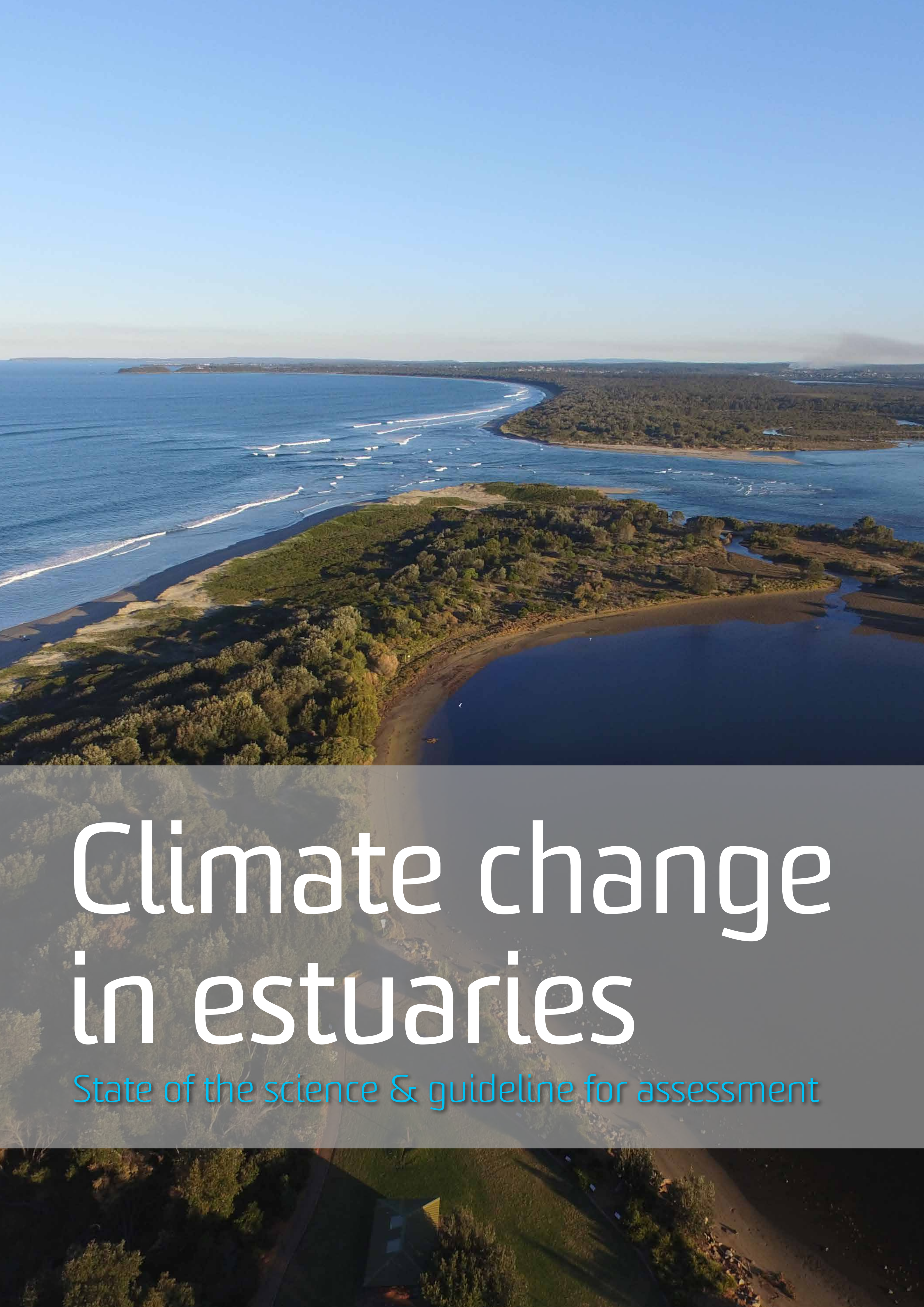

Climate change in estuaries

State of the science & guideline for assessment

“Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks.” (IPCC Fifth Assessment Report)[1]

Intertidal ecosystem, Patonga Creek, NSW; Photo: Valentin Heimhuber, WRL, UNSW

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 upon by all project partners based on their extensive knowledge and experience in the field of estuaries and climate change with advice from the scientific community. The Guide has been published as a series of modules. Each module is a stand-alone document addressing an important aspect of assessing climate change risks in estuaries. The following modules are available in the series (titles are abbreviated here):

1. **Introduction (this module)**
2. Changes in climate
3. Changes in the physical environment
4. Changes in the ecology
5. Developmental stressors
6. Application of the framework
7. Review of ecological thresholds
8. Knowledge gaps and research needs

The NSW Adaptation Resarch Hub (the Hub)

The Hub was established in 2013 by the NSW Office of Environment and Heritage to leverage NSW's multidisciplinary science capacities to produce relevant and practical research to directly inform the decision making of NSW agencies and communities. The Coastal Processes and Responses Node is led by the Sydney Institute of Marine Science (SIMS). It studies the assessment and risk management of, and adaptation responses to, the impacts of climate change on coastal and estuary zones.

Contributors

The following people have contributed to one or more modules in this guide: Valentin Heimhuber, William Glamore, Melanie Bishop, Gabriel Dominguez, Peter Scanes, Johana Ataupah, Alejandro Di Luca, Jason Evans, Duncan Rainer, Brett Miller and Priom Rahman.

Summary of Module-1

Module-1 provides a general introduction to estuaries and climate change and serves as a roadmap for navigating the other modules. It introduces the key physical and ecological mechanisms occurring in estuaries and explains the role of climate in these processes. It presents the four main types of estuaries in NSW along with their dominant hydro-ecological processes. This is followed by an introduction to climate change and its likely impacts to estuaries. At the end of the module, the conceptual framework for assessment is presented and explained.

Cover photos

Drone view of the Shoalhaven River during an opening at Shoalhaven Heads. Chris Drummond, WRL, UNSW.

Module-1 should be referenced as

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Peer-review

Module-1 has been peer-reviewed by Dr. Nathan Waltham (TropWATER, James Cook University) and Dr. Melissa Wartman (Blue Carbon Lab, Deakin University).

Disclaimer

Tip for readers

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

Motivation behind this guide

Estuaries are found where the river meets the sea; where fresh waters from upland catchments mix with marine oceanic waters. They are unique and incredibly biodiverse ecosystems that are often influenced by tides and are protected from the full force of ocean waves, winds and storms by surrounding landforms like headlands, sand dunes or coastal floodplains. The New South Wales coastal zone contains 184 estuaries that vary in size from small coastal creeks and lagoons to large lakes and rivers, and they represent one of the most important natural assets of the state. Estuaries are amongst the most productive ecosystems on Earth and provide countless ecosystem services to the coastal communities surrounding them. With more than two-thirds of the state's population living in estuarine catchments, there is no doubt regarding the enormous value that estuaries hold for our society. However, these systems are facing an uncertain future in a world of rapidly changing climate. There are three major reasons why estuaries and their ecosystems may be particularly vulnerable to climate change:

1. **Double whammy impacts:** Estuaries are at the interface between coastal rivers and the ocean and hence, are affected by climate change impacts from both sides. Climate change is affecting oceanic processes such as coastal currents (i.e. Eastern Australian Current), sea levels and wave climate as well as atmospheric processes such as storms (i.e. East Coast Lows), extreme rainfalls and heatwaves. Ocean and upland impacts can potentially superimpose or "team up", such as when upland flooding coincides with a storm surge. Consequently, estuaries are likely to experience substantial changes to their physical environment.

2. **Vulnerable eco-hydrology:** Due to their unique hydrological setting, which often includes shallow, protected, dynamic and nutrient rich brackish waters, estuaries belong to the most productive ecosystems on earth. For the same reasons, relatively small shifts in the ocean or climate system can lead to large changes in the physico-chemical environment of estuaries, making them particularly vulnerable to global climate change.

3. **Existing pressures:** Most estuaries are already facing severe developmental and population stresses stemming from coastal development and agriculture. These impacts may accelerate and amplify the impacts of climate change.

Through the 2016 Coastal Management Act and the 2014 Marine Estate Management Act, the New South Wales Government is setting the course towards sustainable and holistic management of coastal and marine environments. Understanding and addressing climate change-driven threats to coastal ecosystems is paramount for the success of this strategy but climate change impacts in NSW estuaries are presently poorly understood. There are currently uncertainties and theoretical impediments to our quantitative understanding of estuarine processes and their susceptibility to climate change over common planning horizons. This guide addresses these knowledge gaps through a series of modules that together, provide a best-practice roadmap for assessing climate change in estuaries.

Assessing the potential impacts of climate change in estuaries and the resulting risk to ecosystems is not an easy task. Estuarine habitats and ecological communities, water quality, shoreline stability, long-term sedimentation, groundwater, freshwater management as well as the inundation of adjacent land and the built environment may potentially be significantly impacted by climate change. Uncertainties in climate projections for the atmosphere and oceans, the complex physical response of estuaries to a changing climate and poorly-understood ecological feedback loops are just some of the challenges. This guide is intended to help estuarine managers and coastal communities navigate the complexity of assessing climate change in estuaries by providing a summary of the relevant climate, ocean and ecosystem science along with best-practice frameworks for prioritizing risks.

> The purpose of this guide is to help estuarine managers and coastal communities navigate through the complexity of assessing climate change impacts in estuaries by providing a summary of the relevant climate, ocean and ecosystem science along with best-practice frameworks for prioritising risks.

Drone view of Lighthouse Beach, Ballina and Wamberal Lagoon (previous page), NSW; Photo: Chris Drummond, WRL, UNSW

OUTLINE OF THIS GUIDE

This guide is organised into eight separate modules that each address different key components of climate change impact assessments in estuaries. Module-1, provides a general introduction to all aspects of the risk assessment along with a roadmap for assessment and guidance on the usage of the remaining modules. The assessment generally involves four major components, and these correspond to the four core modules: Module-2 (changes in the climate system), Module-3 (impacts to the physical estuarine environment), Modules-4 (impacts to the ecology) and Module-5 (managing local stressors). Module-6 is a peer-reviewed research publication that illustrates how the Framework for Assessment presented in Module-1 and elaborated in Modules 2-5 can be put into practice using a NSW estuary as a case study. Module-7 is a comprehensive review of scientific literature on ecological responses to climate change and provides the theoretical foundation for the Eco-thresholds database, a collation of ecological metadata available for NSW estuarine species. Module-8 provides a summary of key knowledge and data gaps along with a number of suggestions for immediate and future research and funding needs. The infographic on the following page illustrates some of the key challenges involved with assessing climate change risk in estuaries and how they are addressed by the four core modules.

