

Chapter 7: POTENTIAL COASTAL EROSION OF THE SWAN COASTAL PLAIN DUE TO LONG-TERM SEA LEVEL RISE

Andrew Jones
Geoscience Australia

7.1 Summary

It is highly likely that coastal erosion due to long-term sea level rise associated with global warming will have a significant impact on Australia's coastal systems, and any associated infrastructure, over the next century. Long-term coastal erosion is thought to occur largely through sudden-onset storm events. Therefore, attempting to quantify this natural hazard is critical to future development and management of these localities. The potential impact of coastal erosion on the Western Australian built environment between Cape Naturaliste and Yanchep is assessed in this report.

Intergovernmental Panel on Climate Change (IPCC, 1996; 2001) sea level rise figures are the most widely accepted and used in coastal erosion studies. An increase in global temperatures will result in a sea level rise of 0.09 to 0.88 m between 1990 and 2100, with a central value of 0.48 m. Over the next 50 years the projected global sea level rise is 0.05 to 0.32 m, with a central value of 0.18 m (IPCC, 2001).

The nearshore bathymetry and onshore geomorphology of the Swan Coastal Plain is dominated by a series of shore-parallel submarine to emergent Pleistocene carbonate aeolianite ridges. Locally generated wind waves are the dominant mechanism controlling net northward littoral sand transport and determining the nearshore morphology of sandy beaches. The subsurface distribution of the erosion-resistant limestone has been determined in order to assess the erosion potential of the coastline. This reconstruction shows that the upper surface of the limestone is generally above sea level, suggesting the majority of the Perth coastal region is not at risk of significant erosion. At three localities (Port/South Beach, Swanbourne Beach, Pinaroo Point), however, the contact between the limestone and the overlying sand is below sea level. These areas are prone to erosion from storms and sea level rise, resulting in significant risk to urban development.

A Bruun Rule analysis reveals potential erosion rates at Swanbourne Beach over the next century may be approximately 1 m per year. The impact of this modelled recession is not significant due to a lack of overlying infrastructure. Similar erosion at the other vulnerable localities would have a much greater impact.

The majority of the Mandurah to Fremantle sector does not appear to be susceptible to coastal erosion over the next century, despite the fact that the Tamala Limestone is preserved below sea level across the majority of the area. This is due to the fact that this sector has been the primary depositional province for the Swan coast over the last 8,000 years. The Bunbury to Mandurah sector appears to be most susceptible to coastal erosion over the next century. This is because the Tamala Limestone is preserved below sea level, this sector is not well sheltered from offshore swell, and this location is at the southern end of the net northward littoral conveyor that operates along the Swan coast. The Hillarys to Yanchep sector does not appear to be susceptible to erosion over the next century as Tamala Limestone is preserved above sea level along the majority of the coast, and the beaches are well sheltered by three lines of offshore reefs. The Cape Naturaliste to Bunbury sector may be impacted by coastal erosion associated with long-term sea level rise.

A Bruun Rule calculation should be undertaken as a preliminary methodology in planning for coastal recession due to sea level rise. Future research should be focussed on the Bunbury to Mandurah sector, the Cape Naturaliste to Bunbury sector, and the Port/South beach area of Fremantle. The two significant problems that must be overcome before more modelling can be undertaken in the region are a lack of data (particularly sector specific wave data and more detailed subsurface data) and a lack of sophistication in current models that do not allow calculation in areas where the nearshore/offshore includes competent substrate.

7.2 Introduction

The latest IPCC report states that an increase in the concentration of greenhouse gases will cause global sea levels to rise over the next 100 years (IPCC, 2001). This sea level rise will cause extensive coastal erosion of many sandy beaches; more than two-thirds of the world's sandy coastlines have retreated in the past few decades (Bird, 1996). For example, it is estimated that over the next 60 years erosion may claim one out of four houses within 150 m of the US shoreline (H. John Heinz III Centre for Science Economics and the Environment, 2000).

With eight out of nine major Australian cities located on the coast, and the potential impact of this natural hazard still essentially unassessed, detailed risk assessments are critical to future planning. In this context, the Institution of Engineers (2000) identified marine climate change and its effect on the coastal zone as the most important research priority for coastal and ocean engineering in Australia. With extensive deposits of coastal sand, some of which host significant urban developments, Perth is an excellent example of a major city that may be at risk from sea level rise.

This report identifies areas of the Swan Coastal Plain between Cape Naturaliste in the south and Yanchep in the north, which may be susceptible to coastal erosion over the next century due to long-term sea level rise associated with global warming (Figure 7.1). The analysis is based on an integrated investigation of the Swan coastal system, comprising an examination of the geomorphology of the region in the context of coastal dynamics and sediment budgets. The key stage in this process involves a number of regional geographic information system (GIS) datasets that are used to reconstruct the three-dimensional architecture of the shoreline geology, to comment on the potential erosivity of the substrate and shoreline.

In order to present meaningful results along this 300 km section of coast, the study area is divided into sectors (Figure 7.2). The sectors are defined primarily by the data available for analysis, from a potential field of: bathymetry; LandSat; significant wave height; 1:50,000 scale environmental geology; microtremor; Seismic Cone Penetrometer Test (SCPT); geotechnical borehole; and Digital Elevation Model (DEM). The sectors are described in the following order, based upon the relative abundance of data (sectors are listed in order from that which contains the most data to that which contains the least):

- Fremantle to Hillarys (equivalent to the northern part of Searle and Semeniuk's (1985) Cape Bouvard – Trigg Island sector);
- Mandurah to Fremantle (equivalent to the southern part of Searle and Semeniuk's (1985) Cape Bouvard – Trigg Island sector);
- Hillarys to Yanchep (equivalent to the southern part of Searle and Semeniuk's (1985) Whitfords – Lancelin sector);
- Bunbury to Mandurah (equivalent to Searle and Semeniuk's (1985) Leschenault – Preston sector);
- Cape Naturaliste to Bunbury (equivalent to Searle and Semeniuk's (1985) Geographe Bay sector).

It should be noted that the accuracy of susceptibility interpretations varies between the sectors, in correspondence with the data that were available for analysis. Interpretations made in regards to the Fremantle to Hillarys sector are of a confidence level higher than the remaining sectors. Furthermore,

interpretations in the Mandurah to Fremantle are of moderate confidence, whereas confidence in the other sectors is relatively low (primarily due to the lack of onshore subsurface data (Figure 7.1).

Given the overlap with the sectors of Searle and Semeniuk (1985), their comprehensive descriptions of morphology and sedimentation/erosion are utilised in outlining the geomorphology and sediment budgets of the sectors within this report.

A quantitative evaluation of potential erosion rates over the next century using a conventional two-dimensional coastal behaviour model is presented for one site within the Fremantle to Hillarys sector. Similar quantitative evaluations within the remainder of this sector, and throughout the other sectors, were precluded by a lack of data and/or more sophisticated models. This will be discussed in more detail in each of the sections describing the coastal sectors.

