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National sediment compartment framework for Australian coastal management

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Abstract

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National Sediment Compartment Framework for Australian Coastal Management

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ABSTRACT

The concept of coastal sediment compartments was first used in the 1960s in the United States. It has since been recognised as appropriate for defining sections of the Australian coast, but had not been uniformly adopted around the nation in the way that has underpinned management, as in other countries. In 2012, the Australian Government supported a project to better understand coastal sediment dynamics using the sediment compartment approach as a framework within which to consider future shoreline behaviour and the impacts of climate change, including rising sea level, changing wave climates and sediment budgets. This paper outlines the sediment compartment project and uses case studies to demonstrate its application. The project consisted of three steps. The first step involved delineation of a hierarchy of coastal sediment compartments following a nationally agreed set of criteria, integrating the onshore/offshore geologic framework with known patterns of sediment movement and those inferred from surface landforms. This identified more than 100 primary compartments bounded by major structural features such as headlands or changes of shoreline orientation. At a finer scale, approximately 350 secondary compartments were identified, many of which encompass smaller scale structural features that define tertiary scale compartments or cells. For verification of this sediment compartments approach to coastal planning and management, the second step of the study comprised case studies of contrasting compartments with different patterns of sediment supply, transport and deposition. The third step, involved embedding all secondary compartments around the continental coast into the Shoreline Explorer, within the *CoastAdapt* toolbox (National Climate Change Adaption Research Facility). Information regarding the sensitivity of shorelines to change was compiled at the compartment scale, based upon evidence such as substrate, sediment transport attributes and oceanographic forcing, including waves, tides and storm processes. Presentation of information through *CoastAdapt* within the compartments framework provides a resource to facilitate improved coastal planning and management over different implementation levels, from national strategy scale down to local policy scale. Case studies from several contrasting settings around the Australian coast demonstrated the potential and feasible application of the sediment compartment approach at different spatial and temporal scales.

Keywords: Sediment compartment; cell; longshore transport; coastal planning; Australia

1. INTRODUCTION

A sediment compartment approach has been used in a number of countries as a means to improve coastal management at a range of spatial scales, through a better understanding of sediment mobility and transport within and between each compartment. The concept was first outlined in the United States (Inman and Chamberlain, 1960; Bowen and Inman, 1966), where it was incorporated into beach management by Komar (1976). Sediment cells, also called littoral drift cells, were delineated for much of the coast of the United Kingdom, based on perceived interruptions to movement of sand and shingle along beaches (Motyka and Brampton, 1993; Bray et al., 1995). These cells form the basis for shoreline management plans in England and Wales (Cooper et al., 2001, 2002; Cooper and Pontee, 2006; Nicholls et al., 2013).

In Australia, the concept of the coastal sediment compartment was introduced by Davies (1974). He recognised the nature of sediment compartments and a hierarchical structure of these around the Australian coast (Davies, 1977, 1980), where significant quantities of sand are transported northwards along both west and east coasts (Short, 2010). Efforts were made to understand the sediment budget for the Gold Coast (Chapman, 1981), and these concepts were applied along New South Wales (NSW) in a monograph focused on coastal management (Chapman et al., 1982). Searle and Semeniuk (1985) proposed a natural sectors approach that guided overall management of large-scale coastal works in southern Western Australia.

As indicated above, there is no standard usage nor definition of the terms cell and compartment, with littoral or sediment cell, coastal cell, sediment compartment and coastal compartment all utilised to define a section of coast (Cowell et al. 2003; McGlashan et al., 2005; Woodroffe et al., 2012; Eliot, 2013;George et al., 2015; Tecchiato et al., 2016). The terms are sometimes used interchangeably and at other times may mean somewhat different things. Despite the use of the term sediment cell in the UK and USA, general Australian usage prefers the term cell employed at a smaller spatial scale than compartment. In Western Australia, both cell and compartment terms and concepts have been used, with the smaller cells nested with larger compartments. For instance, Eliot et al. (2011) focus on compartments defined by broad scale structural elements. This contrasts with more recent reports by Stul et al. (2012, 2015) which place emphasis on transport processes at a finer scale and use the concept of cell to reflect connectivity of mobile sedimentary features. Much depends on the purpose of the investigation. In this study undertaken at a continental scale, it was agreed to use the term sediment compartment within a much broader hierarchical classification.

In 2012, the Australian Government supported a project to better understand coastal dynamics for the entire continent including consideration of potential climate change impacts. The project was seen as providing a method for assessing present and future natural hazards and impacts to coastal assets at risk from extreme events and climate change. The approach is based on an understanding of Australia's coastal geomorphology and sediment pathways using geologic frameworks for understanding movements of sediments and shorelines at present-day and future time scales. The approach and definition of the hierarchal coastal sediment compartments are provided in section 3 and section 5.2 identifies some key compartment characteristics relevant to assessing hazards.

The project built on previous recent work supported by the Australian Government, which assessed climate change risks to Australia's coasts (Harvey and Woodroffe, 2008; DCC, 2009; Harvey and Caton, 2010). It involved a *First Pass National Assessment* and incorporated a detailed shoreline classification termed *Smartline* (Sharples et al. 2009). In 2011, the Australian Government agreed that steps should be undertaken to assess risk through the application of the nationwide sediment compartment approach, especially given its initial successful application in Western Australia (WA) in relation to coastal planning (Stul et al., 2007; Eliot et al., 2011). This has led to the step-wise evolution of the *Coastal Sediment Compartment Project* (Thom, 2015), which was initially supported by Geoscience Australia (GA) and subsequently by the National Climate Change Adaptation Research Facility (NCCARF) as part of the Shoreline Explorer tool within *CoastAdapt* (*https://coastadapt.com.au/*).

The project comprised three steps. The **first step** consisted of a national hierarchical classification of the entire 30 000 km long Australian coast identifying boundary points for provinces, divisions, regions and primary and secondary compartments each defined by orientation, geologic and topographic characteristics (Hazelwood et al., 2013; McPherson et al., 2015). Sitting within the secondary compartments are smaller tertiary compartments or cells with identifable pathways of sediment movement driven by waves and currents. The dynamics and connectivity of sediment transfers from sources to sinks within these compartments, operating over differing time scales, indicate areas of potential vulnerability to the impacts of extreme events and climate change.

The **second step** was to undertake two pilot studies: one at two sites in WA on the west coast (the Swan and Pilbara regions, Eliot, 2013), and the other in NSW on the east coast at two sites (Avoca Beach in central NSW, and Cabarita Beach in northern NSW, Mariani et al., 2013) (see **Figure 1** for locations). These studies examined ways to assess complex geomorphological relationships between the underlying geology and coastal sediments, including the direction and magnitude of sediment transport, the sediment budget and the vulnerability of the shoreline and assets to extreme events and scenarios of climate change.

The **third step** was developed as part of *CoastAdapt*, a NCCARF phase-2 project to support coastal stakeholders and communities in Australia manage risks associated with a changing climate, funded by the Australian Government through the Department of Environment (changed in 2016 to Department of Environment and Energy). It was agreed in 2015 that a team of coastal scientists with expertise in coastal geomorphology should pool their knowledge to examine characteristics of compartments around the Australian coast at three spatial scales, primary, secondary and tertiary. The emphasis was on the secondary scale, of which there are around 350 mainland compartments. The emphasis has been on providing preliminary information on the nature of and potential impacts in each compartment, in a user-friendly format, in order that users would be better equipped to make use of the compartment approach in adaptation planning.

Use of this multi-scale sediment compartment approach, in which sediment movement is linked to geological frameworks and coastal processes, better accounts for the varying coastal conditions around the Australian coast. It offers a powerful tool that can be used to make robust and consistent assessments of sea-level rise and changes to other forces associated with regional variations in the impacts of climate change. Recent advances in technology and coastal science have improved the nation's capacity to use the approach, including capture of the fine-scale form of seabed texture and structures through remotely-sensed techniques. Interest has already been shown by state governments in the potential for application of the approach at state and regional levels. There is recognition that more information on sources and movements of sediments, especially offshore, will give potential users a greater capacity to make decisions on use of coastal lands than exists at present.

2. BACKGROUND

2.1 Concept of Coastal Sediment Compartment

Coastal sediments move along a number of pathways over time as they are transported by various processes into temporary or permanent coastal sinks. Sources of beach material, their modes of transport across and beyond the surf zone, and their longshore transport, were described by Cuchlaine King in her synthesis of beach processes (King, 1972). She recognised the pioneering work of Californian researchers in developing the sediment cell concept. This concept goes back at least to Inman and Chamberlain (1960) and Inman, et al. (1963) who developed the littoral compartment/cell concept for southern Californian and Kauai respectively. Inman and Frautschy (1966) then identified four littoral sediment compartments along the central California coast, whereas Bowen and Inman (1966) identified positive and negative contributions to a littoral sediment budget. Komar (1972) in reviewing the California research went on to examine the various sources of coastal sediments, their means of transport and losses, and Rosati (2005) described approaches to determining a sediment budget. Sediment cells also underpin management of much of the coast of Great Britain (Motyka and Brampton, 1993; Cooper and Pontee, 2006; Nicholls et al., 2013), forming the framework for shoreline management plans.

In Australia, Davies discussed coastal sediment transport systems, including sediment sources, transport, and sinks, putting these factors together to present the concept of a coastal sediment compartment, with its inputs, outputs and store (Davies, 1974). In 1977, he applied this concept to his overview of the Australian coast which he divided into four segments (Davies, 1977): warm temperate humid, warm temperate arid, tropical arid and tropical humid. Chapman et al. (1982) used the sediment budget approach to assess both the evolution and present stability of coastal compartments along the NSW coast. The northern NSW coast is dominated by longshore transport of sand to the north, as discussed below; whereas the southern NSW coast is more embayed with prominent headlands that interrupt longshore sand transport. Chapman et al. (1982) mapped all major compartments discriminating whether their boundaries were closed or leaky to longshore transport.

Recently, several studies have diagrammatically and quantitatively depicted some of the different ways sediment systems operate on the Australian coast (Woodroffe et al., 2012; Eliot, 2013; Mariani et al., 2013), following the concepts introduced by Davies (1974). These studies show how coastal investigations can capture the relative importance of sediment processes in relation to shoreline behaviour. The power of such studies is their ability to determine changes in sediment volume along vulnerable shorelines where natural and built assets are at risk from erosion or inundation under different sea-level and wave conditions.

Building on earlier work by authors such as Searle and Semeniuk (1985), recent reports in Western Australia on coastal compartments (Eliot et al., 2011) and sediment cells (Stul et al., 2012, 2015) provide separate physical frameworks for marine and coastal planning. In the 2011 report, available descriptions of geologic features and large landforms were used to identify compartments at strategic, regional and local scales currently used for coastal planning and management. The more recent work of Stul et al. (2015) focusses at a local government and site scale. In WA, these multi-scale frameworks facilitate comparison and analyses of environmental data across and within each compartment as well as between different levels in the hierarchy (Eliot et al., 2011). Critically, they are seen as steps in coastal risk analysis that will ensure more efficient allocation of resources. They also address issues of present sustainability and adaptation to climate change, the latter including both sea-level rise and potentially disastrous impacts of more extreme events on the economy and society.

It is recognised that investigations at the tertiary sediment compartment scale are most useful to define and analyse active geomorphic processes that move sediments into, along, and out of, a section of coast. Calculation of a sediment budget within a tertiary compartment can be extended to the secondary scale if appropriate. Essentially there is a “store” of sediment within a tertiary compartment comprising landform units, such as beaches, barriers and dunes, which are capable of being mobilised under different process conditions of varying magnitude and frequency. The nature of those processes could change over time, especially as sea level rises and wave climate changes.

The concept of the ‘closed’ coastal sediment compartment was applied to the southeast Australian coast by Davies (1974). The concept was expanded in this region by Chapman et al. (1982), who showed how differences in the supply of marine sand over the last 6000 years have led to the evolution of different types of coastal barriers (see also Thom, 1974; Roy et al., 1994; Woodroffe et al., 2012). Thom (1989) simplified the concept into two types: ‘closed’ and ‘leaky’, and this contrast is illustrated in **Figure 2**. Recently it has been shown how consideration of headland characteristics can be used to infer the extent to which longshore transport along the coast of California is impeded (George et al., 2015). As noted by Woodroffe et al. (2012), this approach in NSW has been considered a useful tool in the estimation of sediment budgets, following procedures outlined in the NSW Coastline Management Manual (1990).

2.2 The national need for the sediment compartment approach

In its report to the Minister for Climate Change and Energy Efficiency in 2011, the then Coasts and Climate Change Council recommended that the Australian Government establish a science-based program that would develop and deliver consistent information on climate change risk. Such a program should involve centralised access to information on the physical effects of climate change, including the use of regional modelling, in order to assist with hazard assessment and coastal management planning and decision making. In the view of the Council, state agencies and local governments would benefit from access to such information. Intergovernmental collaboration was suggested as part of the program as this would minimise duplication and make for more efficient use of funds and technical resources. Although this Council ceased to exist in 2012, the incoming Minister for Environment in the Australian Government, agreed that there was a need for a national analysis of risk to coastal local governments in managing impacts from climate change and supported the recommendation for further work on the sediment compartment approach.

The need for information on Australia's many coastal regions, and more coordination between levels of government with coastal management responsibilities, was identified in the report of the Standing Committee on Environment to the House of Representatives in 2009 (HORSCCCWEA, 2009), the DCC Coastal First Pass Risks report (DCC, 2009), and the Baker and McKenzie legal liability study commissioned for Australian Local Government Association (Baker and McKenzie, 2011). This need follows past recommendations to the Australian Government through national inquiries as far back as 1979 advocating a stronger role for the Australian Government in coastal management similar to that in other federated nations. In Australia, coastal planning and management is largely the responsibility of state and territory governments with varying levels of delegation to local governments. There is a very limited role for the Australian Government (Harvey and Caton, 2010). Stakeholder engagement prior to the development of *CoastAdapt* indicated that stakeholders wanted more information about the most appropriate scales for climate adaptation planning, access to better information and guidance on sediment and coastal dynamics, as well as on the susceptibility of the coast to climate change effects. All these interests are addressed by the sediment compartments approach, with the secondary compartment chosen in this study to provide a regional assessment of the sediment behaviour and budget, while acknowledging at an operational level the tertiary compartment and its behaviour is the key to both understanding present conditions as well as predicting future impacts at a more local level.

