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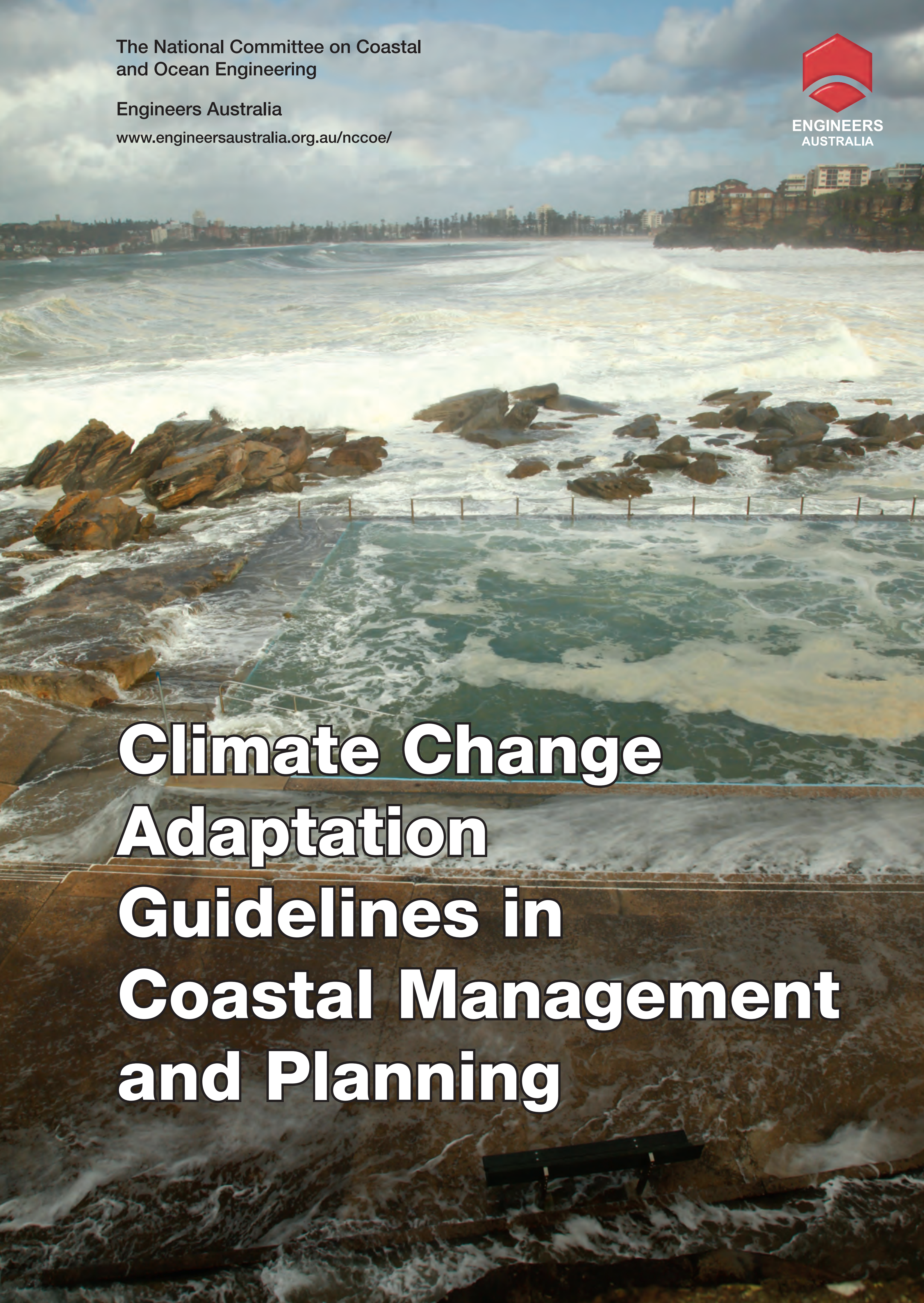

Climate Change Adaptation Guidelines in Coastal Management and Planning

Disclaimer
This document is prepared by the National Committee on Coastal and Ocean Engineering, Engineers Australia, for the guidance of coastal engineers and other professionals working with the coast who should accept responsibility for the application of this material.

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Cover photo: Freshwater Baths looking south towards Manly Beach. (Source: Mr Larry Paice, WRL, UNSW).

PREFACE

The National Committee on Coastal and Ocean Engineering (NCCOE) is a specialist sub-committee of the Civil College within Engineers Australia (EA). It represents the professional interests of Australian coastal and ocean engineers.

This document has been developed by the NCCOE with the support of the Department of Climate Change and Energy Efficiency (DCCEE). It is the third guideline in a series produced by NCCOE, the others being:

- *Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering* (NCCOE, 2012a); and
- *Coastal Engineering Guidelines for Working with the Australian Coast in an Ecologically Sustainable Way* (NCCOE, 2012b).

This set of three documents provides guidance to coastal engineers, coastal managers and planners in responding to the challenges of our changing climate. They are complementary and each provides relevant information for consideration.

This guideline *Climate Change Adaptation Guidelines in Coastal Management and Planning* is a new document in the series. It is directed at local government engineers and managers whose area of responsibility includes a section of the Australian coastline. It is designed to assist in making appropriate decisions in managing coastal development problems subject to climate variability and change including when to call for additional expert advice.

The NCCOE recognises that changing climate is a key agent affecting coastal management practice in Australia and future decision making for ongoing management of the coastal zone. The first guideline in this series, published by NCCOE in 1991, summarised the understanding of climate change at that time and included an approach to be adopted by engineers to ensure that the relevant impacts of projected climate change were considered in engineering investigation and design. In doing so, it drew on the information published in the first IPCC report. That document predated the wider development of detailed climate change policy around Australia and has proven a valuable guide for coastal engineers and coastal managers in the intervening 20 years.

The first guideline in the series was updated in 2004 and reflected the developing understanding of climate change based on the IPPCC third assessment report (TAR). It was released simultaneously with the first version of the second guideline addressing sustainability requirements in coastal engineering. These two documents were closely related through the recognised significance of climate change to coastal engineering and coastal zone management.

In 2012, the NCCOE has again revised the first and second guideline following the release of the IPCC fourth assessment report AR4 (IPCC, 2007). The NCCOE trusts that this new third guideline will be as valuable in the future as the first two volumes have been over the past decade.

This is a live document that will be regularly updated. Coastal and ocean engineers and other related professionals are encouraged to provide ongoing feedback and examples. Comments should be sent to the National Committee on Coastal and Ocean Engineering, nccoe@engineersaustralia.org.au.

CONTENTS

1 INTRODUCTION

1.1 The Objectives of this Guideline

This guideline is specifically aimed at coastal managers and planners working in Local and State Government around the approximately 60,000 kilometre coastline of the mainland and nearshore islands of Australia.

"The decades ahead will witness increased numbers of people, infrastructure, and ecosystems at risk in the coastal zone. National and local leaders across all sectors must begin now to engage stakeholders in assessing vulnerability and designing adaptation strategies that are technically, financially, and politically achievable." (USAID, 2009)

It is a response to the volume of information currently being prepared within the scientific and engineering communities, specifically looking at the way forward in managing the coast under various climate change projections. Its purpose is to assist the local coastal manager in identifying the risks associated with a particular decision or solution and hence to ask the correct questions in gathering data, designing monitoring programs, preparing consulting briefs or evaluating a particular option.

A coastal manager must presently make decisions relating to both minor development approvals and major new infrastructure. Such decisions cannot always be based on perfect information and frequently cannot be delayed until new science, research or understanding is available. However, such decisions made now may determine how a particular part of the coastal zone is used for many years into the future, at a time when the local climate extremes and concomitant hazard to that development/land use may be very different.

While recognising the breadth of adaptation issues, this guideline deals more specifically with coastal structures and physical interventions. Such measures include seawalls, breakwaters, groynes, artificial reefs, configuration dredging, nourishment, etc. These interventions are undertaken within an exposed and hostile environment, often necessitating large scale and expensive engineered solutions. They will occur within the overall planning framework and may only provide a solution through protecting development for a limited time. Ultimately as climate changes, areas of land may be deemed unsuitable for the existing use or occupation and may need to be abandoned.

The objective of this guide is to provide a simplified and structured framework to assist the coastal manager considering physical intervention options both under present day conditions and with climate change. This includes identifying the key issues (coastal values and hazards) and understanding the relevance of local coastal processes and how the coast may respond during extreme events now and into the future with and without intervention.

Most importantly the guideline assists with identification of the suitability and possible adverse impacts that may arise from particular physical works or adaptation strategies. Incorrect decisions have the potential to change the existing coast for many decades and at locations many kilometres from the site under consideration. The cost of rectifying or managing these impacts can far exceed the immediate benefits from the decision.

This guideline is intended for coastal managers, decision makers and elected representatives in various levels of government and interested community stakeholders. While some readers may have training in coastal management, coastal engineering, planning and environmental sciences, it is assumed that many readers will have no formal training and limited experience in any of these areas. Readers faced with decisions regarding adaptation options should be prepared to seek expert technical advice from appropriately qualified coastal engineers and other relevant professionals.

1.2 Using this Guideline

This guideline is broadly presented in two parts. The first part (Sections 1 to 6) introduces climate change adaptation, key coastal processes, planning frameworks and assessment methodologies including modelling. The reader is encouraged to read through this first part of the document as it contains information generic to all coastal management and references more detailed texts for further reading.

The second part (Sections 7 to 11) provide an understanding of a range of intervention strategies that can be considered to address each of these hazards to development or land use within the coastal zone. The reader is encouraged to seek out particular sections relevant to the intervention options being considered for implementation. In each section the issues and concerns associated with different options and varying coastal environments are discussed. It is intended to provide an understanding of both the advantages and disadvantages of the various types of options for a particular setting. Importantly it is hoped that the reader will be awake to any potential adverse impacts of a favoured strategy and that expert independent advice be sought if any doubt emerges.

An extensive reference list incorporates material referenced in the report and provides an up to date list of relevant information that may be a useful starting point for the reader in accessing further detail. Terms that may not readily be understood have been included in the glossary along with commonly used terms. It provides a useful aid to familiarise coastal managers with some specific terminology widely used by coastal practitioners and hopefully will facilitate the preparation of technical briefs and review of technical proposals.

1.3 Using the Other Two Guidelines in the Series

The series of three guidelines are intended to be used concurrently. Together they provide a valuable and readily accessible source of information relating to climate change, and how this can be managed to achieve ecologically sustainable outcomes within the coastal zone allowing for historical variability and an uncertain climate future. The key areas covered in the first two guidelines are:

Volume 1 – *Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering* (NCCOE, 2012a).

This guideline is intended specifically for professional engineers with expertise and responsibility for works and facilities within the coastal and ocean field, but is a valuable reference document for coastal managers generally. It is an update of the original 1991 publication and retains the time proven structure and methodology developed by the profession and documented at that time. The document may be read in two parts:

- A summary of the relevant climate change science in coastal areas based on the findings of the IPCC Fourth Assessment Report (2007) and with some more recent relevant information.
- A methodology and illustrative examples relating to the selection of relevant allowances for key coastal process parameters and their applicability to specific types of coastal projects.

Volume 2 – *Coastal Engineering Guidelines for Working with the Australian Coast in an Ecologically Sustainable Way* (NCCOE, 2012b).

This guideline is aimed primarily at professional engineers practising in the coastal area. It presents a comprehensive Australia wide approach to ecologically sustainable engineering related practice in the coastal zone. It broadly covers three main areas:

- The ethics and responsibilities of the coastal engineer within the national sustainability policies and framework.
- Consideration of coastal systems and coastal development for ecological sustainability.
- Coastal engineering methodology for delivering ecologically sustainable projects.

The document includes detailed supplements on various types of contentious coastal projects.

1.4 What this Guideline Does Not Provide

This guideline is not intended as a design manual. It does not provide extensive details on coastal processes nor design procedures required for selection and implementation of coastal structures or in assessing the longer term impacts of such works. Relevant codes and manuals exist for this purpose along with the unpublished and ever increasing body of local data, site specific assessment and climate adaptation reporting.

Detailed research and assessment lie within the realm of the expert coastal engineer, scientist and manager. Specific design of coastal structures and their specification and construction supervision all require the services of an appropriately experienced and qualified professional engineer. This guideline is not intended as an alternative to such professional advice. Rather, it is hoped this guideline will assist coastal managers, planners and stakeholders to identify where expert advice is required and to better understand the relevant issues and questions when engaging, supervising and reviewing such services.

The importance of the social and environmental aspects of future climate change cannot be overstated, particularly in developed coastal environments. However, these issues are not the focus of this guideline and are dealt with for example by relevant coastal planners, economists, biologists, archaeologists and managers during the determination and subsequent implementation of any adaptation strategy.

1.5 The Climate Change Impacts for which Adaptation May Be Required

As mentioned above, the first volume in this guideline series (NCCOE, 2012a) summarises the relevant information in the most recent IPCC report and gives an interpretation and methodology for Australian coastal engineers. Specific issues of relevance include sea level rise, changes to the El Niño/La Niña cycle, changes to Asian summer monsoon variability, possible changes in tropical cyclones and extra-tropical storms and associated alteration of dominant wind and wave direction as well as extreme rainfall, wind and wave energy. Impacts of importance to coastal communities include:

- inundation and displacement of wetlands and lowlands
- eroding (or accreting) shorelines
- increased risk of damaging extreme winds
- increased coastal flooding by catchment runoff and ocean storms
- salinity intrusion of estuaries and aquifers
- altered tidal ranges, prisms and circulation in estuarine systems
- changed sedimentation patterns.

The detail given in the first volume is not repeated here as we expect to update that guideline as scientific knowledge improves and with the release of another IPCC report. Additionally the reader should ensure relevant state/territory legislation and other bureaucratic guidelines are followed. The second guideline in the series (NCCOE, 2012b) contains an appendix summarising policy and programs for each of the States and Northern Territory.

2 CLIMATE CHANGE ADAPTATION & COASTAL MANAGEMENT

2.1 What is Climate Change Adaptation?

Definitions of adaptation to climate change are many and varied in the literature. The focus of this guideline is on that portion of the climate change adaptation hierarchy involving the consideration and selection of physical intervention measures to address existing coastal hazards and future increased risk posed by these hazards as climate changes. An appropriate definition for this purpose was put forward by the UK Climate Impact Program as *"The process or outcome of a process that leads to a reduction in harm or risk of harm, or realisation of benefits associated with climate variability and climate change"* (UKCIP, 2003).

The IPCC Climate Change 2007 Synthesis Report (IPCC, 2008) advises that *"there is a high confidence that neither adaptation nor mitigation alone can avoid all climate change impacts …"* The IPCC acknowledges the necessity for both short and longer term impacts of changing climate to be addressed for even the lowest stabilisation scenarios assessed. It further advises that *"unmitigated climate change would, in the long term, be likely to exceed the capacity of natural, managed and human systems to adapt"*. This is particularly relevant where existing land use and development may become increasingly at risk from coastal hazards in the foreseeable future and in some instances existing or proposed land use may not be sustainable over longer timeframes.

2.2 The Adaptation Decision Making Framework

The adaptation decision framework is broadly used in decision making where there is significant uncertainty. It is cyclical, incorporating continual monitoring and review which results in adjustment to the decisions taken to ensure the management objectives are achieved. It can be applied to planning for climate change and forms the basis of the widely used coastal management planning process throughout Australia.

The decision-making framework is commonly expressed in eight stages (UK CIP 2003):

- *Identify problem and objectives*
- *Establish decision-making criteria*
- *Assess risk*
- *Identify options*
- *Appraise options*
- *Make decision*
- *Implement decision*
- *Monitor, evaluate and review.*

Rather than comprising a single decision, the implementation of a coastal management strategy for a developed area will usually require a combination of planning measures to control the type and location of development and land use possibly together with some physical works designed to manage or mitigate the identified coastal hazards, particularly where intensive land use and/or development already exists. The interaction and balance between these intervention and planning approaches may change over the life of an adaptation plan with trigger conditions or events signifying the time to change from a protect/accommodate strategy to withdrawal of assets. The individual decisions taken must be integrated to achieve ongoing coastal management. They must also be identified as early as possible in the management process.

2.3 The Coastal Management Process

The coastal management process is based on the local coastal process understanding discussed in Sections 3 and 5. It underpins the reliable and organised preparation and implementation of coastal zone management planning in all Australian jurisdictions and is widely applied internationally.

Figure 1 presents the key steps in this adaptive management system. Variations in emphasis on the different stages of the process resulting from: reliability and availability of information; available funding; and time available for decision and implementation to occur. Frequently these are outside

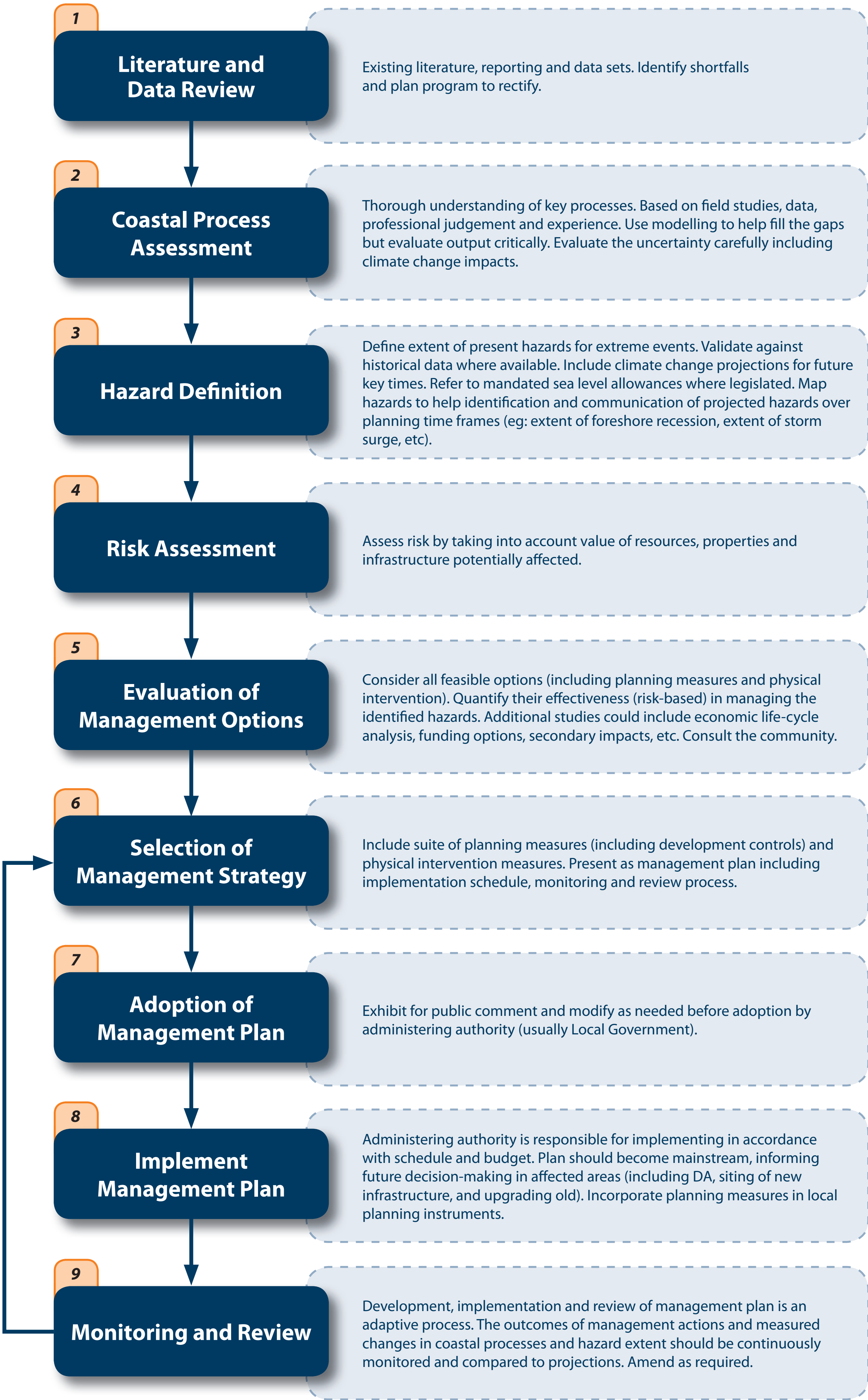


Figure 1. Key steps in the coastal management process.

of the control of the coastal manager, guided by the seriousness of the perceived hazards, the value and intensity of the foreshore land use or other site specific factors. The process can involve fewer steps with some of the stages combined. This is often a result of time pressures with a desire to reach the implementation phase (i.e. "problem solving") within a shorter timeframe and to reduce the investigation and planning budget. For smaller areas and where there is a low perception of hazards, this may result in the first five stages being combined.

Fundamental to this management process is the identification and amelioration of coastal hazards in an economically achievable manner, minimising the potential for adverse impacts (social, environmental or economic) resulting from the measures proposed and the subsequent land use.

3 COASTAL PROCESSES

Any decision to implement options that modify the natural coastal forces of wind, storm surges, waves, tsunami, currents and water levels or that alter the morphological responses of the shoreline or sediment transport at the shoreline must be founded on a valid and comprehensive understanding of the behaviour of the coastal zone as well as the likely coastal impacts of climate change.

To understand the likely impacts of such changes into the future with or without climate changes, it is imperative that the present conceptual understanding of sea level processes and shoreline or sediment transport response is sound and based on reliable process data.

3.1 What are Coastal Processes?

Coastal processes are the hydraulic and sedimentary processes driven by tides, currents, waves, coastal winds and tsunamis. Forces exerted by wind and water act on the ocean floor and shoreface to drive currents, move sediments, erode exposed bedrock and shape the coastline, estuaries and the nearshore seabed.

Coastal processes relevant to a particular location include, but are not limited to:

- Winds
- Waves
- Water levels (tides, storms, waves etc.)
- Currents (rip currents, alongshore currents, density currents, surface wind currents, continental shelf waves, large ocean circulations etc.)
- Rainfall and runoff
- Tsunamis.

The origin and interaction of these processes, illustrating the complex interactions and feedbacks with human activities are shown in Figure 2. Future climate change will be an integral part of these interactions.

Consideration of the following processes and parameters may also be required:

- Waterborne sediment transport (alongshore sand movement, onshore/offshore transport, entrance scour, storm erosion etc.)
- Wind-blown sediment transport (dune stability, onshore sand losses)
- Storm surge
- Wave overtopping
- Shoreline stability
- Slope stability
- Sediment type
- Vegetation cover (seagrasses, dunes etc.).

Detailed information on coastal processes and their definition, computation and application are published in many manuals and texts and will not be repeated in detail here. Further reading relevant to beach management and the Australian situation could include for example: NSW Government (1990), CIRIA (2010), U.S Army Corps of Engineers (2002), Nielsen (2009).

3.2 Uncertainty and Diversity in Coastal Processes of the Australian Coast

Coastal processes are location dependent and extremely variable over time. This variability can be expressed in statistical terms of average values or extreme values measured or assessed over varying time periods (typically seconds to centuries). However, considerable uncertainty exists within the

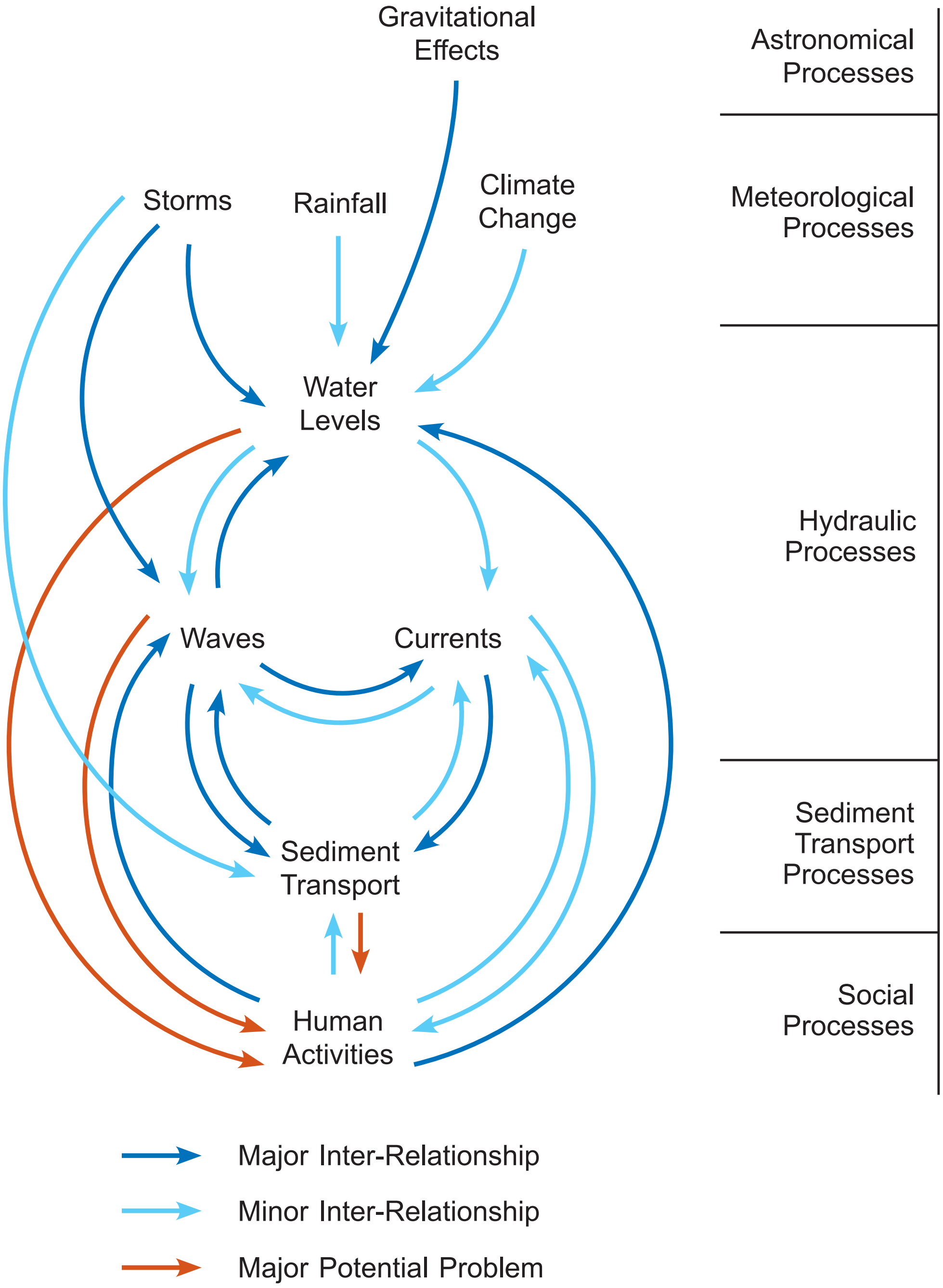


Figure 2. Interaction between coastal processes and human activity (adapted from *NSW Coastline Management Manual,* Figure B1.1, 1990).

statistical representation of coastal processes. Around the majority of the Australian coastline there is a paucity of reliable measured data. In locations where data are rigorously collected, records tend to be short, making the definition of engineering design conditions problematic. Common timescales for various processes are discussed in Appendix A and presented in Table A1.

Uncertainty pertaining to climate change must be considered alongside uncertainty in defining the current design conditions. For example, the longest continuous tidal records in Australia are a little over 100 years while the longest measured wave records are less than forty years. From these data we often extrapolate out to 100+ year design records. At many locations no measured tidal data or measured wave records are available and conditions are commonly extrapolated from other locations. Often, significant coastal development decisions are made on the basis of limited local measured

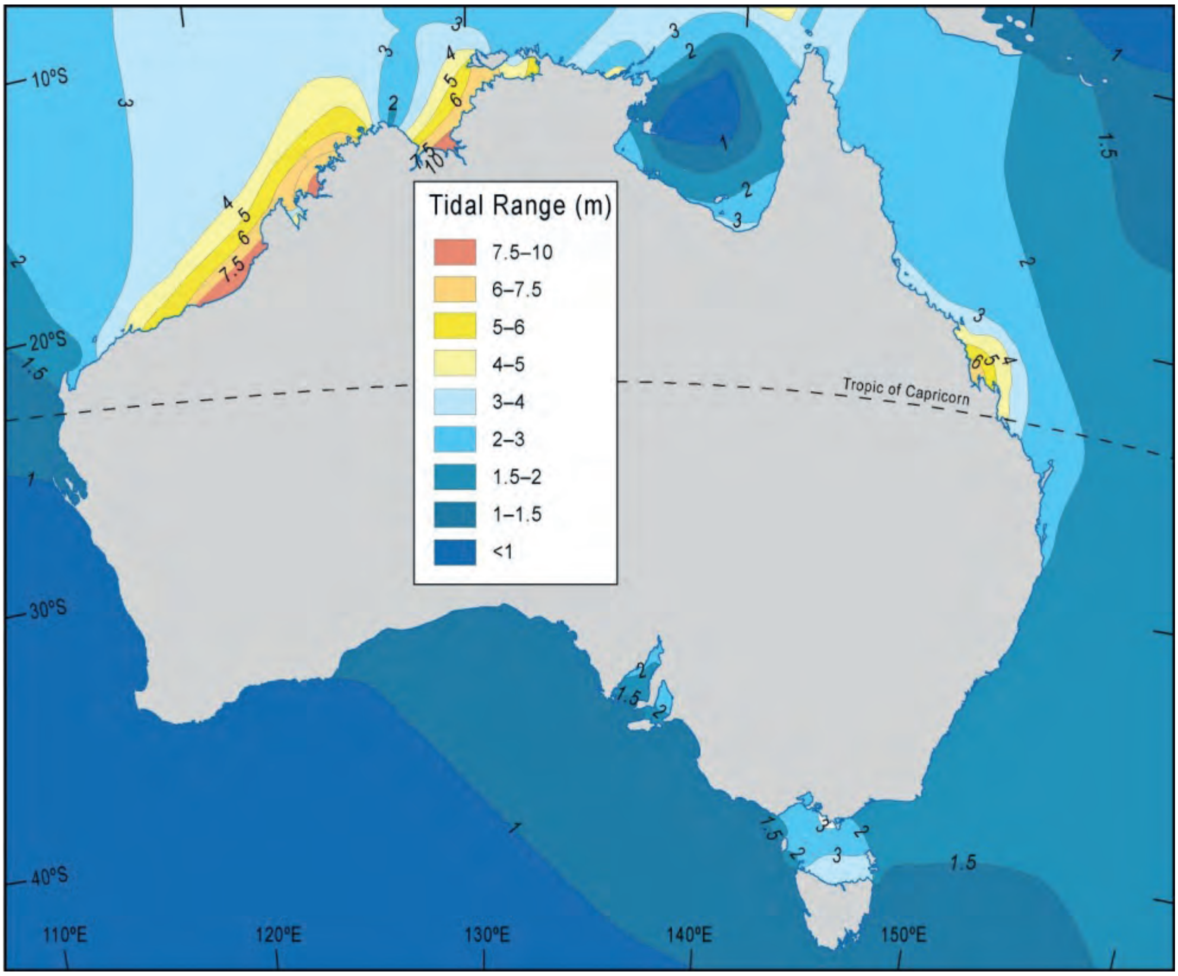


Figure 3. The variations in Spring tide ranges around the Australian coast.