Sea level rise

Based on tide gauge data, the rate of global mean sea level rise during the 20th century is in the range 1.0 to 2.0 mm/yr (IPCC, 2001). This rate of sea-level rise is consistent with recent satellite altimeter data (Nerem *et al.*, 1997), which directly measures eustatic variations in sea level. IPCC (1996; 2001) future sea level rise figures are the most widely accepted and used in coastal erosion studies, as they are compiled by an international panel of climate change experts using what is considered the most reliable data and modelling techniques (Atmospheric and Oceanic Global Circulation Models (AOGCM's)). The IPCC (2001) climate models indicate the globally averaged surfaced temperature will increase by 1.4 to 5.8°C over the period 1990 to 2100. This increase in global temperatures will result in a sea level rise of 0.09 to 0.88 m between 1990 and 2100, with a central value of 0.48 m. Over the next 50 years the projected global sea level rise is 0.05 to 0.32 m, with a central value of 0.18m (IPCC, 2001).

The local rate of relative sea level change may diverge from the global change due to a number of processes, including coastline subsidence or uplift. Tectonic movements, isostatic subsidence, compaction of sediments, or extraction of groundwater, oil, and/or gas can cause subsidence. Uplift, as a result of postglacial isostatic rebound or tectonic processes, reduces or reverses relative sea level rise. This is very significant in coastal erosion studies as the validity of using global estimates to determine erosion rate is dependent on establishing the fact that the relative sea level change at any given locality is similar to the global baseline. Where this has the potential to impact on recession estimates in this study, this concept is explained in more detail.

Regional geomorphic setting and oceanographic conditions

The Rottneest Shelf encompasses the continental shelf between the Abrolhos Islands and Cape Leeuwin (Clarke, 1926; Carrigy and Fairbridge, 1954). However, this study is focussed only on the Rottneest Shelf adjoining the Swan Coastal Plain, from Yanchep in the north to Cape Naturaliste in the south. The 50 m isobath is over 50 km from sections of the coast along this part of the shelf (Figure 7.2); hence the slope of the inner shelf is gentle (Masselink and Pattariatchi, 2001).

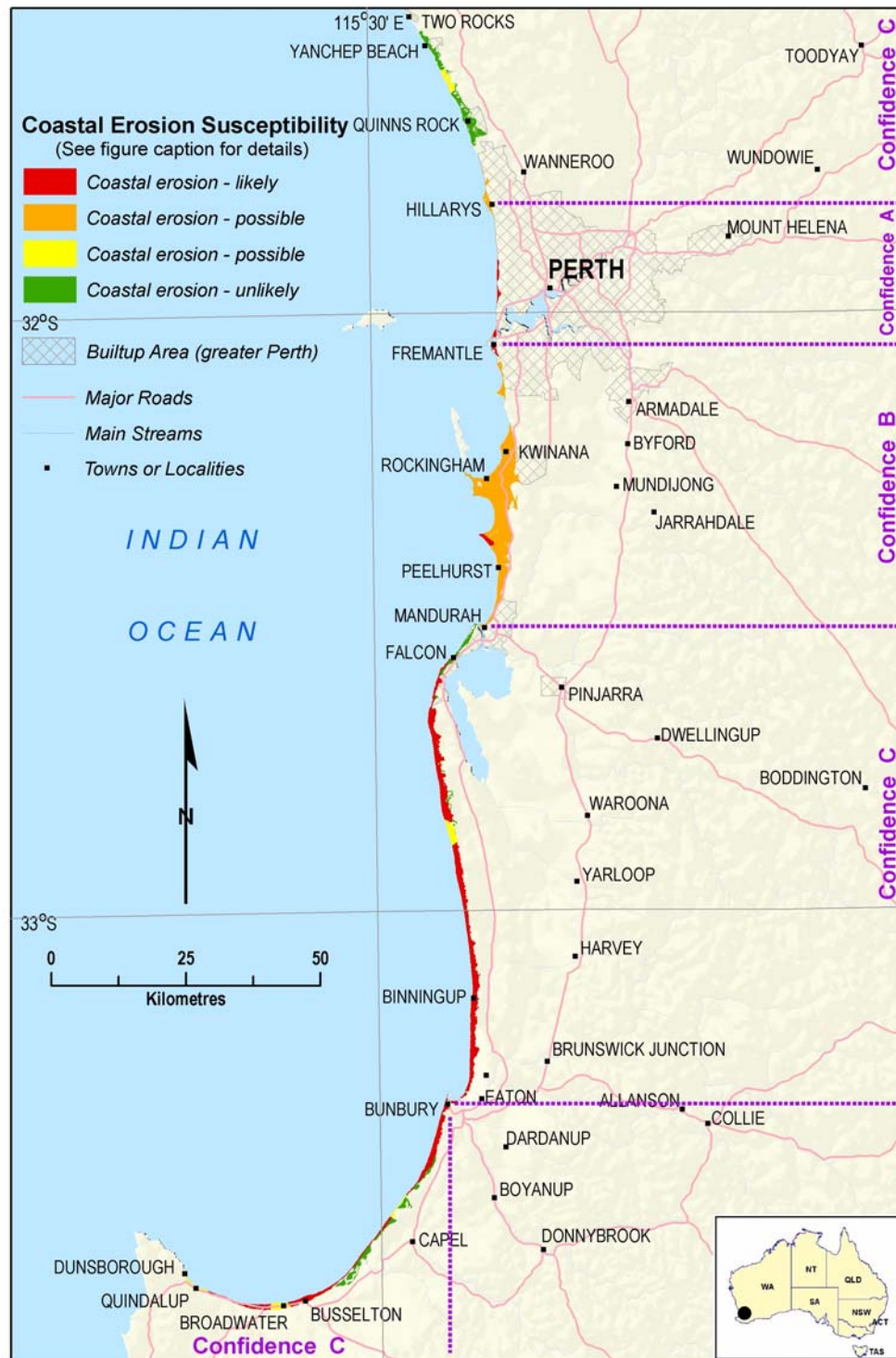


Figure 7.1: Potential coastal erosion due to long-term sea level rise for the greater Perth region. Details for colour key: Red – Coastal erosion likely as competent lithologies are preserved below sea level and external sediment input is minimal; Orange – Coastal erosion possible as competent lithologies are preserved below sea level, but external sediment input appears sufficient to fill any accommodation space created by sea level rise; Yellow – Coastal erosion possible as competent lithologies are preserved close to sea level, more detailed subsurface data necessary to more accurately delineate this surface in these areas; Green – Coastal erosion unlikely as competent lithologies are preserved above sea level.

