, during times of entrance closure there are limited opportunities for mobile species to migrate and avoid unfavourable environmental conditions.

Since these type of estuaries are regularly exposed to periods of full freshwater conditions, species such as true estuarine fish, saltmarshes, seagrasses and mangroves are often absent.[38] Changes in entrance opening dynamics will influence opportunities for exchange of organisms and resources with the adjacent coastal environment.

Module-3 provided an estimation of the sensitivity of physical estuarine processes to climate change for different types of estuaries. Here, this approach is extended by estimating the potential level of exposure for ecological communities within each of the four types of estuaries found in NSW (see Module-1) to climate change stressors. Table 1 shows a summary of these estimates, where the level of exposure was rated as:

Low

Ecological communities within this estuary are relatively protected from changes in the environmental variable.

Moderate

Ecological communities are weakly to moderately exposed and may be affected in some degree by changes in the environmental variable

High

Ecological communities are exposed and likely will be influenced significantly by changes in the environmental variable

Table 1. Estimation of the potential level of exposure of estuarine ecological communities to climate stressors in different types of estuaries

Estuary type	Environmental variable				
	Temperature	Salinity	Acidity-CO_2	Dissolve O_2	Sea level
Open embayments	Moderate	Low	Low	Low	High
Tide-dominated	Moderate	Moderate	Moderate	Low	High
Wave-dominated	High	Moderate	Moderate	Moderate	High
ICOLLs	High	High	High	High	Moderate

5.2 Sensitivity of estuarine communities

The sensitivity of estuarine communities to environmental stressors is determined by the physiological thresholds and potential ecological responses of their key species. As ecological communities differ in their species composition and location within the estuary, their tolerance of environmental factors and ecological processes (e.g. predation, competition, facilitation) are likely to vary, resulting in divergent responses to environmental change. For example, seagrass distributions, which are limited by light availability, will be negatively impacted by sea level rise because sea-level rise will reduce the amount of light reaching estuarine bottom sediments. Mangroves, by contrast, may exhibit little change in area in response to moderate sea-level rise because they can trap sediments and accrete vertically. However, despite their relative resilience, the ability of mangroves to keep pace with sea level changes depends on multiple site-specific variables which make predictions complicated.[39]

Saltmarshes, which display lower rates of vertical accretion than mangroves, may be more vulnerable (independent of the site-specific conditions) to sea level rise than mangroves, and may be “squeezed out” if mangroves encroach into their existing habitat. For intertidal oyster beds and rocky shore communities, the risk of sea-level rise depends on the presence of suitable abiogenic habitat into which the community can migrate. For example, some rocky shores are constrained by vertical cliffs on their landward side that will not provide suitable horizontal hard substratum for the migration of oyster species. Unvegetated subtidal systems are, by contrast, expected to be less affected by sea-level rise.

Estuarine species in general tend to be resilient to changes in salinity. However, for many estuarine plants including mangroves, that resilience is significantly lowered during the early life stages.[40] Although some mangrove species and saltmarshes plants can survive in highly salinity environments, seed germination rates decrease with increasing salinity, with many species displaying no germination under seawater conditions.[41] Other estuarine organism like oysters, crustaceans and fish have efficient osmoregulation (ability to maintain internal salts and water balance) mechanisms. However, osmoregulation consumes high amounts of metabolic energy and may potentially negatively affect growth rates and development under prolonged saline conditions.[42] On the other hand, freshwater organisms are highly sensitive to changes in salinities (even to small increases). Most fish and plant species cannot tolerate salinities over 30% seawater and in early life stages this limit may be reduced to about 10%.[43,44] For that reason, saltwater intrusion due to sea level rise may have an extreme impact on upstream freshwater ecosystems.

The impact of increasing pCO_2 concentrations in estuarine waters, and of resultant acidification, is not as well studied as the impact of salinity or of sea-level changes. However, in general, growth and biomass production by photosynthetic organisms is expected to respond positively to high CO_2 levels.[45] Hence, estuarine vegetated communities like seagrass, mangroves and saltmarshes will likely display increased production under increased CO_2 levels, in the absence of sea-level rise and other environmental constraints.[46,47] Instead, seawater acidification may have a significant negative impact on the fertility, growth rates and anti–predator defenses (i.e. shell thickness) of bivalves, making shellfish beds highly sensitive to those predicted changes.[5,48] Studies on other estuarine invertebrates are scarce. However, crustaceans (prawns, crabs, shrimps) have been shown to have more efficient mechanisms to regulate internal water-acidity balance than shellfish, thereby displaying greater resilience to changes.[49] Responses of fish to ocean acidification are highly variable among species, but in general marine fish tend to be highly resilient to moderate acidification.[50,51]

The effect of increases in temperature is highly species-specific, and more difficult to generalize at the functional group level (i.e. habitats). Within species, there may also be significant spatial variation in the thermal tolerances and adaptation capacity of different populations. For example, Madeira et al. (2012),[52] showed that upper thermal limits on different species of estuarine fish, crustaceans and molluscs were more related to their latitudinal distribution than to taxonomic differences. Overall, however, species with narrow latitudinal distributions will be more susceptible to temperature changes.