	MODULES		CONTENT
	1	Introduction	Introduction to estuaries, their ecosystems, climate change and the framework for assessment.
Core modules for assessment	2	Determine changes in climate boundary conditions	Guideline on how to project and prioritize changes in estuary climate boundary drivers and summary of relevant changes in NSW.
Core modules for assessment	3	Determine changes in the physical estuarine environment	Guideline on how to determine changes to the physical estuary environment resulting from changes in climate boundary conditions.
Core modules for assessment	4	Determine the response of estuarine ecosystems	Assessing climate change impacts to estuary ecosystems, the role of the physical environment and feedback loops.
Core modules for assessment	5	Assessment and management of local stressors	Managing local developmental stressors to enhance the resilience of estuarine ecosystems to climate change stressors.
Supporting modules	6	Conducting the assessment	Peer-reviewed research paper: Practical application of the framework for assessment using a case study estuary in NSW.
Supporting modules	7	Estuarine species and climate change – literature review	Review of estuarine species-specific environmental thresholds in support of the Eco-thresholds database.
Supporting modules	8	Knowledge gaps, limitations and research needs	Factsheets on: Knowledge gaps; research needs; recommendations for monitoring, infrastructure and adaptation programs.

Framework for assessment

The conceptual workflow for the risk assessment

Assessing climate change impacts in estuaries

↑ MODULE 2

Global climate models are the primary tool for projecting future climate but even though these models are constantly evolving and regional climate models can resolve local scale climate processes much better, significant uncertainties remain for future projections. The global climate system is highly dynamic and contains many complex feedback loops, which make the projection of long-term changes an extremely difficult task. Understanding the uncertainties involved with future projections of climate and ocean processes and managing them appropriately is one of the main challenges for the risk assessment.

↑ MODULE 4

Knowledge about the tolerance of estuarine species to changes in the physical environment is sparse. In addition, there are several unknowns about feedback loops among species and between species and their physical environment. This lack of knowledge is a key challenge in the risk assessment.

Intertidal vegetation communities such as saltmarshes and mangroves have the ability to migrate vertically through building up sediment (accretion) and horizontally (to adjacent more elevated land) under rising sea levels. The speed of accretion and the potential for horizontal migration remains very hard to predict and depends on future land use development.

Changing rainfall regimes may alter catchment rainfall-runoff and thereby the amount of freshwater and sediments being mobilized and delivered into the estuary. Detailed hydrological modeling is necessary to generate projections of future freshwater inflows and sediment loads from climate model outputs.

Changes in mean sea level will alter the tidal prism of estuaries. Together with potentially altered freshwater inflows and sediment loads, these changes might alter the hydrodynamics and geomorphology of estuaries. These changes are complex to predict and typically require detailed hydrodynamic modeling.

MODULE 3

Human development in and around estuaries often has a pronounced impact on the eco-hydrological estuary system. Urban expansion, agriculture and drainage of intertidal zones typically lead to reduced water quality and loss of ecosystem components. Differentiating between human and climate change induced changes represents a significant challenge.

An additional source of complexity is introduced when catchments are developed, meaning that the water balance is significantly altered by human activities such as agricultural and water resources development.

MODULE 5

MODULE-1 - INTRODUCTION

1 ESTUARIES – WHERE RIVERS MEET THE SEA

Estuaries are found where rivers and streams meet the sea and fresh waters from upland catchments mix with marine oceanic waters to form dynamic and diverse aquatic environments. Estuaries can either be permanently or intermittently connected to the ocean and are often protected from the full force of ocean waves, winds and storms by surrounding land forms like headlands, sand dunes, sand bars or coastal floodplains. They are amongst the most productive ecosystems on the planet, provide countless ecosystem services to society, and often form an integral part of the lives of people who live nearby.

1.1 Environmental value

It is estimated that many species of coastal fish depend on estuaries at some stage in their life history.[1] Estuaries provide crucial habitat to many iconic species of birds, fish, marine mammals, plants and often represent critical stepping stones for migratory shorebirds.[2] More information on estuarine habitats is provided in Module-4.

1.2 Socio-economic value

Over 80% of the NSW population live in the coastal zone and directly or indirectly benefit from estuaries as places of recreation, transport and trade (i.e. ports and shipping) or as providers of food and raw materials.[3] Estuaries are highly productive ecosystems that supply a wide range of seafood including oysters, prawns, crabs, and fin-fish. Collectively, NSW commercial estuarine fisheries are worth $29 million per year (30% of the total NSW fisheries production), with estuarine aquaculture industries contributing over $65 million per year to the NSW economy.[1] Additionally, estuarine habitats can play an important role in protecting shorelines and settlements from erosion and inundation, while assisting in maintaining good water quality.

> "Every acre of saltmarsh captures and converts at least 3.2 metric tons of carbon dioxide into plant material and sediment annually—equivalent to the greenhouse gas emissions of driving 7,000 kilometers."[4]

Estuaries also play a significant role in the climate system due to their ability for sequestering and storing carbon. Aquatic plants such as mangroves, seagrass and saltmarsh grasses remove carbon dioxide from the atmosphere during photosynthesis and convert this into plant material, most of which remains locked away in the sediments for millennia. This sequestered carbon is called "blue carbon" and estuarine plants are exponentially more efficient than terrestrial plants in producing it.

1.3 Why assess climate change risk in estuaries?

The extent to which estuaries and their eco-hydrological systems will be affected by a changing climate remains poorly understood and quantified. There is, however, no doubt that estuaries are already experiencing adverse

effects of human and climatic stressors that will continue into the future if left unmanaged. Warming air and water temperatures, rising sea-levels, acidifying waters and changing salinities are compounding the effects of coastal development, which commonly includes the loss and degradation of habitat and invasion of foreign species.

> "Up to 60% of coastal wetlands have been lost or are showing evidence of serious degradation."[3]

To ensure that future generations can continue to benefit from the wide range of ecosystem services that estuaries provide, these systems need to be managed in an ecologically sustainable way. The NSW government recently implemented a new coastal reform, which provides the legal framework for the sustainable management of the NSW coast now and into the future. The Coastal Management (CM) Act 2016 establishes the framework and overarching objectives for coastal management in NSW. "The purpose of the CM Act is to manage the use and development of the coastal environment in an ecologically sustainable way, for the social, cultural and economic well-being of the people of NSW."[5]

As part of the new coastal reform, local governments are required to develop coastal management programs, which "set the long-term strategy for the coordinated management of the coast, with a focus on achieving the objects and objectives of the Coastal Management Act 2016 (CM Act)."[5] The coastal management programs need to identify coastal management issues and outline solutions and actions to address these issues.

Understanding how, in addition to existing stressors, climate change is impacting estuaries now and over the course of this century is a critical component of this assessment and integral if sustainable long-term management is to be achieved.

> "A healthy coast and sea, managed for the greatest wellbeing of the community, now and into the future."[6]

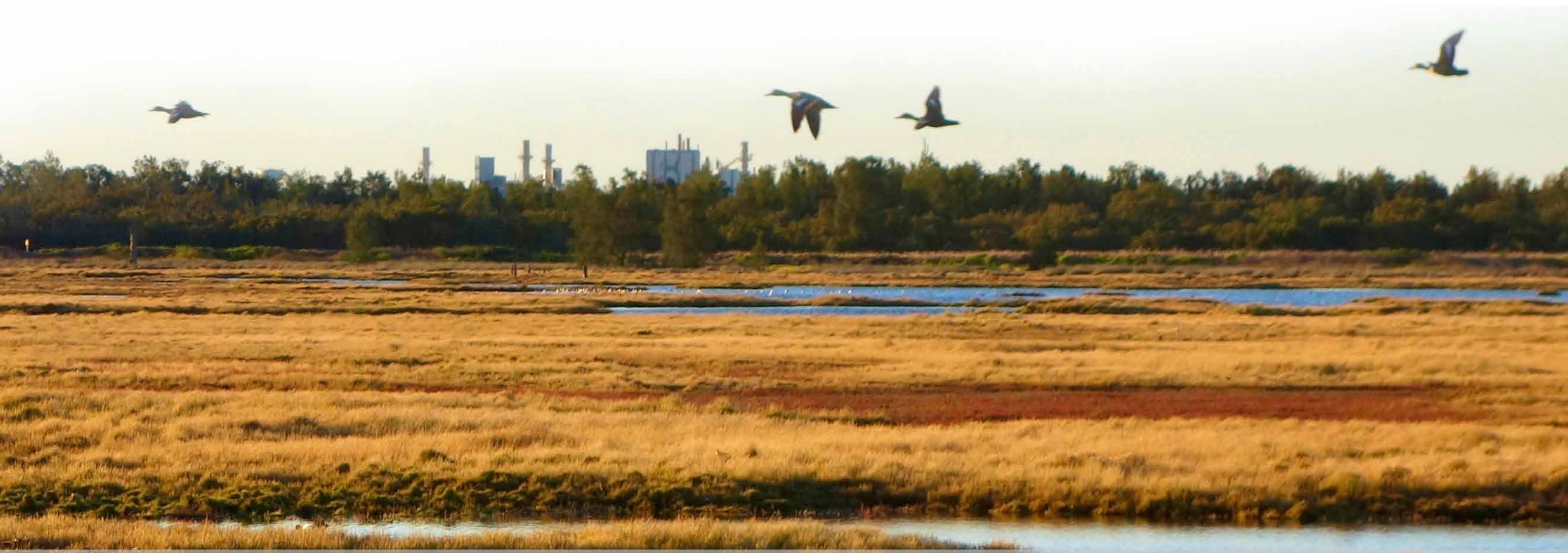
The NSW Marine Estate Management Act (MEMA) 2014 and corresponding Marine Estate Management Strategy is another core legislation aimed at establishing sustainable and holistic management of the NSW marine estate.[6] The marine estate comprises all coastal waters including estuaries, lagoons and coastal wetlands. The Marine Estate Management strategy *"coordinates the management of the marine estate over the next decade"* by *"balancing economic growth, use and conservation."*[6]

Promoting healthy and biologically diverse coastal ecosystems and identifying priority threats to those systems is amongst the key principles of the MEMA. Therefore, understanding and prioritizing the potential impacts of climate change to estuaries and the ecosystems they support can be considered as an important step towards the successful implementation of the Marine Estate Management strategy.