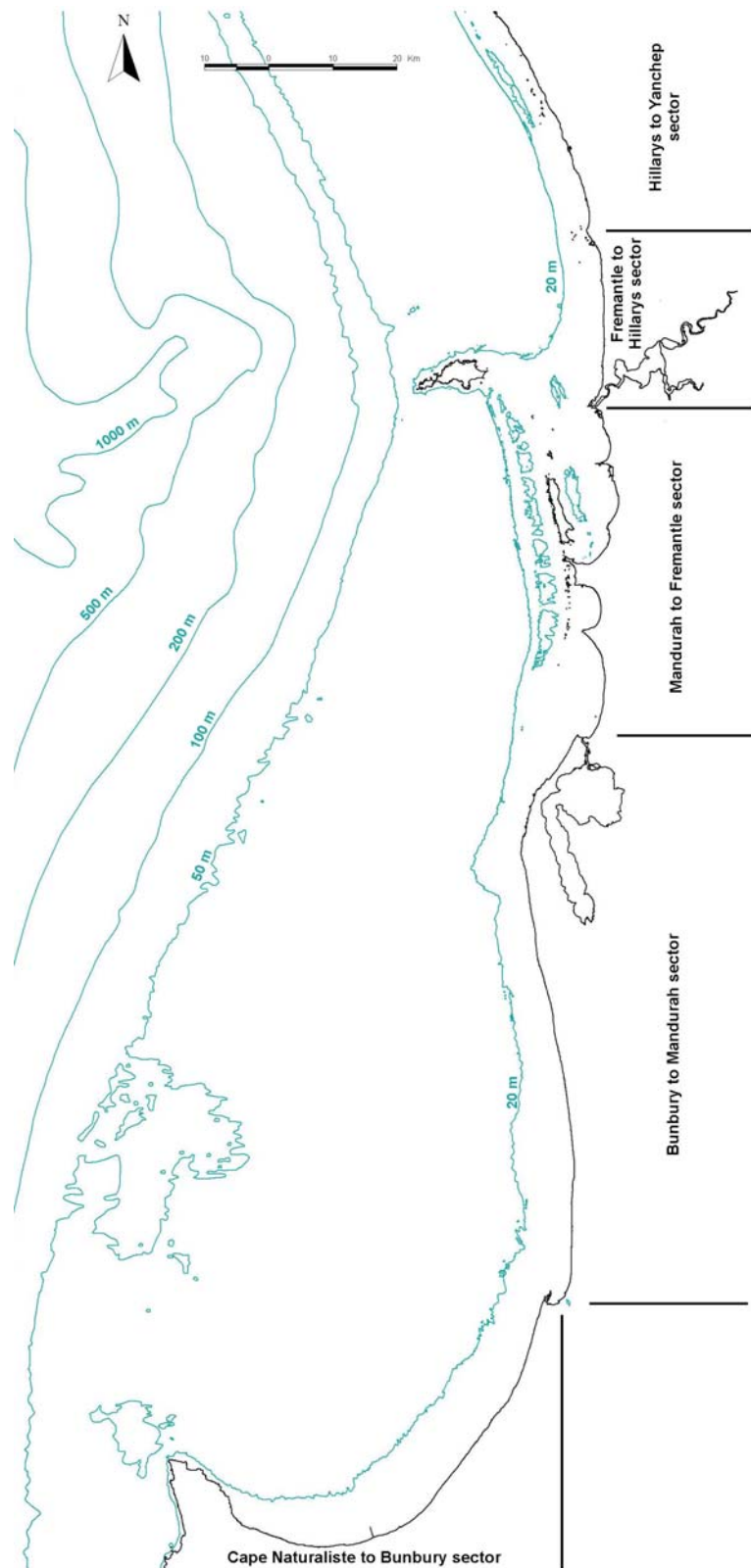


Figure 7.2: Map showing the location of the sectors within the study area. Note the relative width of the continental shelf, and the simple bathymetry of the southernmost two sectors relative to the remaining three

The coastline of the Swan Coastal Plain is dominated by a series of shore-parallel submarine to emergent Pleistocene carbonate aeolianite ridges and associated depressions. Onshore, this aeolianite comprises the Tamala Limestone (Playford *et al.*, 1976). The Tamala Limestone also forms the core of nearshore and offshore islands, and dominantly underlies the extensive continental shelf in this region (Collins, 1983; Searle, 1984; Searle and Semeniuk, 1985). The coastal dune and beach sediments of the Swan Coastal Plain are termed the Safety Bay Sand (Passmore, 1967; Playford and Low, 1972; Playford *et al.*, 1976). This formation extends discontinuously along the coast and is best developed in embayments, sheltered bays and tombolo settings where it forms prograded sediment bodies (Searle and Semeniuk, 1985).

Throughout the year offshore oceanographic conditions are dominated by oceanic swell with average significant wave height of 1.5 m and period between 10 and 20 seconds (Sanderson and Eliot, 1999). This swell is attenuated both as it crosses the continental shelf, and as it passes across any offshore reefs. On average, 39% of the offshore incident wave energy is filtered or dampened (Steedman, 1977), with local topography potentially attenuating up to 90% of the swell (Hegge, 1994; Lemm, 1996). Therefore, the inshore wave regime is relatively quiet, with an average significant wave height of less than 1 m and a period of approximately 10 seconds (Data courtesy of the Western Australian Department of Planning and Infrastructure (DPI)).

In contrast to the subdued wave regime, the Swan coast is exposed to one of the most energetic sea-breeze systems in the world (Masselink and Pattiaratchi, 2001). A significant feature of the sea breeze along the west coast of Australia is that it blows parallel to the shoreline (i.e. from the south-southwest; Pattiaratchi *et al.*, 1997; Masselink and Pattiaratchi, 1998). This is in contrast to a 'typical' sea-breeze system, which blows perpendicular to the shoreline (Hsu, 1988; Abbs and Physick, 1992; Simpson, 1994). In the summer months, the sea breeze is present more than 60% of the time (Hounam, 1945) and the mean sea breeze velocity at the coastline is about 8 m/s (Masselink and Pattiaratchi, 2001). In winter, low pressure cells impinge on the Perth coastline, and disrupt the sea-breeze system (Bureau of Meteorology (BOM), 1969; Gentilli, 1971). The winds associated with the approach of a depression are initially from north and increase in strength while shifting to the northwest (Masselink and Pattiaratchi, 2001).

Sediment dynamics

Due to the subdued wave regime and the energetic sea breeze activity that exists along the Swan Coastal Plain, the locally generated wind waves are the dominant mechanism controlling littoral sand transport and determining the nearshore morphology of sandy beaches (Pattiaratchi *et al.*, 1997; Masselink and Pattiaratchi, 1998).

The southerly sea-breeze system induces a northward sediment transport, whereas sand is moving south during winter as a result of southward flowing currents generated by the northwesterly storms. This oscillatory north–south motion of sand occurs on an annual cycle along the Swan coast with a resultant northerly bias (Silvester, 1961; Masselink and Pattiaratchi, 2001). Therefore, the northward longshore sediment transport induced by the sea breeze accounts for the net littoral drift that occurs along this part of the coast (Masselink and Pattiaratchi, 1998).