In NSW, many saltmarsh species are restricted to temperate latitudes, with only a few species extending to tropical areas.[53] Hence it is expected that as a group, saltmarsh may be negatively influenced by warming. By contrast, the two dominant species of mangroves in NSW (*A. marina* and *A. conrniculatum*) have large geographical ranges that extend from tropical to temperate climates, and have ranges that are broadly acknowledged to be influenced by overnight lows (and frosts) versus high temperatures. These are expected to be relatively tolerant of warming temperatures. As temperatures warm, it may also be expected that some of the many tropical and sub-tropical species found in Queensland may be able to extend their ranges south into NSW.[54]

Seagrasses also span tropical and temperate areas.[55] However, there is increasing evidence that warming water is one of the factors affecting the global reduction of seagrass meadows suggesting that many species already are thermally stressed.[56] Oysters and intertidal invertebrates on hard substrates (such as rocky shores) may be particularly sensitive to warming as many already live close to their upper thermal maxima and low tides that coincide with summer mid-afternoon temperature peaks may heat dark rock surfaces to temperature in excess of 60°C.[57] By contrast, sediment-dwelling invertebrates that live in mud or sand may, to some extent, be buffered from warming temperatures by the sedimentary matrix. Southward geographical range expansions have been reported for several tropical species of fish and invertebrates.[58]

Additionally, increasing temperatures will decrease the solubility of oxygen in seawater, depleting the amount of dissolved oxygen in temperate oceans and waterbodies. Also, where temperature influences water stratification (e.g. shallower thermoclines) it increases the risk of hypoxia, especially in semi-enclosed waterways, such as estuaries. The effects of hypoxia are most likely to be felt by sessile (or largely immobile) subtidal animals, which live on or close to the estuarine bottom. Because intertidal species are periodically exposed to the air at low tide, low dissolved oxygen is generally not limiting. Low dissolved oxygen levels can have devastating impacts on the survival of subtidal fish and invertebrate species, which do not photosynthesize and require externally-sourced oxygen for respiration.[59] However, subtidal plant communities may be more tolerant to low oxygen levels, at least for a short period. Studies examining effects of chronic exposure of aquatic plants to low oxygen levels are needed to better predict long term effects.

In Module-7, we present a detailed review of physiological thresholds and ecological responses for several key estuarine species which we use to determine sensitivity levels to climate change. Additionally, this information is collated in an interactive online database with the meta-data on ecological thresholds collected for this guide. This database can be accessed via the following link:

http://estuaries.wrl.unsw.edu.au/index.php/climate-change/eco-thresholds-database/

A summary of the estimated sensitivity of ecological communities to climate-related environmental stressors is provided in Table 2. The sensitivity is categorized into three levels as follows:

Low

The ecological community is unlikely to be affected by changes in the environmental variable.