Further reading

Estuaries in NSW: http://www.environment.nsw.gov.au/topics/water/estuaries

Estuarine habitats: https://www.dpi.nsw.gov.au/fishing/habitat/aquatic-habitats/estuarine



Saltmarsh in the Hunter River Wetlands, Newcastle, NSW; Photo: Valentin Heimhuber, WRL, UNSW

2 HOW ESTUARIES FUNCTION

2.1 How climate shapes estuaries

Before examining the impacts of climate change in estuaries, it is critical to first understand the key processes that occur in these systems and how the surrounding climate affects these processes. There are many inter-related processes occurring in estuaries that make them unique, productive and constantly changing environments. For assessing the risks of climate change, it is useful to group the multitude of estuarine processes into physical and ecological processes. *Hydrodynamics, Geomorphology* and *Water Quality* processes shape the physical estuarine environment, which is largely driven by broad climatic variables or *Climate Drivers*. Together with the *Ecological Processes,* which includes living organisms, the physical environment forms the estuary ecosystem. The hierarchical relationship between these first, second and third order processes can be expressed by the conceptual diagram shown in Figure 1.

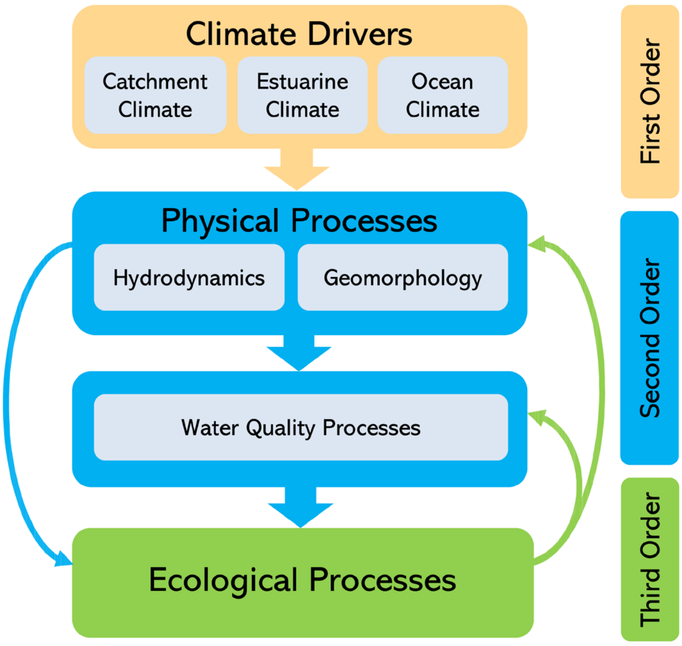


Figure 1: Conceptual diagram illustrating the hierarchical role of climate drivers in estuarine processes.

Ecological or third-order processes are closely-linked with physical or second-order processes, often through complex feedback loops. The climate exerts a first-order control on estuarine ecosystems by determining tides, freshwater flows and wave-action. The relative strength of these three processes determines an estuary's physical and chemical (i.e. second-order) properties, including its hydrodynamics, geomorphology and chemistry. These second-order processes, in turn, exert a filter on the species that can persist and reproduce within the ecosystem.

2.2 Ecological processes

Due to the complexity of physical processes, salinity is broadly considered one of the key structuring features of estuarine ecosystems.[12] The species found within estuaries include those adapted to restricted salinity ranges (i.e. marine species, found at the estuarine mouth, and freshwater species found above its tidal extent) and true estuarine species, which are able to tolerate variable salinities (or brackish conditions). The number of species that can tolerate highly variable salinity conditions is lower than the number that are adapted to a restricted salinity range. The species richness is generally lower in the mid-reaches of an estuary than at its mouth or landward extent.

Despite their relatively low diversity, true estuarine species are unique to these ecosystems, which makes them extremely relevant for global biodiversity conservation. Benthic (bottom-dwelling) habitats are an important component of estuarine ecosystems and substratum type (e.g. rocky, sandy, muddy) and the depth of overlying waters are important controls of estuarine habitat distributions. Finally, biological interactions may make the environment more or less habitable for particular species. For example, the structural habitat provided by aquatic vegetation and shellfish reefs can reduce waves and currents, trap food resources and protect invertebrates and juvenile fishes from predators.

2.3 Physical processes

2.3.1 Hydrodynamics

Hydrodynamics refer to the movement of water through a system, which ultimately affects all geomorphological and water quality related processes. The movement of water within an estuary governs the level of mixing and is mainly driven by sea level fluctuations (i.e. tides), freshwater inflows (catchment runoff), waves and wind.

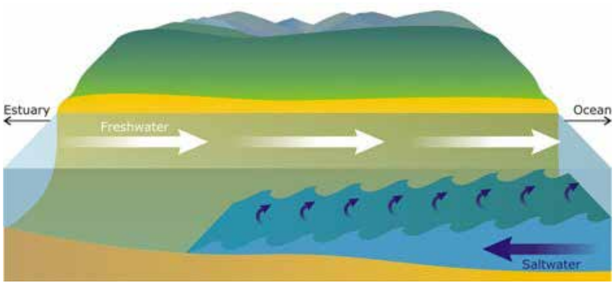


Fig. 2: Simplified representation of estuarine hydrodynamics illustrating the balance between freshwater and oceanic flows.

Tides, the harmonic fluctuations of sea levels, are driven by gravitational attraction of the moon and the sun which causes periodic oscillations of sea levels. Tides in NSW are semidiurnal meaning that they contain two main cycles per day. While ocean tides are rather uniform along the NSW coast, the tidal variations within estuaries are often complex and dependent on the shape and geomorphic type of estuary. Some estuaries have higher tidal fluctuations than the open ocean (tidal amplification) while others display significant attenuation or even no tidal variation at all. The unique tidal dynamics of an estuary directly influence the amount of ocean water that enters and leaves the system during a single tidal cycle and this volume of water is called the tidal prism. The NSW Office of Environment and Heritage provides tidal plains[7] and tidal prism volumes for the majority of estuaries in NSW[5] in addition to recent scientific publications on sea level rise impacts on coasts and estuaries.[8,9]

Freshwater inflow to an estuary is primarily controlled by runoff generated in the upstream catchment in response to rainfall. Runoff volumes can be amplified (e.g. through vegetation removal and replacement with impervious surfaces) or reduced (e.g. through water extraction and retention) as a consequence of land-use change. Freshwater flows directly impact on estuarine hydrodynamics through changes in circulation and mixing. Freshwater inflows are also important in influencing salinity, transport of sediments and nutrients from catchments to coasts and in contributing to stratification of estuarine waters.

Wind and wave processes can have highly variable impacts to estuaries. Whilst hydrodynamics in a narrow estuary is predominantly influenced by tides, wind forces can significantly modify circulations and turbulent mixing in wider environments. Strong coastal winds may cause localised storm surges which can induce large flow volumes and inundation. Winds also directly impact on the level of stratification and mixing within the estuary. In shallow estuaries, tidal flows are strongly dampened, and wind driven forces can dominate the circulation of water.

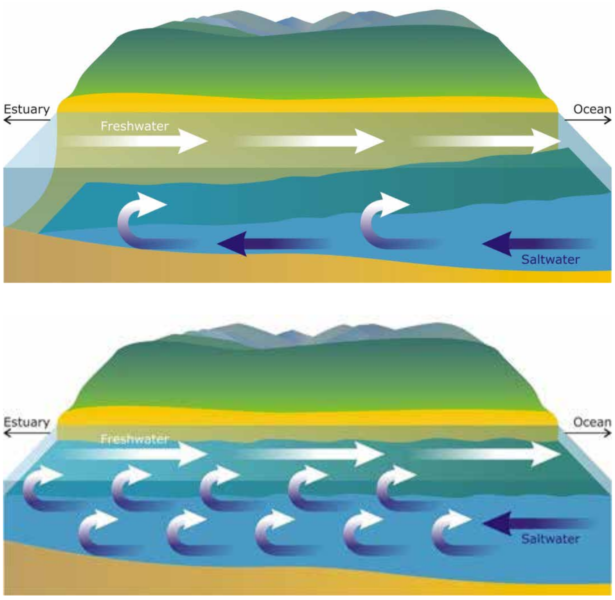


Fig.3: Simplified representation of estuarine hydrodynamics illustrating the intrusion of salt water during oceanic storm surge or low freshwater flow conditions

Mixing refers to the horizontal and vertical circulation and exchange of water and its constituents within the estuarine water body. Mixing, or a lack thereof, can lead to locally variable physical and chemical conditions in estuaries (i.e. stratification) and is brought about by a combination of advection and dispersion. Advection refers to the transport of material or a pollutant through the motion of water. Dispersion is the spreading and mixing caused by turbulence and molecular diffusion. Vertical mixing in an estuary is often limited and due to the higher density of saltwater as compared to freshwater, estuaries often exhibit pronounced stratification or layering of fresh and oceanic waters as shown in Figure 2.

Flooding of an estuarine system can be considered as an extreme or rare hydrodynamic state. Estuarine flooding can be triggered by either intense rainfall events over coastal catchments and/or due to elevated ocean levels during storm surges pushing landward through estuary entrances to inundate the lower lying foreshores and floodplain areas (Figure 3).[10] Floods often lead to higher flow velocities, which can increase the rates of erosion and sediment delivery.

2.3.2 Geomorphology

In the context of estuaries, geomorphology refers to the origin and evolution of topographic (i.e. around and near the estuary) and bathymetric (i.e. under water or within the estuary) landforms.