7.3 Methods

Assessing the erosivity of the Swan coastline requires differentiation between the 'erosion-prone' sand and 'erosion-resistant' limestone, which dominate the shoreline geology of the Perth coastal system. Environmental geology maps (eg, Gozzard, 1986) provide a spatial distribution of shoreline geology at the surface, but accurately assessing erosivity requires understanding of lithology distribution at depth. In order to reconstruct the three-dimensional distribution of the limestone in each of the sectors, environmental geology maps were combined with geophysical (microtremor) and geotechnical (borehole descriptions and SCPTs) data. The availability of this data varies between sectors, therefore the datasets and methods utilised for each sector are described in the relevant sections. The remainder

of this section outlines the way in which the limestone architecture is reconstructed using each of these datasets.

Geotechnical boreholes

The location of approximately 28,000 boreholes was supplied to Geoscience Australia (GA) by the Western Australian Department of the Environment (DOE). In addition to the locations, DOE supplied a spreadsheet of lithological descriptions for some of the boreholes (comprising over 80,000 rows of data). The boreholes were drilled primarily with the aim of exploring for aquifers across the Swan Coastal Plain. The coverage of these boreholes in the region is excellent, and as such is the only onshore data available in a number of the sectors, but the lithological descriptions are highly variable in terms of their detail. In most cases broad descriptions of grain size were documented for relatively coarse intervals, disregarding any differences between consolidated and unconsolidated sections. For example, shales and siltstones are often described as mud or clay. Therefore in many cases it was necessary to interpret the lithological strata in the context of published descriptions of the Quaternary stratigraphy. Another limiting factor of this dataset is due to the fact that the holes were drilled with the aim of delineating aquifers. In many places along the coast it was therefore unnecessary to drill to the top of the limestone, given that the overlying Safety Bay Sand comprises the primary superficial aquifer. Consequently many of the logs that have an associated description do not penetrate sufficiently deep to assist in the reconstruction of the upper limestone surface.

Where geotechnical boreholes with sufficiently detailed lithological descriptions were available, the height at which the ground surface lies at that point was determined by relating the borehole position to a DEM. The depth at which the top of the limestone was penetrated was then taken away from the ground height relative to the Australian Height Datum (AHD) to determine whether or not that limestone surface lies above or below sea level.

Seismic Cone Penetrometer Tests

In seismic cone penetrometer tests (SCPTs), a conical penetrometer tip is pushed slowly into the ground and monitored. The device contains electrical transducers to measure both tip (Q_c) and side (F_s) resistances as the instrument is advanced. A friction ratio is calculated by relating the sleeve friction to the tip resistance (F_s/Q_c). Coarse-grained sediments such as sands and gravels tend to resist penetration at the tip, whereas finer grained sediments such as clays and silts resist penetration along the sleeve, therefore there is a direct relationship between the friction ratio and lithology. The higher the friction ratio, the finer the sediment grain size. In addition to providing an estimation of lithology, SCPTs measure the seismic velocity of the sediments.

GA has undertaken 58 SCPTs around Greater Metropolitan Perth as part of a study of earthquake hazard in the region (Figure 7.3). The usefulness of these SCPTs for reconstructing the upper surface of the limestone is limited due to both their sparse coverage across the Swan Coastal Plain, and because the test terminates for a number of reasons (including encountering a competent substrate). The first point is highlighted by the fact that only three tests were undertaken in Safety Bay Sand directly adjacent to the coast. The second point, that SCPTs cannot penetrate limestone, means the logs produced from these tests are only useful if the test went below sea level. If the test terminated above sea level then it is impossible to determine if termination was due to encountering limestone, as opposed to hitting a buried boulder or a very coarse sand layer.

The most useful aspect of SCPTs in this study is seen in the fact that they provide a measurement of the seismic velocity of sediments. This seismic velocity is used in association with the microtremor data to estimate the limestone architecture (see below).

Microtremor data

One of the most useful tools in reconstructing the three-dimensional architecture of the sand and limestone is a microtremor dataset collected during an extensive GA field survey (Figure 7.4). The survey involved using a ground seismometer and measuring the resonant vibration of unconsolidated regolith (T), as created by phenomena such as wind, waves and anthropogenic influences (eg, traffic).

Where the unconsolidated Holocene sediments of the Safety Bay Sand overlie ‘competent’ rock (Tamala Limestone), resonant vibration in the sediments occurs for shear waves with a wavelength of four times the sediment thickness. In this case:

$$V_s = 4 \frac{H}{T}$$

Equation 7.1

where V_s is seismic shear wave velocity in metres per second, T is resonant period of the fundamental mode of vibration in seconds and H is sediment thickness in metres. Therefore to estimate the thickness of the sand, and correspondingly determine the position of the upper surface of the limestone, it is necessary to have measurements of V_s and T .

Shear wave velocities measured in the Safety Bay Sand (V_s) during the SCPT’s were averaged and related to natural period of ground vibration (T) at each point in the microtremor survey, to yield an estimate of regolith thickness (H). This theory was utilised to reconstruct the position of contact between the limestone and the overlying sand.

7.4 Fremantle to Hillarys

Geomorphology and sediment dynamics

The nearshore bathymetry and onshore geomorphology of the Fremantle to Hillarys sector is dominated by Spearwood Ridge of Tamala Limestone, which forms the north–south trending shoreline in the lower part of the sector and 330° trending nearshore reefs in the upper part of the sector (Figure 7.5). Holocene coastal sedimentation in this region has formed minor stable dunes and pocket beaches flanking the seaward side of the Spearwood Ridge (Searle and Semeniuk, 1985).

Much of the coastline of this sector is sheltered from the direct impact of swell and storm-wave activity by the extensive chain of reefs formed by the Five Fathom Bank and Garden Island Ridges. As a result of wave refraction and attenuation, wave energy at the shoreline tends to be low (Pattiaratchi *et al.*, 1997).

In the context of sedimentation in this sector the Garden Island Ridge, up to and including Rottnest Island, acts as a barrier to the northward littoral drift (see Mandurah to Fremantle section). The discrete nature of the depositional loci south and west of Swan River outlet suggest that very little sediment derived from the longshore drift reaches the northern Perth coastline. This is supported by observed beach recession/accretion trends, which show that beaches in the southern part of the sector (Port Beach to City Beach; Figure 7.6) experience average erosion rates of c. 1 m/yr, whereas those north of City Beach are characterised average accretion rates of c. 1 m/yr (Silvester, 1961). Long-term beach width measurements on Scarborough Beach (Figure 7.6) demonstrate an accretion rate of 3 m/yr (Clarke and Eliot, 1983). This suggests that sediment taken from the southern part of the sector by northward drift is not being renewed from south of Fremantle. Given that very little sediment is introduced into the sector from longshore drift, Safety Bay Sand along the northern Perth sector has been primarily derived from local benthic assemblages (principally the seagrass assemblage) and from erosion of the Tamala Limestone within the sector (Searle and Semeniuk, 1985). One exception is the sand bank directly adjacent to the eastern point of Rottnest Island, which was likely deposited by the penetration of the longshore drift through the Garden Island Ridge at this point.