Moderate

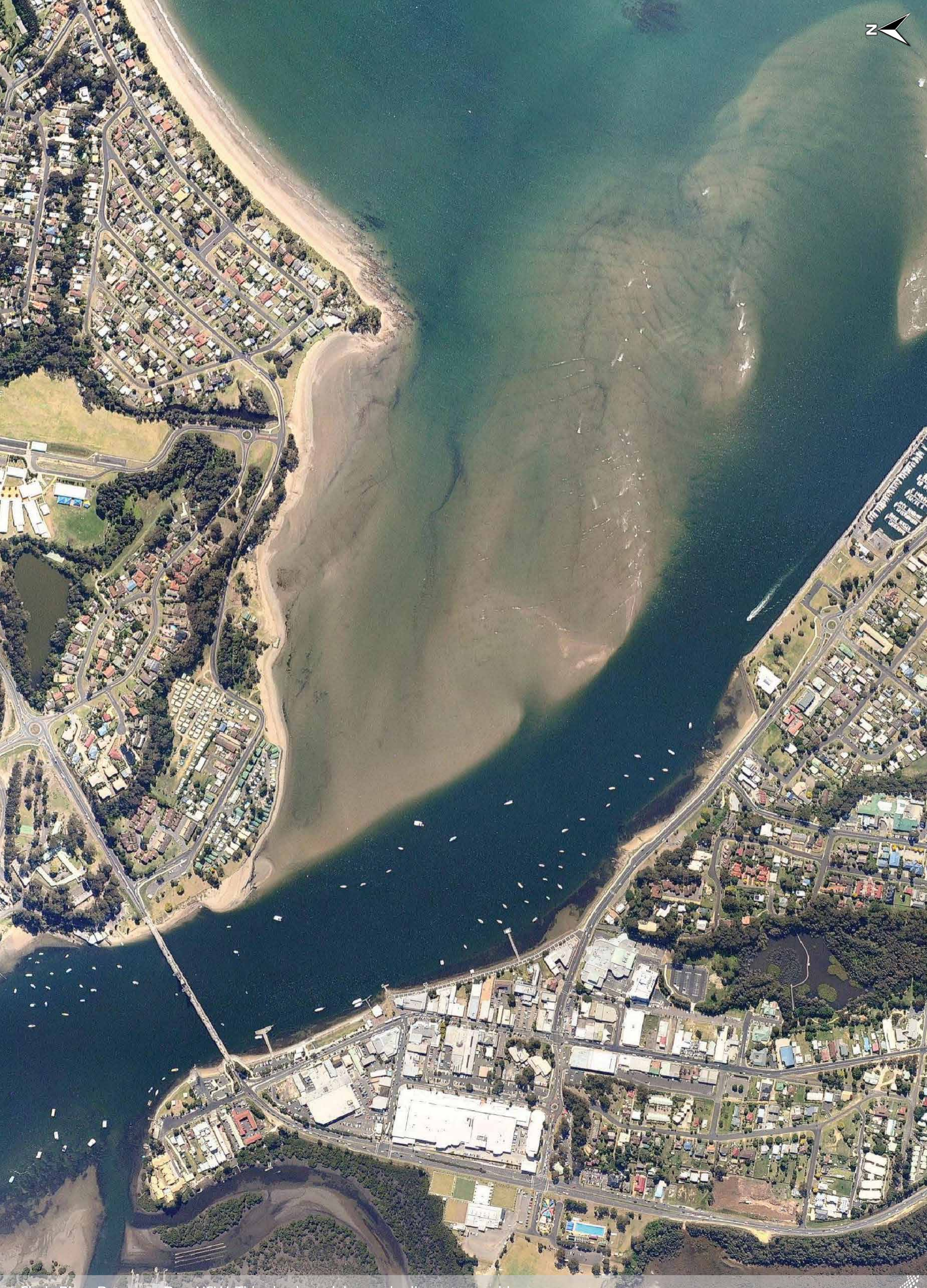
The ecological community is predicted to be weakly to moderately influenced by the environmental variable.

High

The ecological community is predicted to change significantly and/or is dependent on the environmental variable.

Table 2: Qualitative assessment of the potential sensitivity of estuarine ecological communities to environmental stressors. (*) = positive impact predicted

Ecological community	Environmental variable				
	Temperature ↑	Salinity ↑	Acidity-CO_2 ↑	Dissolved O_2 ↓	Sea-level ↑
Seagrass meadows	High	Moderate	Low *	Low	High
Mangroves	Low *	High	Low *	Low	Low
Saltmarshes	High	High	Low	Low	High
Shellfish ecosystems	High	Moderate	High	Moderate	High
Intertidal unvegetated flats	Moderate	Low	Moderate	Low	High
Subtidal sediments	Low	Low	Moderate	High	Low
Intertidal rocky shores	Moderate	Low	Moderate	Low	High
Subtidal rocky reef	Low	Low	Moderate	High	Moderate
Pelagic zone	Moderate	Moderate	Low	High	Low
Adjacent freshwater	High	High	Moderate	Moderate	High



Clyde River, Batemans Bay, NSW; Tide-dominated drowned valley estuary with an open entrance

5.3 Estimating ecological impacts based on exposure and sensitivity

Estimates of the exposure and sensitivity of NSW estuarine communities to different environmental stressors (Table 1 and Table 2) can be used to assess the potential impact of climate change on estuarine communities. A summary of the estimated level of vulnerability of NSW estuarine communities to climate change is provided in Tables 3-6. The estimated level of vulnerability to climate change is divided into the following six categories depending on the respective combinations of exposure and sensitivity:

Extremely vulnerable

If both exposure and sensitivity are high.