Sediment dynamics describe the movement of sediments within an estuary and surrounds over time. Estuarine sediments are derived from the watershed (catchment sediments) and the continental shelf in front of the estuary (marine sediment) and can be transported through wind, waves, tidal or freshwater flows. Lesser sources are erosion within the estuary, biological activity and aeolian transport. The distribution and movement of sediment is controlled by interactions between the available sediments, the bottom morphology and hydrodynamics.[11] Terrestrial and marine flooding events play a critical role in the sediment balance of estuaries since they cause large mobilization and redistribution of sediments. The delivery of terrestrial material is inversely proportional to the size of the flood, with most material being deposited in the estuary during small floods and exported to the continental shelf during large floods.

Morphodynamics: On wave dominated coasts such as NSW, beaches are constantly changing in response to the wave and wind climate and this is commonly referred to as beach morphodynamics. The entrances of wave dominated estuaries exhibit complex morphodynamics, since they are constantly reshaped in response to water flowing in and out of the entrance, sediment supply and the wave and wind climate.

2.3.3 Water quality

Water quality processes influence the physical and chemical constitution of water in an estuary, which is driven by freshwater and marine inflows as well as the multitude of biochemical processes occurring. Due to the complex surface and groundwater dynamics in estuaries, water quality is generally highly variable across space and time.[12]

Physical water quality parameters are those that are not directly involved in chemical reactions such as temperature, salinity and turbidity.

Chemical water quality parameters in contrast, can undergo change or reaction such as dissolved oxygen levels, nutrients (nitrate and phosphate) and acidity (pH).

A summary and explanation of key physical and chemical water quality parameters in estuaries is provided in Table 1. Importnatly, there are many important water quality parameters that aer not introduced in Table 1 and we recommend the learning center provided on www.fondriest.com for more detailed information and additional parameters. Salinity is typically considered as the main structuring factor of estuarine environments.[12] Estuary ecosystems are uniquely aligned with the salinity gradient along the estuary with freshwater species dominating in the upstream areas and marine species inhabiting the areas near the entrance that have salinity ranges similar to the open ocean (Figure 4).

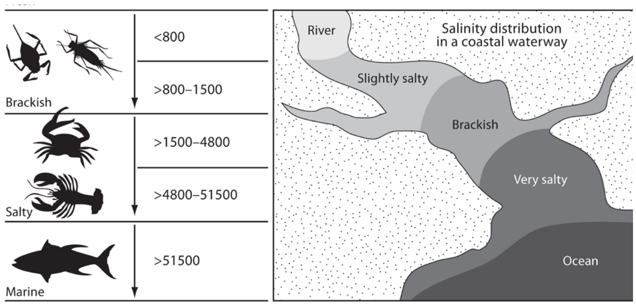


Figure 4: Typical long-term average distribution of salinity in an estuary.Source[12]

The type of classification commonly adopted when analysing the salinity distribution in estuaries is based on the mechanism of salt intrusion. Estuaries are defined into three main types: a) the stratified type, b) the partially mixed type and c) the well-mixed type.[13]

Dimensionless numbers such as the Canter-Cremes number and the Estuarine Richardson number are used in this classification as indicators of the stratification-mixing degree. The Canter-Cremes number represents the ratio between the amount of fresh and saline water entering the estuary during a tidal period, whereas the Estuarine Richardson number represents the ratio of potential energy and kinetic energy that the estuary received, each provided by the river discharge through the buoyancy of fresh water and by the tide during a tidal period. These numbers can inform the type of estuary according to the salt intrusion mechanism classification. A high Canter-Cremes and Estuarine Richardson number (i.e. N > 0.1 and NR > 0.8) indicates that the estuary is stratified, whereas small numbers (i.e. N < 0.1 and NR < 0.08) indicate a well-mixed estuary.[13]

Numbers between these ranges (0.08 < NR < 0.8) are called transitional and these estuaries are classified as partially mixed. An illustration of the three types of salinity regimes in estuaries is presented in Figure 5.

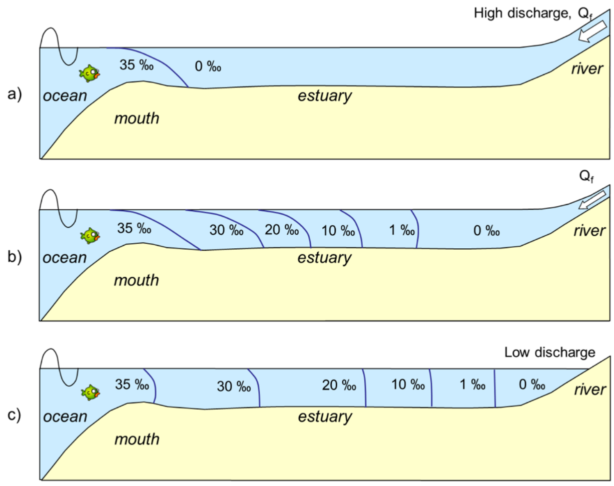


Fig. 5: Illustration of the longitudinal distribution of salinity in three types of estuaries: (a) stratified estuary, (b) partially mixed estuary, and (c) well-mixed estuary. Source[13]

Table 1: Summary and description of key estuarine water quality parameters

Physical	Salinity	Salinity is the amount of salts dissolved in water. It influences the type of species that can live in an estuary and affects physical and chemical processes such as flocculation and the amount of dissolved oxygen (DO) in the water column.
Physical	Temperature	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.
Physical	Turbidity	Turbidity is a measure of water clarity, that is, the ability of water to attenuate light. Turbidity is influenced by the level of organic and inorganic suspended solids and dissolved coloured material in the water column and it is the most visible indicator of water quality.
Chemical	Oxygen	Available oxygen, measured as dissolved oxygen (DO), affects estuarine health. 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 may be indicative of pollution levels.
Chemical	Nutrients	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.
Chemical	Acidity/ alkalinity	Acidity and alkalinity are important for ecosystem health because most aquatic plants and animals are adapted to a specific range of pH. Alkalinity refers to the ability of water to neutralize acids and higher levels generally result in a better ability to buffer acidic inputs.

2.4 Climate drivers

Each estuary exhibits a characteristic combination of physical and ecological processes that form a unique ecosystem. To understand how this complex eco-hydrological system is, and will be, affected by climate change, it is necessary to first understand the links between physical estuarine processes and climate drivers.

In general, estuaries mirror their surrounding catchment and ocean climate. Precipitation patterns and freshwater runoff, ocean levels and temperatures, evaporation, wind and solar radiation all influence the physical estuarine environment and ultimately the habitats and ecosystems that it supports.

> Estuaries mirror the regional geological, hydrological and climate characteristics.

A simple schematic of key linkages between climate and estuarine processes is shown in Figure 6. Some of the key mechanisms of how climate drives estuarine processes are:

Rainfall: Rainfall drives the amount, timing and frequency of freshwater inflows into the estuary.

The intensity of rainfall can influence the amount of sediment that is mobilised in the catchment and delivered to the estuary.

Temperature: Temperature is a primary control on the surface heat budget, which is the energy balance at the land or water surface. Within estuary catchments, the surface heat budget affects soil moisture levels and the amount of runoff generate in response to rainfalls. Within the estuary, it affects the amount of evaporation, water temperature and salinity.

Wind: Wind impacts estuarine environments by influencing sediment transfer, circulation, mixing and storm surge (and therefore flood inundation).

Sea level fluctuations & waves: Estuary depth and salinity are primarily controlled by ocean water levels and the tidal prism. Tides control estuary hydrodynamics, flushing and residence times. The wave climate controls the shape of the estuary entrance, which in return, controls the tidal dynamics and tidal prism.

Oceanic acidity and temperature: Due to the presence and exchange of oceanic waters in estuaries, ocean temperature and acidity levels directly affect estuary water temperatures and pH. The ocean has a high acid buffering capacity, which makes the oceanic side of estuaries resilient to localised changes in pH.