(Source: Short & Woodroffe (2009), Fig 2.13)

data, interpolated and extrapolated using numerical techniques (Section 5 and Appendix A). The extrapolation of these data to incorporate climate change up to 100 years into the future requires a sound understanding of both the measured coastal processes and the numerical approaches being used.

The coastal processes relevant to a particular location and problem need to be identified and quantified, depending on their relevance to the local coastal system or the development proposed. The complexity of climate change means that these processes may change over time as climate changes, making the problem of determining average and extreme values time dependent. For example, average wave conditions (height, period and approach direction) based on existing records may not be representative of those average conditions in 2100. The assessment and significance of these values to be used in assessing future coastal behaviour requires expert judgement.

The first guideline in this NCCOE series *Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering* (NCCOE, 2012a) includes a methodology for determining the likely relevance of a particular coastal process on a particular assessment.

The Australian coastline is extremely varied. The shoreline morphology includes gently sloping mud flats, long sandy beaches comprising carbonates or silica sands, and hundreds of kilometre stretches of high, vertical bedrock cliffs.

There is enormous variation in the ambient coastal processes acting on this varied coastline. For example, spring tidal ranges vary from less than 1 metre in south-western Australia, typically 2 metres across south-eastern Australia to as much as 10 metres along parts of north-western Australia. This variation in tidal range is illustrated in figure 3. There are also widespread variations in other coastal processes around the Australian coast, including winds, storminess, rainfall, waves and ocean currents. Tidal currents along the SE coast are low (except near estuaries), while tidal currents in Torres Strait can reach as much as 5 m/s.

CHECKLIST

- *Literature/Data review completed?*
- *Additional data collection required?*
- *Are local coastal processes understood?*
- *Effects of climate change on coastal processes?*
- *Sediment transport paths quantified?*
- *Shoreline impacts quantified?*
- *Can a reliable conceptual model be described?*
- *Can a sediment budget be balanced?*
- *Are differing time intervals being considered?*
- *Can future change to coastal processes be assessed?*
- *Are additional data collection and modelling required?*

A detailed review of the variability in coastal processes and coastal geomorphology around the Australian coastline can be found in Short & Woodroffe (2009). Site specific variations in coastal processes over relatively short distances are normal and significant. For example, on a single arcuate beach, for a given set of offshore wave conditions, breaking wave heights may vary at the shoreline by an order of magnitude from the sheltered beach section in the lee of a headland to an exposed section of the beach receiving the offshore conditions directly. At a particular point in time, tidal velocities within an estuary might vary from several metres per second at one location to virtually zero at another, depending on the local morphology and the flow paths. Information detailing local coastal processes and available data sets are also included in investigation reports and the scientific and engineering literature. These should be reviewed prior to any development of a coastal understanding or testing of possible management strategies and solutions.

Successful coastal management options at one location may not be suitable for another. For example, a submerged nearshore reef may be a suitable method of protecting a short section of a sandy beach with a low net sand transport rate and small tidal range, but may be ineffective on a section of coastline with a high tidal range and high alongshore sand transport rates.

3.3 An Approach to Understanding Coastal Sedimentary Processes

A major significance of the coastal processes to coastal management is the impact they can have on the seabed and an existing shoreline. Where there is no development and little human use or occupation of the foreshores or adjacent land, the coastal processes will simply cause the slow erosion of exposed cliff lines or the erosion and accretion of unconsolidated foreshores. The shorelines will continue to prograde, recede and evolve as they have done over millennia. Climate change and sea levels are simply accommodated through the movement of this shore.

Primarily, coastal management issues exist where the shoreline is valued for land use, occupation or access. Particularly during severe storms the coastal processes create hazards to the development adjacent to the foreshores and/or to the users of that development. The type and extent of these hazards is dependent on the location of the shoreline at the time a severe event occurs. In addition to the loss of sediment, the extent of wave inundation and coastal flooding may be exacerbated also.

Sedimentary processes warrant a specific discussion in this guideline as they are often poorly understood. In many parts of the Australian coastline they cause changes to the shoreline exacerbating coastal hazards and necessitating coastal management intervention. Understanding sedimentary processes and hence shoreline stability is essential to the decision making process, particularly where intervention measures are proposed that have the potential to alter sediment movement paths, rates and shoreline alignment. Without this understanding it is likely that measures proposed may result in unforeseen and often irreversible coastal changes.

The interpretation of the available coastal process data to compute sediment movement and hence, determine likely shoreline stability and sediment transport under a range of conditions over time, can be extremely complex.

To develop this understanding it is necessary to:

- Define a coastal compartment (or beach cell) with identifiable boundaries across which the rate of sediment transport can be readily estimated (through field measurement, historical analysis or numerical computation).
- Identify and quantify (based on the coastal process understanding) the internal sediment movement pathways within that compartment and corresponding changes to the shoreline and the seabed.
- Quantify any sediment movement across the boundaries of the identified beach compartment (sediment budget).

The sediment budget is analogous to a cash flow calculation. It equates the sum of all sediment inflows, less all outflows across the boundaries to the change in sediment in the compartment. If the total outflows exceed the inflows, the seabed and/or coastline in the compartment is eroding. Conversely, if the inflows exceed the outflows, then the seabed/coastline is accreting. A balance indicates no net change within the compartment (although there may still be redistribution within the compartment).

Isolated movement of sediment across the boundary are termed sources (e.g. shell production, onshore sand supply, etc.) or sinks (e.g. flood tide progradation into an estuary, offshore sand loss to deep water, dredging or sand extraction). The sediment budget may vary over differing timeframes (e.g. changes over a day will be different from changes over a year) and will change in the future as climate and forcing processes change.

A simplified coastal compartment identifying the sediment transport pathways is shown in figure 4.

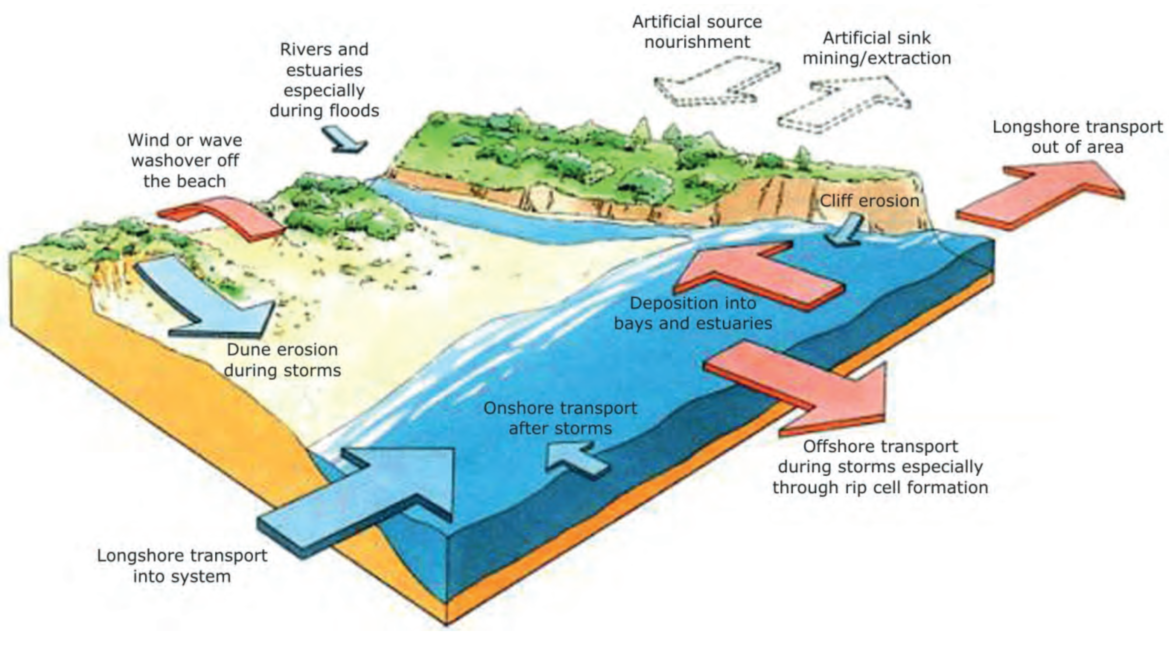


Figure 4. Typical sediment budget (modified from NSW Government 1990, Figure B.7.3).

This sediment budget approach allows an understanding of how the coastal compartment responds to the existing coastal processes. It permits the estimation of the likely impact of any changes to the coastal processes on the shoreline and facilitates the assessment of the impact of any changes to sediment supply or losses. Importantly, when based on a sound coastal process understanding it provides a realistic framework for evaluating the likely impact of intervention options on the coastal system over time.

4 PLANNING APPROACHES

The NCCOE recognises that future land use potential, incorporating adaptation for climate change, is an integral part of the land use planning process. Physical intervention measures form one class of the tools available to implement that planning process. While the focus of this guideline is the use of such intervention measures to reduce coastal hazards as climate changes, it is recognised that the implementation of these measures needs to be incorporated within that planning process.

This section identifies key elements of coastal land use planning and the place of physical intervention options within that planning framework. It is not intended to present a rigorous understanding of all aspects of coastal planning as those guidelines and expertise exist elsewhere. Rather the aim is to identify the types of physical intervention options that may be available and how they fit within the overall planning framework. In many instances planning measures, without any physical intervention, may be the preferred option for adaptation.

4.1 Planning for Adaptation

Taking action on adaptation is challenging. However by considering coastal climate change in short, medium and long-terms (as appropriate to the time frame of the design life of the project or development), planning to reduce vulnerabilities and strengthen resilience can be achieved, especially when integrating these considerations across the range of sectors in local government (Gurran et al., 2011).

This chapter is a resource illustrating a user-friendly step-by-step outline of planning matters which may be considered for coastal climate adaptation within existing state and territorial legislation and policy frameworks with the ultimate goal of accommodating coastal climate adaptation into these and future frameworks. Hence this chapter may assist end users to incorporate climate change adaptation considerations into strategic planning and development assessments.

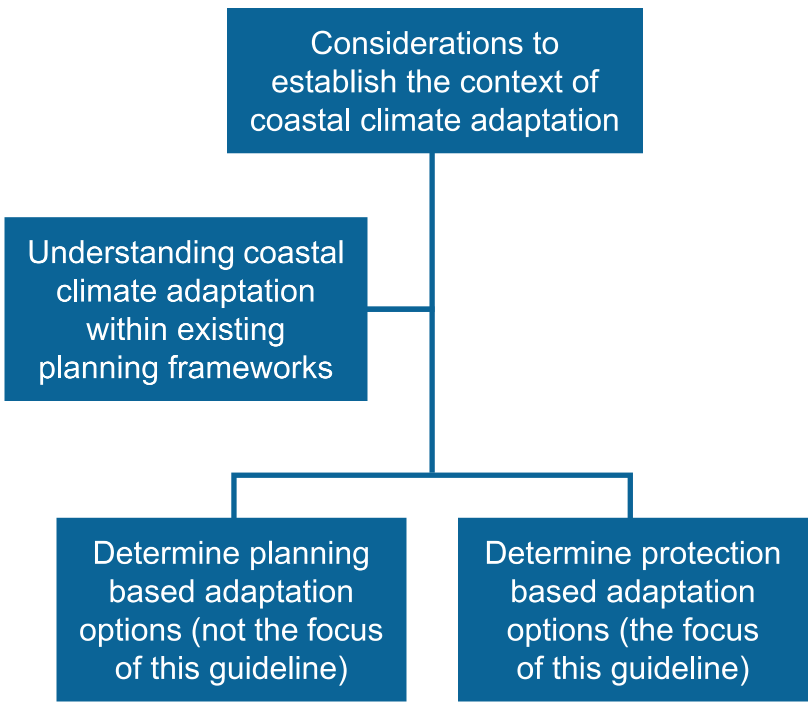


Figure 5. The planning approach for coastal climate adaptation described in this chapter.

Although it is acknowledged that there have been several calls for national guidance and consistency in planning for impacts of climate change in coastal areas across Australia (Coasts and Climate Change Council, 2011; Booth et al., 2011), most State and Territory governments continue to operate independently and, as such, coastal climate adaptation is at different stages of development. Notwithstanding this, there are frameworks that should be used to generally consider and plan for coastal climate adaptation. Figure 5 presents the outline of the planning approach described in this chapter.

Firstly, there is a need to situate coastal climate adaptation into the overarching Ecologically Sustainable Development (ESD) framework. Further details on this can be found in Volume 2 of this NCCOE series *Coastal Engineering Guidelines for working with the Australian Coast in an ecologically sustainable way* (NCCOE, 2012b), in particular Supplement F.

Integrated Coastal Zone Management (ICZM) incorporates the goals of ESD which in turn is related to implementing policy, catchment management, environmental planning, urban and regional development, biodiversity, transport and infrastructure planning, to name a few (Dovers in Lazarow et al., 2006). These connections are important in the implementation of coastal climate adaptation within an ICZM and an ESD framework, as lessons can be learnt from all other sectors in ways to move forward in what is a "rolling" management framework. The principles of ICZM and ESD, that make these approaches and tools (of which there are many useful examples) worthwhile for addressing coastal climate adaptation, allow the opportunity for revision and change, which is important considering the uncertainty of the science and the need for ongoing revisions as new science comes to light.

4.2 Strategic Planning – Adaptation as Part of the Planning Framework

This section illustrates the need and suggests a way to embed climate adaptation into existing policy and legislation frameworks while measuring the success of adaptation measures within management plans.

Relevant legislation can be found by searching legal databases such www.austlii.edu.au using keywords such as "coastal planning" and "climate change". Appendix 2 of Volume 2 of this series *Coastal Engineering Guidelines for working with the Australian Coast in an ecologically sustainable way*, provides a summary of relevant coastal policies and programs.

Relevant legislation can be found by searching legal databases such as www.austlii.edu.au using keywords such as "coastal planning".

Planning Horizons and Design Life

Climate change adaptation strategies require long-term strategic and land use planning solutions that are required to be considered within current regional strategies and local environmental planning instruments. Such strategic planning would define settlement patterns, development areas and associated essential services infrastructure. An appropriate planning horizon should be considered in conjunction with design life of any infrastructure and how this can be incorporated into the realistic development potential of the area. For example, while a seawall may protect against erosion for a nominal design life of 50 years, beyond that timeframe inundation from sea level may result in the land becoming unusable for residential development.

Existing and Future Development – Greenfield and Urban Areas

The type and scale of development (existing and future) are key considerations in the assessment of appropriate adaptation options. The following is a brief outline of land use types:

Greenfield areas have no existing infrastructure (urban, industrial, residential, etc.) that may currently be at risk and may be subject to consideration for development in the future. In greenfield areas there is an opportunity to ensure that new development be sited and designed in a way that does not expose new infrastructure to unforeseen or unmanageable coastal hazard over its design life (i.e. the intended design life of the proposed land use, not a particular construction on the land). There may also be merit in retaining publicly owned buffer zones (e.g. only permitting restricted public recreational development) or restrictive zoning (e.g. trigger point released leasehold) to enact a managed retreat policy in all perceived future coastal hazard areas (e.g. up to 2100 hazard line). The objective is to ensure that any future use of the site does not become "at risk" as climate changes or that such future risk can be addressed, including through the future reversion of the land to a lower land use potential.

Brownfield areas are existing urban areas that include built up zones, areas committed for urban development (e.g. future urban zones, master plan areas, urban development areas) and mixed use development (e.g. tourist areas, industrial areas, non-urban areas). In brownfield areas existing infrastructure and essential services that are at risk require serious consideration of appropriate adaptation options. Key considerations include, but are not limited to, the need to avoid further intensification of development, managing urban consolidation (infill development such as nodal settlement patterns), installation of appropriate coastal protection works (soft and/or hard engineering structures), possible development of relocatable or sacrificial structures, proactive planning, etc.

Considerations to establish the context

Establishing the context of coastal climate adaption is a key part of the decision making process. In a recent survey and study (Gurran et al., 2011), the main issues that councils identified as areas of concern within the process of coastal climate adaptation include:

- physical exposure (sea level rise, inundation)
- potential development in vulnerable locations, loss of foreshores/recreational areas, impact on existing public infrastructure
- legal liability in planning decisions
- impact on existing private homes
- capacity of emergency response systems
- economic impacts
- increased population and
- lifestyle impacts.

Table 1 provides a flowchart and checklist which outlines questions and considerations that may assist in establishing the context of the coastal management for climate adaptation.

Adaptation as part of the ICZM Framework

Within ESD and ICZM frameworks there is an opportunity to assess issues in an integrated manner, not in isolation, thereby capturing a range of issues such as those listed in the previous Section. In addition, there is merit in regional collaboration in implementing coastal climate adaptation where common issues may be addressed, measures that may be made more cost effective, opportunities to build capacity through lessons learnt may arise and a clearer understanding of key concerns for councils, including liability of insurance, may evolve. There may be potential economy of scale benefits in taking a regional approach and the physical processes often span jurisdictions.

A staged approach for coastal climate adaptation within existing planning frameworks is presented in Table 2. Throughout this process, relevant stakeholder engagement and community consultation should be undertaken in order to educate and involve community/stakeholders within the decision and associated adaptation framework.

The key value obtained from Table 2 is that it allows practitioners to ask "why should I understand the planning framework" and illustrates how to do so in the context of coastal climate adaption; resulting in a final outcome of the implementation of adaption options (Stage 5). The best case scenario is presented in Stage 5, where adaption options chosen would be implemented into existing and new instruments/plans/strategies and these would be flexible enough to review and refine as required. This may be a difficult task for many practitioners, however, in the essence of completeness of a staged approach, is presented here as the "best outcome" approach.

Table 1: Considerations to establish the context of coastal climate adaptation.

1	**Key broad considerations**
•	What are the issues arising in the context of coastal climate adaptation?
•	What objectives need to be addressed?
•	What are the primary drivers for coastal management in each area – physical processes, political pressure, etc.?
•	What is the planning timeframe?
•	What are the spatial and temporal boundaries?
•	What will be protected – the coast and / or the assets?
2	**Aims within a coastal management framework**
•	Answer key questions such as "where are we now?" and "where do we want to be?"
•	Decide on focus, e.g. retreat, accommodate or protect existing infrastructure in coastal environments and maintaining foreshore access, amenity and open space.
•	Consider land use in its current state or zoning and the capability of that land.
•	Identify how/if new growth may be accommodated within existing development.
•	Limit the number and value of future assets at risk.
•	Determine an appropriate infrastructure strategy to deliver services, safety and access.
3	**Adaptation considerations**
•	What is the land use and where does it occur?
•	What is the density of development?
•	How many people live within the coastal zone?
•	What are the values of assets? (social, cultural, environmental, financial, etc.)
•	Is there any critical infrastructure within the area? (e.g. hospitals, transport, schools, utilities)
•	Is the value of assets likely to rise in the future?
•	Are the number/type of assets at risk likely to increase substantially as climate changes or the coast evolves?
•	Is access to development (including emergency access during extreme events) secure at present and in the future?
•	Are assets easily re-locatable or removable?
•	Are assets able to be retrofitted to prolong usable life?
•	Do existing assets have a reasonable/usable period remaining before coastal hazards are unacceptable?
•	What alternative, less vulnerable/critical uses of the land are there?
•	What are costs of zoning or planning modifications?
4	**Assess**
•	Likely impacts of climate change (what they are planning for, in terms of sea-level rise benchmarks and other localised impacts).
•	Nature of the physical environment (including its level of vulnerability and desired level of resilience) (refer Section 3 – Coastal Processes).
•	Relative advantages of various adaptation strategies, such that the most appropriate and effective measures may be selected (Gates & Cox, 2012).

Table 2: Staged approach for coastal climate adaptation within existing planning frameworks.

Stage 1	**Understanding your planning environment**
	• Review ESD and ICZM principles. • Review relevant legislation, policy, guidelines and strategies for the relevant State or Territory. • Understand how the coastal planning environment fits into existing Regional and LGA planning instruments. • Identify the spatial and temporal influence of the planning instruments.
Outcome:	Identification and understanding of the relevant planning environment.
Stage 2	**Understanding your coastal environment**
	• Identify characteristics of your coastal environment e.g. wave or tide dominated, coast, or estuary/river entrance, etc. (refer Section 3 Coastal Processes). • Identify coastal processes and associated hazards (including sea level rise) – based on previous studies, identify data gaps and undertake new assessment if required.
Outcome:	Understanding of coastal process and associated hazards for the site.
Stage 3	**Understanding your vulnerabilities and risks**
	• If appropriate, map coastal risk areas (based on coastal processes and hazard profile over time) and rank levels of existing and future risk. • Based on Stages 1 and 2, identify (and estimate value of) public and private assets at risk for various timeframes, relevant zoning and planning instruments.
Outcome:	Site specific understanding coastal climate change risks.
Stage 4	**Assess risks and identify adaptation options**
	• Employ a risk based decision process that considers suitable planning horizons (for specific development and longer term land use), spatial scale of hazard/s and area/s at risk, social, environmental and economic impacts, and scale of development within LGA, i.e. greenfield, brownfield or infill. • Identify range of suitable adaptation options – planning and/or protection/ amelioration options. If staged development (including any preliminary short-term works), clearly articulate schedule. • Undertake sensitivity analysis for key climate/process changes.
Outcome:	Determine suitability of coastal climate adaptation options
Stage 5	**Implementation of adaptation options/pathways**
	• Select preferred option/suite of options. • Incorporate adaptation option into planning instruments and development control plans and, where appropriate, within regional strategies, including incorporating flexibility to deal with changing risks and uncertainties. • Establish funding mechanisms and governance arrangements. • Seek opportunities to incorporate adaptation into all new and existing developments within the coastal zone (i.e. mainstream the adaptation strategy). • Continue to monitor, review and refine adaptation options on a regular basis.
Outcome:	Implementation of coastal climate adaptation options within a coastal management framework that can be reviewed and revised on a regular basis. (Refer to Section 2 – Climate Change Adaptation).

4.3 Adaptation Options

The main goal of planning and implementing adaptation options should be to build resilience by protecting or reinstating natural coastal ecosystems, which perform as a natural buffer to avoid and reduce coastal risks for landward infrastructure or by adapting existing development to accommodate identified coastal risks and timeframes. Changes in climate may have diverse implications for land use planning, impacting on infrastructure, community services and natural assets (Gates & Cox, 2012). Early engagement with community is recommended in order to fully evaluate the advantages and disadvantages of options in order to select the most appropriate option/s and the best timing for implementation. A systematic evaluation of relative advantages of each option needs to be undertaken as part of this process (Gates & Cox, 2012).

Available Adaptation Options (Planning and Protection / Amelioration)

Adaptation options can range from being:

- Technological solutions
- Ecosystem based adaptation options, or
- Behavioural, managerial and policy approaches (European Environment Agency, 2010).

These can be considered in a traditional coastal management framework of retreat, accommodate and protect. The aim of implementing any of these adaptation options is to decrease vulnerability and increase adaptive capacity through anticipatory / proactive or reactive approaches.

Where accommodation of risk is not feasible due to the level of risk or level of development, soft or hard engineered protection measures may be required. It should be remembered that in some areas, existing coastal risks may not be able to be cost-effectively mitigated even by protection structures and retreat or removal of development from these areas may be the only feasible option in the longer term. The challenge to communities will be to consider the increasing need for coastal protection/ amelioration versus the concept of retreat, while accommodating principles of sustainable coastal management and meeting values/expectations of community and other stakeholders.

The following brief section focuses on Planning Adaptation Options, while Protection/Amelioration Adaptation Options are addressed in the following Chapters (refer Chapters 6 to 10).

Planning Adaptation Options

Planning adaptation options fall under three main categories:

1. Environmental Planning
2. Development Control Conditions, and
3. Financial Measures.

Application of these planning adaptation options should be considered with regards to the following:

- Levels of existing development (greenfield or brownfield/urban).
- Type of coastal environment, e.g. exposure, wave or tide dominated coasts, littoral drift potential, the main associated coastal hazards, etc.
- Level of coastal vulnerability and risk now and in the future as climate changes.
- Anticipatory / proactive or reactive approach (precautionary principle); and
- Retreat, accommodate and protect strategies including assessment of the appropriate design life of these options.
- Scale of development

It is important to note that long term regional or LGA specific strategic planning that appropriately addresses coastal climate hazards and risk can guide relevant environmental planning instruments – these planning instruments should incorporate appropriate development control conditions or equivalent. Financial measures may be incorporated in any level of planning instrument depending on the measure and the planning horizon to be considered.

5 MODELLING AND DATA COLLECTION

Planning and designing for adaptation in the coastal zone must be based on sound coastal engineering knowledge and understanding. The starting point is an understanding of the physics (and other sciences) as introduced above in "Coastal Processes". To quantify those processes however we need field data and to predict the outcomes and risks of planned options we must rely on models.

5.1 Field Data

The importance of data to aid understanding in the coast and to support predictive modelling has long been recognised by the professional coastal engineer. An Engineers Australia document "At What Price Data?" has been updated and included in these guidelines as Appendix A. This highlights the need for and the role of data in coastal engineering in general and modelling in particular. Data are required to define the zones being considered, to quantify the present situation of the coast, the assets and uses affected, to enable models to be set up, validated and run, and to monitor the outcomes of management and planning actions. As has already been mentioned, long term data sets are vital to quantify the trends associated with climate change.

Following any new installation or modification of an existing structure, a monitoring field program is needed to detect any changes that have occurred and to check any model predictions. Further examples and rational are provided in Appendix A as well as section 6.4.2 of the second volume in this guideline series *(Coastal Engineering Guidelines for working with the Australian coast in an ecologically sustainable way)*.

Figure 6. Argus system for monitoring beach movements and breaking waves.

(Source: Water Research Laboratory, UNSW)

Quantitative models such as numerical, physical and even desktop are only as good as the available input data. The more sophisticated the model, the more detailed and comprehensive is the data required. A major issue, especially for modelling the impacts of climate change is the duration covered by the data set(s).

Data such as topography, bathymetry, wave climate, wind climate, water level fluctuations (including tides and tidal anomalies), currents, water quality and ecology are required to construct the models and then reallife data on the performance of the prototype is required to calibrate then verify and finally to run the model(s). The data required to effectively use models as coastal engineering tools is a subject in itself which is beyond the scope of this guideline. Organisations specialising in data collection or combined modelling/data should be consulted for expert advice.

5.2 Modelling

In common with many practical sciences, coastal engineering is as much an art as it is a science. Modelling provides a vehicle by which coastal engineers can illustrate complex interactions, test theories, examine and rank the performance of design options, interpolate information, risk manage extrapolation of information and predict/project future situations/outcomes. Models are therefore vital tools but depend heavily on the skill and competency of the person using them, the availability of data, circumstances of their use and on a rigorous regime of peer review. Modelling has an important role in examining situations of uncertainty, particularly the risk management and the effectiveness of options and the quantification of "what if" scenarios; it is therefore well suited for examining scenarios for the potential coastal impacts of climate change, the effectiveness of adaptive strategy options and the likely impacts on coastal structures. Kamphuis (2000) provides further commentary on the appropriate use, and limitations, of models and the importance of modelling as a coastal engineering tool.

Modelling can be divided into five categories. Often at least two of these and in some circumstances all five will be required to meet duty of care standards. The categories are: Conceptual Models; Prototype Models (analogous real-world examples); Desktop Models; Numerical Models and Physical Models. Table 3 gives an overview of these classes of models.

Figure 7 presents examples of numerical (wave modelling in an embayment) and physical (testing the stability of breakwater units) models.