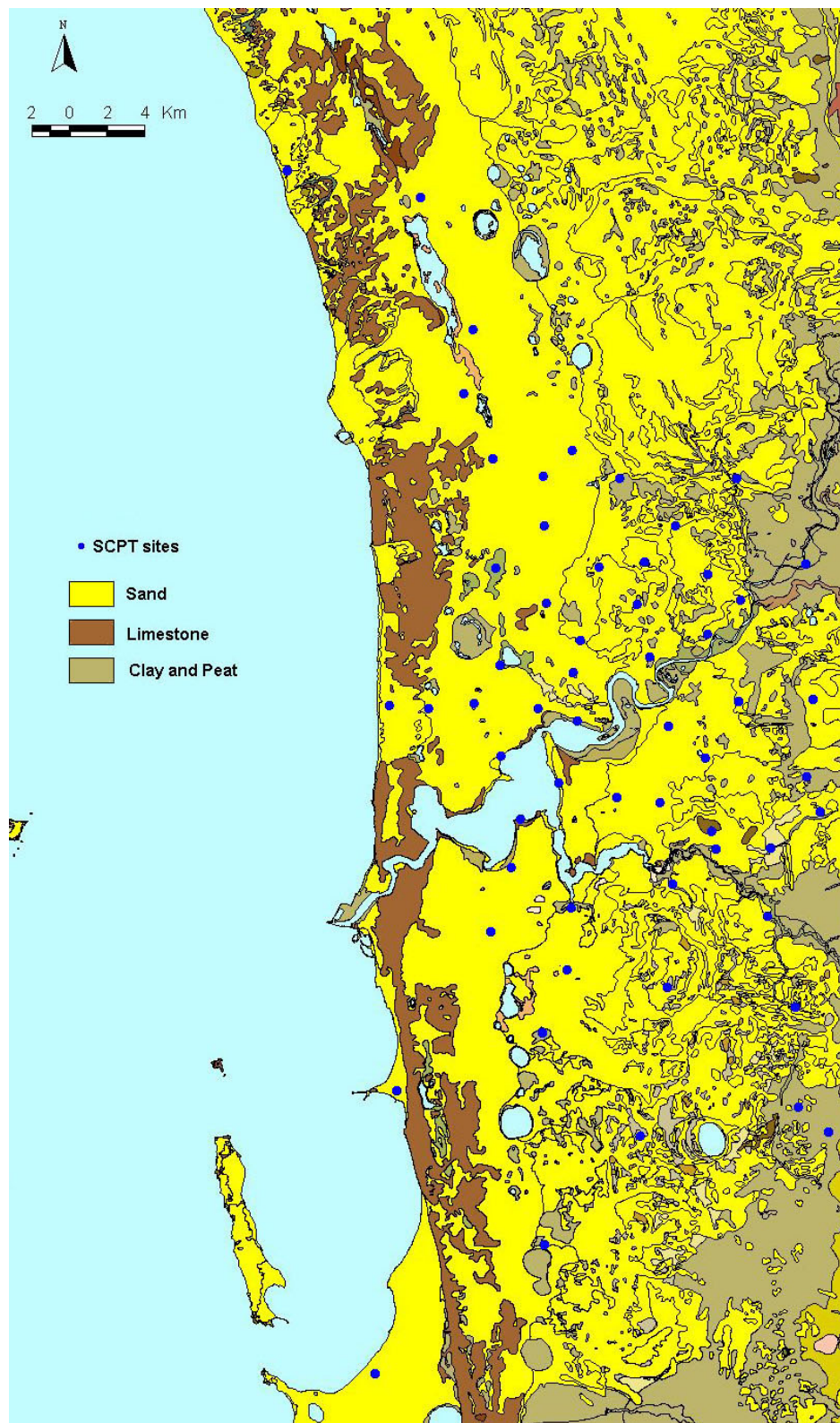


Figure 7.3: Location of SCPTs undertaken by GA as part of its earthquake risk assessment in the Perth region. Depth data from a number of these tests were utilised to reconstruct the three-dimensional architecture of the limestone. Measured seismic velocities were also used, in association with microtremor tests