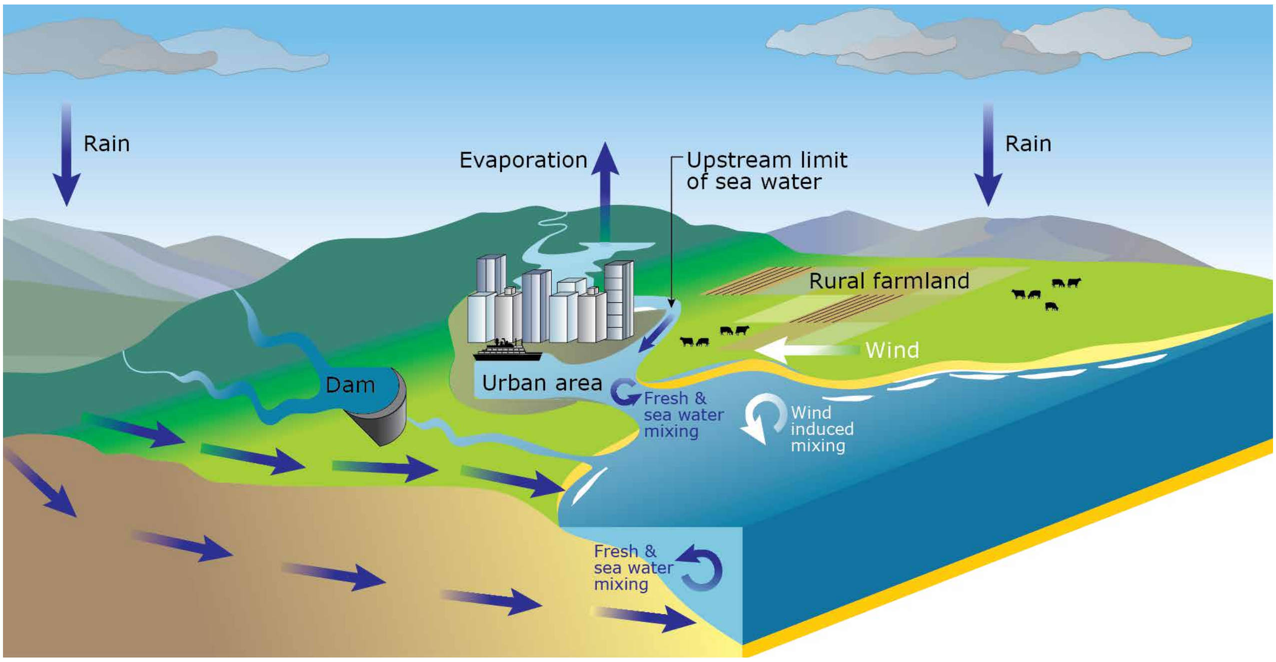
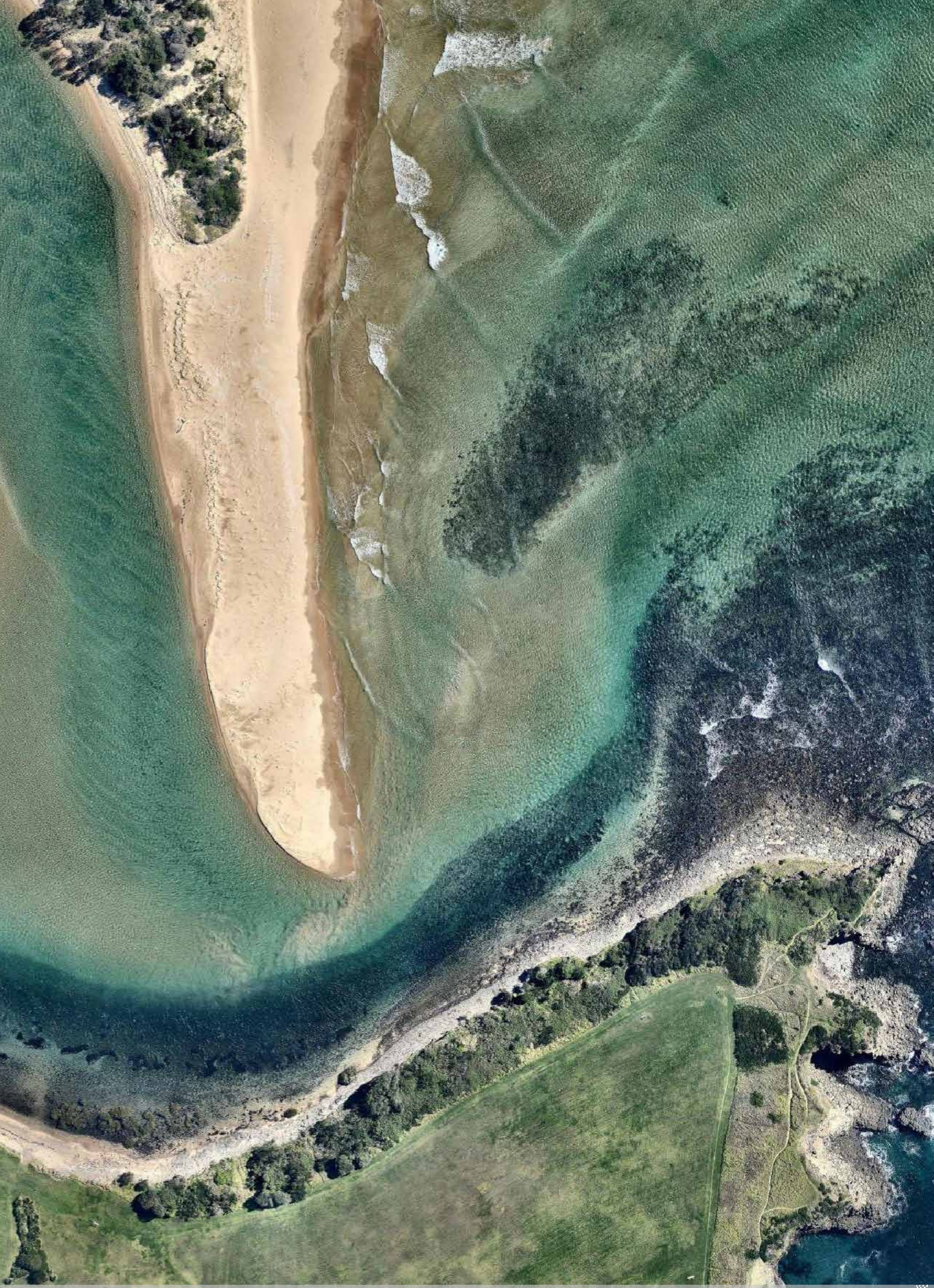


Fig. 6: Linkages between key climate drivers and physical estuarine processes



Minnamurra River - Wave dominated estuary - [-34.627, 150.859]

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3 TYPES OF ESTUARIES

There are 184 estuaries in NSW, of which 90 are bigger than 1 hectare.[14] Estuaries vary in size and shape, according to the relative influence of tidal, wave and riverine processes shaping them. Estuaries in Australia are commonly classified using the dominant forces present during the evolution of the estuary which are waves, tides or river flows. In NSW, estuaries are generally classified into four main categories: oceanic embayments, wave-dominated estuaries, tide-dominated estuaries and intermittently closed and open lakes and lagoons (ICOLLs). These categories differ in topography, geomorphology and their relationship with the open coast. The majority of estuaries in NSW (about 70) are ICOLLs, although their cumulative volume is comparatively small.[15]

3.1 Categories used in this guide

Different types of estuaries are affected by climate change in very different ways. The categorization presented here is therefore considered throughout all components of this guideline. For instance, shallow waters within ICOLLs and wave dominated estuaries that experience limited tidal flushing, are more susceptible to warming by rising air temperatures than the deeper waters of well flushed estuaries. It is important to remember, however, that estuarine categorization is a simplification of the complexity of estuarine systems, with no two estuaries in NSW being the same. In addition, many estuaries in NSW are developed, with flows managed through engineered systems such as trained entrances, upstream dams or floodplain levees. A detailed overview of estuarine typology across Australia is provided by the OzCoast portal.[16]

3.2 Oceanic embayments

Topographic Features: Semi-enclosed systems that are largely open to the coast (e.g. Jervis Bay or Botany Bay).

Hydrodynamic Processes: Primarily driven by tides and/waves, with limited freshwater inflows.

Water Quality Processes: Have a large tidal range and frequent tidal flushing. High salinity near entrance.

Ecological Processes: supports a diverse range of marine and estuarine organisms as it is a transitional environment. Often supports saltmarshes and mangroves, as well as swamps and freshwater wetlands that form behind protruding sandbars.

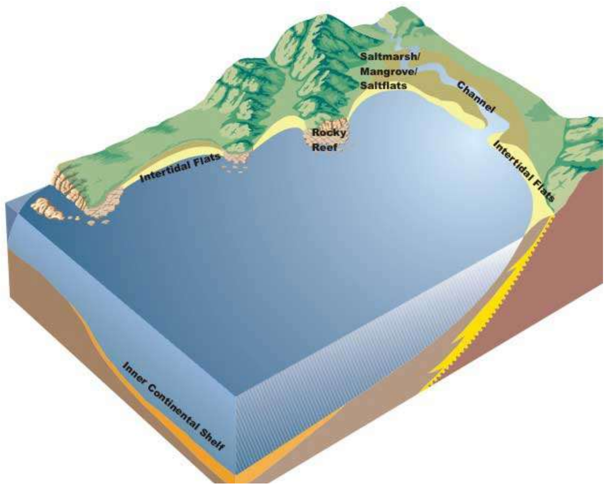


Fig. 7: Schematic of an oceanic embayment. Source: OzCoasts[16]

3.3 Tide-dominated estuaries

Topographic Features: Funnel shaped valleys with large, deep entrances (e.g. Hawkesbury River).

Hydrodynamic Processes: Mixing is largely driven by tidal fluctuations.

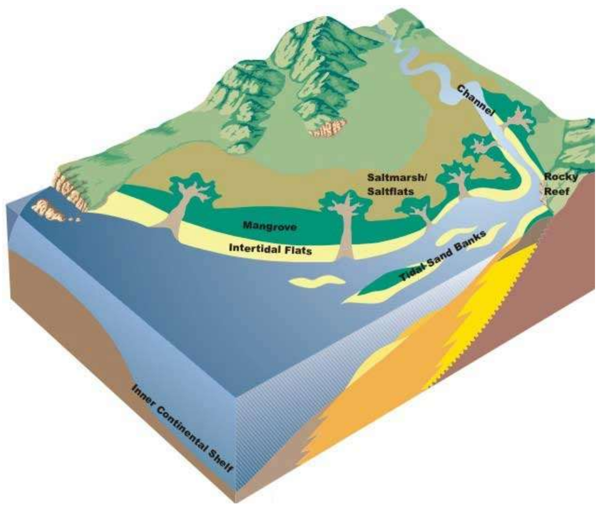


Figure 8: Schematic of a tide-dominated estuary. Source: OzCoasts[16]

Water Quality Processes: Tidal range similar to open ocean, so system is well flushed. Generally high salinity.

Ecological Processes: The entrances are often bounded by intertidal environments, such as mangroves or saltmarshes. These habitats typically support both transient and permanent marine species.

3.4 Wave-dominated estuaries

Topographic Features: Consist of tidal inlets constricted by sandy beaches (e.g. Bega River).

Hydrodynamic Processes: Primarily driven by waves. Tidal range 5-10% of open coast.

Water Quality Processes: Some tidal flushing occurs, brackish water present.

Ecological Processes: These estuaries support true estuarine species that thrive in brackish water.

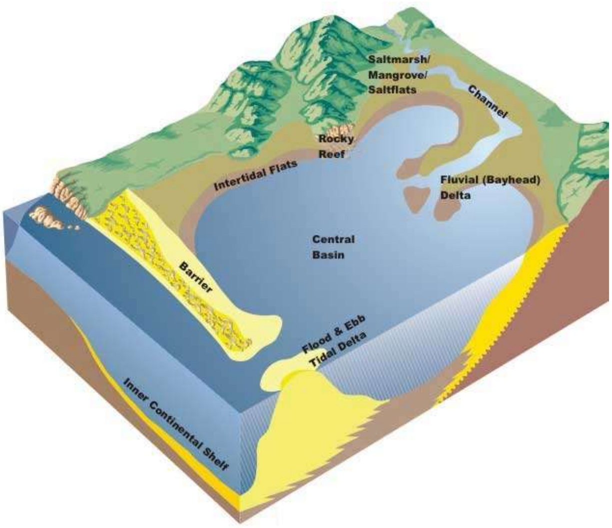


Figure 9: Schematic of a wave-dominated barrier estuary. Source: OzCoasts[16]

3.5 Intermittently closed and open lakes and lagoons (ICOLLs)

Topographic Features: Waterbodies that become isolated from the ocean for extended periods, often due to sand and sedimentation. The system generally becomes open to the ocean after substantial rainfalls and will naturally close in dry periods. A number of ICOLLs in NSW are manually opened from time to time.