Highly vulnerable

If one factor (exposure or sensitivity) is high but the other is moderate.

Moderately vulnerable

If both factors are moderate or if one is high and the other is low.

Slightly vulnerable

If exposure or sensitivity is moderate and the other is low.

Stable

If both exposure and sensitivity are low (no significant changes are predicted).

Increase

If the effect is positive (i.e. an increase in abundance or area is expected).

It is important to remark that the vulnerability tables presented in Box-1 are based on a qualitative estimation of risks using a broad characterization of estuarine types and communities in general. However, assessing and quantifying the potential impact of these environmental stressors on a particular estuary requires more detailed information and site assessments. This includes the geomorphological characteristics of the estuary assessed, projections of future environmental conditions for that particular area based on climate change projections (Module-2) and numerical modeling (Module-3), the ecological community distribution within the estuary, the species composition of those communities, the ecological thresholds of their key species (Module-4 and Module-7) and co-occurring anthropogenic stressors (Module-5). An application of the climate change *Framework for Assessment* presented in Module-1 is provided in Module-6, as a case study using current and future quantitative environmental and ecological data for assessing climate change risks in the Hunter River and Lake Cathie estuaries in NSW.

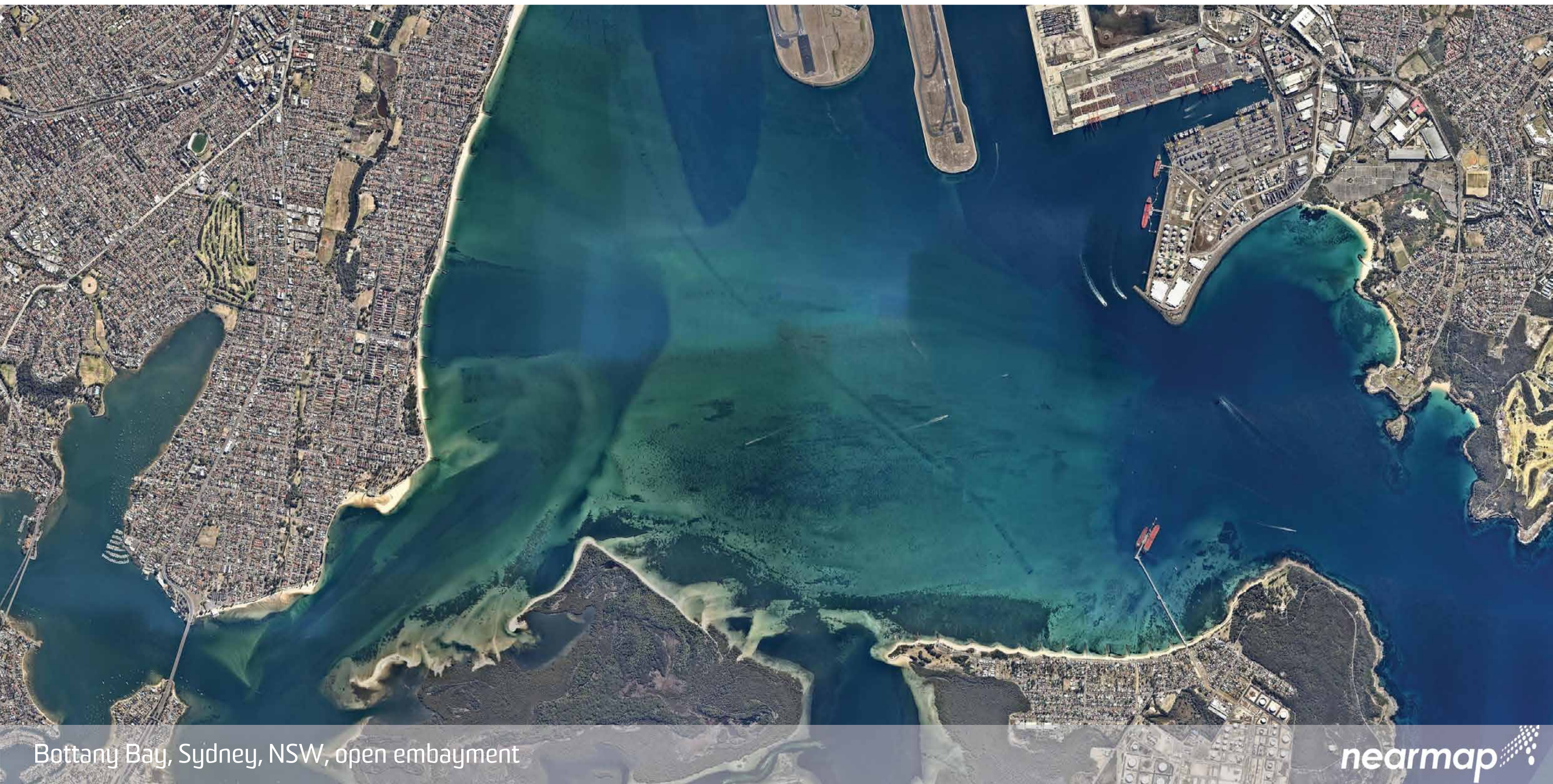
In summary, this Module presented a framework to estimate potential climate change risk on ecological estuarine communities in NSW, following these steps:

1. Defining relevant estuarine communities and key estuarine species.
2. Determining potential ecological responses to environmental stressors due to climate change.
3. Assessing the level of exposure of ecological communities to climate stressors for different types of estuaries.
4. Evaluating the sensitivity of ecological communities to climate stressors based on physiological and ecological tolerance of key species.
5. Estimating the vulnerability of NSW estuarine communities to climate change based on their level of exposure and sensitivity.

Module-5 will provide an overview of existing antropogenic stressors affecting estuaries in NSW and their interactions with climate change stressors. It also gives recommendations on managing these local stressors in order to minimize the impacts of climate change on estuary ecosytems.

Table 3: Vulnerability of key estuarine communities to climate change stressors in open embayments. Open embayments are estuarine systems highly-exposed with strong oceanic influence. Therefore, intertidal communities in these types of estuaries are particularly vulnerable to sea level rise and oceanic heat waves. On the other hand, the constant exchange with the open ocean makes them more resilient to changes in salinity, pH or dissolved oxygen compared to shallow and more isolated systems. Organisms that live in these estuaries are adapted to relatively stable environmental conditions that are comparable to the open coast. Consequently, they may be affected by smaller changes in their physical environment than organisms in estuaries with naturally more variable conditions.

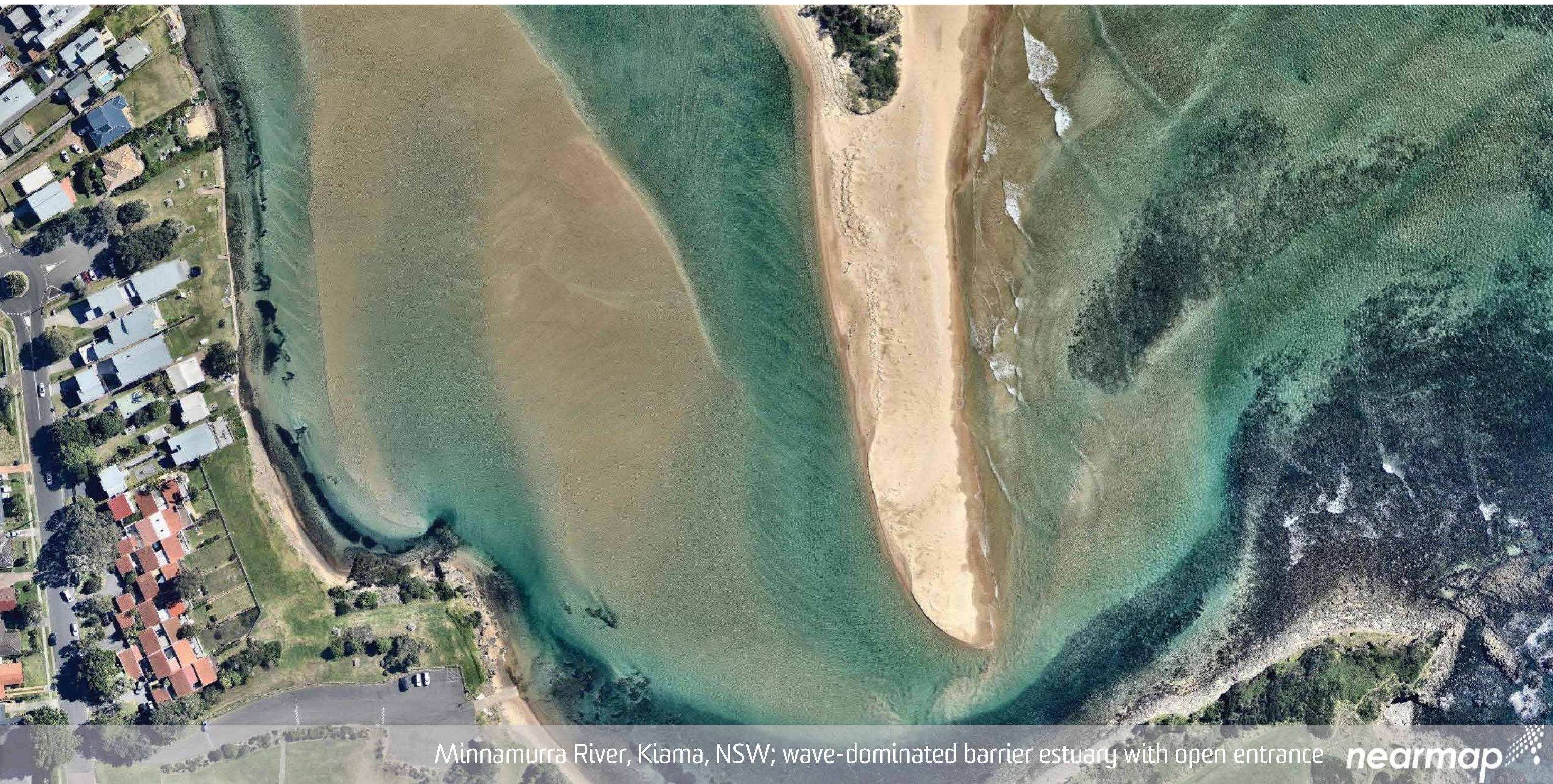
Open embayments	Environmental variable				
	Temperature	Salinity	Acidity-CO$_2$	Dissolved O$_2$	Sea-level
Seagrass meadows	Moderately vulnerable	Stable	Increase	Stable	Extremely vulnerable
Mangroves	Increase	Moderately vulnerable	Increase	Stable	Moderately vulnerable
Saltmarshes	Highly vulnerable	Moderately vulnerable	Increase	Stable	Extremely vulnerable
Shellfish ecosystems	Moderately vulnerable	Slightly vulnerable	Moderately vulnerable	Slightly vulnerable	Extremely vulnerable
Intertidal unvegetated flats	Moderately vulnerable	Stable	Slightly vulnerable	Stable	Extremely vulnerable
Subtidal sediments	Slightly vulnerable	Stable	Slightly vulnerable	Moderately vulnerable	Moderately vulnerable