The scientific basis for adopting a national approach to assessing hazard impacts and consequent risk to built and natural assets emerged from the *First Pass National Assessment* (DCC, 2009). Differences in geology, climate, geomorphic processes, ecological conditions, and projections of impacts of climate change drivers on sections of the Australian coast highlighted the need to develop methods that would capture the direction and rate of present and future coastal change needed in decision making. These geographic differences have been well established in national reviews of coastal Australia including the work of Bird (1971, 1993), Davies (1974), Galloway et al. (1984), Thom (1989), and Short and Woodroffe (2009). However, it was the work of DCC (2009) in highlighting the huge cost to the Australian taxpayer of impacts of climate change, in particular sea-level rise, which drove home the future requirement for a national, coordinated approach. Successive federal governments have resisted the opportunity to take a clear leadership role leaving state and local governments to address issues with their own resources. Nevertheless, the federal government did recognise that NCCARF, a university-based facility, should be supported at least until 2017 to assist in providing improved tools, such as *CoastAdapt*, for state and local governments to use in addressing climate change problems. To this end the sediment compartment approach has been tested by integrating the coastal and seabed geology with known patterns of sediment movement and those inferred from depositional landforms. Sediment compartments can be applied at different spatial and temporal scales and information made available as a resource to facilitate improved coastal planning and management. While the spatial scale is defined by the compartment boundaries, the temporal scale will consider the contemporary compartment behaviour, as well as predicting future behaviour based on relevant climate scenarios.

3 THE NATIONAL HIERARCHICAL CLASSIFICATION

As a way to achieve a consistent approach to understanding changes to coastal conditions in the future, a decision was taken at the national level to adopt a hierarchical geographic classification. Within this classification secondary compartments, the focus of this study, are located.

Geoscience Australia (GA) coordinated the development of this hierarchical division of the Australian coast into compartments. The approach was based on previous multi-scale work in WA (Eliot *et al*. 2011). This provided a framework for the national classification undertaken by a group of experts working initially with GA. Expert judgements were used to define compartment boundaries down to the secondary scale and to establish boundary points based on the criteria outlined below. The results were quality checked by others including representatives of state governments and are now available on the GA website (https://data.gov.au/dataset/primary-and-secondary-coastal-sediment-compartment-maps).

The following indicates the hierarchical classification adopted in this project:

- **Provinces (2):** Based primarily on climate and divided roughly along the Tropic of Capricorn (between North West Cape 21°45'S and Sandy Cape 24°40'S) into the northern *tropical* coastal province and southern *temperate* coastal province In other countries climate, orientation and other major delineations may be involved.
- **Divisions (7):** Based on *province*, then primarily coastal orientation (NW, NE, SE, S and SW), apart from the Gulf of Carpentaria.
- **Regions (23):** Based on *division*, then geology, with some contribution from coastal orientation/configuration, as in Tasmania, an island with three distinctive coasts, and the irregular South Australian gulfs.
- **Primary compartments (102):** Based on *regions*, which are then subdivided at major physical coastal boundaries into primary compartments. Primary coastal compartments are sections of the coast that are bounded by major, usually distinctive, structural features such as rocky headlands or major changes in orientation of the coast.
- **Secondary compartments (>350):**   Based on *primary compartments*, with subdivisions into secondary compartments recognising secondary coastal

boundaries. Secondary compartments are also formed by structural elements within which there may be sediment exchange. Secondary boundary points are identified at scales between 1:100000 and 1: 25000.

- **Tertiary compartments (>1000):** Based on *secondary compartments*, which are sub-divided at obstructions (usually headlands) into tertiary compartments, some as small as an individual beach. Tertiary compartments may act as self-contained sediment compartments or be linked to adjoining compartments. These typically occur at scales less than 1: 25000.

In order to obtain a national overview of coastal behaviour now and into the future, the decision was made to focus on the secondary compartment scale (**Figure 1**). At this scale it was considered by the authors that sufficient information was available to provide a national understanding of the sensitivity of shoreline change building on earlier national scale work by Sharples et al. (2009) using the *Smartline* method (which provides a linear segmentation of the Australian shoreline based on characteristics of form and fabric). To this end, ~350 secondary compartments have been identified; several further compartments may be added when outlying islands are considered in more detail (for example, Torres Strait). In some cases the relevance of information will be increased by studies focused at the tertiary scale that have been, or should be, undertaken to better inform decision makers. Pilot studies were undertaken at a tertiary level to demonstrate the influence of compartment structures on coastal dynamics at this scale.

4 PILOT STUDIES

The aim of Step 2 was quite specific: to use pilot studies to investigate the potential application of the sediment compartment approach in characterising how specific sections of coast would respond under present and future conditions. This involved two projects on either side of the continent to examine geologic and landform characteristics, oceanic and sediment transport processes, and sediment budgets at four locations to test the applicability of the approach. In Western Australia, the project was undertaken by Damara Pty Ltd which has experience in working with WA state agencies in applying similar concepts. The company selected contrasting sites in microtidal wave-dominated Swan coastal plain in the southwest and arid, macrotidal Pilbara in the northwest (see Eliot, 2013). In New South Wales, the Water Research Laboratory (WRL) of the University of New South Wales studied two sites, the embayed Avoca Beach in central NSW and longer more open Cabarita Beach in northern NSW (Mariani et al., 2013).

The **Damara** project investigated two Western Australian sites and, using late Holocene coastal landforms in very different coastal environments, demonstrated that a compartment hierarchy supports improved representation of long-term coastal dynamics. The project provided examples of geomorphic and geologic setting influence on coastal response to sea-level rise. For the southwest site, significance of discrete pathways for shelf-shore sediment exchange through coastal reef systems was identified, influencing the spatial distribution of expected response within larger scale coastal compartments. For the northwest site, the roles of episodic sediment supply from rivers and the wide area of coastal floodplain were examined through landforms and available sediment budget evidence. This suggested that the coastal floodplain response to sea-level rise is likely to change systematically along a coastal compartment, reflecting the relative availability of sediment and its ability to be transferred across the floodplain. The contrast between the geomorphic features defining the active compartment between the southwest and northwest sites suggested there may be a need to identify compartments in different ways according to their setting.

The **WRL** sites represent contrasting closed and leaky tertiary scale compartments. This project examined shoreline response to extreme events and climate change at both sites and tested the applicability of deterministic and probabilistic approaches for the assessment of coastal change. Sediment budgets were inferred with consideration of present day and future climate change scenarios out to 2100. Probabilistic modelling was seen as a method for evaluation of long-term shoreline responses that would most assist planning and management decisions.

In all four study areas, the inherited character of landforms of late Quaternary age, including but not confined to deposits emplaced during the last 6000 years, offered investigators a sediment exchange history that can be shown to influence shoreline change at both multi-decadal and short-term storm impact scales.

Some of the **key lessons** learnt from the pilot studies in **Step 2** include:

- There is a fundamental need for high quality bathymetric data. Often areas of concern around the Australian coast lack such data from low tide to depths of expected sediment movement on the inner continental shelf, so-called "closure depth". These depths will vary with compartment type, sediment type and energy conditions (e.g. 10 –60 m water depth). However, modelling studies require good bathymetric control which is usually available on land but less so below sea level.
- Coupled with bathymetry is the need for data on surface sediment texture from the beach-beach to the inner continental shelf (10's of metres depth), which is essential for modelling. Sediment data can be obtained through mapping of sediment bedforms and rock features (for instance, by using marine LiDAR or other forms of bottom and sub-bottom mapping and profiling); and, by coring and dating the sediment sequence at shallow depths to measure the depth of reworking and evaluate the shoreface evolution over the past several hundred years.
- Barrier and preferably shoreface chronology is desirable to set the present coast within its evolutionary framework. Knowledge of barrier evolution provides data on rates of sand supply and impacts of longer term changes in drivers such as wave climate and sediment budget. Work by Goodwin et al. (2006) in northern NSW and Oliver et al. (2017a, 2017b) in southern NSW has been able to reconstruct Holocene sediment budget and its variation though time in response to changing climate, sediment supply and/or degree of embayment infilling. On a regional scale, Short (2010) used the volume of Australia's barrier systems to calculate rates of onshore Holocene sand supply around the coast.
- Large sections of northern Australia, like the Pilbara, experience high tidal ranges and low waves, and have a mix of sand and muddy sediments, often

interacting with mangrove communities. Sediment movements in such locations require careful mapping and understanding of processes of sediment exchange, often developed through fine-scale transitions and interactions between wave and tidal current forcing. These regions also have low-lying coastal plains that experience cyclone-driven river floods, extreme waves and marine inundation. In such locations, coastal change can be the result of episodic state-changing events, followed by lower energy wind, wave and tidal conditions. These can produce sequential, ephemeral and relict landforms. Assessment of potential climate change impacts requires an understanding of these complexities at different scales.

- Another highly desirable data set should come from long-term monitoring nearshore, beach/intertidal and backshore environments. The WRL report (Mariani et al., 2013) concludes that high quality topographic surveys, preferably in concomitance with wave data, will allow validation of models of shoreline change including capacity of beaches and dunes to recover from the impact of erosion events. Surveys of beaches influenced by the presence of intertidal rock surfaces (such as the different types of "perched" beaches described in the Damara report, Eliot 2013) require special attention due to inherent difficulties in applying standard modelling techniques.
- Modelling of shoreline change using the sediment compartment approach involves consideration of complexities beyond those normally invoked in standard numerical modelling approaches such as the Bruun Rule (see Woodroffe et al, 2012, section 3.4 for a review of the issues in using the Bruun Rule for coastal planning and management). Eliot (2013, p. 33) cautions against reliance on a tool that gives a fixed allowance for a setback suggesting that the method used in WA under the State Coastal Planning Policy has "partly stifled sub-regional assessment of the threat provided by sea-level rise". Both pilot studies examined the need to understand geomorphic and sediment transport factors in any model of shoreline response to extreme events and to sea-level rise.
- Pilot studies offered support for a close examination of the drivers of sediment movement and how models should best incorporate that knowledge in assessing shoreline change, inundation and risk to assets. They highlight the need for both maintaining and indeed expanding wave and tide recording systems as a spatial network around the Australian coast.
- Both the WRL study (Mariani, et al. 2013) and the Damara report (Eliot, 2013) showed how the sediment compartment approach at both tertiary and secondary scales can assist in determining rates of alongshore/littoral transport. The rates vary over time as well as between different sites highlighting the need to consider time scales. This point is made in the Damara 2013 report in their evaluation of how carbonate sand moves through and along different calcarenite reefs on the inner continental shelf. It is also an issue along the NSW coast where there is uncertainty over the connection between so-called relict offshore sand bodies and the nearshore.

5 NCCARF NATIONAL COASTAL COMPARTMENT PROJECT

5.1 Framework and method

The team of coastal experts that divided the Australian coast into provinces, divisions, regions, primary compartments, and secondary compartments made an assessment of the ~350 secondary compartments in relation to the sensitivity of its shorelines to change over time. This is the **third step** in the evolution of the Australian approach to using the coastal sediment compartment concept.

Access to this information can be obtained from the NCCARF website under the heading of *Shoreline Explorer* in *CoastAdapt.* This shows boundaries of each compartment, an attribute table describing location, general geomorphology, and sensitivity to change. The table also contains a pdf link to more information for that compartment including in some cases specific details on selected tertiary compartments or cells. The scale of such compartments, in general, makes them convenient on a national scale to assess present-day changes in shoreline position and hence potential for modification under changed climate conditions. It was assumed that present-day exposure and vulnerability of assets are reasonable guides to where problems are likely to arise as a result of ongoing sea-level rise and therefore where adaptation efforts may be needed.

5.2 Assessment of sensitivity of compartments to change

One of the key objectives of the project at a national scale was to assess the sensitivity of different shoreline types to change over time. While no specific time frame was defined, it was assumed that the drivers for change in any given secondary compartment would interact with available sediment and landform conditions at both a regional and local morphodynamic level (following principles outlined in Wright and Thom, 1977; Cowell and Thom, 1994; Wright, 1995). Accordingly, information is provided for each secondary compartment on sensitivity to future change, including sea-level rise. A sensitivity rating was assigned to each compartment to which is also attached a confidence rating.

5.2.1 **Sensitivity**: A key purpose for which the sediment compartments project was undertaken was to provide information on the sensitivity of coastal landforms to climate change. Sensitivity was assessed using expert opinion based on available information in the geographic area. This is focused primarily on their morphodynamic behaviour in response to sea-level rise over coming decades, but includes potential impacts through changing wave climate (height, direction), including increasing mid-latitude mean and extreme wind speeds generating increased local wind-waves, altered cyclone intensity, duration and tracks, and more subtle adjustments to tidal amplitude, sea-surface temperature, or changes in terrigenous sediment delivery as a result of changes in rainfall and runoff. The sensitivity of unconsolidated sandy and muddy coasts as well as weakly lithified rocky shores within each secondary compartment has been ranked according to the following scale (see https://coastadapt.com.au/sites/default/files/factsheets/Datasets_guidance_1_present.pdf):

1. Shorelines that are presently accreting and are likely to continue or accelerate their accretion as sea-level rise continues (as a result of increased supply of sand from an alongshore source or from river/tidal channel sources).
2. Shorelines that are currently stable but are likely to start accreting as sea-level rise continues (includes shorelines that periodically grow seaward but may be subject to episodes of erosion).
3. Relatively stable shorelines which may be subject to periodic erosion followed by recovery (accretion), but no long-term recession expected in the next few decades since the sediment budget remains sufficiently balanced over time from offshore, alongshore or terrestrial sources.
4. Shorelines that currently do not show evidence of long-term recession but are likely to begin receding with continuing sea-level rise (based on sediment availability onshore and offshore).
5. Shoreline recession is occurring now (typically documented by historical shifts in shoreline position) and the shoreline is likely to continue to recede as sea level rises (possibly at a faster rate depending on local conditions).

Sensitivity scores in many heterogeneous secondary compartments vary from one tertiary compartment to another, indicating the importance of focusing at the appropriate scale when making coastal management decisions. The significance of the principal factors influencing the sensitivity scores is outlined below.