Hydrodynamic Processes: They can be non-tidal for extended periods of time between rain events. Experience only freshwater inflow and wind-driven mixing during dry periods.

Water Quality Processes: ICOLLs can be closed to the ocean for long periods, meaning the water is often irregularly flushed. Salinity may be hypersaline during dry periods but can be similar to the open ocean when open.

Ecological Processes: Only species that can tolerate highly variable salinity conditions thrive in ICOLLs.

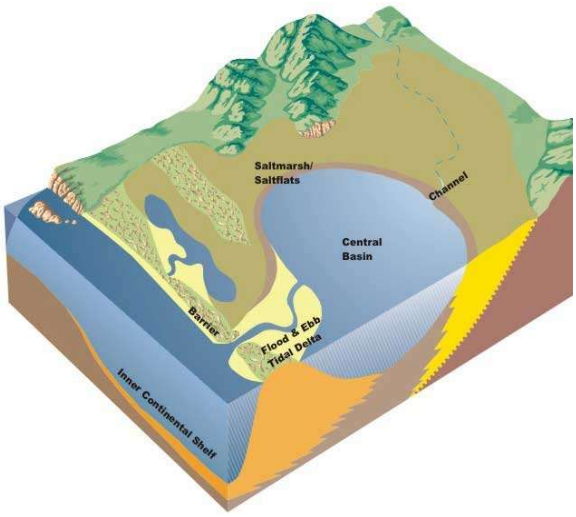
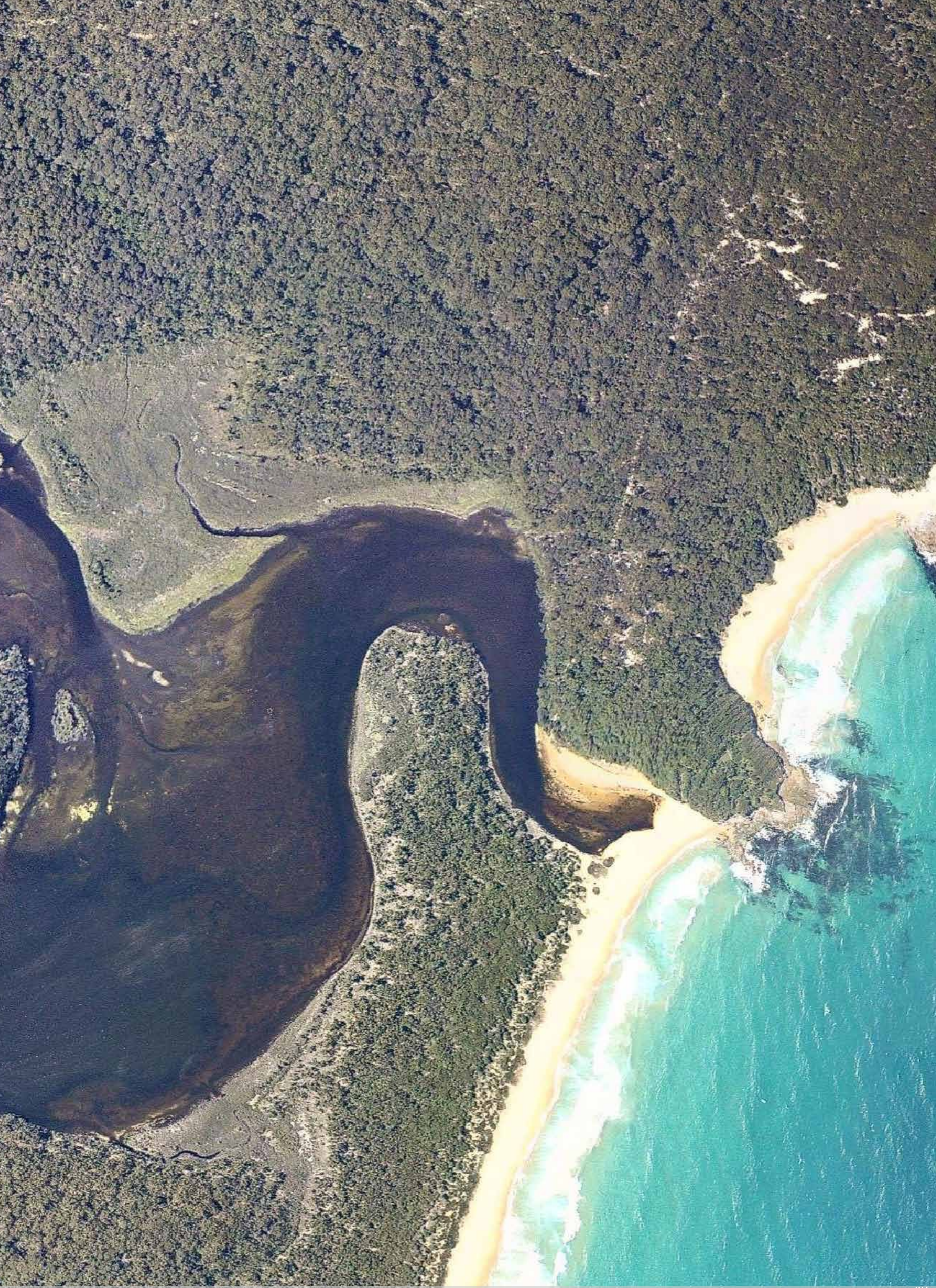


Figure 10: Schematic of an ICOLL. Source: OzCoasts[16]

3.6 What type is my local estuary?

The NSW Office of Environment and Heritage maintains an extensive inventory of all estuaries in the state.[17] Information provided on this web portal includes the type of estuary, the size of the catchment, the entrance location, the estuary volume and its average depth. These parameters can be accessed for all estuaries in NSW under the following link:

https://www.environment.nsw.gov.au/topics/water/estuaries/estuaries-of-nsw/search-nsw-estuary-profiles17



Termeil Lake, NSW - ICOLL- [-35.461, 150.392]

4 HOW DOES CLIMATE CHANGE AFFECT ESTUARIES?

4.1 The press-pulse framework

A useful concept for describing the physical and ecological responses of estuarines to climate change stress is the press-pulse framework shown in Figure 11.[18] The framework decomposes the experienced weather signal (i.e. air temperature - panel d in Figure 11) into three components: long-term variability (panel a), short-term variability (i.e. extreme events - panel b) and the increasing trend resulting from climate change (panel c). The increasing trend in the climate driver exerts a "press" on the biological system, which will respond with behavioural or physiological adaptations[18]. In addition to the press, extreme weather events act as discrete "pulses" or disturbances on the biological system that can adversly affect the distribution and abundance of species (panel e).[18] Even without changes in the magnitude and frequency of extreme events (short term variability), the increases in the baseline caused by climate change (panel c) leads to more frequent exceedance of survivable and extinction thresholds of species. For many climate drivers, climate change is also causing changes to the magnitude and frequency of extremes (i.e. pulses)[19] causing these thresholds to be exceeded more often. If thresholds are exceeded too severely or too frequently due to climate change, ecological communities may not be able to recover to previous population sizes and the ecosystem may suffer long-lasting and irreversible impacts (panel e) .[18]

The press-pulse framework assumes that ecological communities are adapted to presses and pulses that are within the envelopes of natural (i.e. recent historic) climate variability. With extreme inter-annual and inter-decadal climate variability in Australia,[19] establishing those natural variability envelopes, as well as the survivable and extinction extremes, is a challenging task. In line with the conceptual diagram shown in Figure 1, the first step for assessing climate change risks in estuaries is to quantify how much relevant climate drivers are deviating from their natural variability envelopes. The next step is to translate those changes in the climate drivers to changes in the physical estuarine environment, which forms the basis for assessing the impacts of climate change to ecological communities. These three levels of impacts are briefly introduced here and explained in detail in Modules 2, 3 and 4.

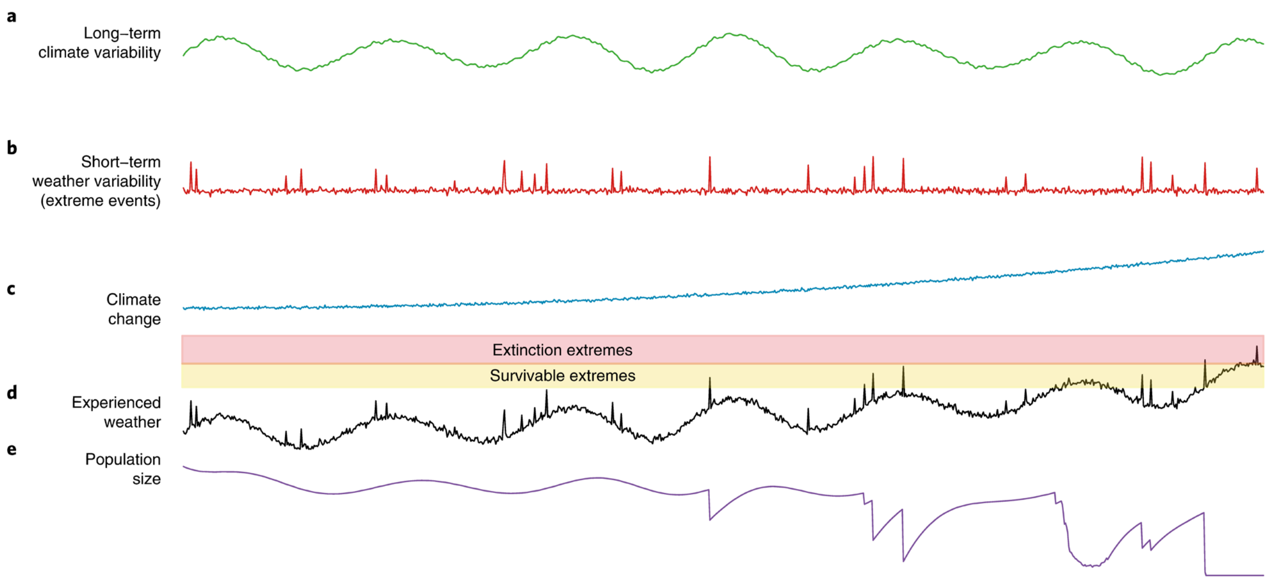


Figure 11: The press-pulse framework, showing the components of climate change and climate variability experienced by biological systems. a-d. Many organisms have adapted to cope with long-term (a) and short-term variability (b), but as the climate change trend increases (c), both the magnitude and frequency of extreme events is expected to increase (d). The threshold between survivable extreme weather events (yellow) and extinction extremes (pink) is therefore crossed more frequently, preventing recovery to previous population size. (e) the cumulative effects of the climate press and extreme pulses may have long-term consequences for population size, and potentially for persistence. Source: Harris et al. (2018)[18]