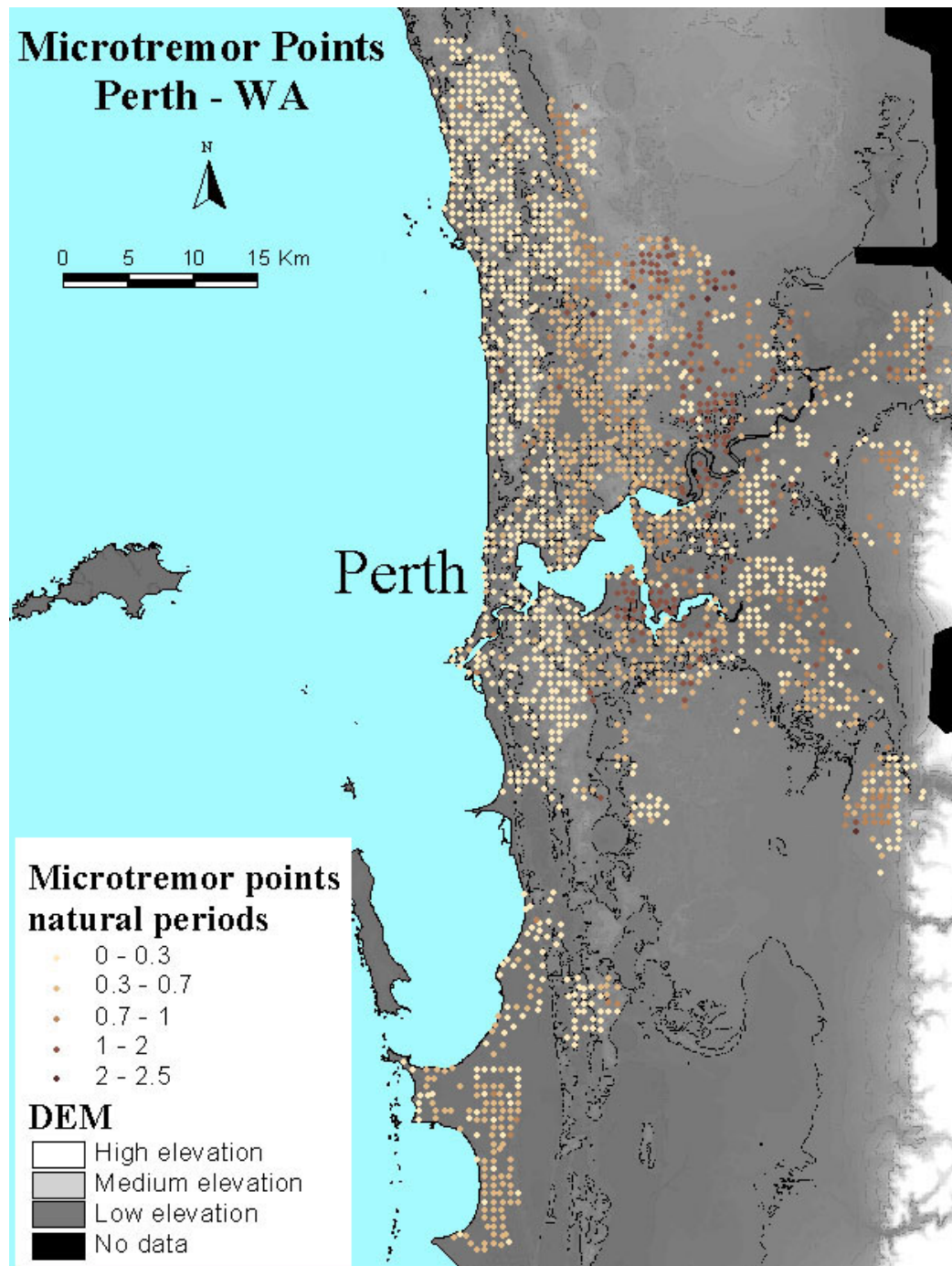


Figure 7.4: Location of microtremor tests undertaken by GA as part of its earthquake risk assessment in the Perth region. Measured natural periods at these sites were used in association with seismic velocities from SCPTs to estimate depth to limestone

The source of the sediment lobe adjacent to the coast 5 km north of the Swan River outlet is ambiguous (Figure 7.5). The lobate morphology suggests the sediments are allochthonous and the position of the lobe (with the flat edge adjacent to the coast) suggests the depositional mechanism was not longshore drift. The preservation of shore perpendicular channel features across the top of the lobe suggests this sediment lobe was likely deposited as a delta (Jones and Hayne, 2003). The delta was probably deposited during a relative sea level highstand approximately 6,000 years ago (Semeniuk and Semeniuk, 1991). Alternatively, it may have formed during a Pleistocene highstand, although if this is

the case it is difficult to reconcile the preservation of the lobe and associated channel features with the length of time that it has existed in a relatively high-energy environment.

Erosivity of the coastline

The microtremor dataset was utilised in reconstructing the upper limestone surface within this sector due to the excellent coverage of this part of metropolitan Perth. This reconstruction, displayed in Figure 7.7, shows that the upper surface of the limestone is generally above sea level, therefore the majority of the Fremantle to Hillarys coastal sector is not at risk of erosion. At a number of localities, however, the top of the limestone is below sea level, suggesting that overlying sediments and infrastructure is vulnerable, as storm events have the capacity to erode sand into the offshore. Three regions in particular may be at risk (Figure 7.8): the Pinaroo Point region; the Swanbourne to Floreat Beach region; and the Port/South Beach region at the Swan River outlet (Jones and Hayne, 2003).

Borehole data from the region adjacent to the coast (Figure 7.6) provide information on the accuracy of this reconstruction. Recorded heights of the upper limestone surface from 35 boreholes within 2 km of the coast were compared with values estimated from the contours shown in Figure 7.6. Significantly, the reconstruction gave only two localities where a value above sea level and the borehole value below sea level failed to correlate. At all other localities values corresponded, being either both above or both below sea level, suggesting the method is suitable for broad scale mapping of sediment interfaces.

Qualitative assessment of erosion hazard in susceptible areas

The majority of the coastline in this sector (Leighton to Cottesloe Beach and Brighton to Sorrento Beach), and the associated infrastructure, appears to be at little risk in terms of major recession due to erosive events and long-term sea level rise over the next century (Figure 7.1; Figure 7.7). It is possible that any narrow beaches backed or underlain by limestone may disappear, leading to coastal cliffs dominating the coastline geomorphology. While this erosion is unlikely to have a major impact in terms of land-loss and infrastructure damage, it may have some consequences in the context of recreational activity use. Due to net northward littoral drift through the sector the impact is likely to be more evident in the short term in areas such as Leighton Beach, as opposed to areas such as Trigg Beach.

The three localities in the northern Perth region that display some potential for erosion in the future can be ranked in order of relative hazard by examining their spatial distribution in the context of sediment dynamics for the region (Jones and Hayne, 2003). The Port/South Beach area is likely to be most vulnerable, as it is in the most southerly position (Figure 7.1). The net northward longshore drift is stripping sand from this part of the coast; therefore there is less of an erosional buffer. This hazard may be offset somewhat by the fact that the majority of storms influencing this part of the coast do so in winter (BOM, 1969; Gentilli, 1971). During this season there is a reversal in the longshore drift direction, and consequently the beaches are at their widest (Masselink and Pattiaratchi, 2001).

The Swanbourne to Floreat Beach region is likely to be the second-most vulnerable locality (Figure 7.1), although the relative hazard is somewhat ambiguous for two reasons: first, the area is in a quasi-steady state in the context of longshore drift as it is close to the boundary point between accreting and eroding beaches (Silvester, 1961); and second, the microtremor coverage in the Swanbourne region is relatively poor (Figure 7.7) due to restricted access to that part of the coast. It is possible that the Tamala Limestone is actually at, or above, sea level at this location, and that the vulnerability is considerably less than suggested by Figure 7.8. There is some evidence of this in that modern beach-rock is periodically exposed along Swanbourne Beach (I. Eliot, University of Western Australia, pers. comm., 2002), but the thickness and continuity of this unit is unknown.