Intertidal rocky shores	Moderately vulnerable	Stable	Slightly vulnerable	Stable	Extremely vulnerable
Subtidal rocky reef	Slightly vulnerable	Stable	Slightly vulnerable	Moderately vulnerable	Highly vulnerable
Pelagic zone	Slightly vulnerable	Stable	Slightly vulnerable	Moderately vulnerable	Moderately vulnerable
Adjacent freshwater	Highly vulnerable	Moderately vulnerable	Slightly vulnerable	Slightly vulnerable	Extremely vulnerable



Bottany Bay, Sydney, NSW, open embayment

Table 4: Vulnerability of key estuarine communities to climate change stressors in wave-dominated estuaries. Wave-dominated estuaries are semi-enclosed estuarine systems, which are partially proteced from open ocean conditions by sand barriers. However, these partially-enclosed conditions and the influence of riverine inputs make them more exposed to changes (and extreme levels) in water temperature, salinity, oxygen and pH. Ecological communities in these estuaries are adapted to a sensitive equilibrium between oceanic and riverine inputs, making them highly-vulnerable to changes in rainfall regimens, droughts, temperature and sea level rise.

Wave-dominated	Environmental variable				
	Temperature	Salinity	Acidity-CO_2	Dissolved O_2	Sea-level
Seagrass meadows	Highly vulnerable	Slightly vulnerable	Increase	Slightly vulnerable	Extremely vulnerable
Mangroves	Increase	Highly vulnerable	Increase	Slightly vulnerable	Moderately vulnerable
Saltmarshes	Extremely vulnerable	Highly vulnerable	Increase	Slightly vulnerable	Extremely vulnerable
Shellfish ecosystems	Highly vulnerable	Moderately vulnerable	Highly vulnerable	Moderately vulnerable	Extremely vulnerable
Intertidal unvegetated flats	Highly vulnerable	Slightly vulnerable	Moderately vulnerable	Slightly vulnerable	Extremely vulnerable
Subtidal sediments	Moderately vulnerable	Slightly vulnerable	Moderately vulnerable	Highly vulnerable	Moderately vulnerable
Intertidal rocky shores	Highly vulnerable	Slightly vulnerable	Moderately vulnerable	Slightly vulnerable	Extremely vulnerable
Subtidal rocky reef	Moderately vulnerable	Slightly vulnerable	Moderately vulnerable	Highly vulnerable	Highly vulnerable
Pelagic zone	Moderately vulnerable	Slightly vulnerable	Moderately vulnerable	Highly vulnerable	Moderately vulnerable
Adjacent freshwater	Extremely vulnerable	Highly vulnerable	Moderately vulnerable	Moderately vulnerable	Extremely vulnerable