4.2 Changes in climate drivers

Ongoing greenhouse gas emissions are driving changes in the global climate and ocean system, including warming air and water temperatures, rising sea levels and oceanic acidity and altered wind, storm and rainfall patterns.[19] These changes in climate vary in space and time such that NSW estuaries will vary in their exposure to climate change. For some climate drivers, such as temperature, factors influencing the direction and rate of change are well understood, whereas for others, such as rainfall, waves and wind that have naturally high levels of inter-annual and inter-decadal variability in NSW, future trajectories are less clear. There are five changes in climate drivers generally identified as highly relevant to physical estuarine processes, which are summarised in Figure 12. Module-2 provides a detailed breakdown of recent historic and likely future changes in these climate drivers.

4.3 Changes in the physical environment

Physical estuarine processes are regularly fluctuating and are constantly altered by weather events of varying frequency and magnitude. Since climate change is altering average and extreme weather patterns, it also affects physical estuarine processes, and will cause the physical estuarine environment to reach previously unobserved states (i.e. extreme pulses). Importantly, the physical responses of an estuary to changes in climate drivers will depend on the hydrological and geomorphic regime of the estuary. For instance, an estuary that is dominated by tidal processes is likely to be highly impacted by sea-level rise and changes in ocean temperature and acidity. Module-3 illustrates how to quantify the likely physical responses of estuaries to the projected changes in the climate drivers.

Ultimately, changes in climate will transform the eco-hydrological estuary system through a complex chain of processes and feedback loops. As each estuary is unique, these impacts will vary across Australia and the rest of the world.

4.4 Changes in the ecology

The physical environment of estuaries is highly dynamic with conditions varying on time scales of semi-diurnal tidal cycles (i.e. salinity), to seasons (i.e. inflows of freshwater and sediments) to years (i.e. tidal anomalies, ENSO cycles and upwelling). Reflecting the high physico-chemical variability of the estuarine environment, estuarine species typically display a high capacity to tolerate variability (i.e. presses and pulses) in conditions

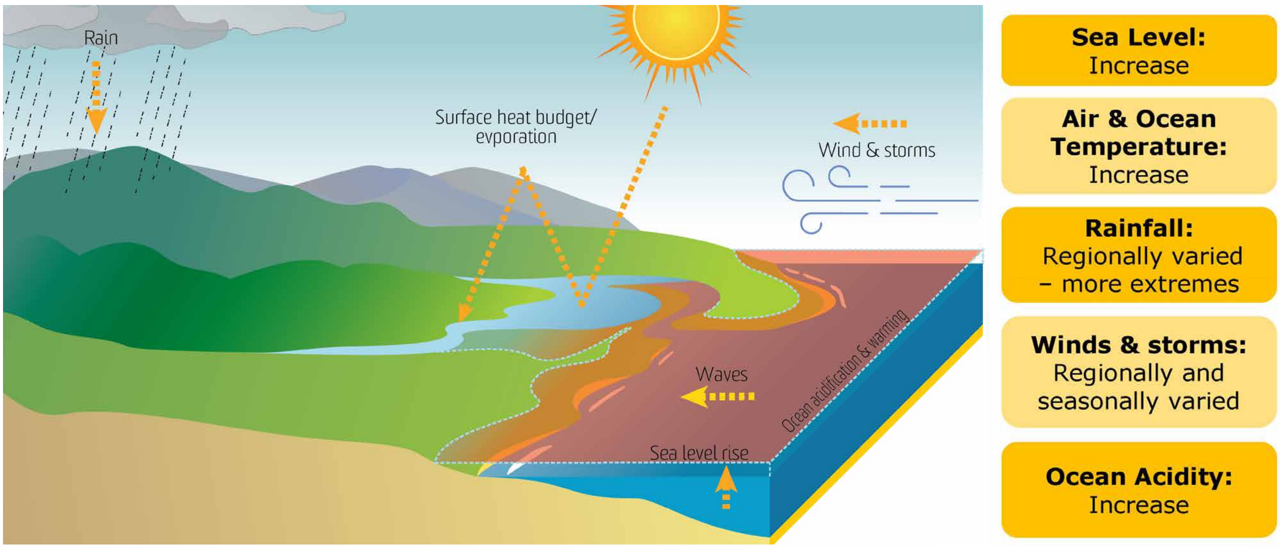


Fig. 12: Changes in climate drivers most relevant for estuaries

such as salinity and temperature.[20] Nevertheless, the combination of changes in the average (i.e. presses) and extremes (pulses) of climate drivers resulting from climate change can lead to more severe and frequent disturbances to estuarine ecological communities (Figure 11).

Ecological resilience is the ability of an ecosystem to respond to a disturbance by resisting collapse and recovering quickly.

The capacity of ecological communities to resist change (i.e. pulses) and return to a previous state is commonly referred to as resilience.[21] Ecological resilience is influenced by community composition, as well as characteristics of the disturbance, including its intensity, frequency and the area that it affects. Generally, connectivity and species diversity are important ecosystem attributes that provide a greater capacity to resist change and recover. Coastal development and catchment land use change have a direct impact on these attributes in estuaries reducing their capacity to withstand further change. If the boundaries of ecological resilience are exceeded to often or to severely, the ecosystem might enter a new altered state as illustrated in Figure 13. Importantly, the response of coastal ecosystems to local and global stressors is far more complex in reality due to for example physiological adaptation and interactions between different species.

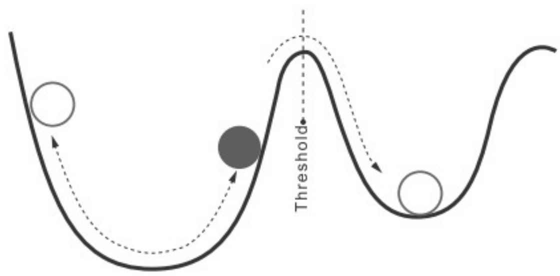


Figure 13: Simplified illustration of the ecological resilience concept. Source[21]

Ecological responses to "presses":

Gradual changes in climate drivers such as increases in average temperature or mean sea levels will impact physical and ecological estuarine processes. Most organisms have a limited range of environmental conditions under which they can survive (i.e. water temperature, salinity and hydroperiod) and within this range may vary markedly in abundance as conditions move from sub-optimal to optimal. Initially, as environmental conditions change, organisms will increase or decrease in abundance according to whether the environment becomes more or less suitable. Eventually, however, organisms may be exposed to conditions that are outside a range they can tolerate. This leaves three possibilities:

1) Migration to suitable conditions;
2) Adaptation to the new conditions;
3) Perish.

The net effect of migration and extirpation (local extinction) is shifting distributions of many species, the most well documented of these being poleward range shifts in response to warming temperatures. Species vary markedly in their sensitivity and exposure to climate change, with some displaying large increases, others large decreases and some little change in their distributions and abundances. As a consequence, ecological communities are increasingly being reorganised into novel combinations of species, often including large numbers of species that would have once been considered non-native in origin. Although there has historically been an assumption that non-native species introductions will lead to a loss of biodiversity and important ecological functions, the proportion of non-native species that proliferate to damaging pest species status is small.[22]

Ecological responses to "pulses":

Historically, estuarine processes and ecosystems have typically had recovery periods shorter than the average recurrence interval of extreme events. While organisms may be able to tolerate a single disturbance event (pulse), if multiple disturbance events occur in quick succession, or become increasingly severe, their capacity to recover may be impeded (Figure 11).


Willinga Lake, NSW - ICOLL- [-35.501; 150.389] photo: Chris Drummond, WRL, UNSW

5 Conceptual framework for assessment

Assessing the impacts and associated risks of climate change in estuaries is a challenging task. Uncertainties in global climate models (for the atmosphere and oceans), the complex physical response of estuaries to changes in climate drivers, and feedback loops between ecosystems and the physical environment are just some of the challenges involved. The *Conceptual Framework for Assessment* (see Box-1) serves as a roadmap for navigating this complexity when assessing and prioritising climate change risks in estuaries.

The *Conceptual Framework for Assessment* illustrates the main steps and data sets necessary for assessing climate change risk in estuaries. The assessment consists of four major components that are closely aligned with the conceptual chain of climate change impacts introduced in Figure 12 and each step is covered by one of the four core modules for assessment.