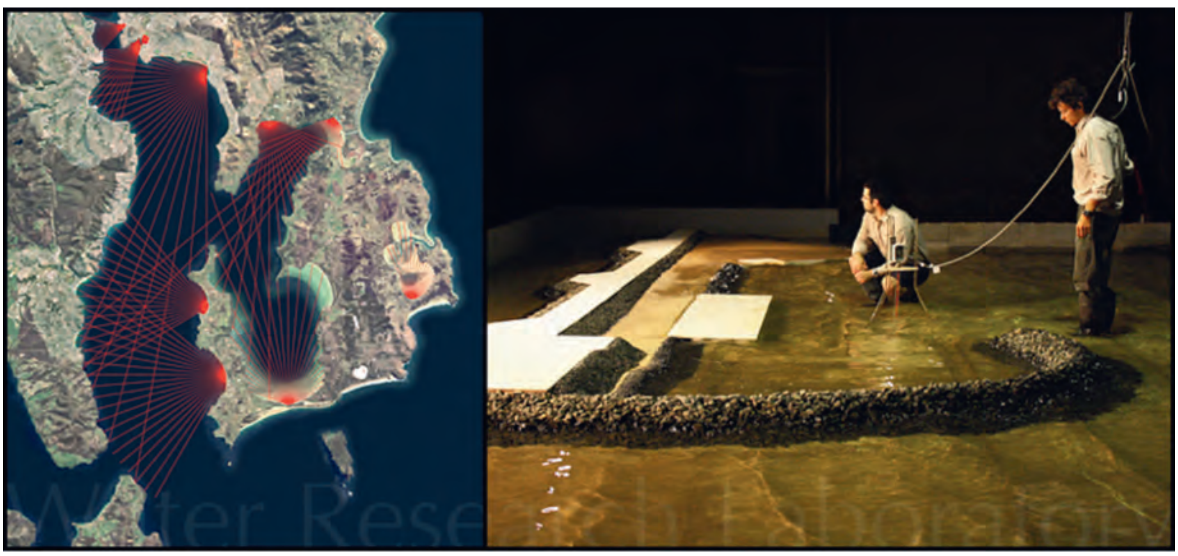


Figure 7. Examples of wave penetration numerical and physical models.

(Source: Water Research Laboratory, UNSW)

Table 3. Summary of model categories.

Model class	Summary	Limitations	Benefits
Conceptual	Identify relevant parameters and their interactions. Should be done before any other type of modelling. Provides "sanity check" and strategic framework for de-tailed studies.	Qualitative rather than quantitative.	Ensures processes and parameters are not overlooked. Focuses/ identifies key issues. Can be undertaken in a cost and time effective manner.
Prototype (analogue)	Use experience gained from similar situations to deduce behaviours for project. An often neglected powerful tool, especially if a close match can be found.	Depends on availability of analogous situation. Care needed since application to another site requires extrapolation extrapolating. Skill required to identify and interpret relevant prototype situations.	Real life examples of operating systems similar to that proposed provide an excellent risk managed decision making environment and practical insights into potential options as well as opportunities to obtain quantitative data.
Desktop	Usually simple equations representing the important physics on very much simplified geometry, forces, etc. Can provide quantification. Useful to explore mechanisms even for more complicated situations.	Geometry and processes are very simplified. There may be a tendency to see/drive desktop studies as a low cost alternative to more detailed numerical modelling.	Quick and cost effective answers, including sensitivity testing, and to select scenarios for numerical modelling.
Numerical	Solves sets of equations representing the physics (necessarily a subset) on a computational grid spanning the area of interest. 1D, 2D and 3D versions exist. Very useful to compare alternatives. With care, can provide quantitative predictions.	Model parameters (particularly those related to pollutant mixing and to sediments) can be difficult to set correctly. Providers often overoptimistic in reliability of predictions. May not have sufficient data to verify. Need very long run times to simulate variability.	Vehicle for speedily and economically assessing concepts, scenarios and options. Provides quantitative information on potential/impacts of climate change and sensitivity testing of scenarios.
Physical scale	Geometry, forces, etc. are replicated at smaller scale in a laboratory. Test facilities include wave flumes (2D) and wave basins (3D) either of which may include tidal capability.	Cannot model regional areas or very long time periods. Scale effects can compromise results, particularly for mobile bed models. Similar lim-itations to numerical re-garding data and boundary conditions. Need random forcing and lengthy operation to simulate variability.	Clear visualisation of the processes. Can provide fine detail around structures and in limited segments of the coast. Invaluable for fundamental studies of processes.

5.3 Conceptual Models

Conceptual modelling is the strategic level that identifies the relevant parameters for the particular situation and their likely interactions. These models provide the vehicle for experienced specialist input, and play a vital role in injecting the "art" into any coastal modelling study. They not only form the framework for model investigations, and assist in selecting the parameters to be quantified, but also provide the basis for "sanity checking" results from the overall modelling studies.

Scenario testing of climate change effects is imperative because, as yet, the potential variability of many of the parameters involved is poorly understood. And even for those parameters such as sea level rise, where a range of projections has been identified, there are still great uncertainties as to what the outcomes will be at specific locations.

A sediment budget conceptual model of an embayment provides a simple illustration (see Figure 4 in Section 3). If more sediment goes into an embayment than leaves then the embayment accretes. However, if more leaves than enters the embayment will erode. The real power of conceptual modelling is in the examination and sensitivity testing of the complex process of how sediment enters and leaves embayments and the manner in which processes may alter if affected by climate change. For example, sediment entering around a headland at one end of an embayment may come as "slugs" during certain storm events or may be continuous depending on the mechanisms operating at the headland. Climate change may alter the rate/type of movement around the headland as a result of changes to wave energy and/or direction or frequency of storms and/or interactions with ocean currents). Within the embayment a change in net wave direction due to a shift in weather patterns (climate change) will alter the beach alignment which may mean more sand will tip out of the embayment for some years but, may then progressively return to a more constant loss that may well be different to that prior to climate. Or, the shoreline may retreat simply due to sea level rise. This may increase the effective projection of the headlands hence alter the flow of sediment both into and out of the compartment. Sand may be lost or gained from offshore, and in particular losses to offshore "sinks" such as the Cape Byron lobe (Gordon, 2011) may increase or decrease depending on the wave climate and the ocean current regime.

5.4 Prototype Models (analogues)

Prototype models are arguably the most underrated and underutilised type of model. When undertaking modelling it is often beneficial to search for a prototype situation similar to that being considered, or one nearby that will provide both qualitative and quantitative data. Prototype modelling can be done in conjunction with conceptual modelling.

An example of a prototype model is a headland that acts like a groin. Cape Byron is a prime example of a mega groin on a net northerly drift coast. There are many other similar examples at different scales that provide an insight into how coastal alignments respond to differing wave climates.

Garden Island in Western Australia, and Moreton and Frazer Islands in Queensland are extreme examples of natural offshore breakwaters on energetic coasts, and the Great Barrier Reef in Queensland is a prime example of offshore reef type coastal protection. The low sand barrier island formations along some of the eastern shores of the Eyre Peninsular in South Australia demonstrate coastline response to a far lower wave energy climate while the Esperance coast of Western Australia has numerous examples of natural rock, shore parallel offshore breakwaters and reefs. Examination of these differing situations provides insight into the interaction of coastal processes and the relative magnitude responses in differing energy environments thereby providing guidance as to the sensible limits for climatic change sensitivity testing.

As well as the wide range of natural features there are many manmade features that provide both an insight into coastal processes and their response to intervention as well as valuable data to assist with quantification of those processes. Sand bypassing programs at the Nerang in Queensland and at the Tweed in NSW (Boswood et al., 2005) have generated invaluable data on gross and net littoral drift. Information for less energetic coasts has been obtained from the sand management program for Adelaide beaches in South Australia (Tucker & Penney, 1989). In Port Phillip Bay, Victoria, the impacts of, what are effectively offshore breakwaters in the form of Sandringham and Brighton Marinas, can be readily seen in the sand accumulation features inshore of these structures.

Figure 8. Breakwaters at Eden.

A widely used example of a model by analogy is the "Bruun Rule" (Bruun, 1962, revised 1983) originally devised by observing beach changes that took place along the shorelines of the Great Lakes in Northern America and now used for estimating coastal retreat associated with sea level rise at many locations around the world including where exacerbated by sinking land (e.g. the Gulf coast of the USA, London and Venice).

The above examples of prototype learning situations are simply indicative of the wide range of opportunities that exist, which enable a competent and experienced coastal engineer/coastal zone manager to understand coastal process behaviours in differing situations, and to assess meaningful sensitivity testing limits for potential changes brought about by climate change.

5.5 Desktop Models

It could be argued that desktop models are a subset of numerical modelling; the simplest form of a numerical modelling. It is, however, useful to recognise them as a separate class of model as they do not require sophisticated computers or programs to run and can give useful results for simple situations in an economical and timely manner.

Examples of desktop models would be the use of the European "Rock Manual" (CIRIA, 2007) for sizing breakwater armour stone and estimating wave overtopping and application of the Bruun Rule to calculate shoreline recession due to sea level rise. A further, but slightly more complex example might be the determination of the change in plan shape of a long straight beach if a groyne was introduced and/or the wave climate changed giving rise to an alteration of the longshore transport rate.

Models like any tool can be:

- *blunt yet effective*
- *blunt and inappropriate*
- *sharp giving excellent outcomes*
- *or sharp with dangerous results.*

It all depends on the skill and competency of the person using them, the availability of data, and the circumstances of their use.

Desktop models do not usually require a high degree of skill to operate however the person in charge of the project needs a great deal of experience to know which method and techniques are appropriate and their limitations.

5.6 Numerical Models

The advent of "user friendly", computer based numerical modelling has revolutionised the ability to undertake coastal studies and designs. In turn this has facilitated the examination of a range of management/development options, design solutions and enabled sensitivity testing of those options/

solutions when considering issues such as climate change. Numerical modelling has therefore significantly enhanced the ability to achieve more efficient and effective designs and better risk manage solutions.

Numerical models are sets of equations representing a subset of the physical processes being solved by computers throughout a grid or network on an iterative basis. Originally such models were based on a "finite difference" approach, and were one-dimensional, however, development of computer technology and modelling techniques opened the way for two- and three-dimensional modelling. Many modern numerical models use the "finite element" technique that provides a more convenient way to represent natural shoreline and seabed geometries. A common difficulty is how to deal with the boundaries and how to examine smaller scale effects within the model. A commonly used technique is to "nest" models in a series of increasingly more extensive domains and sparser grids. Coastal models invariably include some aspect of hydrodynamics (currents, waves, tides) but may also include sediment and pollutant movements with the relevant equations all embedded in the one model.

However, the more complex and sophisticated a model is does not necessarily imply the better the outcome will be and the more precise the result is no indication of its accuracy. Models must be matched to the situation being studied, which requires an experienced modeller who understands the limitations of the model and the results. More complex models generally have longer "run" times; require greater computing power and more and better quality data input. For simple situations often a one-dimensional model will provide a meaningful result. For example, if examining simple onshore-offshore profile changes at a beach to changing wave or sea level conditions, a one-dimensional model is likely to be adequate. However, if investigating beach alignments to changing offshore wave conditions or wave action in harbours then a two-dimensional model is essential. If more complex situations, such as deep-water outfall interactions with ocean currents, or the spread of a plume of sediment being dumped from a dredge are to be examined, a three-dimensional model is appropriate.

On occasions the type of model required can change as an investigation progresses. For example, a two-dimensional model (or even a 1D shoreline evolution model if the beach is long and straight) may be adequate to investigate shoreline and nearshore response to the construction of an exposed offshore breakwater. However, if sea level rise means the breakwater will, in time, become submerged, and hence behave more like a reef, then a three-dimensional model may be more appropriate. As an investigation progresses it may be necessary to "nest" a detailed model within the overall grid so that a particular phenomenon or system behaviour can be better understood.

Care is needed to avoid being overly influenced by impressive output graphics and animations. It is important to appreciate what processes are missing from any model, what time and space scales are being simulated and what parameters have been adjusted to achieve verification. A competent numerical modeller recognises that the model is just a tool and that the results need professional interpretation. When dealing with uncertainty in modelled parameters due to an ill-defined future climate, a modeller also needs to have the understanding required to undertake credible sensitivity testing so that the confidence limits of results can be understood. For example, a numerical model study established to investigate development setbacks behind a beach needs to include a range of sea level scenarios and test the sensitivity of the relationship between sea level rise and shoreline recession as well as the realignment of the overall shoreline of the embayment due to changes in the wave energy flux resulting from shifts in weather patterns and changes in storm intensity. A competent coastal engineer will use model results to develop professional advice on the likelihood of the shoreline reaching a particular location at a given point in time and the confidence the client can have in the result. Carley et al. (2008; 2009) present a good example of the use of conceptual modelling and a range of numerical models to provide advice to a local government authority regarding their coastal hazards and the possible range of climate change impacts based on various scenarios.

Numerical modelling requires an understanding of the difference between the precision of model results and their accuracy. The advent of electronic calculators and computers has meant that results to several decimal places are the norm; this precision of the machine is often confused with the accuracy of the result. Outcomes are dependent on the accuracy of the input data, the assumptions required and the appropriateness of the "engine(s)" driving the model, not the precision of the machine.

5.7 Physical Models

Prior to the advent of numerical modelling, physical models, i.e. scale models of the prototype situation, were the major tool available for examining coastal processes. However, physical models still have a major role to play in coastal studies including those aimed at adaptation. Physical models come to the fore, for example, when optimising breakwater or seawall crosssection and wharves, marinas and floating breakwater designs. Desktop models are used for preliminary design of breakwater and seawall armour units (including stone) and to investigate overtopping. A physical model of a preliminary desktop design, in the hands of an experienced physical modeller, can substantially reduce construction costs and/or manage risks of these inherently expensive structures. A physical model still provides the best information on the performance of such structures, particularly if both uniform and random waves can be used in testing. The physical model not only allows for optimisation of the design but also insight into the risks and likelihood of failure, particularly if a future climate were to alter sea levels or wave conditions.

Physical models can be fixed bed, often modelled in cement mortar, or moving bed, meaning that the model bed is formed up of sediment that can be transported by the waves and currents generated in the model. Moving bed models are especially difficult to design and operate as it is usually not possible to accurately scale the sediment; too fine and it behaves cohesively; too coarse and it either is not entrained and/or the bed forms are not in keeping with a prototype situation (often too large). Moving bed models are arguably the most difficult models from which to obtain meaningful results. Modellers require both competency in the "art form" and experience in operating and interpreting results. It is very rare that sediment movement time scales can be replicated; however, a competent modeller can achieve surprisingly good end results particularly in situations where complex interaction of processes and features mean that numerical modelling outcomes are questionable.

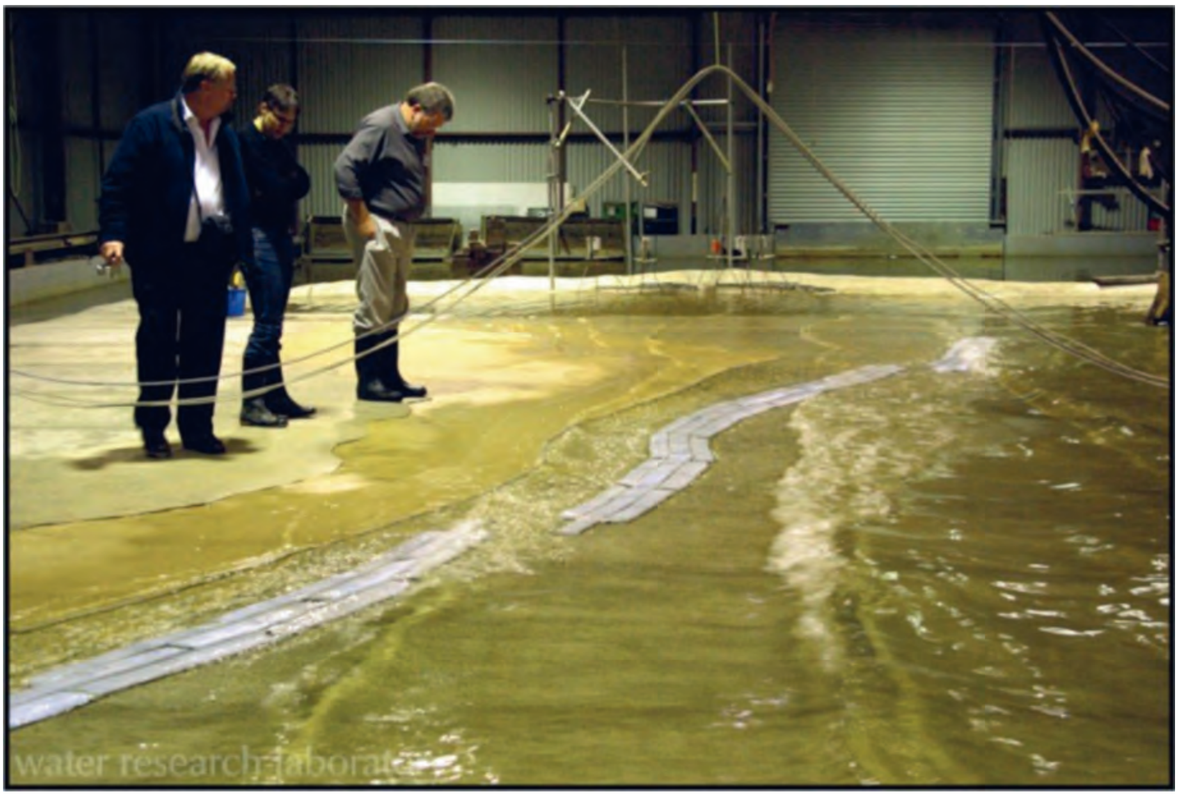


Figure 9. Inspecting a physical model. (Source: Water Research Laboratory, UNSW.)

Terminology for scale can be confusing. A scale of 1 in 100 (or a 100 scale model) means that the model geometry is 1% of the real world (in modelling jargon called "prototype"). A small-scale model (say 1 in 500) has features modelled which are relatively small, and conversely a large-scaled model (say 1 in 10) means that the features are large. Typically, in coastal engineering, small-scale models are used for harbour and estuary investigations whereas large-scale models feature in the testing of breakwater and revetment cross sections.

Physical models can be constructed to a natural scale (same vertical as horizontal) or a distorted scale where the vertical scale is smaller than the horizontal scale. Often river or tidal models are built to a distorted scale to help overcome bed frictional effects. However, wave models are seldom to a distorted scale because, while model bed friction is an issue, a distorted scale would introduce other problems in regard to meaningful wave transmission throughout the model with adverse effects on combined interaction of wave refraction, diffraction and shoaling. Distorted scaling has however been used to effect in some moving bed wave models (Gordon, 2011). In undertaking physical modelling, attention must be paid to scale effects such as viscosity, surface tension, air entrainment and bed friction. The latter is always an issue with large-scale models as model boundary layers are laminar whereas they are turbulent in prototype. Hence there is generally significantly more energy lost in the model, leading to, for example, excessive reduction in wave height as the waves move across the model. In small-scale models such as flume models of revetments, seawalls and breakwaters, air entrainment, specific gravity of the armour units and/or friction between units can be issues.

Typically the type of machinery used in a coastal physical model can generate either random or regular waves and replicate currents and tides. Some models have provisions for investigating multi-density situations such as the performance of ocean outfalls, while others include wind-generating machinery to examine wave and surface current development. Today, most physical modelling machinery is computer controlled as are the instruments recording the data and the analysis of that data is through specialist software. These advances improve flexibility when sensitivity testing.

Unlike numerical models, physical models can be more forgiving of data limitations because the modeller can readily observe/detect anomalies. Calibration and verification in a physical model can therefore often be more easily and confidently achieved. However, the modeller needs the necessary experience to recognise whether the model is indeed reproducing processes reasonably.

For high cost structures and/or those where failure will result in substantial losses it is often prudent to take a combined approach using both numerical and physical modelling. The numerical modelling allows rapid evaluation of options and sensitivity while the physical model provides the vehicle for design optimisation and process/risk checking. Such hybrid or dual modelling is also useful where physical interactions are complex. As with numerical modelling, a physical modelling study benefits from an initial conceptual and prototype modelling approach.

6 AN OVERVIEW OF COASTAL PROTECTION/AMELIORATION

The remainder of this Guideline focuses on specific physical intervention options. While it is acknowledged that each of these will have particular environmental, social and heritage impacts fundamental to the decision making process, these are not addressed here.

6.1 Selecting an Option

The definition of the management problem to be addressed requires an understanding of the behaviour of the coastal compartment based on historical assessment (geology, geomorphology and coastal processes) together with the best available prediction of future changes to the coastal processes and the shoreline (including any climate change). The best overall strategy may require a mixture of planning measures, development controls and physical intervention works.

Importantly, this mix may change with time (as climate changes and/or shorelines evolve). It is important so far as possible to identify the "end game" – whether and when the site will become unsuitable for the current land use or proposed development at some future stage as a result of natural shoreline evolution or as a result of climate change. Such a scenario does not necessarily mean the site should not be used for the purpose now proposed but rather that the triggers that will result in a need to change the usage or terminate the development approval need to be recognised now. These sunset provisions must be incorporated into the overall management strategy and may impact the selection and design of any intervention option/s to be implemented. For example, there is little point designing a protection seawall for the ambient sea level predicted for 2100 if the proposed protection structure will only have a 50 year working life. Likewise, it is incongruous to approve a residential development with a fifty year design life when the available information indicates the land is likely to be submerged regularly within that time period.

The suitability of a particular intervention option is site specific, depending on the local conditions such as geology, geomorphology, shoreline stability, exposure and sediment movement. The choice may also be affected by the availability and cost of materials (e.g. sand sources for ongoing nourishment, suitable rock for revetment construction, construction access, etc.), funding, timeframes and adjacent development and land use.

There are no specific options that can be applied in all circumstances to address a specific problem. Care should be taken to consider all viable options and to identify the potential for unintended or adverse impacts that could result. The appropriateness of a management approach will depend on the sensitivity of the coastal system. For example, options that intersect the alongshore movement of sediment (such as groynes or breakwaters – see Sections 7 and 8) on a high net littoral drift or receding beach will potentially result in increased recession downdrift of the structures. Similarly, construction of measures to reduce wave climate at the shoreline (such as an offshore reef or breakwater) may increase erosion to the sides of the sheltered area as the shoreline realigns, irrespective of the net sediment balance.

Table 4 provides a checklist for use when selecting a coastal protection / amelioration option.

A decision to intensify land use (e.g. rezoning rural land to residential) will have implications that go well beyond the design life of any current structures proposed. If the land cannot sustain this use indefinitely (e.g. projected erosion hazards or future inundation will render any intervention strategy ineffective), then a process for future down-zoning of the land use should be incorporated through the current management strategy. In this case, any intervention works used in the short term may need to be removed and this cost should be included in the initial evaluation. Ultimately, the question to be resolved for each future point in time is whether the existing or proposed development can be

Table 4: Check list for option selection.

- Is the issue clearly defined? (Cause, consequences, spatial and temporal scales/extents)
- Are the design constraints clearly understood?
- What amount of climate change (SLR, storminess, etc.) can be accommodated?
- What is the expected date that the limit will be reached?
- Have all reasonable options been considered?
- How effective is the favoured option likely to be?
- Can additional opportunities arise from the proposed option?
- Will the option become ineffective at some future date?
- Is the option part of an overall planning and management strategy?
- Who is responsible for any adverse impacts?
- Is the monitoring and maintenance strategy clearly defined?
- Has a thorough environmental/social impact assessment been completed?
- Has a comprehensive (whole of life cycle) economic appraisal been undertaken?

protected/adapted or should be removed. This future strategy once determined should also guide decisions on infrastructure capacity, location and maintenance as well as other land planning issues such as controls on population densities, etc.

6.2 Responsibility for Construction, Maintenance, Removal and Rectification

It is important to recognise the responsibilities of various stakeholders using and managing coastal areas. Where intervention is proposed, it must be clear who bears the cost of initial construction, ongoing maintenance (and possibly removal) and the rectification of any unforeseen adverse impacts resulting from the intervention measures. This later concern has been a key issue for approving authorities who are keen to avoid any ongoing financial liability that may arise from a management decision taken in good faith. This concern is real as coastal systems can be extremely sensitive and responsive to those activities that disrupt the natural processes. In recent years across Australia we have seen Local Authorities engaged in legal action to determine liability for the impacts of decisions long past. Equally, there are pressures being exerted through the legal challenges to force Local Government to act to protect private land and assets now considered at threat.

The evaluation of any strategy needs to identify the sensitivity (vulnerability) of a coastal system to any planned intervention measures and to recognise those coastal compartments where certain options are more likely to have significant impacts (both in distance and time) resulting from that initial intervention. For example, on a high net littoral drift coastline, works that interrupt the alongshore movement of sediment can result in increased erosion of downdrift beaches as the littoral drift is restored (e.g. construction of a groyne without filling or dredging of a river entrance bar without bypassing the dredged material). The same interruption of supply, to stabilise a receding beach (which will become more common as sea levels rise) can result in a permanent acceleration of erosion rates downdrift as the previous sediment supply from the protected area is denied to the system. Such responses can take decades to centuries to reach a new equilibrium and the effects may be observed for many kilometres along the shoreline from the location of the works.

Unlikely outcomes beyond the sediment distribution must also be considered. There are many examples around the coast where the construction of works for one purpose (such as rock breakwater walls at a harbour or river entrances, groynes or construction of a small sheltered boat harbour) have provided a natural trap for sea grasses removed from the seabed and transported along the beaches. At some locations this has compromised the use and amenity of the works (e.g. artificial recreational boating facilities at West Beach in Adelaide or east of Busselton in Western Australia). Similarly, unanticipated impacts on marine ecology, habitat and usability can result in adverse and possibly irreversible impacts if not fully considered.

6.3 Design Life – Planning Period

Selection of a management option as a component of an adaptation strategy requires consideration of the design life or planning period of the activity proposed. The specific design or working life of an element is determined both by the design standard adopted and the changes to the design conditions over time. It is important to recognise the difference between the planning life of an overall strategy and the individual component or working life of elements of that strategy. Such timescale differences provide opportunities to change the land use at some future time where intervention may no longer be practical or to defer the costs of a higher protection level into the future to a time when that standard is actually required.

There are substantial land use benefits and cost savings through identifying the future hazard extent and planning for it, but deferring the implementation of some intervention strategies until they are necessary. Similarly, the decrease in future functionality and/or increasing costs of adaptation measures as climate changes may preclude the present development of the site.

In considering the cost/benefit of a proposed development where future changes due to climate change may be relevant, it is essential that a whole of lifecycle approach is adopted in costing the adaptation measures proposed. This should include in addition to the initial capital costs, maintenance costs, future upgrades or replacement of the structure and costs of its removal and disposal at the end of the design life.

7 SHORELINE PROTECTION/ AMELIORATION OPTIONS

The impacts of climate change in the coastal areas of Australia are projected to result in rising sea levels and in some areas changes to the wave and storm surge regime. These changes are projected to result in higher water levels and in some areas more energetic waves and stronger currents. There needs to be site specific investigations into the changes for the area being considered. Such changes to water levels, waves and currents may result in erosion (deposition in some cases) or inundation of the coast and nearby infrastructure and development.

This section provides guidance on the common types of shoreline protection that may be suitable to ameliorate the impacts of climate change for particular situations. In addition to the ocean conditions being different from one location to another, the social, environmental and commercial value of the coastal land will vary greatly. Also, the type and quantities of engineering materials that are locally available will not be the same for all parts of the Australian coastline. These factors mean that a type of shoreline protection that is suitable, acceptable and optimal for one location may not be the appropriate approach at another location. Structures/measures discussed in this section include seawalls, groynes and beach nourishment.

7.1 Seawalls

Provision of a strong and durable barrier to coastal erosion can be appropriate for some locations. An engineered seawall could be the last line of defence on an eroding shoreline or may be the extension of naturally occurring protection in the case of a rocky shoreline. A typical seawall design utilising quarried armour rock is shown in Figure 10. Seawalls are built shore parallel, backed by land (or reclamation) and exposed to ocean waves and currents. Such structures contrast with offshore structures such as breakwaters (both attached and detached – which are discussed in Section 8) which have water on both sides. Installation of a seawall may be supplemented by beach nourishment which can have an effect on the performance of the structure.

The aim of a seawall is to provide a strong and durable barrier that can withstand the erosive forces of the ocean. The key considerations in the design of seawalls are:

- Toescour protection to prevent undermining of the structure by seabed or beach erosion.
- Sufficiently strong armour or face materials to withstand the wave and current forces.