Minnamurra River, Kiama, NSW; wave-dominated barrier estuary with open entrance

Table 5: Vulnerability of key estuarine communities to climate change stressors in tide-dominated estuaries. Tide-dominated estuaries are often located in the former deltas of rivers, which make them highly influenced by riverine inputs in addition to the strong tidal/oceanic influences. Communities are highly exposed to changes in sea level and salinity affecting the necessary riverine-seawater equilibrium. Depletion of dissolved oxygen or water stratification due to high temperatures are unlikely due to the high degree of tide-driven mixing. The impact of seawater acidification may be amplified by runoff of sulfate acids in the riverine discharges.

Tide-dominated	Environmental variable				
	Temperature	Salinity	Acidity-CO_2	Dissolved O_2	Sea-level
Seagrass meadows	Moderately vulnerable	Slightly vulnerable	Increase	Stable	Extremely vulnerable
Mangroves	Increase	Highly vulnerable	Increase	Stable	Moderately vulnerable
Saltmarshes	Highly vulnerable	Highly vulnerable	Increase	Stable	Extremely vulnerable
Shellfish ecosystems	Moderately vulnerable	Moderately vulnerable	Highly vulnerable	Slightly vulnerable	Extremely vulnerable
Intertidal unvegetated flats	Moderately vulnerable	Slightly vulnerable	Moderately vulnerable	Stable	Extremely vulnerable
Subtidal sediments	Slightly vulnerable	Slightly vulnerable	Moderately vulnerable	Moderately vulnerable	Moderately vulnerable
Intertidal rocky shores	Moderately vulnerable	Slightly vulnerable	Moderately vulnerable	Stable	Extremely vulnerable
Subtidal rocky reef	Slightly vulnerable	Slightly vulnerable	Moderately vulnerable	Moderately vulnerable	Highly vulnerable
Pelagic zone	Slightly vulnerable	Slightly vulnerable	Moderately vulnerable	Moderately vulnerable	Moderately vulnerable
Adjacent freshwater	Highly vulnerable	Highly vulnerable	Moderately vulnerable	Slightly vulnerable	Extremely vulnerable