Sediment budget is typically the most important determinant of landform sensitivity to sea-level rise for open coast (swell-exposed) sandy beaches (Komar, 1996; Rosati, 2005). Sandy coasts are highly dynamic environments, which may be subject to net gains (positive) or losses (negative) of sediment over time. Sand may be supplied to the compartment by onshore transport from shelf sources, from alongshore transport into compartments including headland bypassing, or from sources such as river input, cliff erosion, or dune headland overpassing. Sand may be lost through offshore transport, by alongshore transport, by landwards transport into mobile dunes, or via tidal current transport into estuaries and flood tide deltas. Some compartments (e.g. deeply embayed beaches) may have a dynamic but balanced sand volume which neither gains nor loses sediment over time. The sediment budget of many compartments is highly variable and can switch from positive to negative, either episodically or in response to a long term change in conditions. In particular, sea-level rise may result in a switch to a more negative budget as higher sea levels result in more frequent erosion events or make greater accommodation space available for sand to be lost into sinks such as estuaries. The periodic storm cut, and recovery, typical of many Australian beaches, can transition into a system which undergoes long-term recession, depending on factors such as the recurrence frequency of storms and the availability of a sediment supply. Whereas the sediment budget on a beach may be quite variable, weakly lithified shores (such as Tertiary-age cohesive clays in southeastern Tasmania, or shores abutting the lateritic soils in the Pilbara in WA, or weakly lithified dune-rock calcarenite across southern Australia) can be considered as always losing. These settings can only lose sediment through erosion, especially their clay and silt fractions, and cannot subsequently recover. Such shorelines may exhibit a relatively early acceleration of prior rates of shoreline retreat in response to sea-level rise (Trenhaile, 2011).

S*ubstrate* or composition of coastal landforms determines erodibility and also the capacity to accrete or recover from erosion. Erodible coastal landforms on the Australian coast are dominated by unconsolidated sandy shores, muddy coasts and semi-lithified 'soft-rock' coasts and are potentially sensitive to sea-level rise. Depending on other conditions, some of these shores, most notably sandy beaches, but also some saltmarsh or mangrove shores, may accrete and recover following erosion, and so may be relatively resilient in the face of sea-level rise.

Wave climate due to both swell waves and locally generated wind waves provides a driving force on open coasts. Waves can cause cross-shore sediment movement in either direction, typically occurring as cycles of storm erosion and recovery. On a high energy beach system, this process may support the coastal adjustment to sea-level rise, by causing a net transfer of sediment from offshore towards the beach. In contrast, sandy shores within tidal but swell-sheltered locations, such as estuaries and tidal lagoons, commonly experience a less balanced erosion-recovery cycle, with increased tendency for horizontal deposition during the recovery phase. This discrepancy in the pattern of erosion-recovery means that lower energy shores can potentially be more susceptible to progressive recession under rising sea levels. Changes in wave climate, particularly in wave height and direction, can have dramatic impacts on sandy shores as they erode and/or realign and change their rates of longshore sand transport.

Extreme events refer to the frequency and intensity of waves exceeding a certain level (e.g. > 3 m) which leads to general beach erosion. High energy wave-dominated beaches (such as those across southern Australia) are likely to begin receding relatively early in response to sea-level rise. This occurs because relatively small rises in sea level enable storm waves to begin eroding the upper beach too frequently for full beach recovery to occur between erosion events. On soft-rock coasts which do not in any case recover from erosion, a higher frequency of erosive storm wave events (including locally-generated wind-wave events) may be expected to result in a greater acceleration of prior retreat rates compared to less stormy shores. In a changing wave climate any increase in the frequency and/or intensity of extreme events will not only erode the beaches but could accelerate shoreline recession.

5.2.2 **Confidence**: Detailed studies of some tertiary compartments, including their sediment budget and Holocene evolution, have been undertaken in NSW and WA (for example those studies noted above in Step 2). However, for the greater part of the Australian coast, relevant information on geomorphic, geological and meteorological and oceanographic conditions is only available at regional scales. In order to provide a characterisation of the sensitivity of secondary compartments to sea-level rise for the entire Australian coast, it has therefore been necessary in many cases to infer potential for change from expert judgement of the relative susceptibility of one landform compared to another. Processes are inferred from what is known about each landform type and its known capacity to change over short, medium and long time scales.

In order to clarify the degree to which the differing sensitivities have been applied to each compartment on the basis of detailed studies as opposed to simply expert judgement based on limited information, a 'Confidence' ranking has been applied to the description and sensitivity ratings provided for each compartment (e.g. Rissik et al., 2005; Maxwell et al., 2015), as follows:

Low	There is limited or no information describing landforms or coastal landform change over the historical period.
Medium	Some information is available on changes to landforms; it may come from multiple sources which may include recent landform change from site descriptions and occasional aerial photographs over past decades.
High	Detailed information is available identifying changes to coastal landforms spanning the historical period, and includes regular remotely-sensed information over the past 30 years or more.

5.3 How to use Shoreline Explorer for coastal compartments

The following are recommended steps to assist users of *CoastAdapt Shoreline Explorer* to access coastal compartment information for application in coastal management and adaptation (see https://coastadapt.com.au/sites/default/files/factsheets/Datasets_guidance_1_present.pdf).

1. Start by looking at the coastal compartments information and identify the level of sensitivity for the compartments that relate to a local government area or location of interest. The sensitivity rating is on a scale of 1 to 5, with higher numbers indicating a greater sensitivity to erosion, and lower numbers a greater likelihood of accretion.
2. If the sensitivity to change is medium to high, for example 4 or 5, a brief indication of the reason is provided in the *Shoreline Explorer* attributes and attached descriptions, however it is useful to get further expert advice on the cause of the erosion risk. For example, this may be needed to understand whether the sensitivity is due to high volumes of longshore sediment transport, or a deficient offshore sand supply. Limited offshore sources of sand are often revealed at beaches where recovery from storm erosion is slow or incomplete. Additionally, a high level of sensitivity suggests that planning may need to consider adjacent compartments.
3. Consider the scale of planned development in the area adjoining a coastal sediment compartment. If a large or high value development is planned, for example a hospital, it is useful to consider the implications of that development at all compartment scales. Detailed impact modelling using local data will also be needed for large developments or for critical infrastructure. For many smaller decisions, it is appropriate to consider implications at a more detailed scale than the scale of secondary compartments.
4. If a planned development is near a sediment compartment boundary, or where a boundary is shared by adjoining local government agencies it is useful to consider the adjoining sediment compartments, as well as for the adjoining councils to consult in planning, assessment and decision-making (see metropolitan case study, section 6.4, and NSW *Coastal Management Act* (2016) section 16 (1) (b) (i)).

Other sources of information will also be required for effective coastal planning and management, particularly where the compartment sensitivity rating is high. For example, designing effective coastal protection measures requires an understanding of the location, nature, volume and transport of local sediment sources. The following section makes use of the compartment approach from a number of Australian cases to show how an understanding of sediment movements over time will be important for planning and management purposes.

6 APPLICATION OF THE AUSTRALIAN APPROACH: CASE STUDIES

It has been possible from this national review of Australian sediment compartments to select a set of locations that clearly illustrate the type of change occurring around the coast, together with an understanding of pathways of sediment movements and estimates of sediment budgets that bring about these changes. Based on these and other cases in Australia, this approach clearly helps explain spatial variation of coastal landforms subject to change as a result of sea-level rise and other effects of climate change, and offers a valuable tool in any assessment of impacts of such changes. There is an increasing emphasis on using a variety of methods to determine rates and directions of sediment movements in and out of compartments at different spatial and time scales. While it is not yet possible to offer any more than initial estimates of the magnitude and direction of such processes, it is a matter of growing interest from government agencies in all states to improve the national capacity to provide both resilient and adaptive actions to protect natural and built assets at risk in locations close to the shore.

Six case studies have been selected. These case studies were selected to cover different climate and environmental conditions and, ranging from tropical to temperate to arid, river-dominated to wave and/or tide-dominated, quartz and carbonate rich, and one metropolitan. Each case is underpinned by a large range of investigations, with some of the relevant papers listed in the pdf file noted in the attribute table in *Shoreline Explorer*, and a subset of references contained herein to highlight the nature of work undertaken to date. Each study makes some indication of potential risk associated with likely future shoreline change is possible based on our interpretation of sensitivity, level of confidence in the information available, and what are considered to be impacts under climate change.

6.1 River-dominated coast

The northern tropical humid coast of Australia has numerous river systems that have built deltas at their mouths. On the northeast coast these are exposed to southeast trade wind and waves, coupled with meso to marco tides which flood to the north, all resulting in predominantly northerly transport of river derived sand. Two examples of river deltaic systems from north Queensland, a tropical humid region with episodic fluvial sediment supply to the coast, are shown in **Figure 3**. The area associated with the Barron River delta, between Trinity Inlet and Buchan Point, includes the low-lying city of Cairns, its airport and urban residential and cane-farming lands to the north. It is characterised by tradewind and tide driven longshore transport, including headland bypassing, and exposure to tropical cyclones. Large tracts of coastal land here are vulnerable to river flooding and storm surges accompanying tropical cyclones and sea-level rise (Nott, 2005). The Barron River supplies ~5000 m^3/yr; however, northerly longshore transport exceeds this amount (**Figure 3a**) leading to a negative sediment budget and ongoing shoreline recession, requiring that the shoreline is protected by armouring. In addition the river channels switch and tend to deliver variable pulses of flood-borne sediment all of which leads to a dynamic and eroding shoreline (BPA, 1984). Future sea-level rise will exacerbate these present trends, and when combined with inundation from river flooding, along with storm surges during projected more intense cyclones, will require considerable planning and investment in infrastructure to ensure the urban and rural areas minimise risk. Sediment moved alongshore accumulates in sinks which should continue to accrete in the future.

The Pioneer River, in the vicinity of the city of Mackay, discharges ~44000 m^3/yr of sand to the coast. The tidal range is ~6 m and there is bi-directional flow of sediment at the mouth as shown in **Figure 3b** (EPA, 2004). Most sand however is transported ~30 km north by trade-wind driven longshore sand transport and headland bypassing into a sink at Sand Bay while Far Beach immediately to the south receives considerably less and is slowly accreting. These processes will most likely continue into the future. Much of Mackay, however, is built on the low-lying Pioneer River floodplain and has a history of inundation from storm surges and river flooding. In this area vulnerability under climate change will largely be an extension of the inundation threats posed since settlement in the 19th century.

6.2 Wave-dominated coast

Compartments along the southeast coast of Australia fall into two basic types, closed and leaky (**Figure 2**). The latter are mainly in the northern part of NSW especially at both secondary and tertiary scales. Closed compartments occur at tertiary scales; they dominate the central and southern part of this state with limited or zero leakage of sand around prominent rocky headlands. Overall the coast is wave-dominated and microtidal and contains numerous headland-embayed beaches rich in quartz sand derived from long periods of reworking terrestrial material on the continental shelf during the Cainozoic (Roy and Thom, 1981). Most of the rivers draining the Eastern Highlands have delivered no sand to the open coast in the Holocene. Sand forming dunes, beaches, flood-tide deltas and nearshore deposits has been transported into the present embayments through onshore and alongshore transport processes during this period.

One of the best known sediment transport systems in NSW was the subject of an early study by Gordon and colleagues in the 1970s (PWD, 1978).They identified sediment budgets and erosional events especially in the vicinity of Cape Byron. Since then several studies have examined sediment transport in this open compartment extending from the Clarence River in the south to, and along, the Gold Coast in Queensland (see summaries in Mariani et al., 2013; Patterson, 2013). Sand pulses around headlands have been shown to be a mechanism of longshore transport generating large migratory updrift rips that erode the beach and expose the backshore-dunes and infrastructure to wave erosion followed by sand wave accretion (Short, 1999, Fig. 9.13d).

Longshore sand transport to the north is considered to be a major factor in the sand budget and shoreline changes in northern NSW (**Figure 4**). As shown by Mariani et al. (2013) in the WRL pilot study and Patterson (2013, Fig.3-26), transport rates have been the subject of numerous, and at times conflicting, estimates both within and between leaky tertiary compartments. However, it is still uncertain as to how much sand is also currently coming onshore, and can continue to come onshore from the inner shelf even as sea level rises, to sustain beach/dune systems along this stretch of coast (Cowell, et al. 2000; Daley and Cowell, 2012; Mariani et al.,2013, Table 11). Clearly more work remains to determine net transport along this stretch of coast, and whether there is any net onshore addition to the sand budgets to these leaky compartments, in order to evaluate the behaviour of shorelines and risk to built assets under climate change conditions.

In central and southern NSW, each of the secondary compartments can be conveniently sub-divided into tertiary compartments as defined by prominent rock headlands that restrict longshore sediment transport (Chapman et al., 1982). The sediment transport system is dominated by onshore-offshore sand exchange following storms and periods of post-storm recovery such as captured by the long-term measurements at Moruya in a tertiary compartment on the NSW south coast (Thom and Hall, 1991; McLean et al., 2010). Rivers play a minor role in supplying sediment to the coast (for example, the Shoalhaven River in southern NSW, see Carvalho and Woodroffe, 2017). Work by Roy, Cowell, Kinsela and others near Forster highlights products of sediment exchange over time within a compartment that has served as a major sand sink during late Pleistocene interglacial and Holocene rising and high sea level intervals (see Kinsela et al., 2016). Where accommodation space is more limited, shorelines undergoing recession today in all likelihood will continue to recede as sea level rises.

Figure 5 shows part of a secondary compartment on the central coast of NSW (Hudson, 1999). The Avoca tertiary compartment, studied by Mariani et al. (2013) as part of the WRL pilot study, sits within this section of coast. The confined occurrence of beach and nearshore sand by rock reefs is clearly shown. Further offshore are shelf sand bodies at water depths greater than 20m that along this section of coast have been defined by side-scan sonar, seismic and drilling investigations (Field and Roy, 1985; Gordon and Hoffman, 1986; Roy and Hudson, 1988; Hudson, 1999). These may offer a source of nourishment sand if beach sand supplies become depleted as sea level rises. It is not entirely clear whether these deeper sand sources on the inner shelf are connected to the confined shoreface and beach system. In all likelihood they are not, but further field studies are required if the beach is to be nourished from an offshore source. However, Mariani et al. (2013, Table 11) in their probabilistic estimates of recession to 2100 involving a sea-level rise of 1.1m, assumed no net onshore drift.