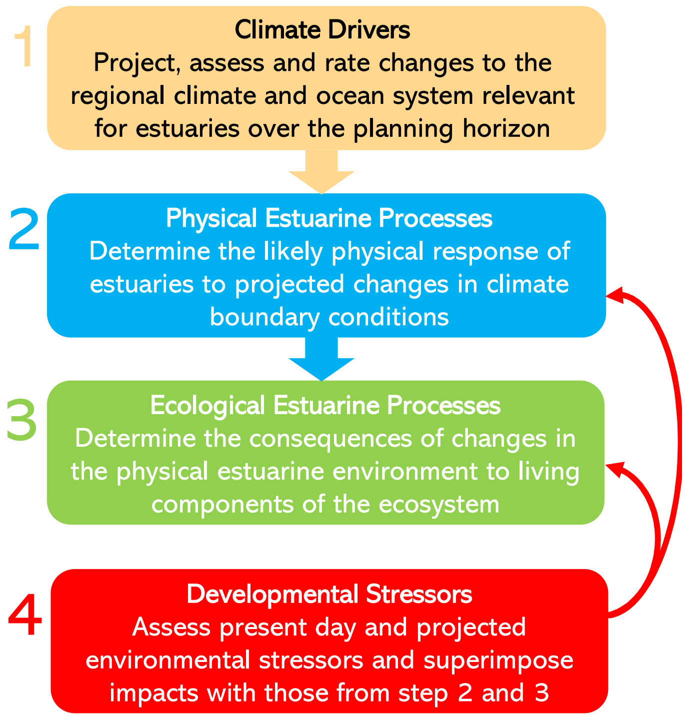


Figure 14: Workflow and steps for assessing climate change impacts in estuaries based on the Conceptual Framework for Assessment. The steps follow the tiered chain of climate change impacts on estuarine processes shown in Figure 1.

Figure 14 summarises those four key steps and illustrates the recommended organisation of the workflow. This workflow diagram can be interpreted as a simplified representation of the *Conceptual Framework for Assessment*, which provides additional details at each step. Notably, an assessment of existing stressors is required in parallel to the assessment of second and third order climate change impacts, since there are direct connections and interactions.

5.1 Core modules for assessment

Module-2 First-order changes (climate drivers): Climate affects all processes that occur in estuaries and the first step in the assessment is to prioritise the likely changes in the atmospheric and oceanic climate drivers. Global Climate Models, sophisticated computer models of the global Earth and ocean systems, are the primary tool for modelling the impact of different greenhouse gas scenarios on the global climate system. Statistical analyses is then applied to these projections to quantify potential trends in average conditions and the magnitude and frequency of extremes in relevant climate drivers. *Module-2* of this guide provides a detailed guideline on how to assess and prioritise first order changes along with a summary of significant changes in climate drivers of NSW estuaries.

Module-3 Second-order changes (physical environment): While climate affects all processes in estuaries, interactions between individual climate drivers and specific estuarine processes are complex and often difficult to quantify. Once the likely changes in the average and extreme states of climate drivers are determined, the next step is to quantify the manifestation of these changes in the physical estuarine environment. Due to the complexity and dynamic nature of the physical estuarine environment, this translation of first-order to second-order impacts typically requires some form of modeling. *Module-3* provides an overview of modeling techniques available for achieving this type of quantification along with a summary of likely changes in the physical environment of NSW estuaries.

Module-4 Third-order changes (ecosystem): The extent to which changes in the physical environment manifest in changes to ecological communities (third-order impacts) will depend on whether physical changes are chronic or acute, of high or low frequency, and/or of weak or severe intensity. Key functional groups of organisms differ in their sensitivity to climate stressors. Additionally, interactions among species may strengthen or weaken the capacity of ecological communities to resist change. *Module-4* provides an overview of key estuarine habitats and communities in NSW, the types of data available for assessing climate risk to these, and a summary of possible responses of different communities to likely second-order changes.

Module-5 Existing stressors and interactions: *Module-5* covers how local impacts of coastal development will influence the susceptibility of estuarine ecosystems to climate change, and how these local stressors can be managed to increase the resilience of estuarine ecosystems to climate change.

5.2 Supporting modules

Apart from the four core modules that underpin the assessment of climate change impacts, there are three additional modules that provide complementary information and guidance.

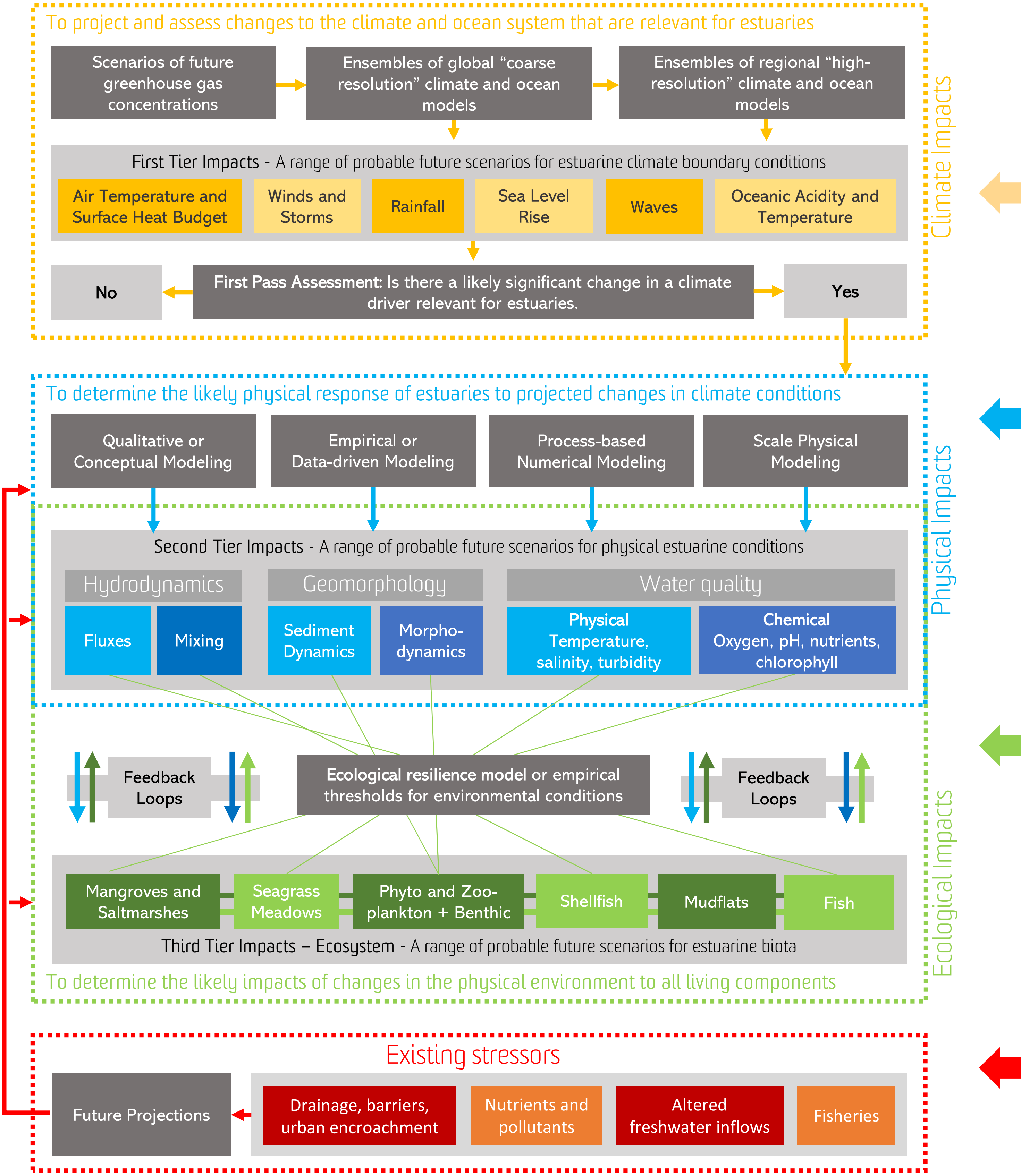
Module-6 shows how the *Conceptual Framework for Assessment* can be put into practice, using the Hunter River Estuary as a case study. This Module is presented in the form of a peer-reviewed scientific journal article and is best used in parallel with Modules 2-5.

Module-7 provides a comprehensive review of existing research in NSW on climate change impacts to estuarine species, communities and ecosystems, highlighting major research and knowledge gaps.

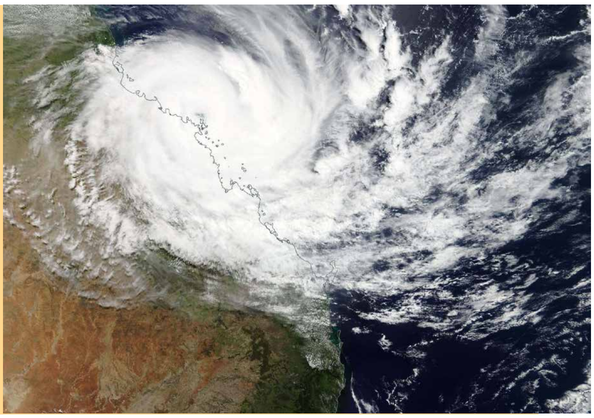
Module-8 provides a brief summary of research and knowledge gaps that currently impede many steps involved in a climate change risk assessment. Based on these knowledge and data gaps, recommendations for future research are provided.

Branch of the Shoalhaven River at Shoalhaven Heads , NSW - Wave dominated barrier estuary [-34.860, 150.743]

Box-1: Conceptual Framework for Assessment



Physical models of the earth and climate system used in conjunction with future development and greenhouse gas scenarios are the primary tool for projecting changes in the hydroclimatic boundary conditions of estuaries, here defined as 'First Order Impacts' of climate change. The first step is to determine a set of first order impacts as the basis for the assessment.



Projections of 'First Order Impacts' are generated A) at scales far beyond the size of most estuaries and B) primarily for external variables such as open ocean temperature and sea levels. Consequently, it is necessary to use modeling for converting first order impacts to changes in the physical environment of estuaries, here defined as 'Second Order Impacts' of climate change.

Estuarine ecosystems consist of unique biological communities and their physical and chemical environment. Changes in the physical environment resulting from climate change affect all living components of the ecosystem, here defined as 'Third Order Impacts' of climate change, which can be direct or indirect and often manifest through complex feedback loops.

The vast majority of estuaries in NSW and around the world are at least partially developed and already facing a range of environmental stressors. Existing stressors interact with second and third order impacts, typically exacerbating them, and need to be accounted for throughout the risk assessment.

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Back cover photo

Mangroves in the Hunter River Wetlands, Newcastle, NSW. Valentin Heimhuber, WRL, UNSW.

Fairy Creek in Wollongong, NSW ; ICOLL [-34.409, 150.900]

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