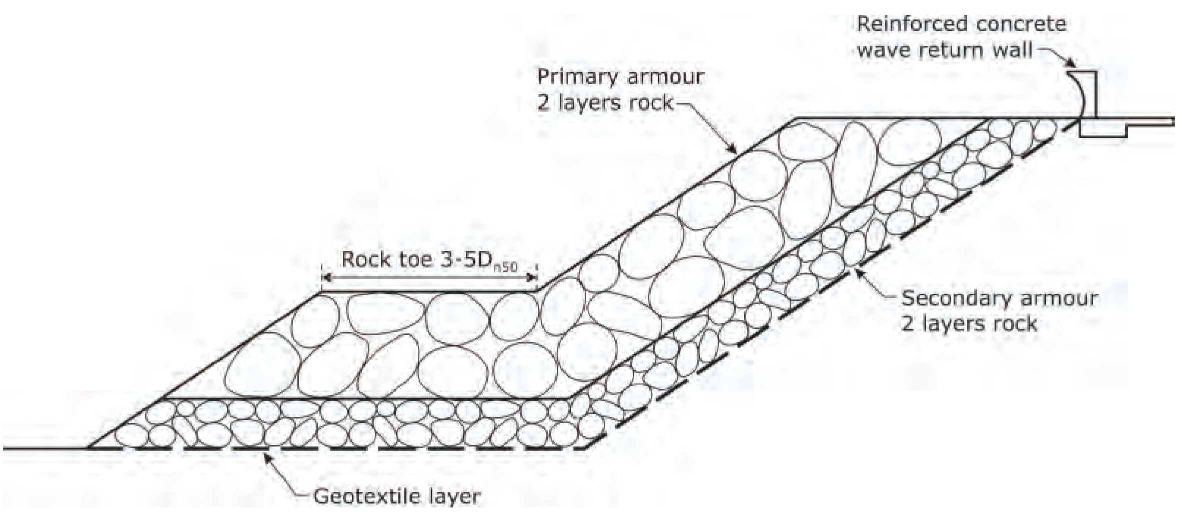


Figure 10. Typical seawall design. (SOURCE: WATER RESEARCH LABORATORY, UNSW.)

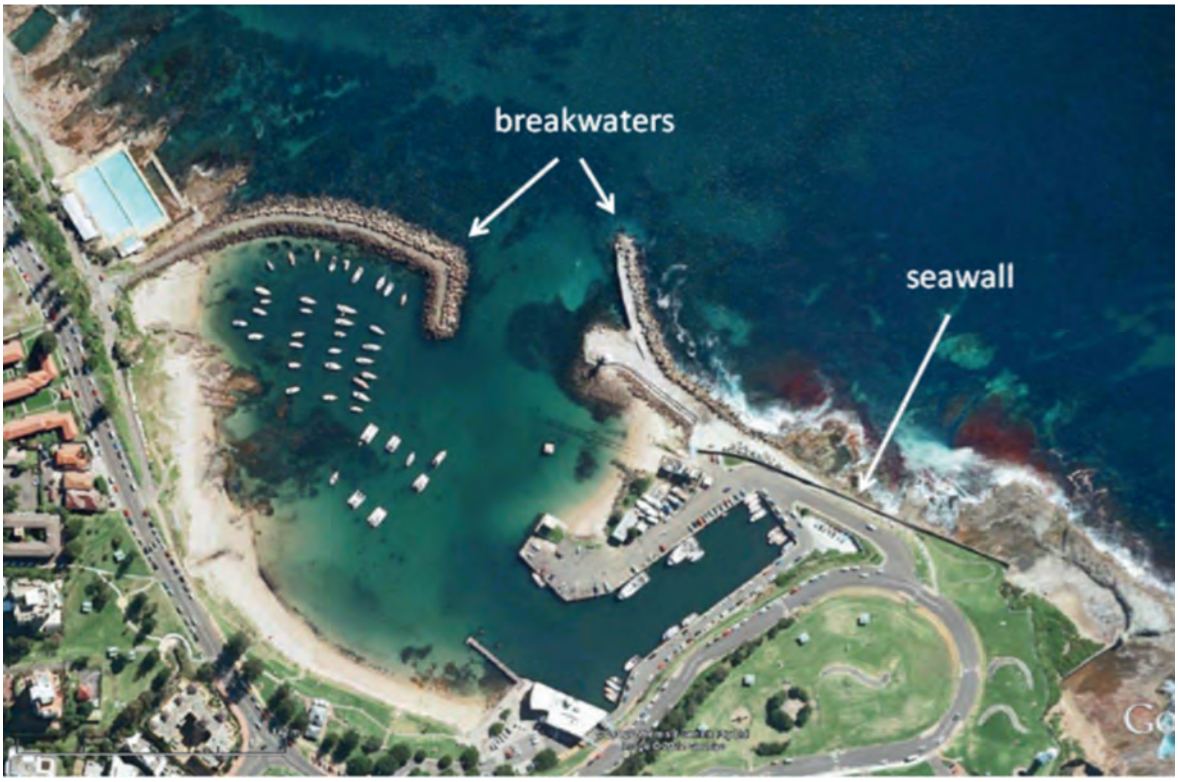


Figure 11. Wollongong Harbour showing typical uses of breakwaters and seawalls. (Adapted from Google Earth)

- Materials with sufficient durability to provide the desired service life without excessive maintenance.
- Filter system behind the armour or face to prevent the loss of underlayers through the outer layer.
- Crest height and splash apron to limit wave overtopping damaging the structure.
- Safe use of the land or area immediately behind the structure.

An example of a site with both breakwater and seawall is shown in Figure 11. The breakwater is designed to protect the vessels and infrastructure within the harbour, while the seawall is designed to protect the land immediately behind.

There have been a large range of seawalls built around Australia as shoreline protection. The type of seawall should be chosen to suit the local site conditions and constraints. Historically, quarried stone has been a popular armour type in many locations due to the relative abundance of suitable rock materials. Alternative concrete armour units have also been developed that provide improved wave resistance. They include simple concrete cubes (wave resistance provided by mass as a direct replacement for rock armour) through interlocking units (e.g. Dolosse, Hanbar, Core-loc, Accropode) or friction/pattern placement units (e.g. Seabees) – Figure 12 (ii-g) and (vi).

For milder wave climates sand filled geotextile containers, concrete blocks fixed to geotextiles, and stone pitched armour may be considered with caution. The local situation can greatly affect the selection of the optimum type of seawall.

The main types of seawall are presented in Table 5.

Some of the seawalls are permanently exposed to the forces of the ocean. Others may be buried beneath a dune formation at the back of the beach and only exposed in severe storm conditions.

Preliminary design of seawalls is generally undertaken utilising either the European "Rock Manual"

Table 5. Primary seawall types.

Seawall Type	Description	Figure References
Quarried Armour Stone	Rock armour stone sourced from a quarry or "waste" from another project.	Figure 12 (i) Quarried Rock Seawall at Port Coogee, WA.
Concrete Armour Units	Armour units constructed of concrete in a wide range of proprietary shapes and sizes.	Figure 12 (ii) Examples of armour units (model scale). a. Tetrapod b. Concrete block c. Hanbar d. Accropode e. Tribar f. Dolosse g. Seabee Figure 12 (iv) and (vi)
Gravity or Tie-back Wall	Gravity or tie-back wall constructed of mass armour units or vertical blocks.	n/a
Concrete Seawall	Concrete stairs, slabs and walls to form the front face of the seawall.	Figure 12 (iii) Concrete seawall at Coogee Beach, NSW
Sheet Piling	Typically steel driven sheet or contiguous drilled concrete piling taken to adequate depths for geotechnical stability.	n/a
Gabions/ Reno Mattresses	Steel cage/mattress filled with small rock material. For mild wave conditions only.	n/a
Flexmat System	Concrete slabs fixed to a geotextile. For mild wave conditions only.	n/a
Geotextile Sand Containers	Geotextile "pillow" filled with sand and placed in multiple layers. For limited wave conditions.	Figure 12 (v) Sand-filled geotextile container seawall under construction at Watermans Bay, WA.

Figure 12. Primary seawall types (see Table 5 for descriptions).

(CIRIA, 2007) or the American Coastal Engineering Manual (US Army Corps of Engineers, 2002). For detailed design, physical modelling is commonly used in Australia to better evaluate the seawall performance in respect to armour capacity and the rates of overtopping.

In recent years there has been significant research in Australia, Europe and Northern America into better ways to utilise quarried rock in breakwaters and seawalls. Optimal use of local quarries can greatly reduce the cost of the project. It can also result in better environment outcomes through less trucking/transport energy use and social disruption.

Another area of research interest has been in the estimation of overtopping rates and the acceptable limits for pedestrian, vehicle and general use of the area immediately behind the seawall. Many research projects into overtopping have been completed in Japan and Europe such as the work completed in the development of the EurOtop Manual (EurOtop, 2007).

Impacts of Seawalls

The design of a seawall requires a comprehensive understanding of the sediment dynamics in the area. The presence of a seawall will change the coastal dynamics when the seawall is exposed and dissipates the ocean energy. Without the seawall the beach sand and dune could be eroded and hence transported to another area alongshore or offshore. With the seawall stopping such erosion the nearby areas will be receiving a different amount of sand feed. Localised erosion in front of the seawall may also be increased by reflective wave energy during storm wave exposure. This effect which is localised in space and time to the immediate area of the seawall during the storm is generally recovered after the storm.

7.2 Beach Nourishment

The coastal erosion and subsequent recession of the shoreline due to climate change could be ameliorated by adding extra sand to the coastal sector. This approach is already used at many sites around the world including Australia, Asia, Europe and the Americas. The sand for beach nourishment could come from:

- Terrestrial sources such as sand pits or waste sand from development activities (Figure 13).
- Offshore marine deposits accessed by dredging or the spoil from dredging navigation channels or harbour development.
- Coastal deposits on beaches that are accreting or have sufficient buffer to safely allow extraction.

Figure 13. Sand extraction at Power Station Beach, North Coogee, WA.

The aim would be to provide sufficient sand to allow a new beach profile to form in response to the raised sea level and changed wave and current conditions (Figure 14). The action of the ocean waves and currents will rework sand on the profile and spread it throughout the active profile.

A detailed and comprehensive knowledge of the sediment dynamics of the area is essential for the design of beach nourishment works. Beach nourishment is often placed with a large initial volume with smaller on-going placements. In some situations, the initial beach nourishment volume may be placed over a period of several years. The benefit in this case is to use the ongoing monitoring program to confirm and refine the design of the beach nourishment works as nourishment continues.

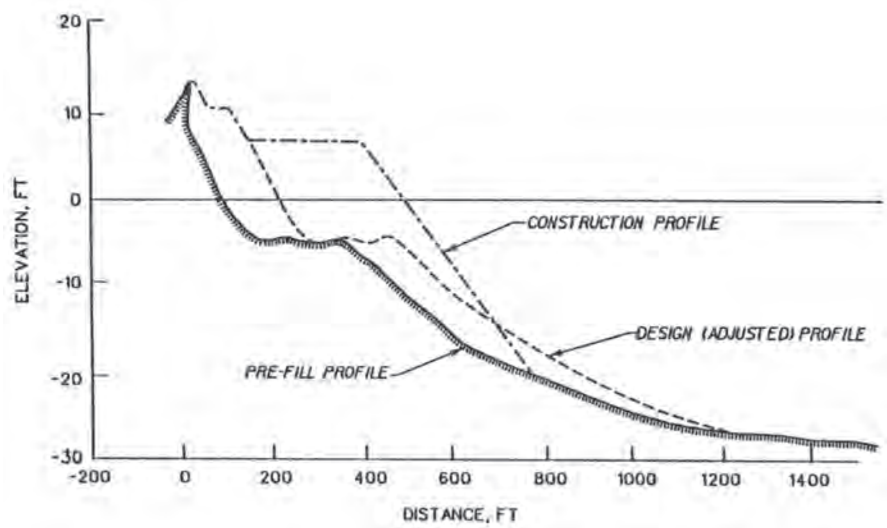


Figure 14. Beach nourishment profile. (Source: Advances in Coastal & Ocean Engineering, 1996)

The volume of sand nourishment required is dependent on a number of site specific factors.

The key considerations in the design of a beach nourishment program include:

- Sand properties – including colour, density, particle size distribution, proportion of fine particles less than 75 micrometres, presence of contaminants and pollutants. To minimise sand losses and develop a beach profile similar to the existing, it is preferred to use sand of same or larger size and density.
- Loss of sand materials during the redistribution by the action of waves and currents – an overfill ratio is adopted to allow for such losses.
- Active height – which is a measure of the area of the beach profile that will be affected by the addition of the sand.
- Erosion scarps in the sand nourishment as it is redistributed by waves and currents.
- Methods of placement of the sand and the resultant social and environmental impacts.
- Environmental impacts and sustainability at the sand extraction site.

It can be cost effective to place the sand nourishment on the visible beach and allow the action of the tides, waves and currents to redistribute the sand throughout the active profile. The bulk of the redistribution process may take weeks to months to occur but movement of sand to the deeper portions of the active profile may only occur during significant storms. Such storms may not be experienced for many years following the beach nourishment.

Although the method can be very cost effective with few environmental impacts, it is often criticised by local communities. As the sand nourishment is redistributed it could appear that the ocean has just washed the sand away and the project can be perceived as a waste of money. Considerable community consultation and information is necessary to fully inform the stakeholders and address such criticisms.

The cost of the sand for beach nourishment can be significant. In some locations coastal engineers have tried to utilise the "waste sand" from other project as productive input to the beach nourishment project. The Gold Coast City Council has developed a very innovative approach and uses sand from inland development sites for beach nourishment. Construction sites within 0.5 km of the beach have supplied in the order of a million cubic metres of sand for beach nourishment since 1985. This is an ideal use of the sand from the construction sites. This practice is now common with many local government areas with an example shown in Figure 13. Dredging of navigation channels and new marinas can also provide sand for beach nourishment.

In addition to an effective engineered seawall along the "A-line" protecting the Gold Coast shoreline from Kirra to Southport, Gold Coast beaches have been maintained by a combination of major and minor beach nourishment exercises since the 1970s, the most notable being the 7 million cubic metres nourishment of the lower Gold Coast beaches between the mid 1980s to the mid 1990s (Strauss et al., 2009). Dredges extracting sand from offshore marine sands may place the nourishment sand underwater near the beach or onto the beach via pipelines or by "rainbowing" (Figure 15). Sand is also being supplied from the Tweed River entrance bypassing project (ref. to section on Entrance Bypassing in Estuary and Entrance Management Options).

Figure 15. Beach nourishment "rainbowing". (Source: BPA Qld)

Beach nourishment is also being considered as a potential adaptive option to offset adverse climate change impacts on Sydney's beaches. Extensive work has been undertaken by Gordon (2009) in determining the volume of sand required to offset climate change impacts and identifying potential nourishment sources, including the analysis of offshore sediment deposits as potential sources. The implementation of such a large scale nourishment program would require the establishment of a special purpose major project authority similar to the Snowy Mountains Project. The work by Gordon (2009) highlights the importance of identifying sand reserves, including offshore sediment, and preserving them for the future.

The US Army Corps of Engineers has completed significant research into beach nourishment. It has useful information on estimating the closure depth of the active zone and the likely overfill ratio. These are important in the correct design of beach nourishment works.

Impacts of Beach Nourishment

Matching the colour of the nourishment sand to the native sand is often of great concern to various stakeholders in the planning phase. Experience has shown that as the nourishment sand is mixed with the native sand in the redistribution processes, the final colour of the beach becomes a blended colour and has less visual impact than may have been expected. Obviously, this depends on the colours of the sands, the nourishment quantities in the works as well as the vigour of the natural processes causing the redistribution of the sand.

When a beach berm is formed with sand nourishment and the waves and currents redistribute the sand, an erosion scarp may form in the sand nourishment. It is important to design and construct the nourishment to control the height of any erosion scarp. Most agencies would like the resultant erosion scarps to be less than 1 to 1.5 m in order to reduce the public risk during the reshaping processes. Higher erosion scarps increase the risk of a sudden collapse. This may inadvertently bury and trap a beach user and result in injury or even death.

Environmental impacts at the placement site may arise from turbid plumes and smothering of the existing seabed. Even 3 to 5% of fines (less than 75 micron) could result in a turbid plume in the littoral zone as the sand nourishment is redistributed. Such plumes can extend hundreds of metres along the beach and be of significant concern to various stakeholders.

Figure 16. Beach nourishment placed to avoid dangerous erosion scarps.

7.3 Groynes

Groynes are constructed normal to the coast from the shore to a sufficient water depth offshore so as to interrupt the wave driven longshore sediment transport resulting in accretion of sand on the updrift side of the groyne. Multiple groynes spaced along a section of the coast are frequently utilised to manage coastal erosion – in such instances sand nourishment should be undertaken conjunctively.

Breakwaters and reefs may also change the coastal dynamics by reducing the amount and direction of the wave energy arriving at the coast. These structures are discussed in Section 8.

Groynes can be constructed using floating or land based equipment and from a range of materials. The materials include:

- Quarried rock armour protecting a core of smaller rock
- Concrete armour units protecting a rock core
- Sand filled geotextiles
- Steel or concrete sheet piles
- Structural concrete in the form of caissons, and
- Timber groynes (these have had limited success when tried in Australia).

The functional design of groynes is complex and detailed modelling of the wave and sediment dynamics is needed. Beach evolution models need to be calibrated to match the existing dynamics and sediment budget. The structures can then be introduced in the model and the changes estimated.

Breakwaters and reefs may also change the coastal dynamics by reducing the amount and direction of the wave energy arriving at the coast. These structures are discussed in Section 8.

Knowledge of the natural variability over several decades is needed to be confident in the assessment of all the dynamics and fluctuations. The natural variability is important as some beaches receive and lose sand under a variety of conditions, as described in Section 3.

Figure 17. Rock Groyne construction at Quinns, WA.

Figure 18. Maroochydore Beach geocontainer groyne. (Source: Cox 2009)

The structural design tools for groynes and breakwaters are similar to those used for seawalls. Armour type and size, filtering requirements to contain the underlayers and core, as well as consideration of toe protection and overtopping are all important.

Impacts of Groynes

Groynes can have a range of impacts on the coastal region in the following ways:

- Downdrift effects on the coastline. Groynes being designed to interrupt the longshore transport of sand and accrete the updrift shoreline concurrently reduce the feed of sand to downdrift areas, which can cause shoreline erosion. Groynes can be positioned so that the downdrift impacts do not affect high value land. Sand Nourishment should also be placed at the time of groyne construction to reduce some of these impacts.
- Social impacts. Different views on groynes exist within the community. Some people and communities object to groynes due to the aesthetics and the barrier to walking along the beach. Other people and communities believe that groynes provide additional opportunities for fishing and a lookout platform. Effective integration of coastal protection with nearshore amenities including promenades, bicycle paths and picnic reserves should always be considered.

7.4 Coastal Flooding & Overtopping

Property located on the coast can be subject to coastal flooding from high ocean water levels resulting from the tide, storm surge and local wave setup. Climate change is projected to increase the level of ocean by increases in the mean sea level, the storm surge and local wave setup. Coastal flooding is different from river flooding. Coastal flooding is often dominated by the tidal cycle, with the maximum coastal flooding often occurring at the peak tidal levels. The tidal cycle also means coastal flooding typically has a shorter duration compared to river flooding.

The drainage of the coastal land may become more difficult with higher ocean water levels.

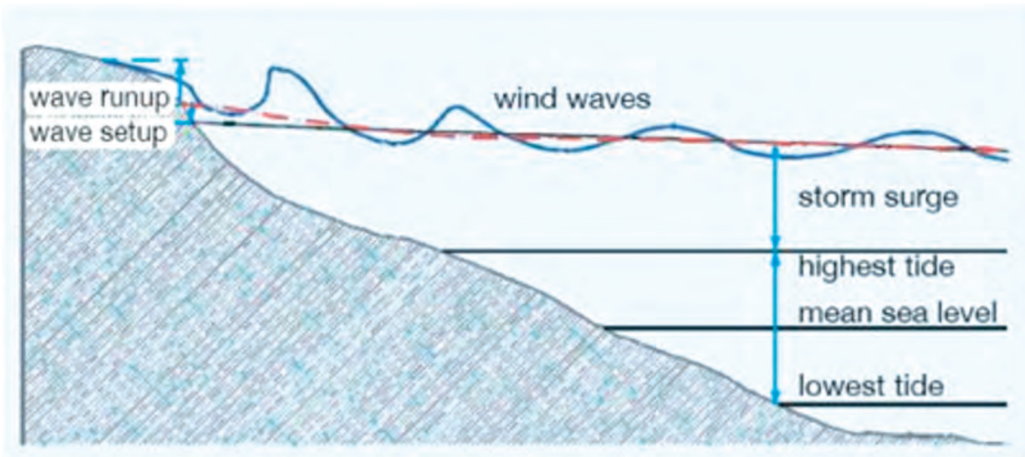


Figure 19. Components of coastal flooding.

Property located very close to the shoreline could be flooded by individual wave run-up above the elevated extreme still water level incorporating tide, surge and wave setup. Where properties are located very close to the shoreline, coastal erosion is also likely to be a significant threat.

Behind seawalls, property may also be affected by wave runup and overtopping. Waves breaking onto the structure at high water levels could cause some of the water to overtop the structure. The frequency and severity of this overtopping is projected to increase with climate change.

Early European settlement was often on flood-prone land – whether from coastal flooding or from rainfall runoff. At the time, the operational efficiency may have justified the flooding frequency. In some cases, knowledge of the flooding risk was not known at the time of development.

Figure 20. Early Fish Cannery at Mandurah, WA. (Source: City of Mandurah)

Figure 21. Seawall with wave deflector (Hong Kong).

As the Australian economy developed and prospered there has become an expectation to provide better protection for property from coastal erosion and flooding – the risk must be commensurate with the value and importance of the development.

In addition, critical infrastructure with an important role in mitigating the impacts from a disaster should be designed with a lower risk of being damaged by coastal erosion or flooding. Such buildings would include hospitals, power stations, emergency services agencies etc. The Queensland Coastal Plan (DERM, 2012) gives guidance on design recurrence intervals and planning periods for different types of development and critical infrastructure. Some industrial and other developments have a functional need to be reasonably close to the coast and seawater level. These types of developments may be able to accept a slightly higher risk of flooding.

There are many different approaches to the issue of coastal flooding used by various agencies around Australia. They have been developed in response to the local history and expectations. The various requirements, regulations and policies need to be investigated for each locality. In broad terms, for freehold residential and non-industrial property, the minimum finished floor level is now often set as the coastal extreme water level with a 100 year Average Recurrence Interval (ARI) plus an allowance for climate change and a freeboard or factor of safety.

In estimating the coastal extreme water level with 100 year ARI, the local storm surge and wave setup should be properly included. There can be significant wave setup within the surf zone during severe storms.

The allowance for climate change should include changes to the mean coastal sea level as well as the storm surge regime and higher nearshore wave setup for areas where the wave conditions are expected to increase with climate change. Different parts of the country are also influenced by different events such as cyclones and cold fronts. No single number is relevant for all areas of the Australian coastline.

There are many established coastal developments around Australia that may have a higher than desired risk of coastal flooding as climate change continues. If a decision is made to maintain the assets then it may be possible to reduce the flooding risk by the following:

- Constructing levees or flood barriers around the development.
- Raising the development level over time, e.g. changing building regulations to ensure that any replacement development is raised and the flooding risk reduced. The planning agency could give notice that in a decade or two, the roads and drainage systems will be raised to new levels and all new buildings must be compatible with the higher roads and drains.
- Adopting more resilient and adaptive building types – for example piled construction with buildings able to be raised rather than inflexible "slab on ground".

Where raising the ground levels presents major challenges, it may be possible to place the habitable areas above the future flood levels and utility areas such as car parking and workshops.

Where development is protected by seawalls, the risk of inundation may be acceptable but the risk of overtopping may be too high. The design of new developments should take overtopping into account. For existing developments, it may be possible to raise the crest of the seawall (or breakwaters as discussed in Section 8) to mitigate the impacts of climate change. Another approach could be to change the crest details to incorporate a wave deflector to reduce the amount of overtopping.

7.5 Effectiveness for Climate Change Adaptation

The shoreline protection options presented in this Section are likely to be impacted by a number of climate change effects. These are also discussed at the end of Section 8. These impacts indicate a need for ongoing monitoring (see Appendix A – At What Price Data?), possible redesign and upgrading of existing structures as well as accommodating these impacts in the design of new protection works.

Seawalls

Most seawalls are likely to be readily upgradable (but at considerable cost) to accommodate the possible effects of climate change, as outlined below:

- Should the wave climate increase due to sea level rise or increased storm severity, the primary layer armour protection will need to be increased. This may require significant re-design and upgraded construction. As outlined in Section 8 under some circumstances an additional layer of larger armour rock may be placed on the outside face of the seawall.
- Should the overtopping rates increase due to sea level rise, the design could be adjusted by increasing the crest height, increasing the crest width or adjusting the use of the land areas immediately behind the seawall. The type of land use could be selected to best suit the overtopping regime. This could range from managed recreational uses close to the seawall, then a public road and then freehold land for commercial or residential uses. Land uses may also change over time.
- For any new structures adaptability can be built into the initial design by such measures as oversizing the toe and designing foundations to accommodate any future extensions.

Regular monitoring of seawalls should be undertaken by a qualified coastal engineer to identify when maintenance repairs and/or reconstructions are required. This monitoring program will assist in identifying if the effects of climate change are increasing the frequency and magnitude of damage with an increased requirement for maintenance and eventual major repair and/or reconstruction of the seawall. Physical modelling in laboratory wave flumes and/or basins may be required in designing seawall and groyne upgrades and/or reconstructions for climate change.

Beach Nourishment

Predicting the impact of climate change on sandy beaches is not simple. The cross shore and alongshore distribution of the sand needs to be understood. Some agencies presently use a gross simplification of the Bruun Rule discussed in section on Modelling and Data Collection (Bruun, 1962; 1983) to estimate the recession that could result from rising sea levels. This simple (to apply) model does not simulate movements of sand along the shore or for changes in wave conditions.

Both may occur in response to climate change. It is noted that to date there are few neither verified nor accepted alternative methods for estimating long term shoreline response to sea level rise. The Bruun Rule should be applied on a site specific basis not as a simplistic rough rule of thumb. The Queensland Coastal Plan (DERM, 2012) gives guidance on adjustments to the Bruun Rule for tidally dominated flat profiled coasts.

There is a need for more research, or at least sitespecific investigations, in this area as the design tools readily available are too simplistic to properly assess the wide range of circumstances that could arise. Better coastal engineering tools to properly evaluate the impacts of climate change on beaches are needed. Detailed beach evolution models that could be run for many decades to a century or more would be useful in the assessment of the impacts of climate change and the performance of beach nourishment works.

Groynes

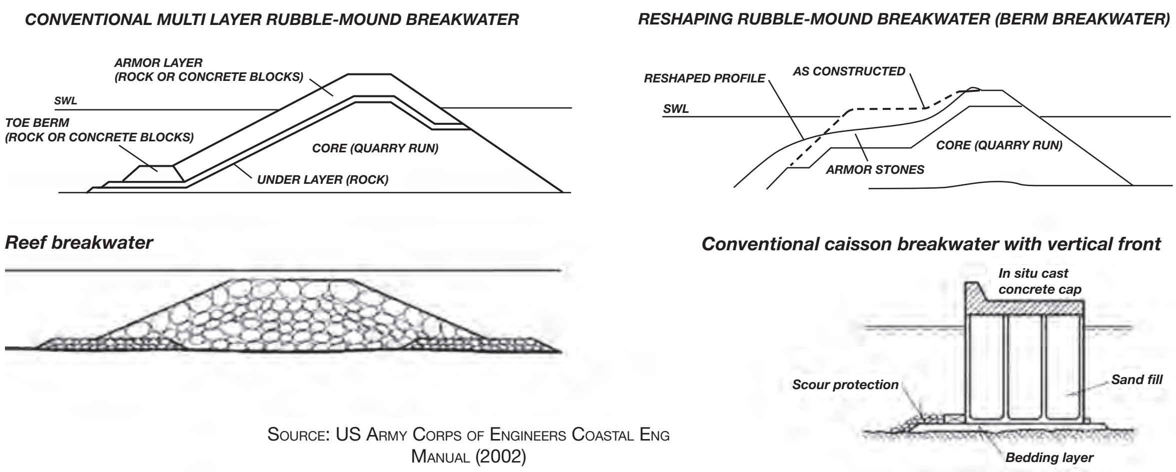
As with beach nourishment, there is uncertainty as to how beach profiles will change in response to sea-level rise and changing wave conditions, impacting on anticipated changes to littoral transport. If a groyne is not functioning as required under changed climate conditions, the groyne can be extended, shortened or even removed. The groyne's structural capacity can also be increased by adding a layer of larger armour rock to the outside of the groyne. The groyne may also require landward extension.

The shoreline response to groynes can be monitored by constructing the groyne in a couple of stages. This provides the benefits of having prototype monitoring data to fine tune the later stages as well as spread the capital expenditure over several years.

8 OFFSHORE PROTECTION/ AMELIORATION OPTIONS

8.1 Overview

When faced with the prospect of loss of infrastructure and property due to the impacts of coastal hazards, communities all around the world usually have a desire to protect those assets. This is reflected in onshore protection (as outlined in Section 7) and by the construction of breakwaters to shelter port and harbour facilities from extreme wave energy, and offshore structures to minimise shoreline erosion by modifying wave transmission to the coast. Breakwaters typically are rubble mound construction (conventional, reshaping or submerged reef) or caisson as shown below (Figure 22).



SOURCE: US ARMY CORPS OF ENGINEERS COASTAL ENG MANUAL (2002)

Figure 22. Conventional breakwater types.

Breakwaters are large and expensive coastal engineering structures, particularly when built on exposed coastlines with extreme storm waves. Rubble-mound breakwaters are constructed with outer layers of armour consisting of large rock or concrete units. They can be built to a level above or below the water surface and can be attached to the shore in the case of harbour protection, or detached from the shoreline (usually shore-parallel). A special type of submerged breakwater is the artificial reef.