6.3 Deeply embayed coast

The deeply embayed secondary compartment of Frederick Henry Bay, southeast Tasmania, offers an opportunity to review interconnected sediment systems (**Figure 6**). This is a south-opening coastal embayment into which Southern Ocean swell penetrates and is refracted with little directional variability once within the bay. The bay is broad (10 km wide) and relatively shallow (mostly less than 20 m deep), with a sandy floor. There is negligible river sand supply, although modelling suggests there may be some ongoing transport from the inner shelf into the bay (Harris and Heap, 2014). Present-day sand transport processes in the bay are inferred to be mainly swell-driven towards the north with ongoing alongshore transport through several leaky tertiary compartments. Two sheltered tidal lagoons, Pittwater and Pipeclay Lagoon, serve as sand sinks; shoreline recession of the most wind-wave exposed soft-rock (cohesive clay) shores in swell-sheltered Barilla Bay appears have accelerated since the 1940s, perhaps as a response to either sea-level rise and/or increased wind speeds driving local wind-waves. Sand is also trapped within several swash-aligned tertiary beach compartments inferred to be closed. The much larger Norfolk Bay is also a sand sink although swell-driven sand transport into the bay is probably weak.

Sediment budget and transport pathways for Frederick Henry Bay are largely inferred from geomorphic evidence. Seven Mile Beach, at the head of the bay, is a prograded barrier (Davies, 1961). A preliminary estimate inferred that ~60,000 m^3/yr of sand had been supplied from offshore since circa 7000 years BP to build this feature (Byrne, 2006). However, the sedimentary history of successive beach ridges records the accumulation of sand from both locally reworked and offshore sources, with at least one long hiatus, and a rate of accretion that appears to have slowed during the past 500 years (Oliver et al., 2017). Detailed studies of erosional events and shoreline behaviour extending back 70 years have been undertaken at Roches Beach (Sharples, 2010, Sharples et al., 2012, and work in progress; Carley et al., 2008). A time-series of 32 aerial photographs from 1947 to 2015 shows a marked long-term (multi-decadal) change in shoreline behaviour around 1980, from stable (with cut-and-fill cycles) to persistently receding, which in this leaky tertiary compartment could be a response to increasing alongshore loss of sand related to more frequent erosion of the upper shoreface under sea-level rise (Sharples, 2010; Sharples et al., 2012; work in progress). Modelling studies coupled with historical air photo analysis have been used to assess long-term risk from sea-level rise for Clarence local council (Carley et al., 2008; Shand & Carley, 2011; Dell and Sharples, 2012). All these studies point to vulnerability of local residential areas in some tertiary compartments as sea level rises (sensitivity 5), given limited onshore sand transport to compensate for net offshore and alongshore sand loss, although beaches in some other (closed) tertiary compartments are inferred to be currently stable (sensitivity 3).

6.4 Metropolitan coast

A highly modified secondary compartment forms the metropolitan Adelaide coast. Located in Gulf St Vincent, South Australia, the coast is exposed to westerly wind waves and occasional southerly swell, which drive a net northerly longshore sand transport. Beaches have been sustained from a predominantly relict Holocene sand source with minimal new sediment entering the system. There are no major rivers and no significant sediment supply from the southern section of coast. A 29-km stretch of sandy coast, from Kingston Park to Outer Harbour is shown in **Figure 7**. Originally backed by Holocene dune and foredune ridges, sediments have been continually transported northward since the end of the postglacial marine transgression resulting in accretion of LeFevre Peninsula, which has acted as a sediment sink for this section of the coast (Bowman and Harvey, 1986; Harvey and Bowman 1987). There is a net northerly sediment transport of ~75,000 m^3/yr in the south, decreasing to the north

(Department of Environment and Heritage [DEH], 2005). Extensive coverage of the seabed by seagrass means there is a lack of a natural offshore sand supply; historic seagrass dieback released ~80,000 m^3/yr to the beach system.

Urban development has progressively removed and/or isolated sediments from the active beach zone thus blocking any natural source of onshore sand replenishment; the deficit for this section of coast therefore requires ongoing beach recycling-nourishment. Periodic dredging of offshore sand deposits provided large volumes of temporary sand nourishment but viable offshore deposits have now been exhausted so that geologically older inland-based sand deposits have been used to offset the deficit.

Natural sediment movement is counteracted by a highly managed system of coastal protection with rock armouring on over half of the coast and an ongoing sand recycling and nourishment program (DEH 2005, Short 2012). Early management practice trucked sand from natural sand sinks to erosion zones. Today there is a combined system of pumping in the south supplemented by trucking further north (**Figure 7**). It is clear that an understanding of the dynamics of future shoreline change and sediment budget for this compartment is going to require more investment in resolving the balance between beach amenity and coastal protection works. Sea-level rise will only exacerbate the existing deficit of coastal sediment requiring further demand on relict sand sources or mining of sandy seagrass beds. At least Adelaide has an institutional structure and a 40-year continuous record of detailed beach profiling data that places it in a position to sustain ongoing cooperation between the three local councils and state agencies in planning for the future.

6.5 Wave-dominated carbonate coast

Secondary sediment compartments between Cape Naturaliste and Cape Peron, in southwestern WA, including the southern part of the Swan Coastal Plain, provide a case study on a high energy carbonate sediment coast. Lithified carbonate features provide a complex geological framework for this coast, including platform and ramp structures across much of the shelf, and multiple chains of reefs and islands that mark previous ancient shorelines. The energetic offshore wave climate, with prevailing southwest swell, provides impetus for south to north coastal sediment transport. However, inside the reef chains, alongshore littoral sediment transport is highly modified by wave sheltering and rock exposed in the nearshore, creating locations of reduced, or even reversed, transport. Rates of alongshore transport in the order of 85,000-100,000 m^3/yr have been identified at Mandurah and Dawesville, where mechanical sand bypassing is used to offset the adverse trapping by navigational channels. For more sheltered locations, alongshore transport can be negligible, and in locations of discontinuous reef, substantial discrete onshore sediment feeds can occur. The consequent alongshore variability in transport, including a mixture of alongshore and cross-shore dynamics, develops source-sink patterns of sediment transfer, with substantial dune barriers that have been active over the late Holocene.

The spatial connectivity of sediment exchange along this coast has previously been identified (Searle & Semeniuk 1985) and the need to integrate coastal management across jurisdictional boundaries has been acknowledged. For this reason, nine local councils have joined into a partnership to develop adaptation strategies to meet the challenges of climate change. The area includes Geographe Bay, which was subject to the first Australian assessment of potential impacts of climate change on the coast (Kay et al., 1992). It has been the subject of several unpublished consultancy reports, as well as the Damara pilot study (Eliot, 2013).

Application of the compartment approach in southwest WA benefited from access to a large data base of onshore and offshore geomorphology and sediment movements. In particular, a combination of marine LiDAR and multibeam sonar bathymetric surveys offered an opportunity to examine in detail topographic features at a range of scales. In offshore waters it was possible to show details of sediment availability and pathways that are rarely accessible to this degree elsewhere in Australia (for example see Stul et al., 2012; Stul et al., 2015). Much of the land can be shown, using airborne LiDAR surveys, to be low-lying and subject to inundation by future sea-level rise. The framework provided by the sediment compartment approach, underpinned by knowledge of geological structures, is seen as a way of assessing thresholds of change across different time scales by considering both susceptibility (long term) and instability (short term) (Eliot, et al., 2011 and Eliot, 2013).

This coast is representative of extensive sections of southern and western coasts of Australia, dominated by calcareous beach and dune sediments. Lithification, particularly of Pleistocene barrier deposits into beach and dune calcarenite, has major ramifications for all Holocene shores and sediment compartments along these coasts. Offshore features at both secondary and tertiary scale in the vicinity of Mandurah are depicted in **Figure 8**. Also shown are the principal pathways for sediment movement at these scales along this calcarenite-dominated coast. Calcareous and quartzose sands mobilised in the late Quaternary have been cemented at present and lower sea levels to form linear ridges, seabed pavements and submarine platforms. Offshore these ridges are undergoing progressive wave, current and biogenic destruction, thus providing some mobile sand for transport, in places across cemented calcarenite pavements. Temperate algae supported by the reefs and seagrass banks on sand sheets between them are bioproductive and contribute a significant amount of calcareous sand to sediment budgets in this region (for example, see Semeniuk and Searle. 1986; Collins, 1988; and Tecchiato et al., 2016). The importance of landform scale is highlighted by a progressive shift in dominant landform characteristics when considered at finer scales, implying a change from swell-dominated longshore transport to more local-scale fluctuations in sandbar formation that are more influenced by cross-shore transport (Eliot, 2013).

6.6 Mixed-energy sub-tropical coast

The compartment approach has been applied on the arid, sub-tropical Pilbara coast of northwest WA. This is a broad and extensive coastal floodplain with a complex geologic and sedimentary structure (Semeniuk, 1993). This region is episodically subject to storm surge inundation during tropical cyclones. It experiences highly variable fluvial input with numerous intermittent streams and rivers discharging either directly into the ocean or into shallow basins on the coastal lowlands. Some rivers, such as the Ashburton and De Grey, have a capacity to deliver large volumes of sediment in single flood events. Most of the sediment is dispersed on the inner continental shelf where it is reworked by tidal currents and wave action. Coastal processes operate in a complex interacting way across the inner shelf, with the role of wave energy increasing towards the shore. Tidal currents, associated with a general tidal range of 2-3m, larger in some locations, change in direction and increase in velocity offshore to a tidal breakpoint, with localised areas of focussing where rock features provide constriction (Eliot, 2013). Connection between the shelf and inshore zones occurs intermittently through sand sheets or more extensive tidal ridges. However, the spatial extent and speed of currents varies over time giving rise to a range of wind, wave and tidally formed sedimentary structures (Eliot and Eliot, 2013; Eliot et al., 2013).

For much of the Pilbara, coastal deposits occur as sand ribbons on the seaward side of limestone ridges, with extensive, flat sandy deposits in the nearshore. The low elevation and distribution of these features, often over-topped by surges during cyclones, and very high tides, indicates that wave transport from the nearshore is limited by sand dispersion from tidal currents at variable delivery rates. This suggests that sediment supply is not determined so much by nearshore processes, but is controlled further offshore with the seabed assuming a structure that matches the supply rate. Also to consider is the exchange of sediments between the coast and landward networks of lagoons and tidal creeks in areas not drained by major rivers. This can constitute a “coastal” plain extending 10-20km to landward of the shore. Rapid switching can occur between erosion and accretion within these networks leading to either import or release of sediments to coastal wave/current processes and hence changes in shoreline position (Eliot, 2013). Estimates of net sediment transport rates in the vicinity of Onslow are shown in **Figure 9**. This information on sediment dynamics has a range of purposes: in the short term it is important in assisting the management of dredged material from shipping channels; it also offers an understanding of pathways for sediment transport and shoreline position which are most likely to keep pace with sea-level rise, or experience drowning leading to future growth of tidal lagoons where there are now tidal flats.

7 SEDIMENT COMPARTMENT APPROACH AND COASTAL PLANNING

The above six case studies illustrate some of the considerable variation in coastal settings and processes on a continental scale. They also illustrate the need to understand the morphodynamics of each sediment compartment, its geology, geomorphology, oceanographic processes and in particular its sediment dynamics. Only with this understanding can useful models of compartment behaviour be developed. This in turn will allow management plans to be based on realistic scenarios of shoreline behaviour incorporating the complexity of interacting processes including the interconnectivity of impacts as expressed in a nationally accepted spatial framework.

To be useful, the sediment compartment approach must be relevant to regional (and local) land use planning and to development assessment. In the report on *Climate Change Risks to the Australia’s Coast* (DCC, 2009; augmented in a supplementary report by DCCEE in 2011), it was clear that many settled areas of the coast have built assets at risk to future changes of shoreline position and inundation from sea-level rise. These assets include private residential property and businesses, and public infrastructure and amenity facilities. There is exposure today to coastal hazards and these reports highlight the probable extent to which risks are increased as a result of climate change.

Continuous pressure to build and rebuild in coastal areas may place more assets in harm's way. The short and long-term social, economic and environmental costs of such activities must be weighed against the benefits. Risk assessments should be informed by the best available methods for understanding the complexity of coastal processes likely to impact adversely on those assets over their lifetime. A method developed in this study involves application of the multi-scale sediment compartment approach, which takes into consideration the sensitivity of compartment shorelines to change over time. Such an approach recognises that some parts of the shoreline will be fast responders, while others will be relatively slow, or hardly change at all until a tipping point is reached in relation to sediment supply required to sustain shoreline position.

Investment in the application of the sediment compartment approach is particularly important in locations deemed to be erosion "hot spots" in order to manage present and future risk. There is a temptation to use less expensive, simplified methods that do not identify sources and sinks of sediments, but rather apply 'rule of thumb' tools to determine future shoreline positions. However, limitations of these less rigorous methods have been made clear in the case studies accompanying this work (Eliot, 2013; Mariani et al., 2013; see also Woodroffe et al., 2012). Unless there is an understanding of sediment pathways over a range of time and space scales, decision makers will be forced to make assessments of hazards and risks to assets without having the benefits of an approach which these case studies demonstrate can enhance the level of certainty in planning and development assessments. These benefits are already apparent in the application of the approach in the UK and California, and initial work in Western Australia. Reform of the planning system in NSW offers potential for further application of the approach at different scales.

As noted above, the UK provides an example of how the sediment compartment approach can inform coastal planning and management at the regional (county) scale. There *Shoreline Management Plans* (SMPs) are built around knowledge of sediment pathways. They have recently been expanded to look at the implications for three climate change scenarios. That work highlights both present and future risk and enables local governments in conjunction with agencies of the UK government to reach decisions on what and where to protect or permit the sea to invade the land (Nichols et al., 2013).

In Western Australia, the Department of Transport commissioned Damara to report on the coastal compartment and sediment cell approaches to assist coastal planning (Damara, 2012; see also Damara report 2011 to Departments of Environment and Conservation, Planning and Transport). In so doing it was acknowledged inherited topographies, particularly the geologic framework, play a major role in how sediments are moved and impact on the use of the coastal zone through landform development (see Eliot, 2013). Although not a novel appreciation, incorporation of this understanding, coupled with information on onshore and offshore sources of sediment in decision-making provides decision-makers in WA with a powerful tool to address management and risk issues, including impacts of extreme events and sea-level rise at local and regional scales.