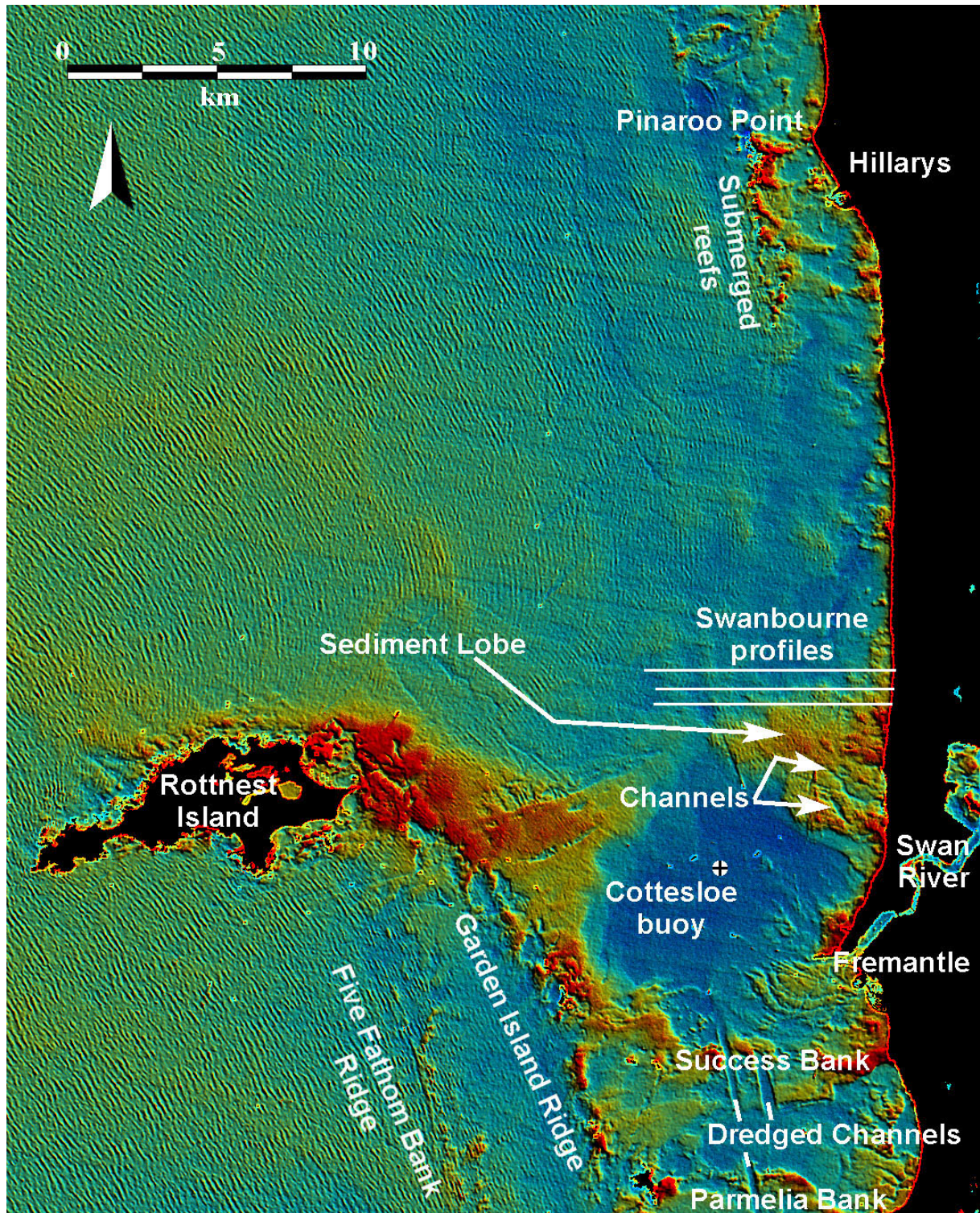


Figure 7.5: A Landsat image of the Fremantle to Cottesloe sector, processed with the GA Shallow Water Image Mapping (SWIM) method to display bathymetry. The ‘hot’ and ‘cool’ colours indicate shallow and deep water respectively. The level of precision displayed in this image is evident in the dredged shipping channels southwest of the Swan River outlet

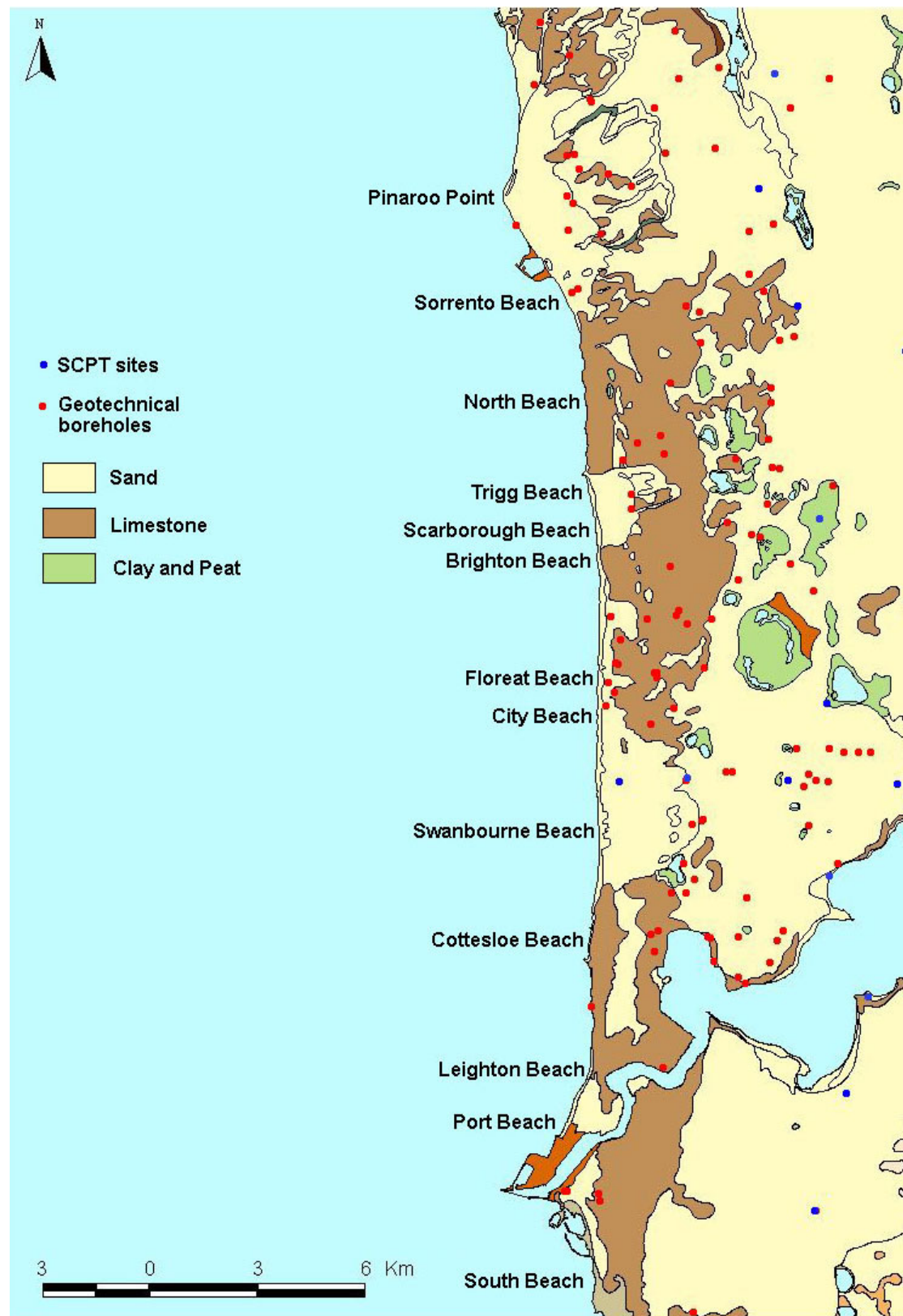


Figure 7.6: Spatial distribution of seismic cone penetrometer tests (SCPTs) and geotechnical boreholes in the Perth region, overlain on the environmental geology of the area from Gozzard (1986)