One major effect of these structures, whether attached or detached, is the creation of currents that can interrupt longshore sand transport processes and cause downdrift coastal erosion, often at some considerable distance from the structure. Detached breakwaters can also cause updrift erosion due to induced longshore currents. The ecological consequences include altered hydrodynamics which influences the dispersion of marine organisms, changes in sediment distribution which affects abundance and composition of fauna and loss of habitat through erosion and alteration of habitat by replacing soft substrata with hard structures (See Cardno, 2010, for a detailed assessment of ecological impacts).

Alternative approaches to offshore protection are also considered in Section 10 of these Guidelines, but generally these are unproven, particularly in the context of climate change impacts and adaptation.

8.2 Attached Breakwaters

The entrances to most major estuaries and certainly most major ports are protected from waves and sand shoaling by large and expensive breakwater structures (e.g. Newcastle and Port Kembla in NSW, Abbot Point Qld, Mackay Qld (Figure 23), Port Hedland WA). Australia's economic prosperity is reliant on its seaports remaining open and undamaged both during and particularly post extreme events.

Figure 23. Breakwater at Mackay Harbour, Queensland. (Source: www.skyscrapercity.com)

Breakwaters are usually designed and constructed with recognition of the extremes of climate variability. However, some structures will be inadequately designed to withstand the larger waves that can be expected to impact them during extreme storms at higher sea water levels projected with climate change.

Attached rubble mound breakwaters are designed with heavy primary/outer armour rock or concrete see (Figure 12 in Section 7 for examples) that are sized to resist the impact forces of waves that can break upon them. Preliminary design of breakwaters is generally undertaken utilising either the European "Rock Manual" (CIRIA, 2007) or the American Coastal Engineering Manual (US Army Corps of Engineers, 2002). Both manuals present empirical formulations (based on physical modelling results from coastal laboratories utilising wave flumes and wave basins) for the sizing of outer rock or concrete units (Figure 24).

Figure 24. Physical Model testing of breakwater design. (Source: Water Research Laboratory, UNSW)

After considerations of cost, constructability, service, maintenance and sustainability most "final" designs are optimised prior to construction by project specific laboratory wave flume and/or basin physical modelling.

Impacts of Attached Breakwaters

Large attached breakwaters can cause major disruption to sediment transport processes, particularly if there is a dominant longshore drift. Deflection of the longshore currents is shown in Figure 23 for the Mackay breakwater. Generally, the shoreline impacts of major structures such as these are similar to that for groynes and entrance breakwaters, as discussed in Sections 7 and 9.

8.3 Detached Breakwaters

Detached breakwaters are a category of emerged or submerged structures most frequently placed parallel to the coast to reduce wave energy transmission, longshore current and transport and, as a consequence, reduce erosion and increase the beach width (Medina, 2012). Detached breakwaters can sometimes be chosen as a coastal control structure as part of a shoreline management strategy aimed at holding the current coastal position, or increasing the longevity of beach nourishment. The effectiveness of these breakwaters in protecting the shoreline depends on the detail design of the structure including:

- Crest freeboard (crest level above mean sea level), the higher the freeboard the higher the visual impact and the lower the wave transmission to the shoreline.
- The length of the breakwater relative to the distance offshore.
- The distance offshore relative to the width of the surf zone.

For shoreline protection detached breakwaters usually are placed a distance offshore of up to twice the surf zone width. Closer inshore, the breakwater tends to act as a toe structure, stabilising a perched beach profile. Where a series of breakwaters are used, the spacing also becomes a critical design parameter.

Breakwaters for shoreline erosion control are generally constructed with crest below mean sea level (i.e. submerged) or with small positive crest freeboard to minimise the aesthetic impact and the cost (ENCORA, 2009). The principal factors affecting current patterns and the corresponding beach response to a series of segmented detached breakwaters are crest freeboard, distance to the shoreline, breakwater length and gap width (Figure 25) (Medina, 2012). The higher the breakwater length and crest freeboard and the lower the gap width and distance to shoreline, the lower will be the resulting wave energy transmission and the higher the induced salient and reduction of longshore sand transport. If the induced salient reaches the detached breakwater, a tombolo is formed (Figure 25 and Figure 27). Low-crested detached breakwaters are common in Europe and a detailed assessment of their performance and design is given by Lamberti et al. (2005). Ranasinghe & Turner (2006) provide a review of submerged breakwaters.

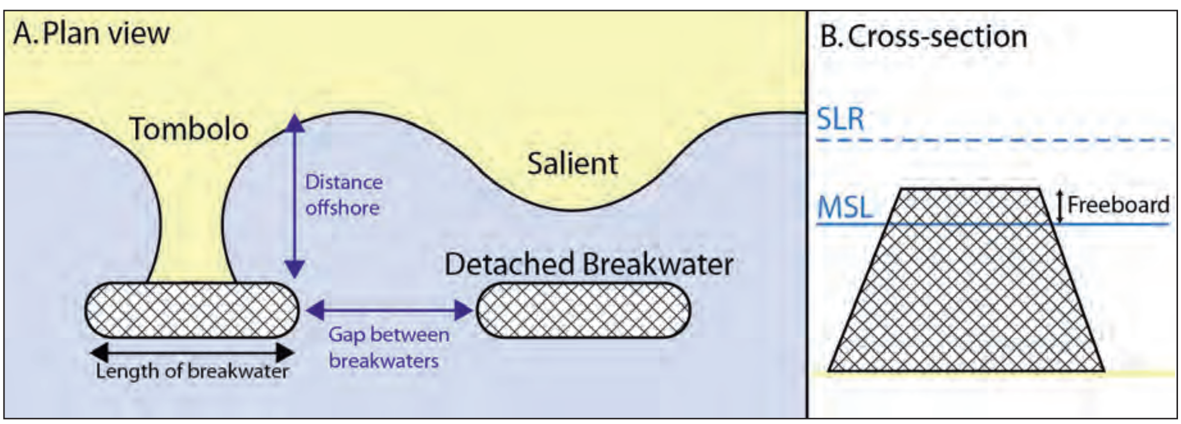


Figure 25. Detached breakwaters can reduce incoming energy and create salients or tombolos.

Figure 26. Detached emerged breakwater in Barcelona, Spain. (Photos: Willy Uribe and Google Earth)

Detached breakwaters reduce the longshore transport of sand (in the same manner as groynes) (see Section 7) and may cause or significantly increase erosion in nearby unprotected beaches; therefore, sustainable erosion control schemes should be analysed from a regional perspective to consider whether a single breakwater or segmented number of detached breakwaters may be the best solution in a specific coastal area.

Detached breakwaters can be constructed from quarry materials, concrete armour units or sand filled geotextile containers, depending on the costs and availability of materials. The prefabrication of concrete elements reduces the environmental impact on the beach, changing the conventional quarry dumping construction by installation of prefabricated concrete elements with a specific design (US Army Corps of Engineers, 2002; THESEUS, 2010).

Detached breakwaters, being sensitive to the crest freeboard, are less effective in regions with higher tidal range.

Figure 27. Detached breakwaters at James Point Beach, Kwinana WA. (Source: Google Earth)

Impacts of Detached Breakwaters

Detached breakwaters impact on the shoreline in a number of ways:

- They provide wave sheltering, although complete sheltering cannot be obtained due to wave energy diffracting around the end of the structure. (Submerged breakwaters provide even less sheltering).
- Overtopping adds water mass and results in return currents being generated.
- Wave set-up is reduced in the lee of the breakwater setting up longshore gradients and eddies with the potential for blocking of longshore currents by these eddies diverting longshore currents around the structure.
- Littoral transport will decrease due to attenuated wave energy and longshore current causing a salient or tombolo to form depending on the design parameters.
- Local erosion will occur close to the head of the breakwater.
- If a tombolo forms there is the potential for erosion to occur on the downdrift side.
- For segmented breakwaters, circulation currents can result in dangerous rip conditions.
- There can be considerable amenity impact in cases where seaweed/grass accumulates.
- There can be considerable visual impact of the structure if the breakwaters are emerged (Figure 28).

Figure 28. A series of emerged breakwaters at Marina di Pisa, Italy demonstrating poor visual impact and tombolo formation. (Source: R. Tomlinson)

8.4 Submerged Artificial Reefs

Submerged artificial reefs function through wave dissipation and wave refraction, which leads to salient growth in the lee of a reef. Wave energy is dissipated on the reef resulting in less energy at the beach in the lee of the reef and the consequent deposition of sediment. Submerged reefs are more effective in areas with small tidal ranges.

Recreational and public amenity can be incorporated through surfing, diving, sheltered swimming, water games, fishing and/or marine habitat. The inclusion of amenity, however, requires the amalgamation of different purposes in the reef design and, consequently, can make the design more difficult than that which may be required for coastal protection only. Even if only coastal protection is required from an offshore reef, it is important to thoroughly understand the local physical processes in order to optimise placement (Jackson et al., 1997; 2007). Indeed, poorly designed and positioned submerged reefs can accelerate erosion if placed too close to the shore by "compressing" the surf zone and increasing alongshore currents (Ranasinghe et al., 2006).

Multi-purpose artificial reefs (Figure 29) are being constructed with sand filled geotextile bags (see Section 10 and the Narrowneck Reef case study below). In some cases reefs have been constructed with rock or concrete blocks, where units are placed on the seabed according to design specifications using an excavator mounted on a barge. CIRIA (2008) provides an overview of all aspects of multi-functional artificial reefs.

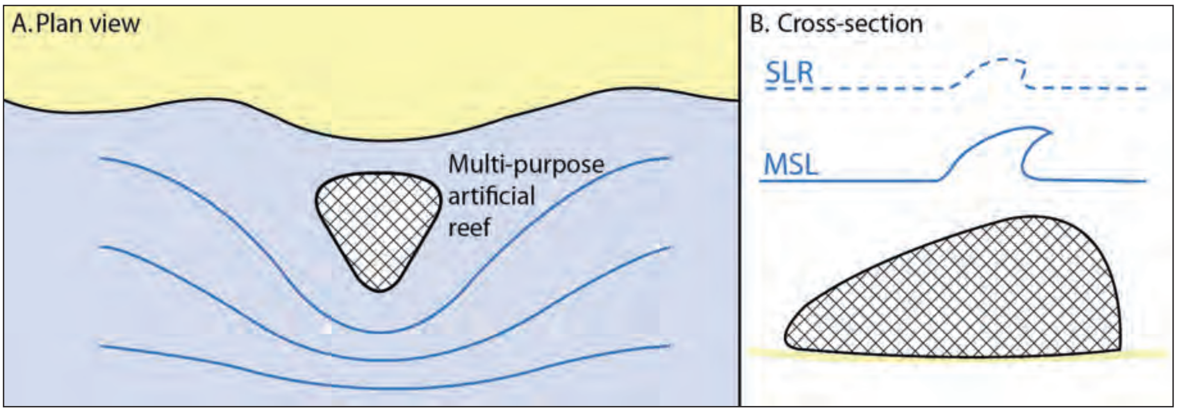


Figure 29. (A) Artificial reefs can be designed to enhance surfing conditions; (B) future sea level rise can reduce the efficiency of these structures and the quality of the breaking waves. However, considering the lifespan of the structure of approximately 20 years, sea level rise is unlikely to affect its functionality.

8.5 Effectiveness of Offshore Options for Climate Change Adaptation

Offshore structures generally have water on both sides and their design will be compromised by all of the predicted coastal climate change impacts. Consequently there will be a need to consider retrofitting for existing structures with typical 50 to 100 year design life-spans. Of the anticipated climate change impacts mentioned in the Introduction sea level rise is particularly relevant because of the increasing breaking wave heights and increased probability of extreme elevated water level (Church et al., 2006).

Sea level rise and changes in the wave climate can affect the efficiency and stability of coastal protection works including breakwaters. While breakwaters can be efficient in the short term, a rise in the sea level or substantial changes in the wave energy and direction can alter their role in beach and shoreline stabilisation.

For emergent breakwaters, the crest freeboard can be submerged by a rising sea level, requiring further interventions to maintain their function. Changes in the wave climate can require expensive changes in the design of the structure (e.g. crest level, armour size, orientation). With the mass of the armour rock/units being proportional to the cube of the impacting wave height, a small increase in wave height due to climate change can be significant in terms of the required armour size. Depending on the original design parameters, there may, in some cases, be little time before the existing structures can be expected to undergo significant damage and require maintenance and/or upgrading. Headland (2011) presents a useful methodology for effective determination of the timing of upgrades in coastal infrastructure with climate change.

Effective upgrading for larger waves may be able to utilise the existing structures as a base with new larger armour rock or concrete units being placed on top (Figure 30). This requires caution and there are many unknown factors to be considered including the sizing of upgrade armour on top of older smaller sized armour for higher design wave conditions and when might it be advisable to utilise concrete armour units and if so which shaped units and of what mass have better performance. The interface between the old and new armour layers can readily become a plane along which catastrophic sliding failure may occur.

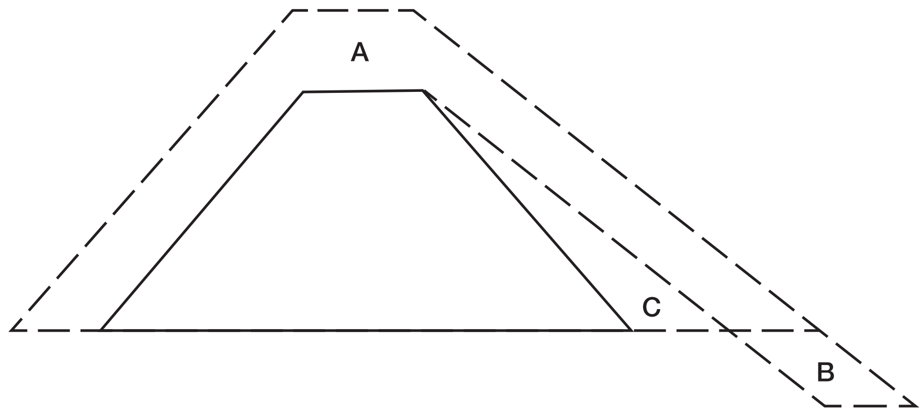


Figure 30. Changes required for breakwaters (A) crest raising; (B) toe modification; and (C) slope protection.

(Source: Townend and Burgess, 2004)

With increased design waves and higher water levels, over-topping of the crest and safety of people and equipment is increasingly important. Raising the crest to compensate may not always be practical, and the use of crest wave deflectors and/or wave absorption devices may need to be considered. Physical modelling in laboratory wave flumes and/or basins will be required in designing breakwater upgrades for climate change.

Detached breakwaters can therefore be seen as a measure to control the shoreline position in the medium term (5 to 20 years) but their efficiency as a long term strategy to maintain the current shoreline configuration is uncertain.

Sea level rise and changes in the wave climate can affect the efficiency and stability of multi-purpose reefs, in the same way it can affect the efficiency of other emerged or submerged structures. Multi-purpose reefs can be combined with other adaptation options such as beach nourishment as part of the broader scheme. The combination of multi-purpose reefs with hard engineering options should be considered on a case by case basis.

Overall the costs of modifying or replacing existing coastal structures will be high. Townend & Burgess (2004) estimate increases in the annual costs of structural replacement and upgrading ranging from 150% to 400% over and above the current level of expenditure for maintenance and replacement, depending on the future climate change scenario.

Table 6 (overleaf) presents an overview of the offshore protection/amelioration options which addresses the suitability of such options under climate change with regard to climate uncertainty, social and environmental impact and cost.

8.6 Case Study: Narrowneck Reef, Gold Coast

Narrowneck multi-purpose reef is located on the northern beaches of Surfers Paradise on the Gold Coast, and was constructed between August 1999 and December 2000 as part of the Northern Gold Coast Beach Protection Strategy. The aim of the project was to undertake beach widening and to provide an increased storm buffer and additional recreational amenity. The project involved a major

Table 6. Multi-criteria overview for offshore protection options.

OFFSHORE PROTECTION		
Climate uncertainty	Effectiveness	Performance dependent upon crest level relative to sea level.
	Flexibility	Modifications of the structure can be carried out. Costs of works will be high.
	Reversibility	Removal of rubble mound or concrete structures is expensive and unlikely. Feasible to remove structures made with geotextile bags.
	No regret	Creation of shelter, shoreline stability. Reduce wave action and risks for swimmers.
	Decision horizon	May require expensive upgrades in the long term under sea level rise conditions. Major infrastructure – 100+ year design life. 20-50 year horizon for upgrades or replacement.
Social and environmental impact	Accessibility	Generally no impact on shoreline access.
	Landscape	Emerged breakwaters can have a negative impact on coastal landscape, including changes in updrift and downdrift shorelines.
	Recreational use	Generally negative impacts on surfing conditions and navigation. Multi-function reefs can enhance surfing and recreational fishing and diving.
	Property values	Protection increases property values, however impacts on landscape can decrease it.
	Impact on ecosystems	Water circulation can be altered. Shelter for species. New habitat (particularly for submerged structures).
	Emergency procedures	No specific benefits or impacts.
Cost	Initial cost	High
	Cost of maintenance	Maintenance is minimal in the short term, except in response to extreme events and settlement. Retrofitting cost will be high under climate change.

beach nourishment program (over 1 million m^3 of nourishment), and the positioning of around 430 geotextile sandbags of approximately 150 to 300 tonnes each, following the complex design which was tested using numerical and physical models. These were filled with sand inside a split-hull hopper dredge. Once filled, the bags were transported offshore and dropped at pre-determined locations in accordance with the design.

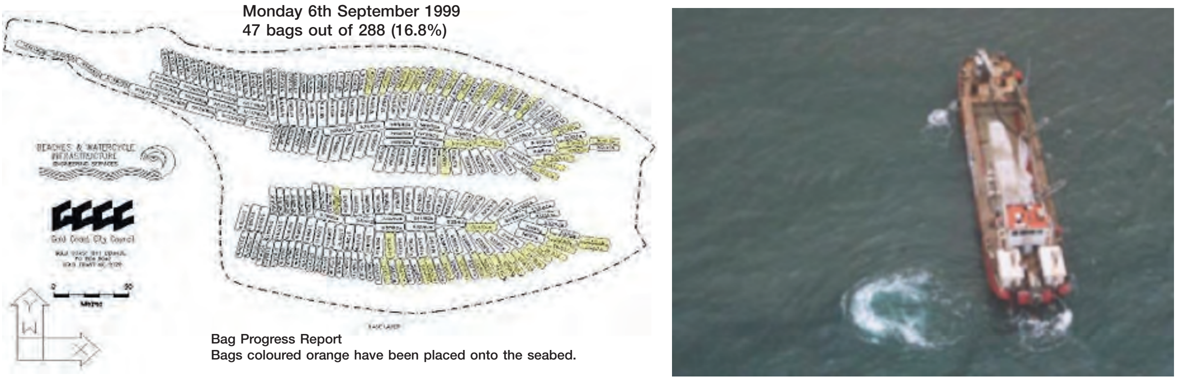


Figure 31. Original layout of geotextile bags and placement technique using bottom-dump barge. (SOURCE: ICM P/L)

The reef extends from a depth of approximately 10 m to 1.5 m below the lowest astronomical tide. The total cost of $8.4 million was divided between feasibility studies ($0.7 million), reef construction ($2.1 million) and beach nourishment ($5.6 million).

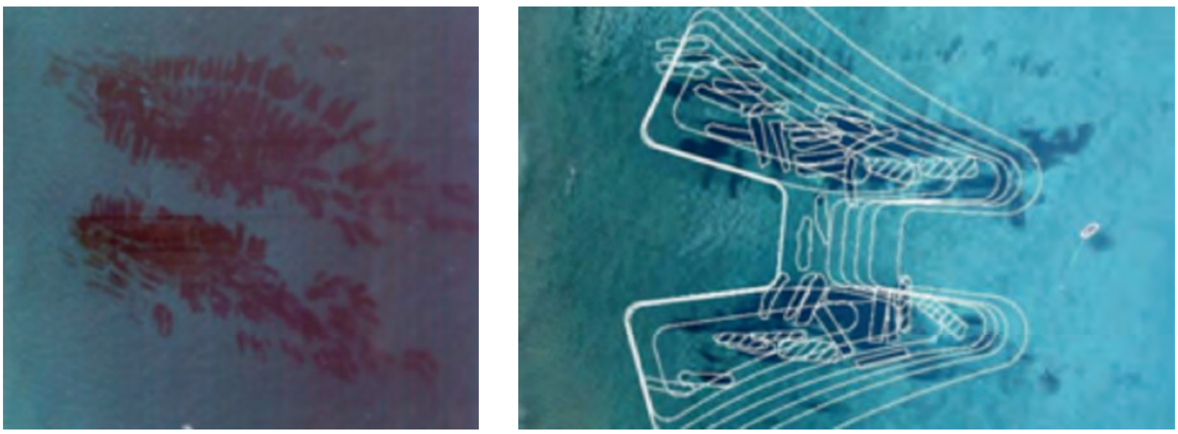


Figure 32. Condition of Narrowneck Reef in 2004 and 2011 showing overlay of bags added to the original construction. (SOURCE: B. CORBETT ICM P/L)

Structural integrity

The structure has been in service for 12 years. Latest monitoring shows:

- no evidence of general deterioration of standard or composite geotextile material
- no evidence of splitting or fraying of seams
- no evidence of failure of closure.

The manufacturer's nominated lifetime is 15 and 25 years respectively for standard and composite geotextile material. Forty-two containers have been replaced as part of regular maintenance. After the container is fully emptied of sand fill, weather events can often result in complete removal of the remaining material, leaving no evidence as to potential cause of failure. There has previously been clear evidence of instances where damage has been the result of:

- propeller damage
- anchor damage
- vandalism.

Ecology

- Detailed monitoring in 2007 showed wide diversity and abundance of species.
- In 2011 areas of high diversity remain concentrated on vertical faces and areas where the reef's structural complexity is high.
- Pelagic fish remain dominated by yellowtail scad – the population of these pelagic species is expected to be variable.
- Major species, including turtles, wobbegongs and stingray are still resident on the reef.
- The abundance of tropical and temperate species suggests that new recruitment is taking place.
- Aggregation of some species and the impact of recreational fishing may need to be monitored.


Figure 33. Kelp on crest container and Wobbegong Shark. (Source ICM P/L)

Impact on shoreline

- The analysis of beach width trends conducted in 2007 suggested that the beach had achieved an equilibrium state following the completion of nourishment in mid-2000.
- Seasonal variability of ~40 m in shoreline position is consistent with the impact of the May 2009 storm event and recovery.
- The beach width from Narrowneck to Surfers Paradise was fairly uniform at around 50-60 m in May 2009 whereas the latest monitoring (October 2011) displays beach width of around 70 m at Narrowneck increasing to 100 m at Surfers Paradise. (This is indicative of the reef providing a minor groyne effect and acting to widen the beach updrift as per the original design).
- The absence of a long term salient on the shoreline suggests that for some wave conditions there is sufficient longshore transport occurring shoreward of the reef to inhibit the formation of a permanent salient.
- The anticipated need for maintenance nourishment of the shoreline north of the reef (downdrift) due to groyne effects has not yet been required.

Figure 34. Narrowneck looking south – 1996 and 2011. (SOURCE: ICM P/L)

Climate Change Adaptation

A key advantage of the bagged-reef technology is the ease with which it can be removed (relative to rock or concrete units) in the event of unforeseen circumstances in the future. On the other hand, construction using mega-containers (typically 4 to 5 m in length) allows incremental crest height increases over time-adapting easily and cost-effectively to sea level rise projections with climate change.

9 ESTUARY AND ENTRANCE MANAGEMENT OPTIONS

9.1 Introduction

The key variables of climate change for estuary entrances are mean sea level, wave climate and rainfall runoff (NCCOE, 2012a). The impacts of climate change on estuaries and their entrances will vary with each estuary type and whether or not the entrance is trained. Digby et al., (1998) developed a national classification of Australian estuaries based on biologically-important and easily-quantifiable physical characteristics including the geological evolutionary stage (after Roy, 1984), the climate and hydrological processes. Three basic types are recognised; embayment estuaries (drowned river valleys), barrier estuaries and saline coastal lakes (Figure 35). While flooding, tidal ventilation and circulation in estuaries are very much a result of their geological evolution and stage of infilling (Roy, 1984), climate change has the potential to alter the hydrological processes.

The southern coastal regions of Australia are wave-dominated environments whereas the northern regions are tide dominated (Ryan et al., 2003). Most drowned river valleys (embayment estuaries) occur in NSW (e.g. Port Stephens, Hawkesbury River/Broken Bay) with some in Tasmania (e.g. Derwent River, Bathurst Harbour). Shallow barrier estuaries predominate on the southeast and southwest coasts (e.g. Gippsland Lakes, Goolwa-Coorong). Along the North West Coast, the Gulf of Carpentaria and the North East Coast a low wave energy environment and a high tidal range have created a drowned coastline characterised by numerous macro-tidal estuaries with deltas rather than barrier structures at their mouths, with infilling along this coastline having been extensive (e.g. Norman River, Burdekin River).

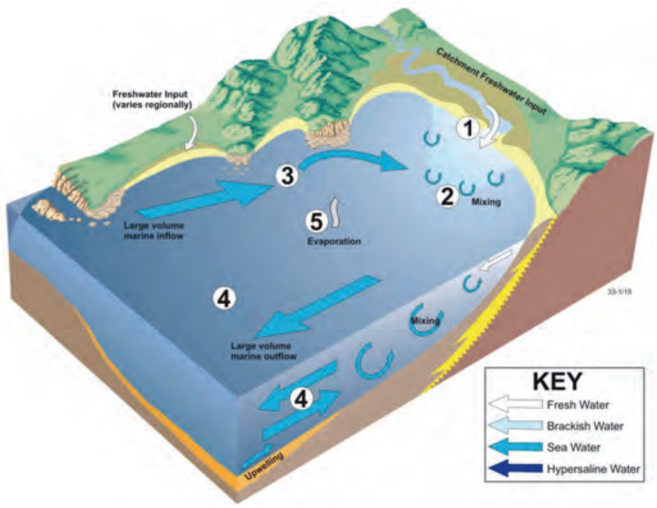
The natural entrances to these various types of estuaries range from deep and/or wide tide dominated inlets (geologically immature downed river valleys and embayments; (Roy, 1984) to wave-dominated narrow and shallow barred river entrances (geologically mature drowned river valleys and barrier estuaries) and intermittently closed or open lakes and lagoons (ICOLLS, see Figure 35). The former admit the full ocean tidal range whereas the latter two can constrict severely the passage of the tide, waves and flood waters, as indicated by the steep tidal gradients and swift tidal currents measured in these inlets (Roy, 1984). Many of these types of entrances have been modified with breakwaters and training walls to improve navigability and the conveyance of flood waters. In many instances, such modifications have instigated far reaching and long term changes to the tidal hydraulics and ecologies of these estuaries (Nielsen & Gordon, 2008). Such estuaries are likely to be sensitive to climate change impacts and, by the same token, to management works that may be implemented at their entrances.

9.2 Impacts of Climate Change on Entrances and Estuaries

Drowned River Valleys and Embayments

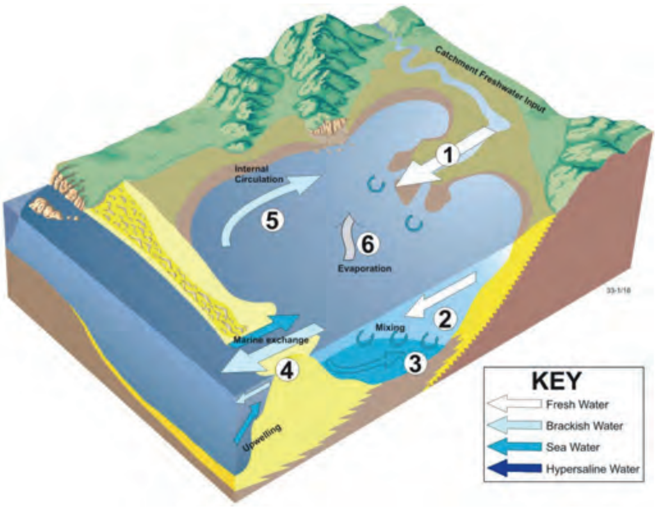
Entrances to drowned river valleys and embayments (Figure 35, top) are wide and located often in relatively deep water (greater than 20 m), allowing virtually the full passage of the tide, waves and flood waters, which are unimpeded by friction. Therefore, changes made to these entrances, unless monumental (such as a tidal or storm surge barrage), would have little impact on these processes and, by the same token, changes to tidal planes, such as mean sea level, wave power, wave direction or increased precipitation would have little impact on such entrances.

However, many embayments that lie in relatively shallow water (less than 20 m) may have been modified already, say, by dredging for navigation, for example, which may have altered wave transformation processes within the estuary and resulted in foreshore changes (e.g. Nielsen et al., 1991; 2011). Further changes to mean sea level and, hence, to water depths could see further



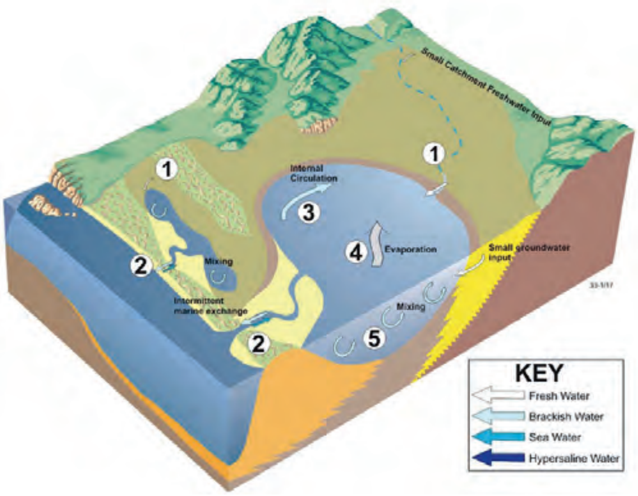
Drowned River Valley/ Embayment Estuary

1. Freshwater input from the catchment varies considerably.
2. Mixing between fresh and salt water occurs rapidly.
3. Flood and ebb tidal streams may have different routes into and out of large embayments.
4. Due to a wide, unconstricted entrance and large tidal prism, the exchange of water between the embayment and the ocean dominates hydrological processes.
5. Despite the large surface area, evaporation over the entire embayment is a relatively minor process.