Coastal reform in NSW, including the passage through Parliament in 2016 of the new *Coastal Management Act*, indicates a way for state and local authorities to develop a new generation of Coastal Management Programs incorporating the sediment compartment approach. Secondary compartments are listed by name in a schedule attached to the Act. This will open the opportunity for local councils and state agencies to be better informed on the nature of coastal hazards at present and in the future. Current approaches based on council and state boundaries do not provide sufficient information on sediment pathways along stretches of coast subjected to common processes. If all the states and the Northern Territory adopt a multi-scale compartment approach similar to that envisaged in WA and NSW, it will be possible to provide a more consistent and rigorous method of assessing shoreline change and inundation risk than exists at present. This multi-scale compartment framework is also the approach recommended in the guidelines of Engineers Australia on adapting to climate change (Harper, 2012), and will be further expanded in the revised *NSW Coastal Management Manual* (2017).

8 CONCLUSIONS

There is scope in Australia for the application of a national approach to coastal management based on sediment compartments involving collaboration between agencies at different levels of government. Experience in the UK is worth considering where the Environment Agency has a lead role in working with council groups divided up into regions, the boundaries of which are defined by sediment compartments or cells. Preliminary work in Western Australia by the Department of Transport shows an interest in this approach by an operational state agency. The fact that NSW has incorporated the compartment concept into legislation is another step in this direction. In that state the Office of Environment and Heritage has commenced offshore surveys using the compartment approach as a framework for management to assist local councils in the development of new Coastal Management Programs as required under the new legislation (*Coastal Management Act*, 2016). In Victoria, the state government is also initiating studies based on the compartment approach. There is now potential for all three levels of government in Australia to commit to a nationally agreed method of assessing coastal hazard and climate change impacts by implementing the sediment compartment approach. Experience in the UK (Cooper and Pontee, 2006) and the USA (Wright et al., 2016) indicates that there will be a permanent need to incorporate new information, new science and new policy arrangements as the new climate change era unfolds.

Current institutional arrangements suggest that there could be a role for federal agencies to provide guidance, thus providing a building block for applying a consistent nationwide approach. Management of national coastal and marine data should be seen as a federal responsibility. Compartment descriptions, as in *CoastAdapt*, will need to be updated and sensitivities reassessed over time; maintaining expertise in this area will require attention. However, given current responsibilities, it is apparent that state governments in conjunction with local councils will play the major role in the application of the compartment approach to coastal planning and management.

Local governments, with few exceptions lack the resources to apply the compartment approach. Also, compartment units frequently overlap council boundaries (see Figure 7). However growing interest in regional hazard assessment and land use planning should encourage increased collaboration between councils and hence demand for more joint technical support to address these issues. The possibility therefore exists for the federal, state and local governments to share information on future risk based on the compartment approach, and in collaboration develop mechanisms to ensure coastal regions are better prepared to meet future challenges driven by the forces of climate change. This can help avoid the "one size fits all" approach towards coastal assessment.

Any agreement to establish a nationally consistent approach must appreciate the cost as well as benefits. Given current responsibilities, it will especially require continued investment by state governments. For the sediment compartment approach to add value to decision making there must be continued investment in collection of data on both land and in offshore conditions: wind and wave climates, bathymetry, as well as sediment type, age and structures. Technologies have been developed for this information to be collected. It is important that mechanisms exist so that experiences in applying these technologies and the data they generate are shared.

There will be opportunities in the future for all levels of government to work in collaboration. An example would be an updated agreement to manage assets at risk in Tweed and Gold Coast which straddles both local and state government boundaries (**Figure 10a**). At present an agreement exists between NSW and Queensland on the Tweed River sand bypass project (**Figure 10b**). This multi-decadal agreement ensures that the sand trapping by river breakwaters on the NSW border does not adversely impact on beaches downdrift located in Queensland (see Patterson et al., 2011, and www.tweedsandbypass.nsw.gov.au). Continuation of the agreement may depend on assessment of future sediment flows under climate change conditions for this section of coast. This could involve participation of the federal government given its interest in the economy of southeast Queensland including the operation of the low-lying Coolangatta international airport.

What is clear from this national assessment of all secondary coastal sediment compartments around the vast coast of this continent, supported by pilot and case studies, is that the compartment approach greatly assists in building capacity of governments to manage changes to coastal conditions. By incorporating geomorphic diversity into the evaluation of coastal dynamics at different scales, it offers a framework for assessing sediment exchanges between adjacent landforms both onshore and offshore. As sediment moves from one place to another, a different response to an external driver, such as sea-level rise, may occur. In this way the link becomes more apparent between sediment compartments and source-pathway-sink behaviour. The compartments, primary, secondary or tertiary, provides a spatial reference for behavioural changes that occur due to proximity to sinks or sources. No simple rule of thumb answer is of much value in such circumstances. As sea level rises or wave climate changes, the nature of sediment movement along the pathway or pathways may increase or slow down so that responses at the source or in the sink will change over time. The compartment approach will improve understanding of possible changes in degrees of stability or resilience of coastal features and hence provide managers with more realistic scenarios for purposes of long-term planning.

ACKNOWLEDGEMENTS

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REFERENCES

Baker & McKenzie, 2011. Local Council Risk of Liability in the Face of Climate Change –Resolving Uncertainties, a report commissioned by Australian Local Government Association, 22nd July 2011, Sydney.

Bird, E.C.F., 1971. The origin of beach sediments on the North Queensland coast. Earth Sci J 5, 95-105.

Bird, E.C.F., 1993. The Coast of Victoria. Melbourne University Press, Melbourne.

Bowen, A.J., Inman, D.L., 1966. Budget of littoral sands in the vicinity of Point Arguello, California. US Army Coastal Engineering Research Center Tech Mem. 19, 1-56.

Bowman, G.M., Harvey, N., 1986. Geomorphic evolution of a Holocene beach ridge complex, LeFevre Peninsula, South Australia. J Coastal Res 2, 345-362.

BPA, 1984, Mulgrave Shire northern beaches. Beach Protection Authority, Brisbane, 366 pp.

Bray, M.J., Carter, D.J., Hooke, J.M., 1995. Littoral cell definition and budgets for central south England. J Coastal Res 11, 381-400.

Byrne, G., 2006. Roches Beach Lauderdale – Coastal Erosion study. Report to Clarence City Council by Vantree Pty Ltd.

Carley, J.T., Blacka, M.J., Timms, W.A., Anderson, M.S., Mariani, A., Rayner, D.S., McArthur, J., Cox, R.J., 2008, Coastal Processes, Coastal Hazards, Climate Change and Adaptive Responses for Preparation of a Coastal Management Strategy for Clarence City, Tasmania; Report by Water Research Laboratory, University of New South Wales.

Carvalho, R.C., Woodroffe, C.D., 2017. Modifications to the Shoalhaven estuary and the coastal sediment budget over the past 40 years, Proceedings of Coasts and Ports, June 2017, Cairns.

Chapman, D.M., Geary, M., Roy, P.S., Thom, B.G., 1982. Coastal Evolution and Coastal Erosion in New South Wales. Coastal Council of New South Wales, Sydney, 341 pp.

Collins, L.B., 1988. Sediments and history of the Rottnest Shelf, southwest Australia: a swell-dominated, non-tropical carbonate margin. Sediment Geol 60, 15-49.
Cooper, N.J., Barber, P.C., Bray, M.J., Carter, D.J., 2002. Shoreline management plans: a national review and engineering perspective. Proceedings of the Institution of Civil Engineers: Water Marit Eng 154, 221-228.
Cooper, N.J., Hooke, J.M., Bray, M.J., 2001. Predicting coastal evolution using a sediment budget approach: a case study from southern England. Ocean & Coast Manage 44, 711-728.
Cooper, N.J., Pontee, N.I., 2006. Appraisal and evolution of the littoral 'sediment cell' concept in applied coastal management: experiences from England and Wales. Ocean Coast Managet 49, 498-510.
Cowell, P.J., Thom, B.G., 1994. Morphodynamics of coastal evolution, In: Carter, R.W.G., Woodroffe, C.D. (Eds.), Coastal Evolution, late Quaternary shoreline morphodynamics. Cambridge University Press, 33-86.
Cowell, P.J., Stive, M., Roy, P.S., Kaminsky, G.M., Buijsman, M.C., Thom, B.G., Wright, L.D., 2000. Shoreface sand supply to beaches, Proceedings 27th International Conference on Coastal Engineering. ASCE, 2496-2508.
Daley, M., Cowell, P.J., 2012. Long-term shoreface response to disequilibrium stress: a conundrum for climate change, Proceedings of the NSW Coastal Conference, Kiama.
Damara WA & the Geological Survey of Western Australia, 2011. Dongara to Cape Burney, Western Australia: Coastal Geomorphology. Prepared for the Department of Planning, Department of Transport and the City of Geraldton-Greenough.
Damara WA., 2012. Coastal Hazard Mapping for Economic Analysis of Climate Change Adaptation in the Peron-Naturaliste Region. Prepared for the Peron-Naturaliste Partnership Coastal Adaptation Decision Pathways (PNP-CAPS) project, Report 169-01.
Davies, J.L., 1961.Tasmanian beach ridge systems in relation to sea level change. Pap Procof Roy Soc Tasmania, 95, 35-41.
Davies, J.L., 1974. The coastal sediment compartment. Aust Geogr Stud 12, 139-151.
Davies, J.L., 1977, The Coast. In Jeans, D.N. (ed.) Australia – a Geography. Sydney University Press, 134-151.
Davies, J.L., 1980. Geographical variation in coastal development, 2nd ed. Longman, London.
Dell, M., Sharples, C., 2012, Clarence City Council Shoreline Monitoring Program; Report to Clarence City Council by Blue Wren Group, School of Geography & Environmental Studies, University of Tasmania.
Department of Climate Change, 2009. Climate Change Risks to Australia's Coast: A First Pass National Assessment, Australian Government. Canberra.
Department of Environment and Heritage, 2005. Adelaide's living beaches: a strategy for 2005–2025. Technical report, Department of Environment and Heritage, Adelaide, 206 pp.
Eliot, I., Nutt, C., Gozzard, B., Higgins, M., Buckley, E., Bowyer, J., 2011. Coastal compartments of Western Australia. A Physical Framework for Marine Coastal Planning: 75pp.
Eliot, I., Gozzard, B., Eliot, M., Stul, T., McCormack, G., 2013. Geology, Geomorphology & Vulnerability of the Pilbara Coast, In the Shires of Ashburton, East Pilbara and Roebourne, and the Town of Port Hedland,

Western Australia. Damara WA Pty Ltd and Geological Survey of Western Australia, Innaloo, Western Australia.
Eliot, M., 2013. Application of Geomorphic Frameworks to Sea-level Rise Impact Assessment. Damara WA Pty Ltd.
Eliot, M., Eliot, I., 2013. Interpreting estuarine change in northern Australia: physical responses to changing conditions. Hydrobiologia 708, 3-21.
EPA, 2004, Mackay Coast Study. Environment Protection Agency, Brisbane, 113 pp.
Field, M., Roy, P.S., 1985. Offshore transport and sand-body formation: evidence from a steep, high-energy, shoreface, southeastern Australia. J Sediment Pet 54, 1292-1302.
Galloway, R.W., Story, R., Cooper, R., Yapp, G.A., 1984. Coastal Lands of Australia. Institute of Biological Resources, Commonwealth Scientific and Industrial Research Organization.
George, D.A., Largier, J.L., Storlazzi, C.D., Barnard, P.L., 2015. Classification of rocky headlands in California with relevance to littoral cell boundary definition. Mar Geol 369, 137-152.
Goodwin, I.D., Stables, M.A., Olley, J.M., 2006. Wave climate, sand budget and shoreline alignment evolution of the Iluka-Woody Bay sand barrier, northern New South Wales, Australia, since 3000 yr BP. Mar Geol 226, 127-144.
Gordon, A.D., Hoffman, J.G., 1986. Sediment features and processes of the Sydney continental shelf, In: Frankel, E., Keene, J.B., Waltho, A.E. (Eds.), Recent sediments in eastern Australia- marine through terrestrial. Geol Soc Aust, Spec Pub, 29-51.
Harper, B.A., 2012. Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering, 3rd edition. Engineers Australia, Crows Nest, NSW.
Harris, P.T., Heap, A., 2014. Geomorphology and Holocene sedimentology of the Tasmanian Continental Margin, In: Corbett, K.D., Quilty, P.G., Calver, C.R. (Eds.), Geological Evolution of Tasmania. Geological Society of Australia (Tasmania Division), 530-539.
Harvey, N., Bowman, G.M., 1987. Coastal management implications of a Holocene sediment budget: Le Fevre Peninsula, South Australia. J Shoreline Manage 3, 77-93.
Harvey, N., Caton, B., 2010. Coastal Management in Australia. University of Adelaide Press, http://dx.doi.org/10.1017/UPO9780980723038.
Harvey, N., Woodroffe, C.D., 2008. Australian approaches to coastal vulnerability assessment. Sustain Sci 3, 67-87.
Hazelwood, M., Nicholas, W.A., Woolf, M., 2013. National Coastal Geomorphology Information Framework Implementation: Discovery and Distribution. Geoscience Australia Record 2013/35.
HORSCCCWEA, 2009. Managing our coastal zone in a changing climate. The time to act is now. House of Representatives Standing Committee on Climate Change, Water, Environment and the Arts, 368 pp.
Hudson, J.P., 1999. Gosford City Beach Nourishment Feasibility Study. Report prepared for Manly Hydraulics Laboratory, NSW Department of Public Works.
Inman, D.L., Chamberlain, T.K., 1960. Littoral sand budget along the southern California coast (abstract). Report 21st International Geological Congress, Copenhagen, 245-246.
Inman, D.L., Gayman, W.R., Cox, D.C., 1963. Littoral sedimentary processes on Kauai, a subtropical high island. Pac Sci 17, 106-130.