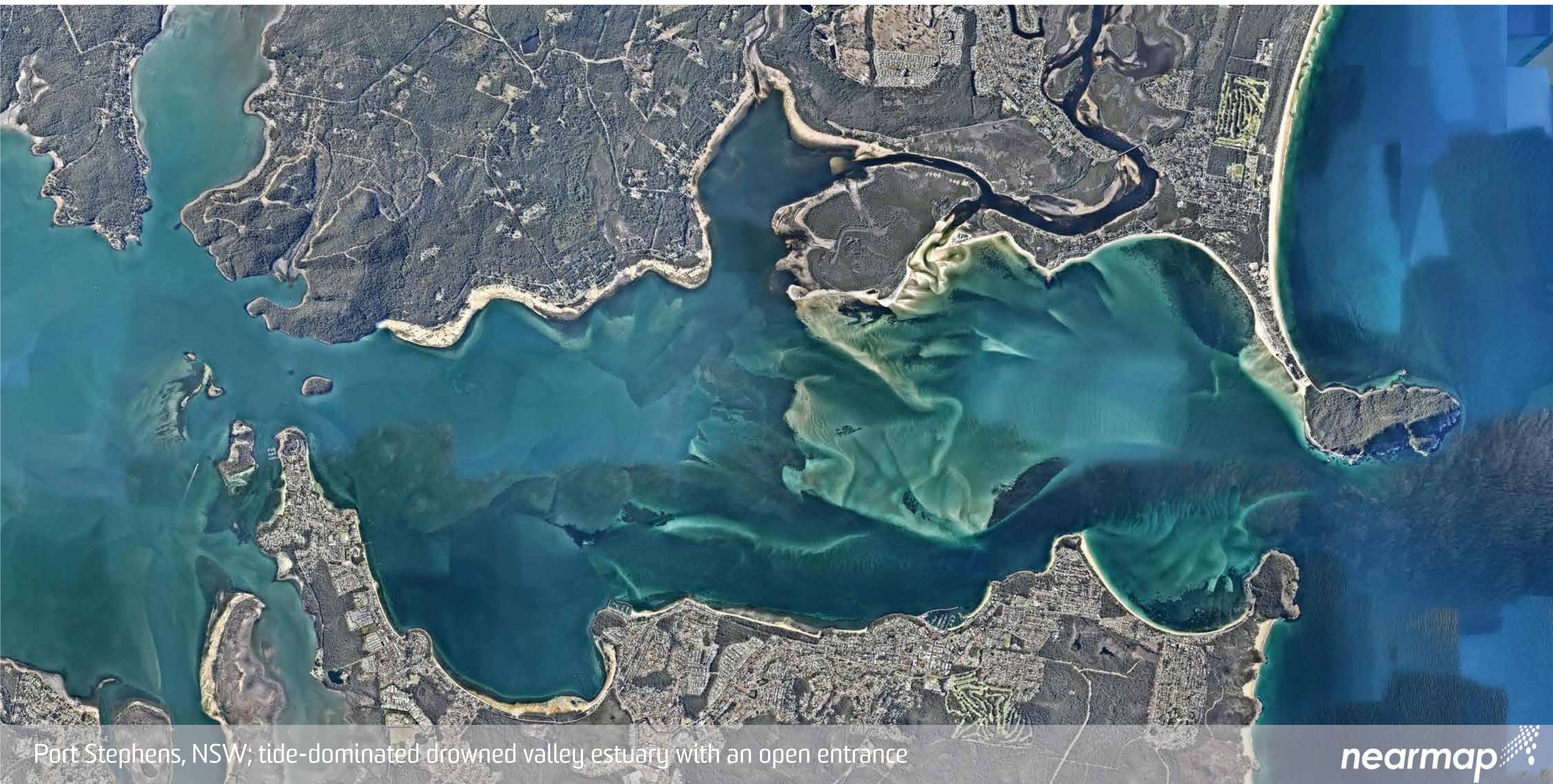

Port Stephens, NSW; tide-dominated drowned valley estuary with an open entrance

Table 6: Vulnerability of key estuarine communities to climate change stressors in ICOLLs. ICOLLs are often small and shallow estuaries that can remain disconnected from the ocean for long periods. This partial enclosure makes them highly-exposed to large fluctuations in their physicochemical environment (i.e. temperature, salinity, pH and oxygen). In this estuary type, ecological communities live under harsh environmental conditions and estuarine fish, seagrasses and mangroves are often absent when periods of enclosure are long. However, partial isolation also provided some protection for intertidal communities against sea level rise and wave energy.

ICOLLs	Environmental variable				
	Temperature	Salinity	Acidity-CO_2	Dissolved O_2	Sea-level
Seagrass meadows	Highly vulnerable	Moderately vulnerable	Increase	Moderately vulnerable	Highly vulnerable
Mangroves	Increase	Extremely vulnerable	Increase	Moderately vulnerable	Slightly vulnerable
Saltmarshes	Extremely vulnerable	Extremely vulnerable	Increase	Moderately vulnerable	Highly vulnerable
Shellfish ecosystems	Highly vulnerable	Highly vulnerable	Extremely vulnerable	Highly vulnerable	Highly vulnerable
Intertidal unvegetated flats	Highly vulnerable	Moderately vulnerable	Highly vulnerable	Moderately vulnerable	Highly vulnerable
Subtidal sediments	Moderately vulnerable	Moderately vulnerable	Highly vulnerable	Extremely vulnerable	Slightly vulnerable
Intertidal rocky shores	Highly vulnerable	Moderately vulnerable	Highly vulnerable	Moderately vulnerable	Highly vulnerable
Subtidal rocky reef	Moderately vulnerable	Moderately vulnerable	Highly vulnerable	Extremely vulnerable	Moderately vulnerable
Pelagic zone	Moderately vulnerable	Moderately vulnerable	Highly vulnerable	Extremely vulnerable	Slightly vulnerable
Adjacent freshwater	Extremely vulnerable	Highly vulnerable	Highly vulnerable	Highly vulnerable	Highly vulnerable

Dee Why Lagoon during an opening, Northern Beaches, Sydney, NSW; ICOLL

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Back cover image

Sunset over saltmarsh in the Hunter River Wetlands, NSW; Photo: Valentin Heimhuber, WRL, UNSW