Barrier Estuary

1. The volume of freshwater input varies.
2. Water circulation ranges from well mixed to salinity-stratified.
3. The distance that the salt-wedge penetrates depends on tidal range and the amount of fluvial flow received by the estuary.
4. Tidal ranges often are small and the amount of exchange of ocean and estuarine waters through the entrance depends on the size and length of the entrance channel and the tidal prism.
5. Wind-induced currents, tides and coriolis effects drive the internal circulation of wave-dominated estuaries.
6. Significant evaporation can occur.



Saline Coastal Lake and ICOLLs

1. Very little freshwater enters from the catchment and the quantity of input can vary seasonally.
2. Entrances tend to remain closed for long periods, only opening during floods.
3. Internal circulation within coastal lagoons is driven by wind and ocean wave and tidal influence is negligible inside the basin.
4. Evaporation may be significant in certain climatic regions, and can exceed freshwater input.
5. Salinity can vary significantly from brackish to hypersaline, depending upon the amount of freshwater input, climate and the frequency and duration of entrance opening.

Figure 35. Conceptual model of hydrodynamics in a tide-dominated embayment (top), wave-dominated estuary (centre) and coastal lagoon/ICOLL (bottom).

(Source: modified from Ryan et al., 2003). © Commonwealth of Australia (Geoscience Australia) 2012 alterations to wave transformation patterns, particularly in shallow waters (e.g. Cleveland Bay, Qld; Botany Bay, NSW; Port Philip Bay, Vic).

Climate change impacts on the foreshores of a drowned river valley and embayment estuaries are likely to be similar to those on open coasts (shoreline advance and retreat, oceanic inundation) and the management of such impacts on the foreshores within these estuaries would be commensurate with those on the coast. However, the management of the entrances to such estuaries to maintain near present conditions with climate change impacts could be a monumental task (see Section on tidal barrages).

Barrier Estuaries

In most cases, the entrances to barrier estuaries (Figure 35 middle) are narrow, relatively shallow and, often, are plagued by shoals of littoral drift causing considerable constriction to the conveyance of the tide, ocean waves and flood waters. This is exemplified by the steep tidal gradients and high tidal velocities measured through such entrances. Any change to the frictional characteristics at these entrances, such as breakwater construction or entrance deepening, has the potential to alter entrance and estuary hydraulics significantly, making these entrances and estuaries sensitive to anthropogenic and climate change perturbations (Nielsen & Gordon, 2008).

Because of the sensitivity of barrier estuaries to perturbation, climate change projections are likely to have major impacts on these estuaries. As tidal flow and the transformation of ocean waves are depth-dependent in shallow waters, any change to mean sea level has the potential to alter entrance and estuary hydraulics.

Where littoral drift is prevented from entering an entrance by breakwaters, a sea level change has the potential to alter tidal hydraulics significantly. Sea level rise would increase the water depth and, hence, allow more of the tide to enter the estuary. This would lead to an increase in the tidal flow velocities, an increase in the estuary tidal range and could trip such an estuary into an "unstable scouring mode" (O'Brien & Dean, 1972; Hinwood et al., 2012) where the resulting channel scour would continue to amplify the processes. Not only would mean estuary levels rise with the sea level rise but the tidal range within these estuaries would increase.. The impacts can be far reaching, ranging from increasing foreshore inundation to changing fringing ecologies, which may take decades or centuries to stabilise (Nielsen & Gordon, 2008). Once started, the changes could be exceedingly difficult to arrest.

In untrained entrances on wave-dominated coasts where the foreshore slopes are in equilibrium with the wave climate, a rise in sea level is likely to be accompanied by a rise in sea bed levels (Bruun 1962; 1983). In such cases the inlet channels would be unlikely to become deeper. However, a further complication to the impact on coastal processes can arise because of the large influence that the adjacent beach processes can have on estuary hydraulics and entrance stability. With climate change projected to increase wave power, the rates of littoral drift transport to these entrances are likely to increase, with the potential to force these inlets to reduce in cross section (Bruun, 1977). For an entrance which was initially close to the tipping point, an entrance may move into an "unstable shoaling mode" (O'Brien & Dean, 1972) leading to closure or to an elevated and restricted entrance (Hinwood et al., 2012) converting to an ICOLL. The impacts would include increasing mean lake levels and flood levels by more than the amount of sea level rise, which may impact fringing development and change fringing ecologies.

One of the major terrestrial concerns with climate change is the alteration of rainfall patterns and this is also of relevance to tidal entrances. Both increases and decreases in mean rainfall are possible for Australian coastal catchments. Such changes are likely to alter the tidal behaviour with consequential impacts on the erosion or deposition in such entrances.

Saline Coastal Lakes

The hydraulic characteristics of the entrances to saline coastal lakes (Figure 35 bottom) are unlikely to be sensitive to climate change perturbations as their entrance condition is mostly closed, opened only intermittently during periods of relatively high rainfall and runoff. Closure often follows quickly after the flood event.

However, as ICOLLs, typically, lie behind beach barriers and their entrances are closed for most of the time, the impacts of climate change sea level rise would be to raise their closed entrance bed levels and to translate their entrances landward should the beach barrier recede. Increases in wave power would hasten closures after breakouts and, while prolonged droughts could increase closure times, intensified precipitation and runoff could increase the frequency of breakouts. Higher beach berm levels would result in increasing mean lake levels and flood levels by the amount of sea level rise, which may impact fringing development and change fringing ecologies.

Macro-Tidal Estuaries

The Northern Territory coast is in most parts low lying with elevations at or slightly below the maximum tide levels, receiving freshwater flood flows from large catchments during the wet season (Williams, 2010; Woodroffe, 1993; 1995; 2003). The coastline in most parts is protected by natural levees consisting of small sand dunes, chenier ridges and vegetated mud banks behind stands of mangroves (Williams, 2010). Along the shorelines are many coastal wetlands that are significant habitats for fisheries, migratory birds and vegetation such as paperbark and mangroves. The estuaries are highly turbid and exhibit sediment trapping efficiencies that result in shoaling (Williams, 2010).

If climate change scenarios of rising sea levels and increased precipitation and runoff are realised then Australia's northern coasts may experience more sediment discharge and resultant shoaling, greater saltwater intrusion into coastal freshwater wetlands resulting in loss of freshwater wetland habitat and increased shoreline erosion threatening infrastructure and habitat (Williams, 2010). Over the past several decades such changes have been noted (Williams, 2010).

9.3 Options to Manage Climate Change Impacts

Storm Surge and Tidal Barrages

Storm surge and tidal barrages have been used around the world to generate power, to prevent coastal flooding due to elevated ocean storm surge levels during extreme events, to prevent the encroachment of sea water into estuaries and to reclaim arable land from the sea. Barrages can be used to mitigate climate change impacts of mean sea level rise and increases in storm surges.

On coasts such as those in The Netherlands, sea level rise and storm surge has been managed by the construction of major barrages across the entrances to embayments, such as the *Afsluit Dijk* (enclosure barrage) across the entrance to the former *Zuiderzee* creating a lake, the *Ijsselmeer*, in 1932 on the north *Waddenzee* coast. The barrage is some 32 km long and 90 m wide at the crest, which is some seven metres above mean sea level. Shipping and river discharges pass through locks and sluice gates. The works were completed in 1932 at a present day cost of some A$1 billion. The remainder of the country is protected by other storm surge barrages and sand dunes that are maintained continuously through marine sand extraction (offshore dredging). The annual maintenance cost of the storm surge barrages in The Netherlands is some tens of millions of dollars.

It is difficult to contemplate works such as the *Afsluit Dijk* for the protection of, say, Moreton Bay, Botany Bay, Port Philip Bay, Gulf St Vincent, Cockburn Sound or Darwin. Smaller scale barrages may be viable for areas with extensive high value foreshore development (e.g. Gold Coast Broadwater). However, other than such monumental constructions, there is little else that can be done to the entrances of such large embayments and estuaries to manage climate change impacts of elevated storm surge levels. Options for the foreshores of such embayment estuaries would need to transition towards those used on the open coast.

Nevertheless, Australia has its own tidal barrage system, constructed on the Lower Lakes at the Murray Mouth (Figure 36 and Figure 37). The barrages were constructed in the 1930s to prevent sea water entering the Lower Lakes (Lake Alexandrina and Lake Albert) and the Murray River. They maintain the lake levels at around 0.8 m above sea level to retain a secure supply of fresh water for domestic, industrial and irrigation use, including metropolitan Adelaide.

The barrages on the Lower Lakes of the Murray would be effective in mitigating moderate sea level rises and protecting the hinterland from oceanic inundation caused by storm surges.

Works such as the *Afsluit Dijk* and the tidal barrages on the lower Murray River have had a major impact on the embayments and estuaries they are protecting, particularly on the ecology where saline habitats have been turned fresh. However, this was the objective of the Dutch in the *Ijsselmeer,* where the soils of the polders that were created were de-salinated, using specific crops, turning the reclaimed land over to productive agriculture.

Another impact of tidal barrages on ocean entrances is to reduce significantly the volume of ocean water exchanged with the estuary on each tide (tidal prism), thereby reducing the ratio of the tidal prism to the rate of littoral drift transport to the entrance. This has the potential to lead to the deposition of littoral drift in an untrained entrance, which can lead to entrance closure. Climate change projections of increases in wave power and, hence, rates of littoral drift transport would exacerbate this situation for untrained entrances. Littoral drift transport to entrances could be reduced by the construction of entrance breakwaters and/or training walls, by dredging or by the construction of sand bypassing systems.

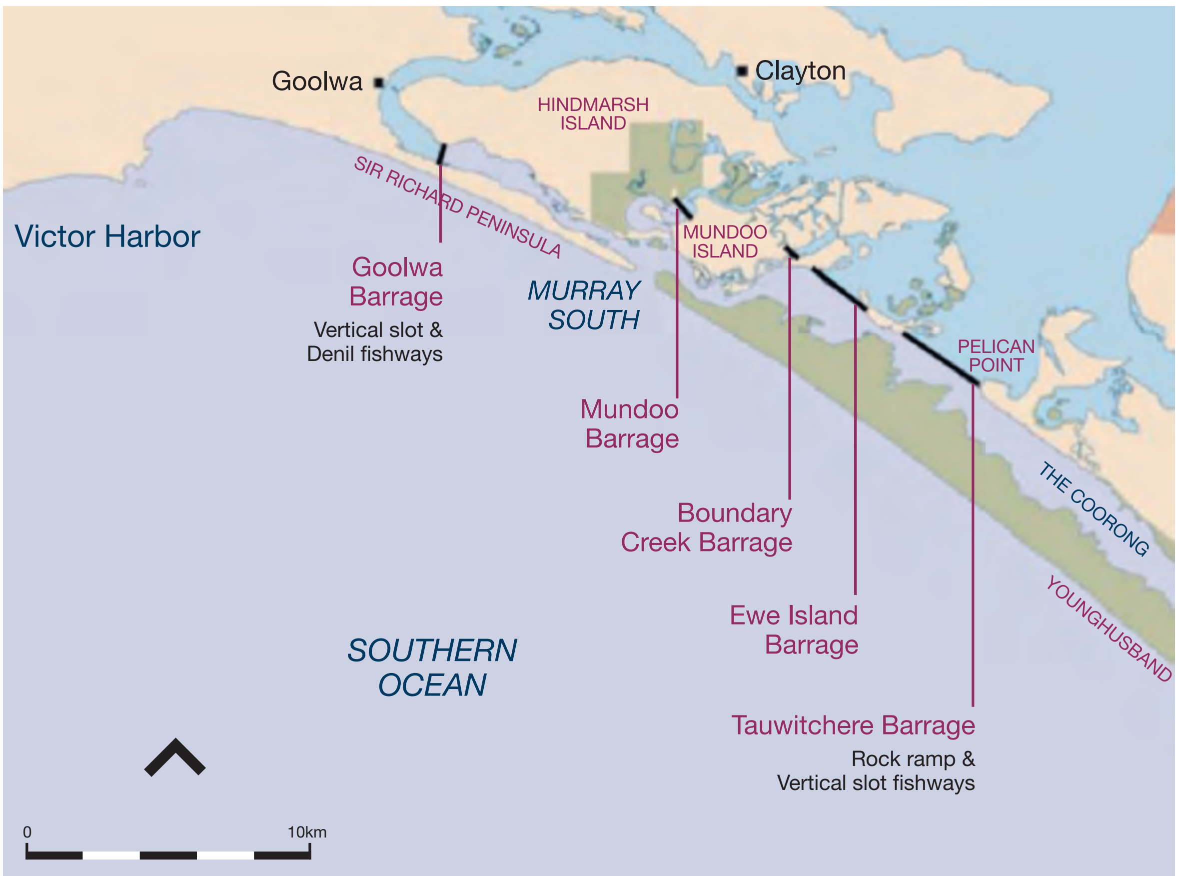


Figure 36. Tidal barrages on the lower lakes at the Murray Mouth and the Coorong.

(Source: modified from Geddes & Hall, 1990. © Murray Darling Basin Authority)

Figure 37. Goolwa Barrage. (Source: Left: Michael Bell; Right: Irene Dowdy © Murray Darling Basin Authority)

Entrance Breakwaters

Untrained entrances to estuaries that may become prone to closure as a result of climate change impacts may be "improved", or kept open, by the construction of entrance breakwaters (Figure 38). There are many examples of this, particularly on the NSW coast, where breakwaters have been constructed on entrances, which were prone to closure, to improve navigation and for flood mitigation.

These works have been spectacularly successful in keeping entrances open, mitigating flooding and improving navigability. However, in some cases there have been unforseen impacts. For example, on the barrier estuaries of Wallis Lake, Lake Macquarie and Lake Wagonga, the entrance breakwaters have tripped these estuaries into an "unstable scouring mode" (O'Brien & Dean, 1972), causing channel scour threatening bridge piling foundations, embankment collapse and increasing lake tidal ranges significantly, thereby altering fringing ecologies (Nielsen & Gordon, 2008).

However, entrance breakwaters constructed on littoral drift coasts have the potential to cause "downdrift" erosion by reducing sediment input and by altering beach alignments through nearshore wave diffraction.

Figure 38. Lake Wagonga Inlet, Narooma. Left, 1966; Right, 2005. (© NSW Lands Department)

The impact of climate change sea level rise on existing entrance breakwaters is likely to result in an increase in water depths, breaking wave heights and overtopping discharges, which may lead to increasing the frequency of significant storm damage to the structures. As outlined in Section 8, there may be a need to raise breakwater crest levels and to strengthen armour and toe protections.

Training Walls

Training walls have been used to protect internal estuary channel banks from scour resulting from the increased velocities induced by entrance breakwater construction and/or migration of flood and ebb tide channels. Often such works have had limited success because the scale of the scour process is very much larger than that of the bank protection works. For example, groynes and rock work bank protection have not been successful in preventing erosion of the Swansea Channel banks at Pelican, Lake Macquarie NSW, where entrance breakwater works have tripped the estuary into an "unstable scouring mode" (Nielsen & Gordon, 2008; Waterson et al., 2010). Rockwork bank protection and rock groyne structures there have been undermined and have been collapsing for many decades, although recent alarming changes, illustrated in Waterson et al. (2010), may have been exacerbated by dredging that could have caused changes to channel alignments and morphology. Entrances to estuaries that have been kept open through the construction of breakwaters may be prone to an "unstable scouring mode", which is likely to be exacerbated by sea level rise.

Dredging

Dredging has been used in estuaries to create navigable channels and to keep untrained entrances open. As a management option it may be effective in adapting to climate change.

The untrained entrance at the Murray Mouth has been prone to closure. In 1981, the entrance was opened by dredging and maintained in an open condition by river flows during the following winter and spring (MDBC, 2005). Dredging was recommenced in October 2002 when the entrance almost closed again. During the long period of drought that followed, dredging was used to keep the Murray Mouth open. By 2010 the dredgers were operating at the river entrance 24 hours a day, seven days a week. Over this period more than 6.5 million tonnes of sand had been removed at a cost estimated to be more than $40 million (MDBC, 2005).

Another case where entrance dredging is undertaken is at The Entrance, Tuggerah Lakes in Wyong Shire, NSW (Figure 39). Here, Council dredges sand from the active tidal delta at The Entrance and places it on North Entrance Beach and The Entrance Beach (Umwelt, 2011). The purpose of entrance dredging is to allow some exchange of ocean water with the lake and for flood conveyance. Placing sand onto the beaches, in the short term, maintains beach amenity and provides a greater sand buffer to mitigate storm erosion.

The volume and rate of dredging at The Entrance is adapted to current sea level and climate conditions. However, properties on the lake's foreshores and low lying coastal land in Wyong Shire have been identified as significant risk areas as sea level is projected to rise over the next century. Council is undertaking studies to develop a better understanding of the coastal processes and hazard risks that need to be managed at The Entrance. Dredging may well play a part in the long term management options.

Figure 39. Council's dredger operating at The Entrance, Wyong Shire, NSW. (SOURCE: © WYONG SHIRE COUNCIL)

Entrance Bypassing Systems

Entrance bypassing systems have been developed for several river entrances around Australia where entrance breakwaters have interrupted the natural transport of littoral drift along the coast. Systems vary from fixed sand pumps located on trestles that extend across the surf zone to shoreline operations using excavators, bobcats and trucks.

A good example of a large sand bypassing system is at the Tweed River entrance in northern New South Wales. Here, sand that moved naturally northwards along the coast had accumulated on Letitia Spit behind the Tweed River's southern breakwater and training wall. It also formed sand shoals across the river mouth that hindered navigation to and from the river. As sand was being trapped, the southern Gold Coast beaches did not receive their natural sand supply and these beaches were unable to recover fully following storm erosion events.

The sand bypassing system comprises a series of jet pumps mounted on a trestle extending across the surf zone south of the Tweed River entrance breakwaters (Figure 40) and a system of pumps and pipelines to pump the sand under the river to outlets on the northern side (Figure 41). From there the sand is transported by waves and currents to nourish the southern Gold Coast beaches.

9.4 Advantages and Disadvantages of Entrance Management Options

Some advantages and disadvantages of entrance management options described in the foregoing are summarised in T able 7.

Figure 40. Aerial view of Tweed River entrance (left); Trestle comprising sand jet pumps (right).

(SOURCE: TWEED RIVER ENTRANCE SAND BYPASSING PROJECT WWW.TWEEDSANDBYPASS.NSW.GOV.AU)

Figure 41. Tweed River Sand Bypassing System.

(SOURCE: TWEED RIVER ENTRANCE SAND BYPASSING PROJECT WWW.TWEEDSANDBYPASS.NSW.GOV.AU)

Table 7. Primary Impacts, advantages and disadvantages of estuary entrance management.

Option	Primary Impacts	Advantages	Disadvantages
Barrage	Eliminates tidal flow from upstream regions, changing ecology from saline to fresh. Will not reduce fresh water flood levels.	Protects inland areas from ocean inundation caused by elevated storm surge water levels. Protects hinterland from modest sea level rises.	Very high capital cost. High maintenance cost. Potential major adverse impacts on the estuary entrance and adjacent coastline. May require pumping to control flooding from upstream. Altered Ecology.
Entrance Breakwaters	Increase the hydraulic conveyance of an estuary entrance that has become prone to closure from the transport of littoral drift to the entrance.	Prevent entrance closure caused by possible increases of littoral drift. Improve entrance navigation. Improve flood conveyance.	High capital cost. Change tidal planes and Increase tidal range within the estuary, changing fringing ecologies and causing inundation. Increase channel velocities and scour of channel banks. Increase sediment deposition within the estuary. Interrupt alongshore littoral drift transport, which may need costly bypassing equipment to ameliorate any adverse coastal impacts. Can change the coastal foreshore alignment.
Training walls	Designed to constrict increases in tidal flows in a trained estuary entrance channel.	Mitigate the impacts of increased channel velocities and scour resulting from raised water levels and possibly increased tidal range. Mitigate increasing tidal range within an estuary.	May create localised scour or high velocities. Reduction of the tidal prism may destabilise the entrance.
Dredging	Used to remove inundation of littoral drift that may be causing unwanted impacts such as entrance shoaling.	May be used to manage possible increases in littoral drift. "Soft engineering" that does not alter the "natural processes". Flexibility. Enhances tidal flushing and flood conveyance. Provides beach sand nourishment.	High long term operational costs. Often requires very large equipment to match "mother nature's" powers, otherwise could be ineffective.
Entrance Bypassing	Used to transport littoral drift that has accumulated on the "up-drift" side of entrance breakwaters to the "down-drift" side.	May be used to manage possible increases in littoral drift. Re-establishes the natural flow of sand that is interrupted by entrance breakwaters. May reduce the natural variability and stabilise the sand supply to "down-drift" shores.	High capital cost, ongoing operational cost and high maintenance cost. May alienate a section of beach.

10 EMERGING TECHNOLOGY AND NOVEL APPROACHES

10.1 Overview

In the last decade, innovative approaches to manage coastal erosion have been formulated and implemented both internationally and within Australia. Interest is growing towards novel methods of preventing beach erosion that imply lower environmental impact, lower costs and easier execution. Despite the interest, publications and documented information are still scarce about the design criteria and performance of these innovative approaches. This section provides a general overview on the latest developments of innovative methods for the mitigation of coastal erosion and inundation hazard. In compiling the available scientific literature for this review, particular emphasis was given to their function and performance in the field. A check list is provided in Table 8.

While traditional approaches can rely on a relatively long history of application and well established engineering design criteria, novel and emerging technologies, by definition, are still undergoing development through laboratory and numerical testing, prototype and field experience. When considering such technologies, field pilot trials and detailed medium to long term monitoring (several years) are always recommended. They should only be adopted if:

- They offer similar function to traditional strategies at a reduced cost.
- They offer potential for improved environmental and/or social outcomes.
- They are better suited for adaptation to climate change impacts, and
- They are part of a research program to test any of the first three possibilities.

Table 8. Emerging technologies and novel approaches.

Check List Emerging Technology and Novel Approaches
• Is there a sound basis in physics for the new technology to perform in the manner claimed? • Has the proposed technology been applied in the field? • Where and what were the design wave and water level conditions? • Did it perform as expected? • Was the intervention independently monitored? For how many years? • What is the cost compared to a traditional intervention? • How would it perform during a storm event? • Is scouring at the base likely? • Is settlement expected? • What is the design life? • What is the design event? • What is the durability of the material? • Are there any adverse impacts on adjacent foreshores? • How adaptive it is to sea level rise and climate change? • What is the cost of removal in case of failure? • Will there be a hazard to public? • Will there be a hazard to environment? • Any Public Liability Issues?

The following methods are discussed in this section and are illustrated in Figure 42:

- Artificial reefs or submerged breakwater, particularly their promotion for multi-use.
- New approaches to artificial dunes and dune reinforcement.
- Natural Defences; and
- Beach groundwater manipulation.

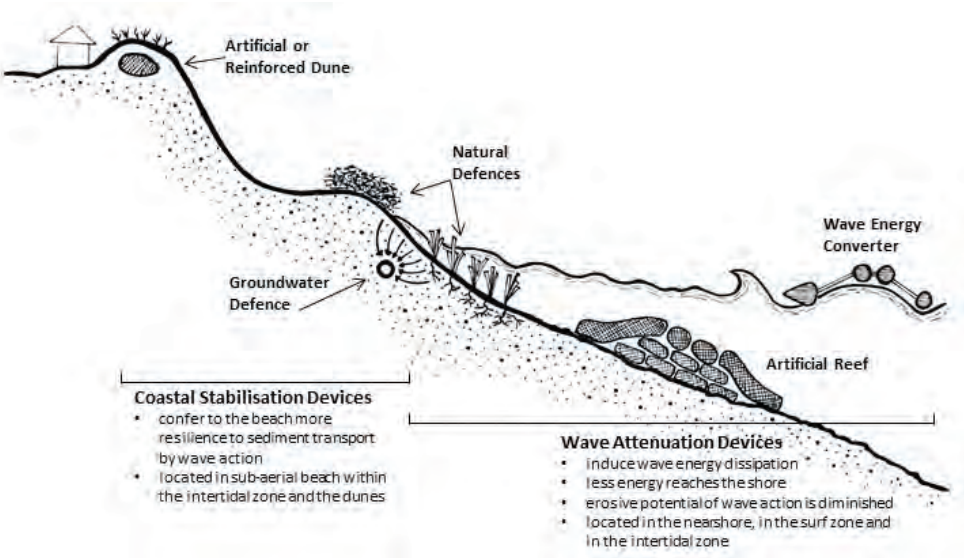


Figure 42. Wave Attenuation devices and coastal stabilisation devices. (Courtesy of Sonia Beato Martins.)

10.2 Artificial Reefs or Submerged Breakwaters (see also Section 8)

Introduction

An artificial reef (as opposed to a natural reef) is a manmade submerged structure (breakwater) typically located in the shallow nearshore zone in depths from 2 to 10 metres. Crest levels are at or below Mean Low Water (MLW) to ensure minimal visual impacts. The primary function of artificial reefs is to induce the incoming waves to break (Figure 43) thus reducing the wave energy reaching the beach leeward of the structure. This generates alongshore gradients in wave height and longshore currents, altering sediment transport and beach alignment.

Secondary objectives are the enhancement of the surf amenity (sometimes promoted as a primary objective) and/or ecology in which case the structures are commonly referred to as multipurpose reefs. The main advantage of artificial reefs compared to traditional emergent structures is that the structure is not visible from the beach at most stages of the tide and therefore does not impact the aesthetics of the location.

Table 9 provides a summary of the advantages and disadvantages of artificial reefs built primarily for shore protection (their use for enhancing fish stocks is not discussed here).

Field Experience

While the use of emergent detached breakwaters, i.e. structures with crest levels above mean sea level, as coastal protection is well recognised internationally, artificial reefs (fully submerged) are rarer and their performance as coastal protection is still the subject of debate. In their review of constructed artificial reefs, Ranasinghe & Turner (2006) revealed that the majority of structures resulted in shoreline erosion in their lee which Ranasinghe et al. (2006) attributed to being located too close to the shore. Observations of salient formation in the lee of natural offshore reefs (Black

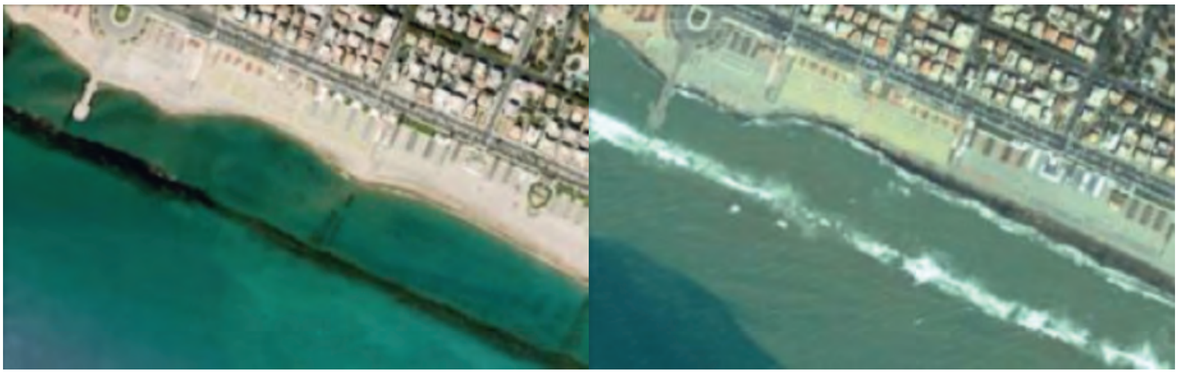


Figure 43. Artificial reef or submerged breakwater in Lido di Ostia, Rome, Italy. The 2,800 m long submerged structure was built shore-parallel in combination with submerged groynes. On the left during calm conditions, on the right with wave breaking on the crest of the structure. (Source: Google Earth)

& Andrews, 2001) as well as physical (Turner et al., 2001) and numerical modelling investigations (Ranasinghe et al., 2006) seem to provide support to the use of such structures as mitigation of erosive processes subject to correct design.

Submerged structures are common in Europe with approximately 20% of the breakwaters being fully submerged (Lamberti et al., 2005) compared with less than 1% in Japan (Uda, 1988) and a negligible number in the US (Chasten, 1993; McIntosh & Anglin, 1988). However, more recent statistics for Japan and US may show an increase in use of submerged artificial reefs. Australia is home to the largest yet to be built multi-purpose artificial reef, the Narrowneck artificial reef on the Gold Coast, Queensland. This is presented as a case study in Section 8.