Inman, D.L., Frautschy, J.D., 1966. Littoral processes and the development of shoreline. Proc. Coast. Eng. Speciality Conf., ASCE, Santa Barbara, 511-536.
Jones, M.R., 1987. Nearshore sediments and distribution patterns, Mackay coast. Geological Survey of Queensland Record, 1987/25, 16 pp. plus figures.
Kay, R.C., Eliot, I.G., Klem, G., 1992. Analysis of the IPCC sea-level rise vulnerability assessment methodology using Geographe Bay, SW Western Australia as a case study. Department of Arts, Sports, Environment and Territories, Canberra.
King, C.A.M., 1972. Beaches and Coasts, 2nd ed. St Martin's Press, New York, 570 pp.
Kinsela, M.A., Daley, M.J.A., Cowell, P.J., 2016. Origins of Holocene coastal strandplains in southeast Australia: shoreface sand supply driven by disequilibrium morphology. Mar Geol 374, 14-30.
Komar, P.D., 1976. Beach Processes and Sedimentation. Prentice-Hall, New Jersey, 429 pp.
Komar, P.D., 1996. The budget of littoral sediments: concepts and applications. Shore and Beach 64, 18-26.
Mariani, A., Flocard, F., Carley, J.T., Drummond, C., Guerry, N., Gordon, A.D., Cox, R.J., Turner, I.L., 2013. East Coast Study Project - National Geomorphic Framework for the Management and Prediction of Coastal Erosion, Water Research Laboratory, WRL Research Report. School of Civil and Environmental Engineering, UNSW Australia, Manly Vale, NSW.
Maxwell, P.S., Pitt, K.A., Olds, A.D., Rissik, D., Connolly, R.M., 2015. Identifying habitats at risk: simple models can reveal complex ecosystem dynamics. Ecol Appl 25, 573–587.
McGlashan, D.J., Duck, R.W., Reid, C.T., 2005. Defining the foreshore: coastal geomorphology and British laws. Estuar Coast Shelf S 62, 183-192.
McLean, R., Shen, J.-S., Thom, B.G., 2010. Beach change at Bengello Beach, Eurobodalla Shire, New South Wales: 1972– 2010, NSW Coastal Conference, Batemans Bay, Australia.
McPherson, A., Hazelwood, M., Moore, D., Owen, K., Nichol, S., Howard, F., 2015. The Australian Coastal Sediment Compartments Project: methodology and product development. Geoscience Australia Record 2015/25.
Motyka, J., Brampton, A., 1993. Coastal management: mapping of littoral cells. HR Wallingford.
Nicholls, R.J., Townend, I.H., Bradbury, A.P., Ramsbottom, D., Day, S.A., 2013. Planning for long-term coastal change: experiences from England and Wales. Ocean Eng 71, 3-16.
Nott, J., 2005. Letter to the editor: comment on the paper 'Quantifying storm tide risk in Cairns' by Ken Granger. Nat Hazards 34, 375-379.
NSW Government, 1990. Coastline Management Manual, Public Works Department, NSW Government Printer.
Oliver, T.S.N., Tamura, T., Hudson, J.P., Woodroffe, C.D., 2017a. Integrating millennial and interdecadal shoreline changes: morpho-sedimentary investigation of two prograded barriers in southeastern Australia. Geomorphology 288: 129-147.
Oliver, T.S.N., Tamura, T., Short' A.D, Woodroffe' C.D., 2017b. Changing rates of sand deposition at Pedro Beach, southeastern Australia: implications for compartment-based management. Proceedings NSW Coastal Conference, Port Stephens.

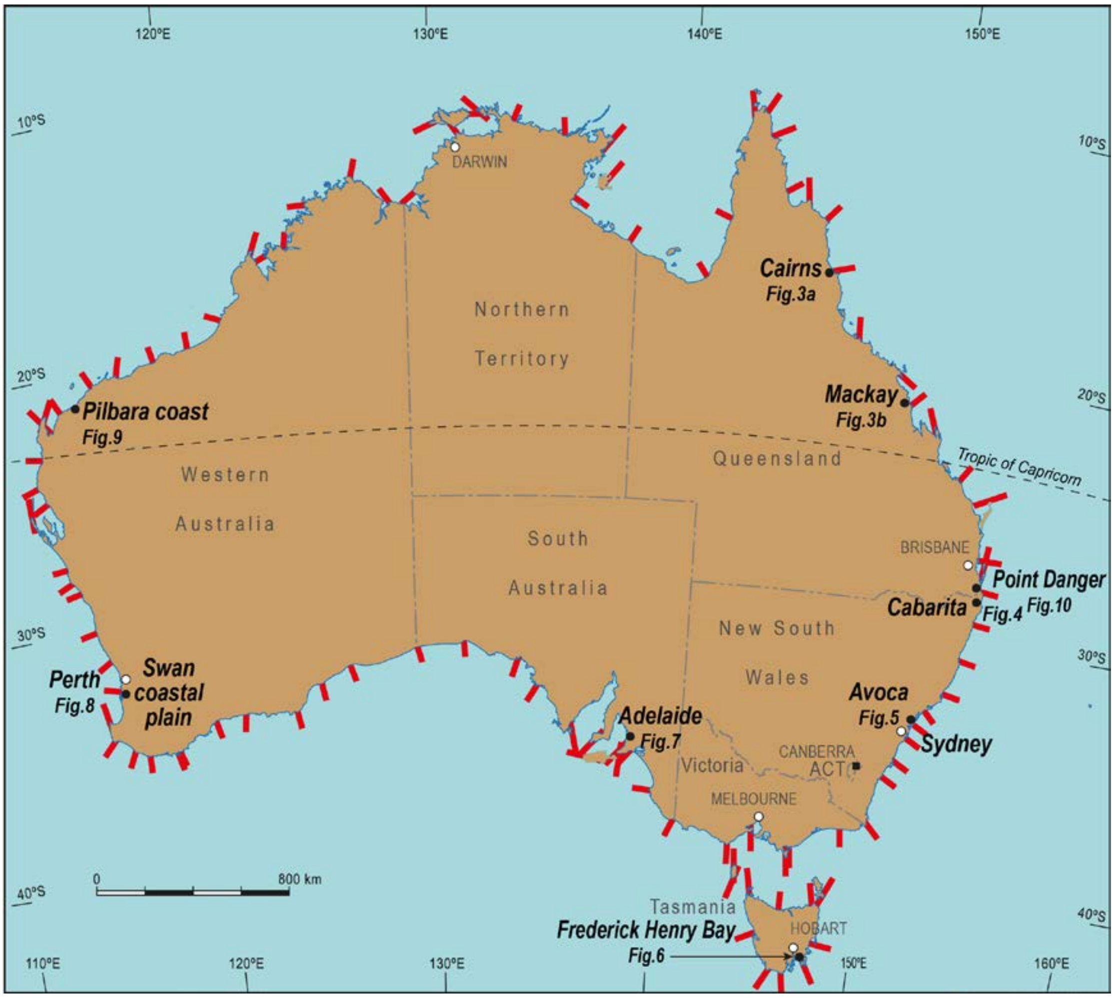
Oliver, T.S.N., Donaldson, P., Sharples, C., Roach, M., Woodroffe, C.D., 2017c. Punctuated progradation of the Seven Mile Beach Holocene barrier system, southeasternTasmania; Mar Geol 386, 76-87.
Patterson, D.C., 2013. Modelling as an aid to understand the evolution of Australia's central east coast in response to late Pleistocene-Holocene and future sea-level change. PhD thesis, University of Queensland.
Patterson, D.C., Elias, G., Boswood, P., 2011. Tweed River sand bypassing long term average sand transport rate, Proceedings of the 20th NSW Coastal Conference, Tweed Heads, NSW.
PWD, 1978. Byron Bay – Hastings Point erosion study. NSW Dept. Public Works, Coastal Engineering Branch Report, PWD 78026.
Rissik, D., Cox, M., Moss, A., Rose, D., Scheltinga, D., Newham, L.T.H., Andrews, A., Baker-Finch, S.C., 2005. VPSIRR (Vulnerability - Pressure - State - Impact - Risk and Response): An Approach to determine the condition of estuaries and to assess where management responses are required. In 'MODSIM 2005 International Congress on Modelling and Simulation, Melbourne, Australia'. (Eds. A. Zerger and R. M. Argent.) 170-176.
Rosati, J.D., 2005. Concepts in sediment budgets. J Coast Res 21, 307-322.
Roy, P.S., Cowell, P.J., Ferland, M.A., Thom, B.G., 1994. Wave-dominated coasts, In: Carter, R.W.G., Woodroffe, C.D. (Eds.), Coastal Evolution: Late Quaternary Shoreline Morphodynamics. Cambridge University Press, 121-186.
Roy, P.S., Hudson, J.P., 1988. Surface sediment samples from the inner continental shelf between MacMasters and Foresters Beaches on the NSW Central Coast: Interpolation and correlation with PWD side scan sonar data. Report prepared for NSW Public Works Department.
Roy, P.S., Thom, B.G., 1981. Late Quaternary marine deposition in New South Wales and southern Queensland: an evolutionary model. J Geol Soc Australia 28, 471-489.
Searle, D.J., Semeniuk, V., 1985. The natural sectors of the inner Rottnest Shelf coast adjoining the Swan Coastal Plain. J Roy Soc West Australia 67, 116-136.
Semeniuk, V., 1993. The Pilbara Coast: a riverine coastal plain in a tropical arid setting, northwestern Australia. Sediment Geol 83, 235-256.
Semeniuk, V., Searle, D.J., 1986. Variability of Holocene sea-level history along the southwestern coast of Australia: evidence for the effect of significant local tectonism. Mar Geol 72, 47-58.
Shand, T.D., Carley, J., 2011. Investigation of Trial Groyne Structures for Roches Beach, Report to Clarence City Council by Water Research Laboratory, University of New South Wales.
Sharples, C., 2010. Shoreline Change at Roches Beach, South-Eastern Tasmania, 1957-2010, Report to Antarctic Climate and Ecosystems Co-operative Research Centre. University of Tasmania, Hobart.
Sharples, C., Mount, R., Pedersen, T., 2009. The Australian Coastal Smartline Geomorphic and Stability Map Version 1: Manual and Data Dictionary v1.1, Report for Geoscience Australia and the Department of Climate Change, by School of Geography & Environmental Studies, University of Tasmania: 178.
Sharples, C., Mount, R., Hemer, M.A., Puotinen, M., Dell, M., Lacey, M., Harries, S., Otera, K., Benjamin, J., Zheng, X., 2012. The ShoreWave Project: Development of a methodology for coastal erosion risk analysis under climate change, integrating geomorphic and wave climate data sets, Report to the

Commonwealth Department of Climate Change and Energy Efficiency. University of Tasmania, Hobart.
Short, A.D., 1999. Handbook of Beach and Shoreface Morphodynamics. Wiley, Chichester, 379 pp.
Short, A.D., 2010. Sediment transport around Australia - sources, mechanisms, rates and barrier forms. J Coast Res 26, 395-402.
Short, A.D., 2012. Adelaide Beach Management 1836–2025, In: Cooper, J.A.G., Pilkey, O.H. (Eds.), Pitfalls of Shoreline Stabilization: Selected 15 Case Studies. Springer, 15-36.
Short, A.D., Woodroffe, C.D., 2009. The Coast of Australia. Cambridge University Press, 288 pp.
Stul, T., Eliot, I., Pattiaratchi, C., 2007. Sediment Cells along the Perth Metropolitan coast, Proceedings of Coasts and Ports Australasian Conference. Engineers Australia, Melbourne.
Stul, T., Gozzard, J.R., I.G., E., Eliot, M.J., 2012. Coastal sediment cells between Cape Naturaliste and the Moore River, Western Australia. Damara WA Pty Ltd and Geological Survey of Western Australia for the Western Australian Department of Transport, Fremantle.
Stul, T., Gozzard, J.R., Eliot, I.G., Eliot, M.J., 2015. Coastal Sediment Cells for the Vlamingh Region between Cape Naturaliste and Moore River, Western Australia. Report prepared by Seashore Engineering Pty Ltd and Geological Survey of Western Australia for the Western Australian Department of Transport, Fremantle.
Tecchiato, S., Collins, L., Stevens, A., Soldati, M., Pevzner, R., 2016. Carbonate sediment dynamics and compartmentalisation of a highly modified coast: Geraldton, Western Australia. Geomorphology 254, 57-72.
Thom, B.G., 1974. Coastal erosion in eastern Australia. Search 5, 198-209.
Thom, B.G., 1989. Global climatic change: issues for the Australian coastal zone. Prime Minister's Science Council, 6 October 1989, Canberra, Australian Government Printing Service Press.
Thom, B.G., 2015. Coastal Compartments Project: summary for policy makers- http://www.environment.gov.au/system/files/resources/4f288459-423f-43bb-8c20-87f91adc3e8e/files/coastal-compartments-project.pdf.
Thom, B.G., Hall, W., 1991. Behaviour of beach profiles during accretion and erosion dominated phases. Earth Surf Proc Land 16, 113-127.
Trenhaile, A.S., 2011. Predicting the response of hard and soft rock coasts to changes in sea level and wave height. Climatic Change 109, 599-615.
Woodroffe, C.D., Cowell, P.J., Callaghan, D.P., Ranasinghe, R., Jongejan R., Wainwright, D.J., Barry, S.J., Rogers, K., Dougherty, A.J. (2012) Approaches to risk assessment on Australian coasts: A model framework for assessing risk and adaptation to climate change on Australian coasts, National Climate Change Adaptation Research Facility, Gold Coast, 203 pp.
Wright, L.D., 1995. Morphodynanamics of inner continental shelves. CRC Press, Boca Raton.
Wright, L.D., Nichols, C.R., Cosby, A.G., D'Elia, C.F., 2016. Collaboration to enhance coastal resilience. EOS 97, https://doi.org/10.1029/2016EO057981..
Wright, L.D., Thom, B.G., 1977. Coastal depositional landforms: a morphodynamic approach. Prog Phys Geog 1, 412-459.

List of Figures

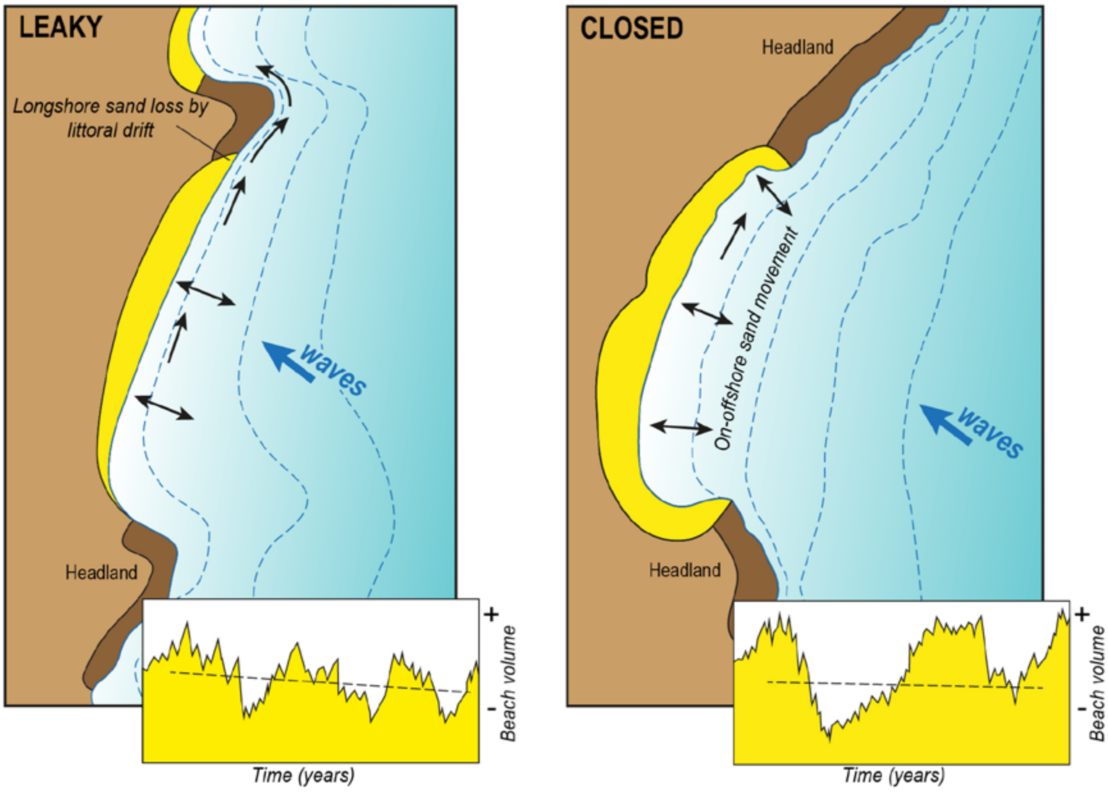
Figure 9. Conceptual sediment budget (cubic metres per year) derived from surface features for a section of the secondary sediment compartment near Onslow on the Pilbara coast, where the Ashburton River delivers sediment episodically (from Eliot, 2013; Eliot and Eliot, 2013).

Figure 10. a) A view of Point Danger which forms the ‘leaky’ sediment compartment boundary between northern NSW (background) and southern Queensland (photograph A. Short). b) an overview of longshore drift (yellow arrows) and the pumping required (orange arrows) to restore sediment bypassing required as a result of breakwaters that train the Tweed River entrance, trapping longshore sand transport (http://ci.wrl.unsw.edu.au/current-projects/tweed-river-sand-bypassing-project/).



120°E
130°E
140°E
150°E
10°S
20°S
30°S
40°S
DARWIN
Cairns
Fig.3a
Northern
Territory
Mackay
Fig.3b
Pilbara coast
Fig.9
Tropic of Capricorn
Queensland
Western
Australia
South
Australia
BRISBANE
Point Danger
Fig.10
Cabarita
Fig.4
New South
Wales
Perth
Fig.8
Swan
coastal
plain
Avoca
Fig.5
Sydney
Adelaide
Fig.7
Victoria
CANBERRA
ACT
MELBOURNE
0
800 km
Tasmania
Frederick Henry Bay
Fig.6
HOBART
110°E
160°E

Fig 1



LEAKY
Longshore sand loss by
littoral drift
waves
Headland
Time (years)
Beach volume
+
-
CLOSED
Headland
On-offshore sand movement
waves
Headland
Time (years)
Beach volume
+
-

Fig 2

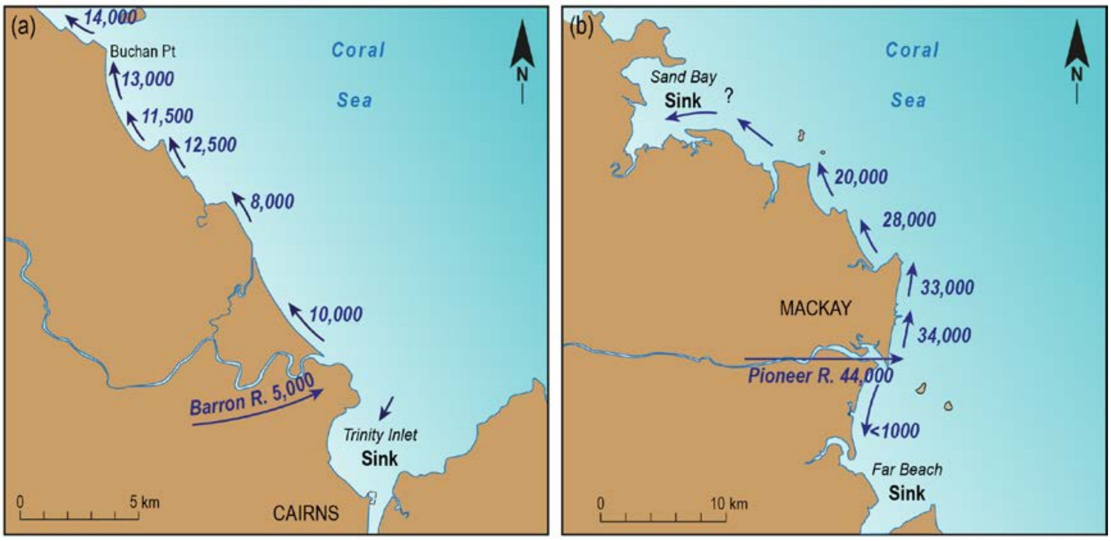
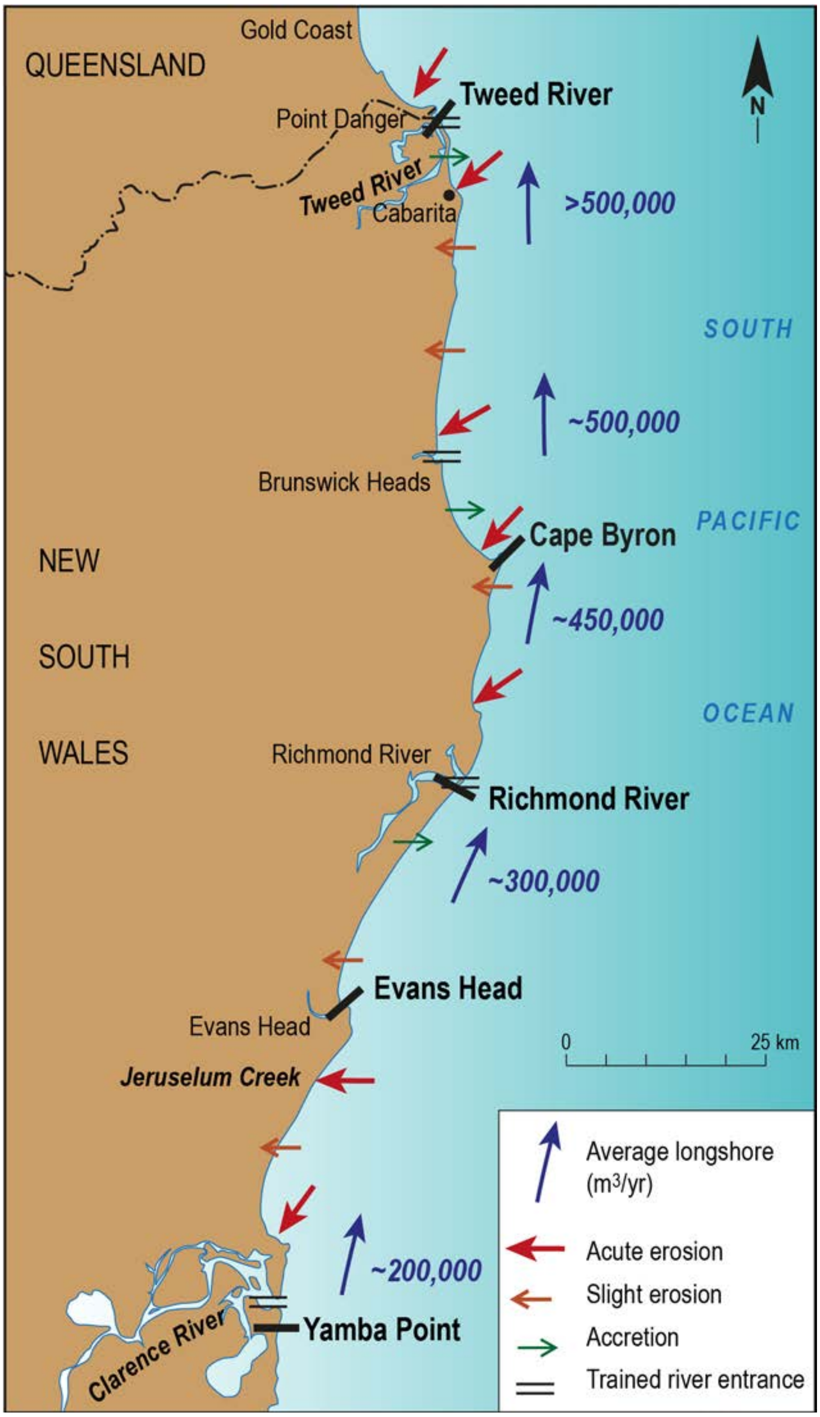
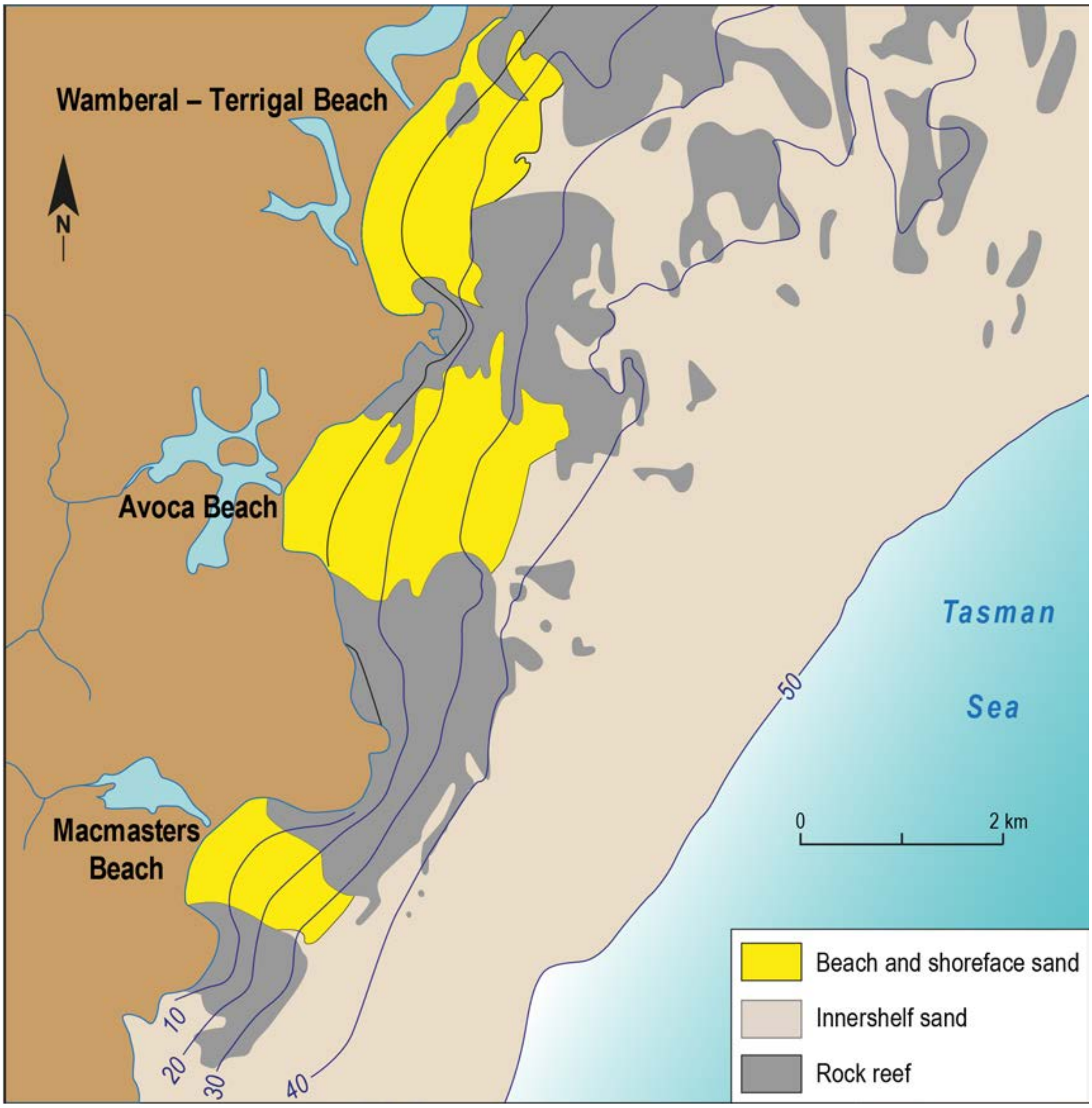

(a)
14,000
Buchan Pt
13,000
11,500
12,500
8,000
10,000
Barron R. 5,000
Trinity Inlet
Sink
CAIRNS
Coral
Sea
N
0
5 km
(b)
Sand Bay
Sink
?
Coral
Sea
N
20,000
28,000
33,000
MACKAY
34,000
Pioneer R. 44,000
<1000
Far Beach
Sink
0
10 km

Fig 3


Gold Coast
QUEENSLAND
Point Danger
Tweed River
Tweed River
Cabarita
>500,000
SOUTH
~500,000
Brunswick Heads
Cape Byron
PACIFIC
NEW
SOUTH
WALES
~450,000
OCEAN
Richmond River
Richmond River
~300,000
Evans Head
Evans Head
0
25 km
Jeruselum Creek
Average longshore
(m3/yr)
Acute erosion
Slight erosion
Accretion
Trained river entrance
~200,000
Clarence River
Yamba Point
Fig 4