A list of major projects involving artificial reefs with their performance in terms of coastal protection, ecological and surfing enhancement (when applicable) is presented in Table 10. The list was based on field cases well documented in published scientific literature to which the reader is directed for additional details on the design and monitoring of these structures. Although not exhaustive, the list of field cases covers a wide range of hydrodynamic conditions with a variety of wave climates and tidal ranges considered as well as different geomorphological settings such as longshore and cross-shore transport dominated coast, exposed or sheltered beaches, etc.

Of the 19 artificial reefs (listed in Table 10) designed and constructed for coastal protection, approximately 50% were reported as successful in mitigating coastal erosion processes. It is to be noted

Table 9. Artificial reefs advantages and disadvantages.

Artificial Reefs	
Advantages	**Disadvantages**
• Aesthetics • Coastal protection (? Variable performance) • Surfing enhancement (? Variable value) • Marine habitat enhancement • In some cases removability • Recreational amenity • In some cases simplicity of placement • In some cases simplicity of constructability.	• Only suitable for small tidal range • Sensitivity to sea level rise (? Depends on tide and depth) • Limited design criteria • Limited protection during storm conditions • Scouring at base, roundheads and gaps • Settlement • Generation of currents may affect swimmer safety • Construction costs (? High to be effective).

Table 10. List of artificial reefs reported in the published literature.

Country	Site	Primary purpose	Primary Successful?	Secondary purpose	Secondary Successful?	Reference
Australia	Cable Station, WA	Surfing enhancement	partially	na	na	Pattiaratchi, 2003
	Narrowneck, QLD	Coastal Protection	partially	Surfing enhancement	minor	Jackson, 2007
	[(1)]Semaphore Park, SA	Coastal protection	yes	na	na	Carley, 2007; Townsend, 2007
NZ	Mount Maunganui, NZ	Surfing enhancement	[2]no	Coastal protection	minor	Weppe, 2009
	Opunake, NZ	Surfing enhancement	[2]no	na	na	Mead, 2011
USA	Midtown Palm Beach, Florida	Coastal protection	no	na	na	Stauble, 2003; Dean 1998
	Dupont Palm Beach, Florida	Coastal protection	no	na	na	Stauble, 2003
	Vero Beach, Florida	Coastal protection	no	na	na	Stauble, 2003
	Avalon, New Jersey	Coastal protection	yes	na	na	Stauble, 2003
	Cape May, New Jersey	Coastal protection	yes	na	na	Stauble, 2003
	Belmar, New Jersey	Coastal protection	yes	na	na	Stauble, 2003
	Cape May #2, New Jersey	Coastal protection	not rep.	na	na	Stauble and Giovannozzi, 2003
	Delaware Bay, Delaware	Coastal protection	no	na	na	Ranasinghe, 2006
	El Segundo, California (removed)	Surfing enhancement	no	na	na	Leidersdorf, 2011
Italy	Lido di Ostia #1, Rome	Coastal protection	no	na	na	Ranasinghe, 2006
	Lido di Ostia #2, Rome	Coastal protection	yes	na	na	Ranasinghe, 2006
	Lido di Dante, Ravenna	Coastal protection	yes	na	na	Lamberti, 1996; Ranasinghe, 2006
	Marche	Coastal protection	no	na	na	Lamberti, 1996; Ranasinghe, 2006
	Pellestrina, Venice	Coastal protection	yes	na	na	Lamberti, 2005
	Punta Marina, Ravenna	Coastal protection	[3]yes	na	na	Sordini, 2011
Japan	Iburi Reef, Hokkaido	Coastal protection	yes	na	na	Hirose, 2002
	Keino-Matsubara Beach, JP	Coastal protection	no	na	na	Ranasinghe, 2006
	Niigata, JP	Coastal protection	no	na	na	Ranasinghe, 2006
UK	Boscombe	Surfing enhancement	partially	Coastal protection	yes	Mead, 2010
	Grand Cayman, [(4)]Cayman Islands	Ecological enhancement	yes	Coastal protection	yes	Harris, 2009
India	Kovalam	Coastal protection	[(5)]yes	Surfing enhancement	[(5)]yes	ASR report, Kerala Dep. Tourism

Notes:
(1) Trial structure originally built as emergent (+1 m AHD), crest was lowered to -0.9 m AHD following the rolling off of top Geocontainers.
(2) Construction incomplete.
(3) Built in 2010, insufficient monitoring period.
(4) British Overseas Territories.
(5) Performance results of this reef are considered preliminary and subject to further monitoring and publishing of results.

that for about half of the field cases considered, beach nourishment was undertaken in conjunction with the construction of the reef, and groynes were used in combination with the artificial reef to stabilise nourishment material. For the cases where ecological monitoring was performed, all the reefs were observed to promote colonisation by marine algae and aquatic species. Six artificial reefs were constructed with the primary purpose of improving surf amenity and three of these were considered partially successful in meeting their design criteria. However, the generally accepted position is that most of these structures have failed to meet their design criteria although the measure of success needs to be cautiously balanced between objective estimation and public expectation (Mead & Borrero, 2011; Shand, 2011).

Settlement into the seabed of the order of 0.5 to 2 m as well as localised bed scouring was observed for all the structures considered. This is an important consideration during design, as scouring can seriously affect the overall structure stability and settlement typically reduces the wave reduction performance of the structure.

Reef Units

A large number of innovative materials such as geocontainers (GCs) and prefabricated reef units have been used in recent years to construct artificial reefs. The main advantages of these novel systems are the simplicity in placement and constructability and cost effectiveness (Pilarczyk, 2005). Another advantage is that, if not performing as expected, the structure can theoretically be more easily removed compared to traditional rubble mound breakwaters. The main limitation in their application is the lack of proper design criteria in particular in terms of unit stability under wave attack. Although a number of devices are being marketed and often patented, few, have been extensively tested in laboratory wave flumes and fewer have been sufficiently tested in the field.

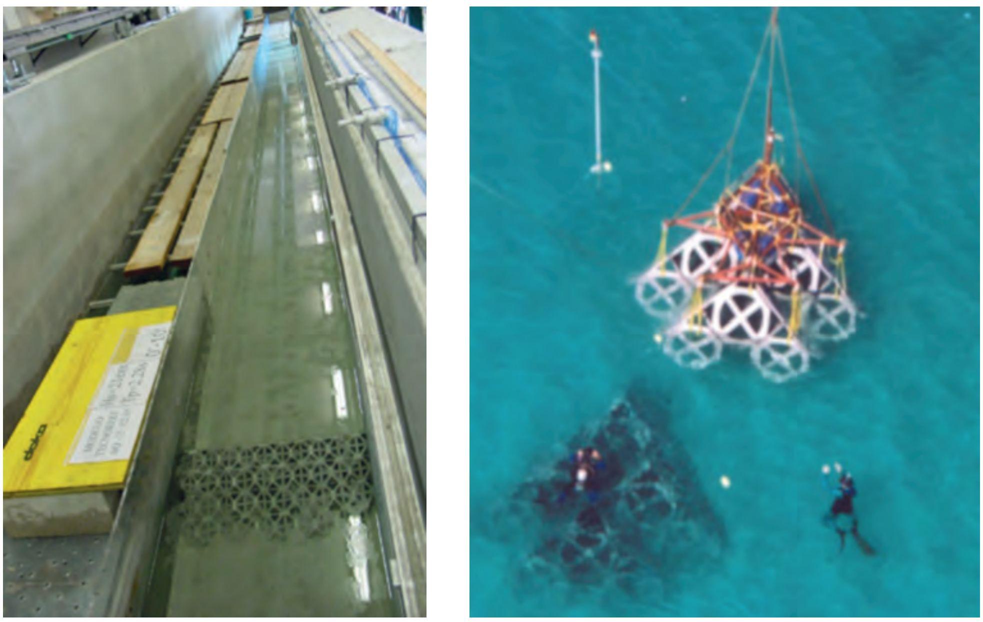


Figure 44 Laboratory wave flume testing and field installation of precast concrete reef units: Tecnoreef™
(Sources: Tecnoreef™)

Artificial Reefs – Summary

Artificial reefs offer obvious aesthetic advantages as they produce minimal visual impact because of their submergence. They can be expensive to construct and are only suiTable for protection works in limited locations (low wave variability and small tidal range). Field experience has shown that submerged structures have been the most successful when used in combination with beach nourishment and possibly shore normal groynes. In the last decade, a limited number of artificial reefs have been extensively monitored in regards to their performance for coastal protection, ecological and surfing enhancement. Based on the documented field experience, if appropriately designed and constructed, artificial reefs:

- Can provide mitigation against erosive processes and stabilisation of nourishment material.
- Do enhance marine colonisation and biodiversity compared to sandy substrates by introducing a new habitat, however, aggregation may also have negative impacts, and
- Potentially provide surf amenity.

It is important to note that in almost 50% of the cases listed in Table 10, these structures have failed to meet their design objectives.

While such structures may provide a potential adaptation measure to be used to address climate change (and in particular sea level rise) their applicability is limited. Before considering such a solution the design objective should be clearly defined and an ongoing maintenance/upgrade strategy considered and costed. Importantly, given the small number of such structures currently constructed for this purpose, careful research into the construction and effectiveness of similar structures in similar wave climates should be undertaken. If trial or pilot studies are undertaken then realistic costing of removal or modification of the structure should be considered in the initial phase, as experience on past projects has shown that this can be comparable to initial construction costs.

10.3 Artificial Dunes and Dune Reinforcement

Wind transport is responsible for the genesis of coastal sand dunes which are complex ecosystems located at the boundary between terrestrial and marine environments. Wave and tide action contribute to the continuous transformation of these coastal landforms through erosive and accretive cycles. Coastal sand dunes play an important and recognised dual role in coastline and beach stabilisation. They provide natural protection to sea-fronting properties and assets against wave impact and storm surge inundation and they constitute an erodible sand supply for the fronting beaches (Dare, 2003). Dunes also provide a natural "trap" for wind-driven sand which by settling contributes to the growth of the dune system while preventing the clogging of stormwater drainage networks.

Dunes are subject to increasing pressure by the growing development of coastal land on one side and recession of the shoreline on the other. As a consequence of this "squeezing" effect, coastal dunes are more susceptible to storm erosion and breaching with significant impacts on the upland areas. However, in the last four decades on a national and international level, recognising their importance as natural coastal defences, the rebuilding and reinforcing of dunes has been undertaken. As an example, Gordon (1989) reports that the entire dune system (13 km) along the Sydney region open coast was completely reconstructed, fenced and stabilised throughout the late 1970s and early 1980s.

The methods available for dune rehabilitation and rebuilding can be broadly divided in four categories:

- wind fences
- vegetation
- management of beach entries, and
- reconstruction and/or reinforcement.

Wind fences reduce the erosive action of the wind promoting sand deposition adjacent to the fences. Colonisation of the dunes by vegetation enhances dune stabilisation against wind and wave action while careful management of beach entries reduces the negative impacts on both dunes and vegetation by pedestrian and vehicular traffic. Dune (re)construction and reinforcement involve using compatible sand transported to the beach (e.g. via trucks or sand bypassing system – see Supplement A in companion guideline on *Coastal Sustainability*) and reshaped mechanically as a natural dune. Alternatively, sand can be mechanically moved from the lower part of the littoral beach system to the dune (beach scraping).

Placing a resistant body within the constructed dune provides a second line defence during storm events. In fact, the dune armouring remains completely buried and not visible during normal conditions whereas it becomes exposed and acts as a hard revetment in case of beach erosion. Buried rock or concrete seawalls have been utilised for the dune core while a variety of patented systems such as stone-filled matrixes, grids, mats and sand-filled geotextiles are being used as buried dune armouring. The use of sand-filled geocontainers (bags or tubes) to form the core of artificially constructed dunes is an emerging practice which may provide an alternative to traditional coastal techniques.

10.4 Natural Defences

Coastal vegetation can be effectively used as a non-structural protection against coastal erosion in sheltered, low wave energy areas. Coastal vegetation includes seagrasses, salt marshes and mangroves.

Figure 45. On the left, seagrass species of Poseidonia oceanica, on the right restoration site combining salt marshes and oyster domes. (Sources:- Theseus, 2010 and MDE, 2006)

Seagrasses are aquatic flowering plants that form meadows in near-shore brackish or marine waters, in temperate and tropical regions. Australia has the most diverse array of seagrass species in the world (Butler & Jernakoff, 1999). Most seagrasses colonise soft sandy substrates in quiescent shallow nearshore waters, however, some seagrasses (such as some Poseidonia) can be exposed to relatively high wave energy.

A salt marsh is a community of plants and animals in the upper coastal intertidal zone. In Eastern Australia, their distribution may overlap with mangrove forests which are usually established in low elevation sites where inundation is more frequent. However, mangroves which comprise several species of trees and shrubs typically extend in tropical and subtropical coastal waterways.

It is recognised that coastal vegetation can provide coastal protection through two mechanisms: wave attenuation and seabed/soil stabilisation (Gedan et al., 2011; Koch et al., 2006). The above ground portion of the plants has a dampening effect through the structural presence of the plants which result in wave attenuation and wave energy dissipation. The consequent reduction in near-bed flow velocities promotes settling of sediment while the plants root system enhances soil cohesion and seabed stabilisation.

Experience

Significant research has been conducted in laboratories to characterise wave attenuation by a variety of coastal vegetation (Augustin et al., 2009; Thomson et al., 2003; Løva & Tørum, 2001; Thomson et al., 2003).

Average decreases in significant wave height of 30% over distances of around 40 metres were measured within seagrass meadows in northwest California (Brandley & Hauser, 2009). Existing measurements of sediment accretion rates within coastal vegetated areas (mangrove forests and salt marshes) suggested that these areas may mitigate the impact of sea level rise with rate of accretion of 0.5 cm/years (Asano, 2006).

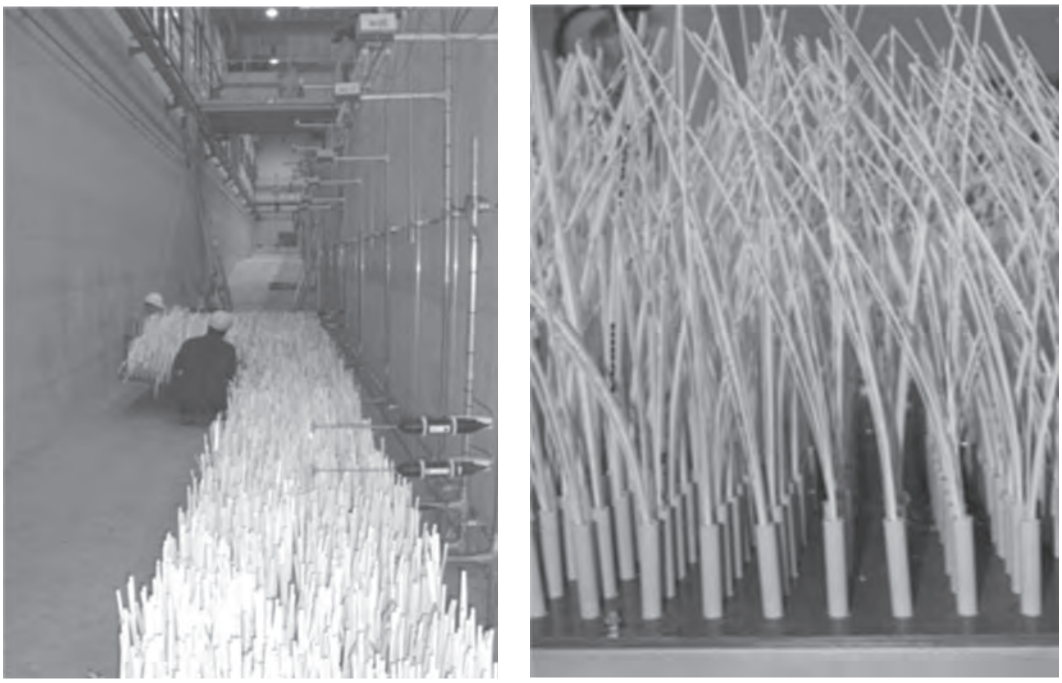


Figure 46. Large scale experiments on seagrass wave attenuation in a wave flume. (Source: Prinos et al., 2010)

Conclusions about Natural Defences

Non-structural shore erosion control projects involving the planting and growth of coastal vegetation can be an effective way of mitigating erosive processes while enhancing the ecological habitat of areas characterised by low wave energy conditions. Coastal vegetation can be combined with protective structures such as low crested breakwaters. These are however restricted to generally low energy estuarine and coastal locations and provide little opportunity for erosion protection on exposed open coasts.

10.5 Beach Groundwater Manipulation

Introduction

Dewatering is a well-established practice on construction sites where the water table is lowered to allow excavation for foundations, shoring etc. However, it is only in the last two decades or so that the dewatering concept has been commercially proposed and applied as an alternative to more traditional coastal stabilisation methods. Beach dewatering consists in the artificial lowering of the groundwater table with its proponents suggesting that this results in enhancing infiltration losses during wave uprush/backwash cycles while promoting sediment deposition at the beach face. The first field experiments of beach groundwater manipulation were undertaken in Australia by Chappell et al. (1979) on Durras Beach, NSW and subsequently by Davis et al. (1991) at Dee Why Beach in NSW. However, it was in Denmark in the early 1980s that the potential coastal engineering application of beach dewatering was first documented through experimental and commercial installations for the purpose of coastal stabilisation (Lenz, 1994; Vesterby, 1994; Turner & Leatherman, 1997).

Lowering of the water table is accomplished through buried gravity drains typically filter pipes running parallel to the shoreline (Figure 47). The pipes can be connected to a collector sump and a pumping station located further inland. The sand-filtered seawater can be returned to sea or re-utilised for other purposes (pools, desalination, cooling systems, etc.). The patent for this particular system belongs to Hans Vesterby of the Danish Groundwater Institute and is commercialised internationally by different licensees such as Ecoplage®.

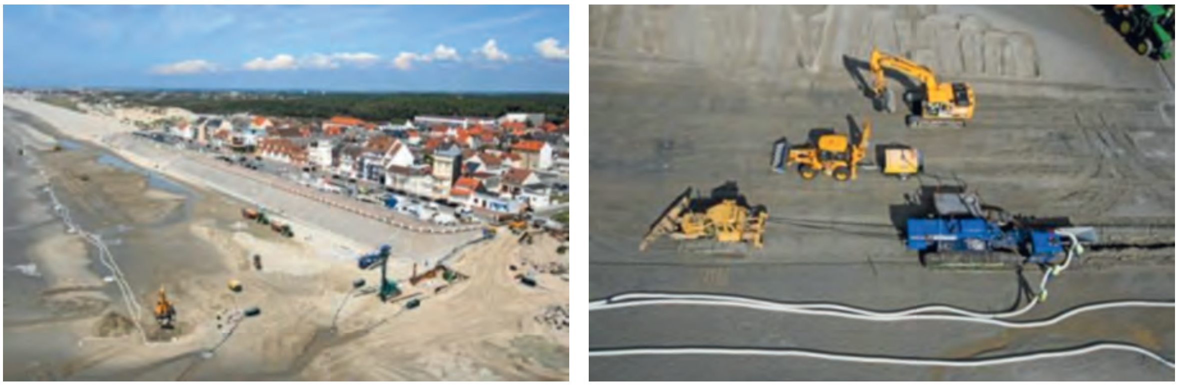


Figure 47. Installation of drain pipes in the inter-tidal zone fronting a seawall at Plage de Gere, France.
(SOURCE: ECOPLAGE®)

Other beach dewatering systems were developed in recent years such as the one installed in Hasaki, Japan where the groundwater table is lowered by gravity through a permeable layer of modular units installed in the cross-shore direction. As an alternative to buried drains, a concept based on vertical beach drains (Pressure Equalisation Modules) has been proposed and actively marketed in Australia, however, this system is not based on recognised physical principles and has not been demonstrated through practical application.

Advantages and disadvantages of beach dewatering are summarised in Table 11.

Experience on Beach Dewatering

Although several beach drainage experimental and commercial installations have been implemented around the world, few were established in combination with an independent scientific review of the effects on shoreline stabilisation and fewer incorporated a monitoring period of the shoreline response longer than 5 years. The prototype system implemented at Dee Why Beach, NSW (Davis et al, 1991) consisted of an array of shore normal strip drains occupying about 160 m of beach with no pumping system added. Monitoring of the site concluded that no discernible reduction of beach erosion could be attributed to the gravity drainage system.

Table 12 depicts a non-exhaustive list of worldwide installations (commercial and experimental) that were independently monitored with results published through technical literature and specialist conferences.

Table 11. Beach groundwater manipulation advantages and disadvantages.

Beach Groundwater Manipulation	
Claimed Advantages	**Disadvantages**
• Beach stabilisation (? Variable performance) • Minimal visual impact • Removability • Constructability • Relative low costs • Dry effect on beach for increased recreational use	• Not suitable for open coast environments • Only suitable for low wave energy areas • No protection during storms • Susceptible to damage during storm • conditions • Durability? • Maintenance costs for pumps • Lack of design criteria

Table 12. List of worldwide commercial and experimental beach dewatering installations.

Country	Site	Beach Stabilisation	Additional BD effects	Drain(s) Length(s)	Period of operation	Monitoring	Reference
Australia	Dee Why NSW	negligible	not reported	shore-normal 160 m section of beach	1991-1992?	~2 years	Davis, 1992
France	Les Sables d'Olonne	yes	drying effect	2 x 1300 m 1 x 1700 m	1999-pres.	6 years	Fattal, 2008
	Villers-sur-Mer	negligible	drying effect	2 x 1200 m	2003-pres.	4 years	Levoy, 2007
	Saint-Raphaël	yes	not reported	600 m	2004-pres.	1-2 years	Lambert, 2007
Italy	Lido di Ostia	inconclusive	not reported	115, 90 & 175 m	2001-2002	1 years	Damiani, 2003
	Isola di Procida	negligible	negligible	325, 390 & 100 m	2002-2004	1 year	Vicinanza, 2010
	Alassio	negligible	(1) morphology	2 x 100 m in parallel	2004-pres.	1 year	Bowman, 2007
	Lido Adriano	yes	not reported	2 x 100 m	2004-pres.	3 years	Ciavola, 2009
	Bibione	yes	not reported	2 x 200 m	2006-pres.	<1 year	Ciavola, 2008
	Metaponto	yes	not reported	2 x 200 m	2006-pres.	<6 months	Ciavola, 2008
UK	Towan Bay	(2) yes	drying effect	180 m	1994-?	6 years	Vesterby, 1995
	Branksome Chine	(3) inconclus.	drying effect	100 m	1998-1998	3 months	Shaw, 2003
Spain	Riumar, Ebro Delta	yes	nearshore water circulation	300 m	1999-?	2 years	Montori, 2002
Denmark	Thorsminde	yes	beyond length of drains	500 m	1985-1991	5 years	Vesterby, 1994
Japan	Hazaki – HORS (5)	yes	recovery rates and sand looseness increased	8 m wide x 88 m long shore-normal	1994-pres.	5 years	Yanagishima, 2003; Katoh, 1996
USA	Sailfish Point	(4) inconclus.	negligible	180 m	1988-1995	5 years	Turner, 1997
	Nantucket Island	inconclusive	(6) Min. on water quality	3 x tot. of 1000 m	1994-1998	2 years	Curtis, 1998

Notes: (1) Berm crest formation and narrow swash zone as opposed to cusped flatter control area.
(2) Not well documented in published literature.
(3) Interrupted due to storm damage.
(4) Stabilisation and moderate accretion observed during the first 2 years of monitoring.
(5) Hazaki Oceanographic Research Station.
(6) Minimal impact on quality of ocean and aquifer waters.

Conclusions on Beach Dewatering

Field experience shows that the water Table below the beach face can be successfully lowered through dewatering systems with morphological responses ranging from negligible effects to possibly effective beach stabilisation (effectiveness is enhanced by the use of pumps). Field evidence also proves the inability of beach dewatering systems to provide adequate protection from storm erosion and this is a major failing in their use for protection on the open coast. Furthermore, beach dewatering systems remain susceptible to storm damage and their durability in the field remains to be proven.

The potential benefits of beach dewatering claimed by its proponents to include as minimal visual impact, relatively low initial costs, maintenance costs and easy removability make beach dewatering a potentially appealing alternative to traditional hard engineering solutions to coastal erosion. However, the lack of established engineering design criteria and conclusive field evidence of positive effects from operating dewatered sites suggest a cautionary approach to this technology.

10.6 Concluding Remarks

New methods and techniques will continue to be developed and promoted, some of which will over time become accepted and shown to be effective. However, many of the new approaches will be shown to be unsuiable for protection or adaptation as climate changes and will result in unnecessary expense and avoidable losses. Many of the new approaches (as is the case with existing tried and proven methods) will only be suiable for certain locations and certain outcomes. Where a method is not proven (including appropriate theoretical analysis and laboratory testing, where no monitored field trials have been undertaken) then the coastal manager is urged to exercise extreme caution. The old adage that *"If it seems too good to be true then it probably is!"* remains relevant.

Other shoreline protection systems that are not necessarily considered emerging are summarised in Appendix B.

11 CONSTRUCTION MATERIALS

11.1 Overview

Climate change may affect coastal structure material selection in three ways:

- Changes in the environmental conditions in which materials have to perform satisfactorily:
    (a) elevated water and air temperatures
    (b) higher sea levels
    (c) higher storm tides, larger storm waves and stronger winds.
- Desire for structures to be modified to recover their pre-climate change performance.
- Public pressure to use materials with a low embedded carbon content.

11.2 Changing Environment

Increasing temperatures

Corrosion reactions are faster in elevated temperatures. Even though increased water temperatures means reduced dissolved oxygen content, in the corrosion susceptible upper tidal and splash zones of structures there is generally plenty of oxygen to sustain corrosion. Diffusion rates into concrete of corrosion inducing chloride ions are also likely to be faster in higher temperatures.

Corrosion

Over time the susceptible upper tidal and splash zones on structures will move upwards. Portions of structures that were not previously in contact with seawater might now be splashed, greatly increasing corrosion susceptibility.

Wave loads on decks

The standard method of designing marine structures is to keep the deck clear of impact by waves (as recommended in API, 1991). The exceptions have been small decks for example those providing access to boats. The reason for keeping decks clear of waves is the wave loadings on decks can be very high. Not only are the forces large due to high wave crest velocities, but decks typically have much larger surface areas than substructures (e.g. piles). For example, as reported by Douglass et al. (2006) waves generated by Hurricane Katrina in 2005 that struck the bridge decks generally demolished these structures or parts thereof. As the sea rises due to climate change, some decks will be struck by waves for the first time.

More severe storms

Extrapolation of past data for storm waves, storm tides, winds and currents to obtain extreme design events might underestimate future storm intensities due to the storms themselves being more intense and higher sea levels reducing wave depth limiting effects. Resultant loads and overtopping are likely to be more severe than in the past.

11.3 Structural Adaption

In the future it is likely that coastal structures' ability to resist higher sea levels and stronger storms will be examined with a view to upgrading. There are some analogies with the examination of the seismic resistance of pre-Newcastle earthquake structures that is ongoing in Australia. These structures were mostly not designed for earthquakes. This examination is codified in AS3826 (Standards Australia, 1998). In summary, AS3826 recommends a combination of bracing highly susceptible components like unreinforced masonry parapets plus acceptance of an increased risk of failure for a structure that is already part way through its working life. Many old structures have heritage values that restrict strengthening options. Adapting structures to climate change in the future is likely to follow similar ideas.

11.4 Low Embedded Carbon Coastal Construction Materials

Anthropogenic carbon dioxide emissions are held responsible for most observed recent climate, hence public pressure exists to minimise carbon dioxide emissions due to the production, delivery and installation of construction materials ("embedded carbon").

Table 13 lists the most commonly used coastal engineering construction materials in order of increasing embedded carbon per kilogram of material.

Table 13. Coastal engineering construction materials approximate embedded carbon content in CO_2e (carbon dioxide equivalent) kilograms per kilogram of construction material.

Material (virgin i.e. untransformed, at source)	Embedded carbon kilograms CO_{2e} (carbon dioxide equivalent) per kilogram of construction material (approx)
Sand and Gravel	0.02
Rock	0.1
Timber (sawn hardwood)	0.2
Concrete (50 MPa)	0.2
Plastic (HDPE)	2.0
Steel (carbon)	3.0
Steel (stainless)	7.0
Aluminium	13.0

Ref: Kellogg Brown and Root embedded carbon estimation tool, priv. comm (2011).

The embedded carbon assessment of a coastal structure must also consider:

1. The strength to density ratio of the material (high for timber and low for steel).

2. Durability. If a material only has short life on the coast then its total embedded carbon mass over the life of a structure (e.g. 50 years) might be higher than a more durable but embedded carbon intense material. For example stable revetment rocks can be very good due to their very long life; sand poor if it gets swept away; untreated softwood very poor due to very rapid marine borer damage and stainless steel quite good due to its long life despite its very high embedded carbon density.

11.5 Coastal Structure Construction Material Selection Strategies for a Climate Change World

Construction material selection co-exists with considerations apart from climate change:

Structure types:

- aesthetics
- cost
- safety both during construction and in service
- environmental impacts
- accessibility, and
- public opinion.

Some recent trends in coastal engineering in Australia that are expected to continue are:

- Larger equipment: hence fewer larger piles; longer spans.
- Modularisation (i.e. large structural components build elsewhere and shipped to the site for assembly).
- Decreasing relative cost of stainless steel.
- Declining supply of large section, durable timber types due these trees being locked up in reserves.
- Increasing use of timber recycled out of old wharves and bridges.
- Public is increasingly wary of chemicals leaching from treated timber into the environment.
- Sand and gravel shortages near some cities (e.g. Sydney).
- Large armour rock shortages in some areas (e.g. Gold Coast).
- High labour costs.
- Increased use of high strength plastics due to decreasing cost and improved durability.
- Improved paint performance.
- Decreasing relative cost of concrete.
- Cheap steel, especially ex China.

Construction material selection for climate change

1. Build high

The current trend of larger equipment, hence fewer larger piles and cheaper steel means that structures like jetties can be supported by just a few very large piles. These piles have very high bending and compressive-buckling load capacities so building a high deck can have very little cost consequence. High decks will better handle future sea level rise in terms of wave loads, overtopping and corrosion susceptibility.

2. Use high durability materials

   a. **Stainless steel.** The high embedded carbon content of stainless steel is more than offset by its very long service life. Stainless steel reinforcement in concrete means that less concrete cover to protect the reinforcement from corrosion needs to be used, hence less concrete is used, which is a saving in embedded carbon.

   b. **High strength plastics.** The advantages are similar to stainless steel with the added advantage of lighter weight. Applications include plastic reinforcement for concrete; vinyl sheet piles, geobags and polyurethane ground stabilisation injection. Some plastics are recycled (e.g. jetty deck planks) (Refer point 3).

3. **Recycle**
   The combination of recycled timber and modern stainless steel fixings can produce very durable structures with very low embedded carbon content. Coastal timber structures must be protected against termite attack by using stainless steel "Termimesh" in the abutments because termites like to live in coastal sand dunes and dine on jetties.

4. **Redundancy**
   A structure has a better chance of surviving future higher than anticipated loads if the structure is technically redundant, i.e. it has more elements than strictly needed:
   (a) Avoid statically determinant structures. If a support is lost or member removed, they collapse.
   (b) Use continuous beams.
   (c) Build in columns instead of using bearings.
   (d) Multi-layer primary armour designs for breakwaters and seawalls preferred over single layer designs.
   (e) Design for overtopping even if it is regarded as being unlikely.

It was observed that a wharf designed with continuous beams and built in columns built in Ulee Lheue Port, Banda Aceh, Indonesia survived a massive overload in the form of the Boxing Day Indian Ocean tsunami, which is believed to have been over 10 m high at this location. This is an example of the superior performance of redundant structures under overload conditions.

GLOSSARY

This glossary includes terms from these Guidelines that may be unfamiliar to some readers. For a more complete Glossary of coastal engineering terms see the companion publication *Coastal Engineering Guidelines for Working with the Australian Coast in an Ecologically Sustainable Way.*

ARI	Average Recurrence Interval – time (years), on average, between occurrence of events such as storms, tropical cyclones, wave overtopping, etc.
armour unit	A rock or concrete block designed to form the outer protective layer for a breakwater or seawall.
barrier island	A bar essentially parallel to the shore, the crest of which is above normal high water level.
bed friction	Loss of wave energy in shallow water due interaction of wave motion with the sea bed.
bed shear stress	Horizontal force (per unit area) due to near-bed water flow.
boundary layer	Region close to the sea bed or coast where the flow is significantly affected by the interaction with the boundary.
caisson	Boxlike structure used in construction work underwater or as a foundation.
celerity	Speed of wavecrest (as opposed to the speed of water particles).
chenier	Beach ridge, usually composed of sand-sized material resting on clay or mud.
coastal compartment	Length of coastline (often an embayment) at the boundaries of which the sediment behaviour is clearly defined.
continental shelf wave	Very long waves (of order 1000 km) that travel anticlockwise around Australia (including Tasmania) generating important coastal currents.
currents	Coastal currents derive from many sources, including tide, waves (particularly broken waves), coastal trapped waves, ocean currents and density influences.
density current	Current due to difference in salinity, temperature or suspended sediment of two bodies of water.
diffraction	When a part of a train of waves is interrupted by a barrier, such as a breakwater, the effect of diffraction is manifested by propagation of waves into the sheltered region within the barrier's geometric shadow.
downdrift	In direction of alongshore current.
geotextile	Strong, resilient, porous fabric used to retain soil without building up water pressure.
Geotubes©	Geo-synthetic fabric container manufactured by Miratech intended for dewatering and containment, but used for other purposes in coastal engineering.
grid	For a numerical model points in space where velocities, water elevations, sediment and pollution concentration etc are computed.

groyne	A shore protection structure built (usually perpendicular to the shoreline) to trap littoral drift or retard erosion of the shore.
laminar	Smooth flow (usually slow) dominated by viscosity with water molecules only slowly changing relative position. Such flow is characterised by very slow mixing of sediment and pollutants. (c.f. 'turbulent')
littoral drift	The sedimentary material moved in the littoral zone (zone extending seaward from the shoreline to just beyond the breaker zone) under the influence of waves and currents. "Gross" littoral drift is the sum of all transport in any direction, while "net" littoral the average over some time period (usually extended).
morphological response	Change of seabed or shoreline due to external influences (waves, currents, wind, etc).
overtopping	Passing of water over the top of a structure as a result of wave runup or surge action.
pelagic	Species that swim in the open sea.
progradation	Growth of sediment deposit inside an estuary (flood tide) or outside as a delta (ebb tide).
prototype	In modelling terms, describes the real world being simulated.
random waves	Waves with irregular successive heights and wavelengths.
refraction	(1) The process by which the direction of a wave moving in shallow water at an angle to the contours is changed: the part of the wave advancing in shallower water moves more slowly than that part still advancing in deeper water, causing the wave crest to bend toward alignment with the underwater contours. (2) The bending of wave crests by currents.
revetment	A facing of stone, concrete, etc., built to protect a scarp, embankment, or shore structure against erosion by wave action or currents.
runoff	Water flowing over land into streams, rivers and estuaries derived from rainwater that has not soaked into the ground or been intercepted by leaves, ground depression, etc.
salient	Bulge in beach alignment forming behind an offshore obstruction.
sand by-passing	Hydraulic or mechanical movement of sand from the accreting updrift side to the eroding downdrift side of an inlet or harbour entrance. The hydraulic movement may include natural movement as well as movement caused by human action.
sediment transport	Movement of sand, silt or clay due to combined waves and current.
separation zone	Region behind a feature (e.g. headland, breakwater, island) not exposed to the direct action of a current but still can be influenced.
sheet pile	Row of interconnected piles designed to retain soil and/or water on one side.
shoal	(n) Region of localised shallower water. (v) Process of getting shallower (and consequential change in wave properties) as shore is approached.

storm surge	Rise in the sea water level on the open coast due to abnormal atmospheric pressure and wind shear stress.
thalweg	Line along channel joining deepest points of sections (German for "valley way").
tidal prism	The total amount of water that flows into a harbour or estuary or out again with movement of the tide, excluding any freshwater flow.
tombolo	A bar or spit that connects or "ties" an island to the mainland or to another island.
trained entrance	Estuary entrance fixed by artificial rock or other armour material walls, often extending seaward of the adjacent shoreline.
transgressive dune	Sand dune that creeps inland under the action of prevailing wind possibly covering roads and property.
transitional	Water depths between "deep" (where the no wave motion is felt at the seabed) and "shallow" (where wave motion is almost uniform from surface to seabed).
tsunami	A long-period wave caused by an underwater disturbance such as a volcanic eruption, earthquake or landslide. Commonly miscalled "tidal wave".
turbulent	Flow (usually fast) characterised by eddies and rapid mixing of sediment and pollutants. (c.f. "laminar")
updrift	Against direction of alongshore current.
validation	Process of adjusting model parameters to match some measured field data.
verification	Testing ability of model to match field data independent of that used for validation.
wave basin	Laboratory facility, broad and shallow in shape, with a wave generating paddle along at least one side and in which model coastal structures can be tested for oblique wave attack.
wave energy flux	Rate at which wave energy passes any vertical lane of water bounded by the seabed, sea surface and a metre width perpendicular to wave direction.
wave flume	Laboratory facility, long and slender in shape, with a wave generating paddle at one end and in which model structures can be tested for perpendicular wave attack.
waves	Here we refer to water motion generated by wind whether local (wind waves) or remote (swell).
zeta curve	Looking from above, i.e. plan view, a log-spiral alignment curve often adopted naturally in embayed beaches with a predominant wave direction.

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APPENDIX A – "At What Price Data"

A.1 The Role of Data

Today we enjoy the benefits of data collection investments made by our forefathers. To cope with tomorrow, and particularly the vagaries of an uncertain climate, we need the programs put in place today. Expediencies of cost cutting of data collection programs due to short term economic "rationalisation" show an ignorance of the return on investment that coastal data has demonstrably yielded in the past. Further, by living off the capital built up by past generations, but failing to reinvest for the future we lay down a legacy of hardship for future generations that our forefathers had the foresight and responsibility to protect us from.

Data is an investment in the future. It is an essential input for planning development, managing assets, implementing programs such as beach nourishment and for the designing and construction of structures in the coastal zone. Data assists in optimising designs, reducing costs and in managing risks. With the increasingly uncertain future due to climate change the need for reliable coastal data has been significantly increased. Data allows identification of potential future trends, provides the basis to test possible scenarios and helps identify future "at risk" areas thereby reducing the potential to place assets in harm's way. It is a fundamental tenet for responsible and cost effective, risk managed strategies.

Data may be collected for a specific project or be part of an on-going program. At times the longer-term benefits of data programs are not immediately obvious. For example, the use of historical tide, wave and rainfall data to quantify long-term trends, including those due to climate change, was not envisaged at the time many of these programs were initiated. They were usually originally designed to obtain information on the recurrence of events, assuming a statistically stationary series, so as to assist in the selection and quantification of coastal engineering design parameters. However, some of the data these programs have generated has been invaluable not only for their original purpose but also to assist in investigation of climate change. The full benefits of data collection programs are sometimes only realised at a later date because of the complexity of natural processes and the limits of our understanding at any point in time. To this end it is important to note that surprisingly little long term data has been collected for many coastal parameters. While some tide records are over 100 years long, the longest Australian wave records at any location are only of the order 40 years! Other parameters such as coastal currents have far shorter records.

Often the community is unaware of the extent to which damage has been minimised during a severe event as a direct result of earlier data collection and analysis programs. Seldom is this on-going benefit factored in as a return on investment, as it should be. Costs of data are often emphasised as they are readily available but, returns are seldom recognised, so data collection programs are often inappropriately judged by costs only, without factoring in the value of the benefits; a flawed analysis.

It is also relevant to note that the historical costs of data collection have, and continue to be, significantly reduced due to technological advances in instrument design, the ready availability of remote sensing devices, the advances in communications networks and the on-going sophistication and ease of computerised data analysis techniques and distribution systems. As the costs reduce and the ease of obtaining data improves, the opportunities for expanding data collection not only grows but also so does the duty of care obligations that dictate appropriate, readily obtained data form an integral role in the diligent undertaking of planning, design, construction and maintenance in the coastal zone.

The on-going development and use of increasingly more sophisticated numerical models demands detailed, and accurate, input data. The trend towards real time modelling of systems as a control tool, (e.g. the use of models receiving real time data to determine ocean outfall performance and hence the control actions necessary to achieve environmental license requirements), has brought an even more sophisticated new dimension to data collection and processing systems. It has also demonstrated the cost effectiveness of integrated data and modelling systems that significantly reduce field monitoring requirements.

Importantly, in conjunction with modelling, data can provide an insight into risk, and of even greater significance, the likely consequences of accepting a risk level. For example, although a high risk situation may be recognised, data may show that the consequence of taking that risk is minimal; as can be the case for low value assets not adversely impacted by inundation, located in apparently high hazard areas where, flooding depth may be significant but the velocity of flow is low, hence likely damage, is minimal.

Data should be seen as an investment in reducing uncertainty and hence ensuring that unnecessary capital is not expended in overdesign or, conversely, that under-design does not lead to expensive failures, or that systems are controlled within their licensed parameters and hence license breaches, and fines, do not occur. Data is at the very foundation of competent resource planning, management and utilisation. In an increasingly litigious society appropriate input data is a vital component of competent professional practice and accountability. The potentially uncertain future projected by the climate change phenomenon and hence the requirement for sensitivity and risk/likelihood/consequence testing of advice (see Carley et al., 2009) only heightens the duty of care obligations.

A challenge for the coastal engineering professional can be the increasingly evolving de-engineering of management decision makers and hence the failure of those decision makers to understand how the fundamental foundation stone data represents to the engineering process. Unfortunately the concept of "economic rationalism" has been inappropriately indoctrinated into many decision makers who attempt to, in ignorance, achieve short-term savings by cost cutting rather than realizing that the economic rationalism concept is meant to be applied to a "whole of life" situation and therefore requires appropriate data programs. While accountability for decisions must rest on the shoulders of the ultimate decision maker, professionals advising the decision maker have a duty of care to ensure they have provided appropriate advice, including but not limited to the need for and/or reliability of the data on which their advice is based.

A.2 Data or Information?

Data is not absolute. Rather it is a relative measure of a phenomenon, to a selected level of accuracy, using particular instruments and/or techniques. The accuracy of data obtained from an instrument should not be confused with the precision to which the instrument reads. Data only becomes information after a competent practitioner with relevant knowledge and experience has meaningfully interpreted it. The relevance of the data to any specific application is dependent on the context of the measurement, the length of record, its accuracy, the sensitivity and limitations of the measuring device and the measurement techniques. Its value as information is dependent on the appropriateness of the data to the issue at hand, the analysis techniques and the skill and competence of the person engaged in interpretation.

A.3 Coastal Data

Data on coastal parameters are required for planning of development, resource utilisation, management of developed and natural assets, the design of coastal structures and for implementation/monitoring of "soft" engineering solutions such as beach nourishment programs. The principal coastal parameters and typical timescales for their data collection are detailed in Table A1. Data collected for any one timescale can often be of more general use; however this is not always the case so particular care is needed in utilising data outside the original intended time scale. For example, water level data from a tide recorder may adequately provide information for tidal analysis however, depending on the recording instrument; it may not be of sufficient accuracy to allow meaningful interpretation of long-term sea level trends due to climate change.

Coastal planning requires data that provides information on:

- Building setbacks from shorelines to avoid damage due to short term erosion and long term recession including the recession potentially resulting from climate change impacts.
- Floor levels for buildings to minimise inundation from rivers, creeks and oceanic flooding (again including future flooding potential from climate change impacts); and
- Other planning issues ranging from beach access to ocean outfall (both stormwater and sewer) locations and analysis of options to manage development at threat.

Managers of public assets have a duty of care for wise stewardship of the community's assets; both natural and developed. Managers of private assets have a similar duty to the owner, whether they are an individual, or the shareholders in a company. Many of the developed assets in the coastal zone share a common problem with natural assets; the management of assets with long useful lives/ or intangible value. Examples are: National Parks; the public beach amenity and coastal structures. Breakwaters, for example, can provide multiple uses with the emphasis on any one use changing over time. The uses can include river flood mitigation, protection of a commercial shipping harbour, provision of a fishing port and facilitation of recreational and tourist activities; one or more of which may apply or dominate at a point in time. This provides a challenging situation for undertaking a meaningful economic analysis of the benefit/cost relationship that can only be rationally addressed if sufficient "whole of life" data is available.

The decision to downgrade the level of maintenance on an asset should often be accompanied by the decision to upgrade/introduce a monitoring program. To illustrate this consider the following scenario. A short-term economic decision is taken to reduce/defer expenditure on maintenance of a harbour breakwater in order to improve the "profitability" of a port. The breakwater deteriorates but its condition is not monitored. A rock near the head is dislodged during a storm event and rolls, undetected, into the entrance shipping channel. A vessel strikes the rock and becomes disabled in the channel. The port is closed and the multiplier effect impacts on the local economy. Other vessels in the port cannot leave so their owners as well as the owner of the affected vessel, and local businesses dependent on the port, seek damages from the port authority. This scenario is based to an actual happening at an Australian port. Fortunately the Port Authority did have monitoring in place and did detect the breakwater head damage before a vessel hit the dislodged rock(s)! A major breakwater maintenance program was quickly reinstated.

The design of coastal structures involves selection of the appropriate parameters, and the environmental conditions, from which the design loads maybe determined (Gordon, 1987). Historically the design criteria have been selected from one of four categories:

- Design Event – a specified event usually based on consequence rather than likelihood of occurrence, for example the elevation of a walking track around a lagoon where the track is desired to be useful for "most" of the time, but if inundated occasionally is of little consequence;
- Base Event – an event selected by a likelihood/consequence criteria such as the conditions relating to, for example, a 10%, 5% or 1% recurrence p.a. event;
- Event of Record – the largest event that has occurred during the period of record; or
- an Extreme Event – the largest event believed possible.

The choice of design criteria is dependent on the specific application and the availability of useful data. In many situations a combination of conditions apply, hence when using a Base Event approach, a joint probability analysis is required. For example, if a 2 m spring tide may occur 6 times a year and a 4 m significant wave height is a 10% event, the joint occurrence of these two as a design criteria may be 1% per annum; always remembering that a 1% pa event has a 26% probability of occurrence in a typical economic planning period of 30 years!

The use of the traditional approach to design of coastal structures now needs to be revised in the light of an uncertain climate future and the data requirements have therefore increased. For example Carley et al., (2008) demonstrate how a present day 10,000 year ARI (ie, 0.01% recurrence p.a.) water level can become a 1 year ARI (ie, 100% recurrence p.a.) in the future, due to a 1 m (at the upper limit of projections for 2100), climate change driven, sea level rise. While the potentially significant implications for structural designs dictate the need for more and better data, it should be noted that, in some cases, if the structure has a relatively short life, say 20 to 30 years, then the design can be based on existing records. However its replacement structure will require the extension of any existing data set. For example a marina with floating units and piles that need replacing every 30 years can be designed on current data records but will require reconsideration of design parameters, such as water levels and wave forces, the next time it is replaced and hence the data to do so. For structures with much longer lives, such as breakwaters, it is now essential to undertake sensitivity analysis based on potential scenarios of changes to climatic conditions such as wave energy, sea levels, storm surges and the like. The challenge is therefore to design data collection programs that will assist in projecting forward into an uncertain future and, more particularly, to develop rational techniques for analysing existing data and projecting it forward in a meaningful and responsible manner. The concept of using Events of Record loses some validity and the estimate of Extreme Events may prove problematic in a world of uncertain future climate. Therefore these approaches must, in the future, be used with caution, if at all, particularly if there is limited data. What is required is sufficient data to detect and analyse trends.

A.4 Duration of Data Collection and Data Quality

The duration for which data needs to be collected is dependent on the use and on the timescales of the processes being measured. A few days visual observation of a "tide board" may provide a first estimate of mean sea level at a location, however many hundreds of years of accurate measurement with a precision instrument is more desirable to determine long term trends in sea level movements. Cordery (1992) contended that, if there is a need to estimate an event which is likely to be exceeded only once in "Y" years then data needs to be available for 3"Y" years, hence estimating a 1% event requires 300 years of data. Contrast this against the previously mentioned 40 years of available wave data that is currently being used to estimate the 1% design waves. Cordery (1992) cites the Lachlan River at Forbes where in the 95 years of record between 1892 and 1986 the two largest floods of record occurred two years apart in 1950 and 1952. They were 1.8 m and 1.4 m respectively larger than the next highest. Inclusion of the two years in the 95 year record had a significant impact on the estimated flood frequency data. Similarly, the Sydney tide record extends over 100 years and of the 10 highest water level anomalies, 70% occurred between 1974 and 1978 with 40% attributed to the storms in 1974. Again, the period 1967 to 1974 was one of the most energetic for wave action in living memory. Unfortunately this was immediately prior to reliable wave data collection at most locations. However Cordery's (1992) observations are only valid for statistically stationary series. In an environment of climate change far longer records are required in order to establish meaningful design/risk management criteria. El Niño/La Niña and decadal oceanic oscillations introduce further complications into determining the duration of data collection programs. Interestingly, the 37 years of reliable wave data now available in Sydney were collected during a period that has been dominated by El Niño events and therefore must be used with caution for projecting long-term trends.

The quality of the data collection device and of the analysis of the data is often a function of the proposed use of the data. Attempts to impose universal standards to all data collection, while arguably desirable, demonstrate a failure to understand the practical and financial constraints that apply to many coastal engineering projects. The quality of data required by a specific project is dictated by what is considered to be reasonable engineering practice. Hence, for example a simple analysis of existing aerial photographs may provide sufficient information on beach recession on a beach in a natural park area, where the issue to be addressed is the location of a low cost picnic shelter behind the beach. On the other hand detailed photogrammetry and accurate survey records are likely to be needed when establishing/monitoring the threat of erosion to high value residential buildings in a similar situation.

A.5 Determining the Value of Data

Abbott (1991) proposed that the value of data is the value of the reduced uncertainty or the improved knowledge; the improved knowledge being quantifiable in terms of reduction of risk of failure or minimisation of over-investment of funds. For example, because rock size for, say a revetment protecting oceanfront homes, is a function of wave height cubed, even a relatively modest underestimate of wave height can result in the selection of a rock armour size that will experience rapid failure and hence potential loss of not only the revetment, but also the asset it is supposed to be protecting. Conversely an over-estimate can result in an unnecessarily expensive structure. Climate change brings in a new dimension to this situation dictating the need for a sensitivity analysis based on likely scenarios, costs and consequences which demands even better data and analysis techniques.

A simple example illustrates the point. The value of ocean front assets in Sydney alone is estimated at $5,000 million (Gordon, 2009a). If the wave data, for say the first 3 years of reliable record, 1975 to 1977, were used in an attempt to estimate the 1% occurrence of a 1 hour wave condition for the design of sea defences, a wave height of 7.75 m would result. If on the other hand 30 years of record were used then the 1% wave height would be 9.6 m (Kulmar et al., 2005). That is, a 24% increase requiring an almost doubling of armour size for say a rock revetment and a substantial increase in crest height in order to provide the same level of protection. Without attempting to speculate on the degree of damage the under design resulting from a 7.75 m wave criteria may produce, it is clear that if, say even only 5% of the assets were damaged, the additional 27 years of record has the potential to save $250 million and hence the data is worth that sum. However say a 1 m sea level rise occurs and the 1% wave height value becomes the 5% recurrence height, then the value of the data and its use for sensitivity testing becomes far greater; arguably over $1,000 million.

Set-back lines for development now generally include an allowance for climate change and the Bruun Rule (Bruun & Schwartz, 1985) is commonly used to determine the additional set-back required to allow for rising sea levels. On the Australian coast the recession associated with 0.1 m long-term sea level rise can be of the order 10 m (Gordon, 1988; 2009b). Hence an underestimate of sea level rise could result in the premature loss of valuable property however, an overestimate may unnecessarily sterilise equally valuable land. Future data on sea level trends improves valuation of the coastal property development it saves or enables.

A further example might be a proposed subdivision in an area affected by oceanic inundation from time to time and the decision is taken to elevate the entire subdivision above the current estimate of the 1% flood level by filling. If the subdivision covers an area of 10 ha and the fill costs $50 m^3 in place then each 0.1 m of elevation costs $500,000, hence a typical freeboard allowance of 0.5 m due to uncertainty has a value of $2.5 million. An allowance for a 1 m sea level rise has a value of $5 million. However an underestimate, assuming a medium density of 25 say dwellings/ha could result in damage to 250 dwellings and assuming $30,000 damage per dwelling the value of improved data would be $7.5 million. Even $500,000 represents many decades of operation and analysis of an automatic water level gauge.

The dollar impact from the uncertainty of wave conditions can be appreciated when evaluating breakwater design. Breakwaters are capitally intensive structures whose armour size is proportional to wave height cubed. Assuming a modest breakwater protecting a port is to cost $100 million, however the wave record available for the site is limited, so the confidence in the 1% design wave height is +/- 10% then, if under-designed by 10%, experience dictates that the breakwater is likely to suffer damage potentially of the order $30 million and if overdesigned by 10% will cost $10 million more than it should. With climate change, many existing Australian breakwaters may experience wave conditions beyond their design capacity. Just as dam safety required a major re-assessment of dams in Australia, so too does breakwater safety. Wave data and the trends embedded therein will be an essential component of such an analysis.

Flood warning systems are increasingly based on real time data collection systems linked to computer based flood models. These systems not only track the progress of flood waters but they also enable emergency services to quickly assess the impact of various scenarios of increased or decreased rainfall during the flood event, changing tidal impacts and other varying tailwater conditions at the river mouth due to storm surge and wave setup. In a catchment where say 1,000 dwellings are flood affected advanced warning to move vehicles and contents out of harm's way in a timely manner can conservatively result in a saving of $20,000 per household; a total of $20 million for the catchment. Such models, combined with their data sets, can also be used to undertake a sensitivity analysis as to the impacts of various climate scenarios in regard to changes in rainfall intensity, frequency and duration.

Data should be valued by its benefits. The costs of obtaining it, particularly when facing the uncertain future associated with climate change should be judged against these benefits. It will be vital to evaluate climate impacts on coastal parameters at key locations around the Australian coast, as it is likely that they will vary. Further, the combined effects of the parameters will be different. With potential shifts in weather patterns, wave and wind energy flux can be expected to change and this change will depend on the latitude of a location. Rivers may experience less but more intense floods or, vice versa. The requirement for competent data collection programs is therefore intensified by the potential for climate change. The increase in value of assets at risk in the coastal zone and the likelihood of damage provides a sound basis for valuing data collection programs, and the uncertainty of climate change impacts dictates sufficient data is collected to enable responsible and meaningful sensitivity analyses to be undertaken.

Table A1. Coastal variables and their timeframes.

Paramater	Short Term	Medium Term	Longer Term
Oceanic Water Levels	Wave run-up Wave setup Tides (daily/monthly and yearly cycles Storm Surge	1%, 2% 5% annual and extreme events Tidal anomalies, cycles and some climate change induced trends. El Niño/La Niña effects.	Decadal oscillations. Climate change induced sea level rises and impacts on wave run-up, setup and storm surge.
Waves	Daily and seasonal variations and hourly for long waves.	1%, 2% 5% annual and extreme events. Some climate change influences. El Niño/La Niña events.	Decadal oscillations. Climate change induced changes in energy and direction (energy flux).
Wind	Gusts, 10 minute, hourly, daily and seasonal variations in speed and direction.	1%, 2% 5% annual and extreme events. Some climate change influences. El Niño/La Niña events.	Decadal oscillations. Climate change induced changes in speed and direction.
Rainfall/runoff	Hourly, daily, monthly intensity, duration and discharges.	1%, 2% 5% annual and extreme events. Some climate change influences. El Niño/La Niña events.	Decadal oscillations. Climate change induced trends in intensity, duration and location.

Paramater	Short Term	Medium Term	Longer Term
Currents (ocean and coastal)	Daily, weekly and monthly fluctuations.	Decadal variations, and some climate change influences. El Niño/La Niña events.	Decadal oscillations. Long term trends of increased/ decreased strength and climatic impacts.
Beach Erosion and Long-term Coastal Recession/ embayment re-alignment	Short term fluctuations (daily/ monthly/seasonally including beach embayment alignment) Average annual long-term recession.	1%, 2% 5% annual and extreme events. Climate change induced alterations in beach alignments. El Niño/La Niña events.	Decadal oscillations. Climate change influences on storm recurrence/intensity and recession due to sea level rise.
Seabed Bathymetry	Daily fluctuations in the beach and surf zone.	Changes due to extreme events and trends as a result of climate change impacts.	Tectonic movements and long term accretion or erosion due to climate change and decadal oscillations.
Sediment Transport (waves, currents and winds)	Gross sediment movements.	Net sediment movements and changes to sediment budgets. El Niño/La Niña events.	Changes in sediment movements due to climate change induced shifts in wave/wind energy flux and decadal oscillations.
Water Quality	Pollution events, fluctuations in concentration of individual substances.	1%, 2% 5% annual and extreme concentrations of individual substances. El Niño/La Niña events.	Changes in background levels, water chemistry and biology due to climate change impacts and decadal fluctuations in ocean currents.

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Appendix B – Alternative Offshore Protection/ Amelioration Options

(Refer to Sections 8 and 10)

Type	Description	Effectiveness	Climate Change
Thin-Line Submerged Breakwaters	Prefabricated concrete units (e.g. PEP) aligned shore parallel.	Expensive Ineffective in high wave energy environments (Florida DEP, 2006).	No flexibility to adjust to SLR or wave climate change.
Bubble Curtain	Air pumped and dissipated through tubes.	On-going operating costs. Ineffective in wave – dominated environments.	Unsustainable
Underwater Screens	Concrete slabs buried in the sea-bed to dissipate wave energy.	Limited (Florida DEP, 2006).	No flexibility to adjust to SLR and change in wave conditions.
Floating Breakwaters	Floating structures, tethered to the seabed – variety of materials can be used – concrete, tyres.	Effective in low tide, low wave environments. Commonly used for marina protection.	Adjustable for SLR.
Wave Energy Geneator	Floating structure which oscillates with waves.	Expensive and unreliable. Suited to calm conditions.	Renewable energy generation. Can adjust to changing conditions.
Artificial Seagrass	Mattresses of plastic "grass" secured to the sea bed.	Ineffective (Florida DEP, 2006).	Relatively easy to deploy new mats in response to changing conditions.
Nearshore Berm	Nourishment placed in a mound offshore.	Acts like a submerged breakwater until sand is dissipated. High operational costs as on-going top-up required.	Top-up or re-configured as required for changing conditions.