Wamberal – Terrigal Beach
N
Avoca Beach
Macmasters
Beach
Tasman
Sea
50
0
2 km
10
20
30
40
Beach and shoreface sand
Innershelf sand
Rock reef
Fig 5

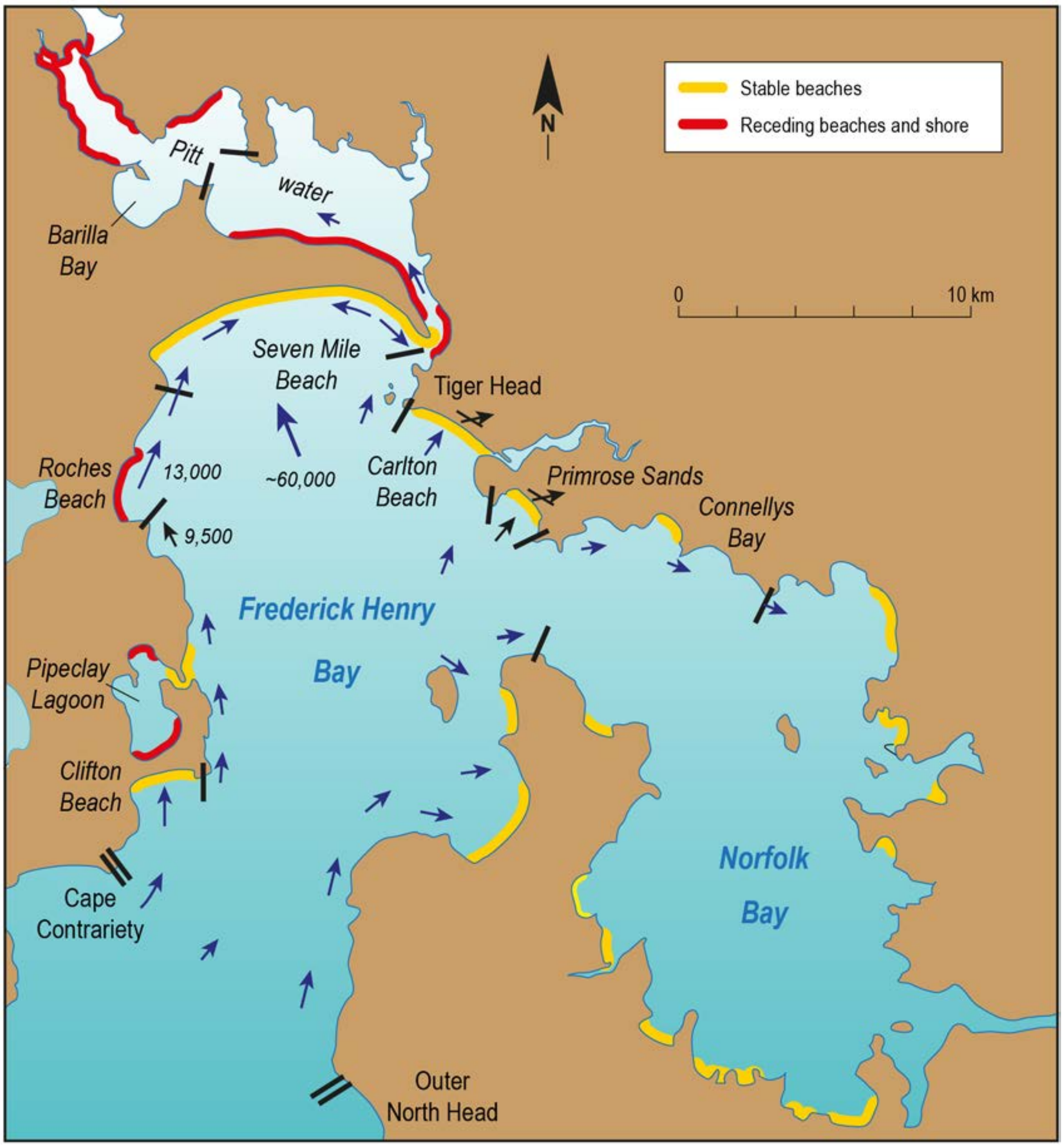

Stable beaches
Receding beaches and shore
N
0
10 km
Pitt
water
Barilla
Bay
Seven Mile
Beach
Tiger Head
Roches
Beach
13,000
~60,000
Carlton
Beach
Primrose Sands
9,500
Connellys
Bay
Frederick Henry
Bay
Pipeclay
Lagoon
Clifton
Beach
Cape
Contrariety
Norfolk
Bay
Outer
North Head

Fig 6

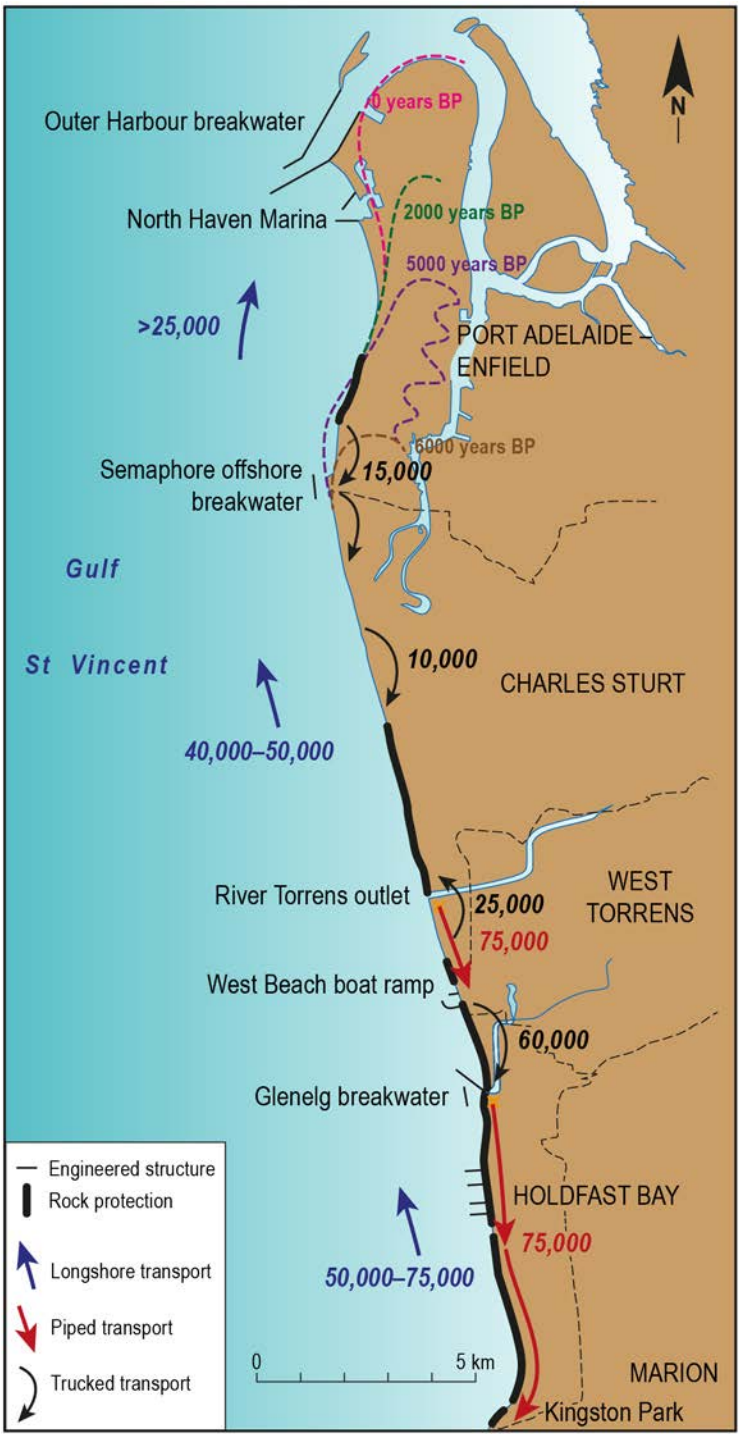

Outer Harbour breakwater
North Haven Marina
0 years BP
2000 years BP
5000 years BP
6000 years BP
N
>25,000
PORT ADELAIDE – ENFIELD
Semaphore offshore breakwater
15,000
Gulf
St Vincent
10,000
CHARLES STURT
40,000–50,000
River Torrens outlet
25,000
75,000
WEST TORRENS
West Beach boat ramp
60,000
Glenelg breakwater
HOLDFAST BAY
75,000
50,000–75,000
0
5 km
MARION
Kingston Park
Engineered structure
Rock protection
Longshore transport
Piped transport
Trucked transport

Fig 7

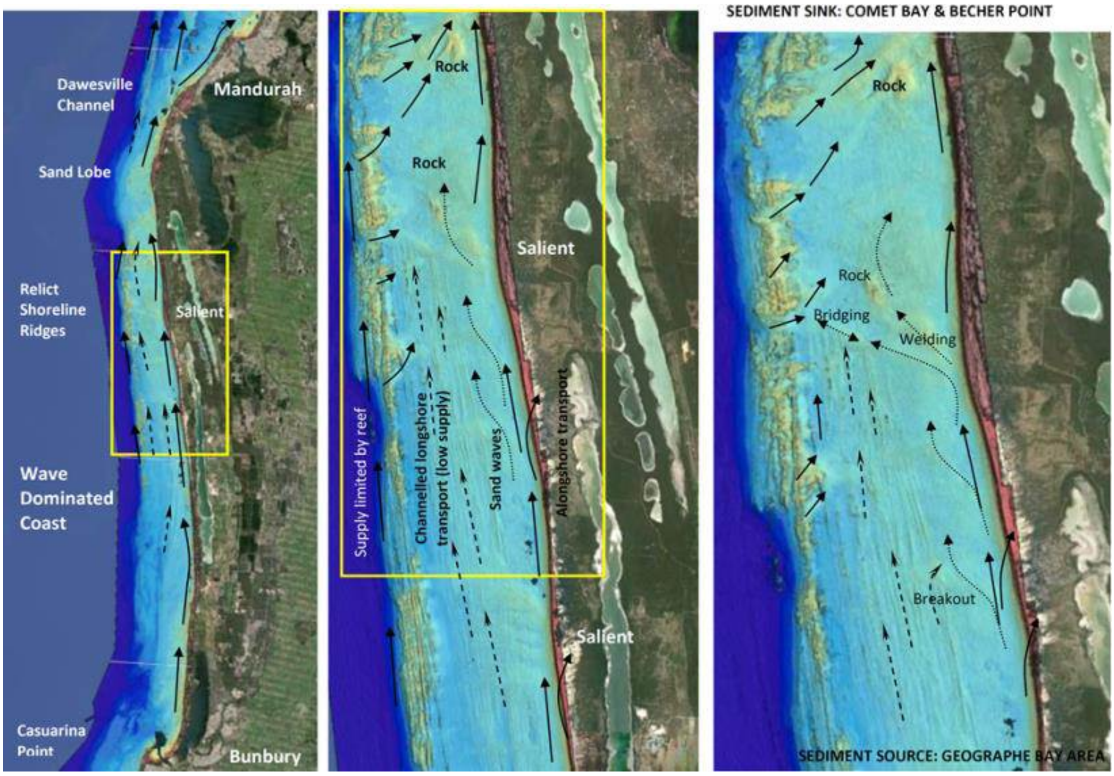

Dawesville Channel
Mandurah
Sand Lobe
Relict Shoreline Ridges
Salient
Wave Dominated Coast
Casuarina Point
Bunbury
Rock
Rock
Salient
Supply limited by reef
Channelled longshore transport (low supply)
Sand waves
Alongshore transport
Salient
SEDIMENT SINK: COMET BAY & BECHER POINT
Rock
Rock
Bridging
Welding
Breakout
SEDIMENT SOURCE: GEOGRAPHE BAY AREA

Fig 8

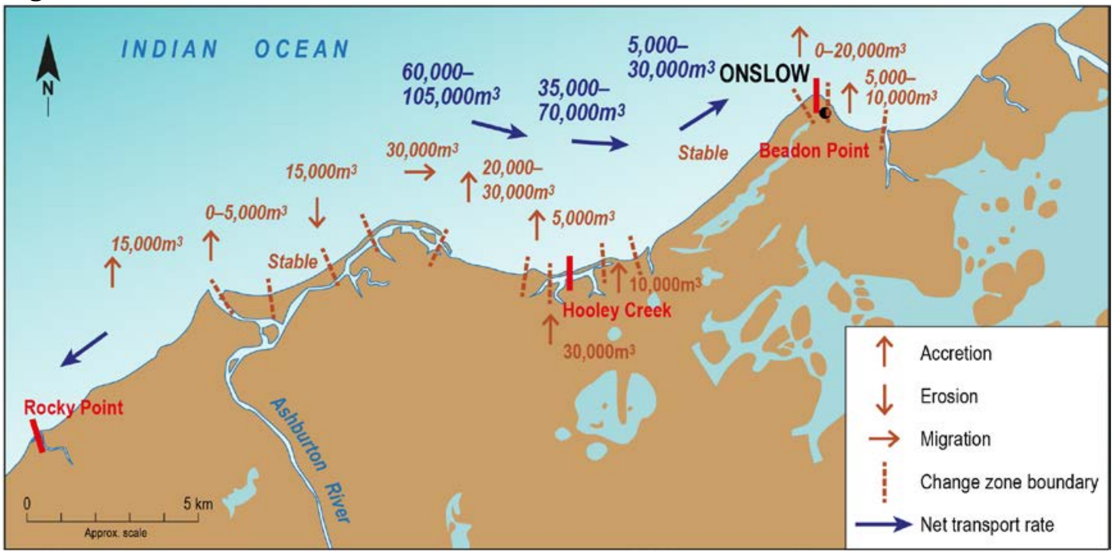

N
INDIAN OCEAN
60,000–105,000m³
35,000–70,000m³
5,000–30,000m³
ONSLOW
0–20,000m³
5,000–10,000m³
Stable
Beadon Point
30,000m³
15,000m³
20,000–30,000m³
0–5,000m³
5,000m³
15,000m³
Stable
10,000m³
Hooley Creek
30,000m³
Rocky Point
Ashburton River
0
5 km
Approx. scale
Accretion
Erosion
Migration
Change zone boundary
Net transport rate

Fig 9

Fig 10a

Fig 10b