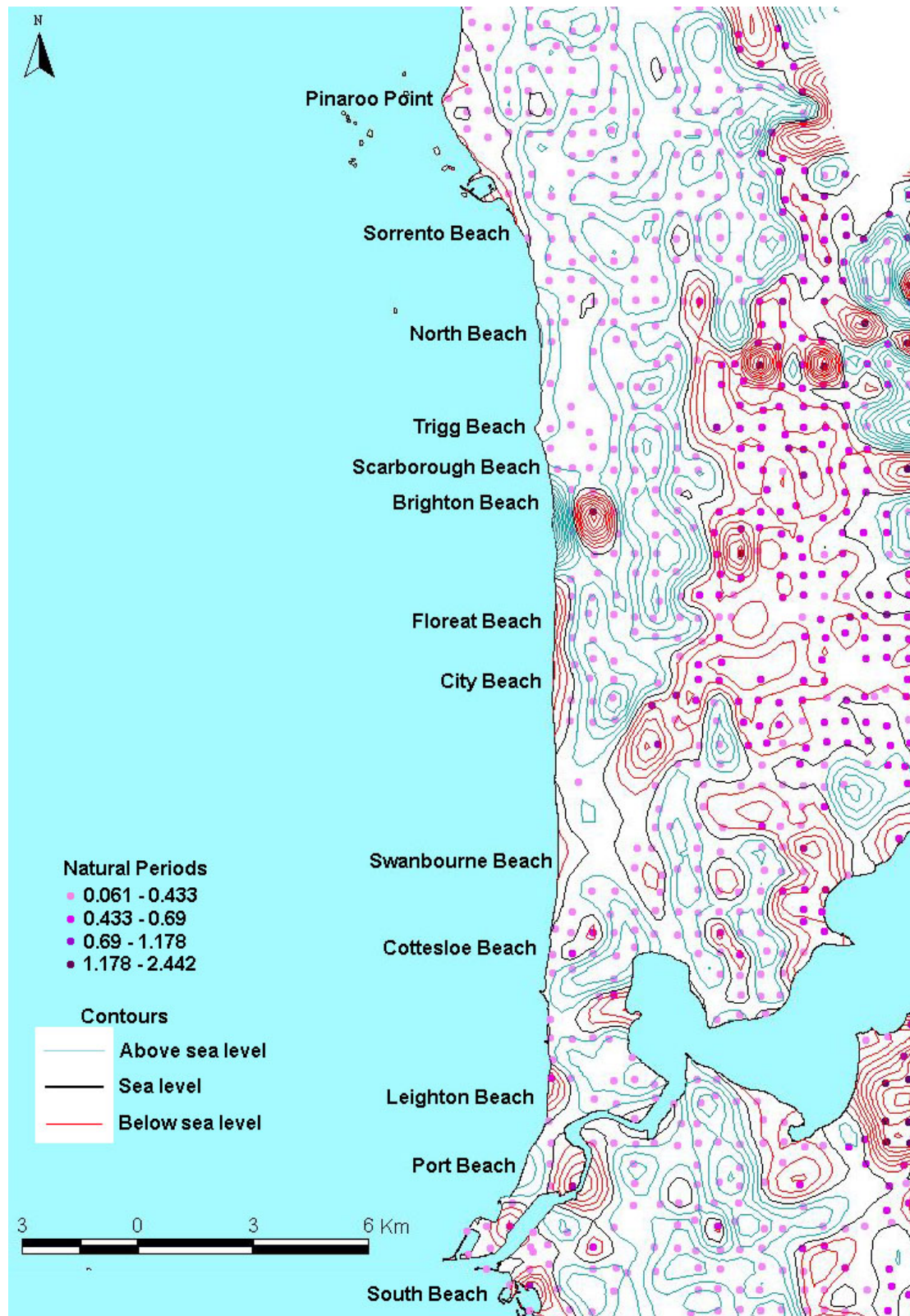


Figure 7.7: Spatial distribution of microtremor tests in the Perth region, and the reconstructed estimate of the upper surface of the Tamala Limestone relative to sea level. The reconstruction is based on the natural period measured at each microtremor test and the seismic velocity of the sand measured in the SCPTs



Figure 7.8: Zones potentially prone to coastal erosion along the northern Perth coastline. The interpretation is based on an intersection of sandy areas in the environmental geology maps (Figure 7.6) with areas in which the upper limestone surface are below sea level (Figure 7.7)

The Pinaroo Point area (Figure 7.8) is likely to be the least vulnerable of the three regions (Figure 7.1), as it is at the northern end of the sector and is supplied with sediment over the course of the year by

net northward longshore drift. The Safety Bay Sand in this area is relatively wide and as such there is a considerable buffer to sudden-impact erosional events. Additionally, any accommodation space created in the offshore by long-term sea level rise is likely to be infilled by longshore drift sediments, and will not require sediment to be eroded from the shoreline.

Potential erosion at Swanbourne following the Bruun Rule

The Swanbourne Beach section of the northern Perth coast was selected as a test case for quantitative assessment of potential erosion rates over the next 50 and 100 years. It was selected for a number of reasons.

- It is one of the areas identified as being susceptible to erosion in the analysis presented above.
- There is no significant input or output of sediment due to longshore drift.
- There is no evidence of a submerged limestone ridge forming a reef adjacent to that part of the coast (Figure 7.5).
- All data necessary for modelling was available.

The bathymetry and topography along three profiles in this area, taken from spot depth bathymetry and a DEM respectively, are utilised in a Bruun Rule analysis to calculate the potential erosion at Swanbourne Beach due to long term sea level rise (Figure 7.5).

The first and best-known model relating shoreline retreat to an increase in local sea level is that proposed by Bruun (1962; 1988). The analysis by Bruun assumes that with a rise in sea level, the equilibrium profile of the beach and shallow offshore moves upward and landward (Figure 7.9). Bruun derived the basic relationship for the extent of shoreline recession, R , due to an increase in sea level, S :

$$R = \left(\frac{L}{B + h} \right) S$$

Equation 7.2

where L is the cross-shore distance to the water depth h , taken by Bruun as the depth to which nearshore sediments exist (depth of closure), and B is the height of the dune. The analysis is two-dimensional and assumes (Scientific Committee on Ocean Research (SCOR), 1991):

- The upper beach is eroded due to the landward translation of the profile;
- The material eroded from the upper beach is transported immediately into the offshore and deposited, such that the volume eroded is equal to the volume deposited; and
- The rise in the nearshore bottom as a result of deposition is equal to the rise in sea level, thus maintaining a constant water depth in the offshore.

Despite its simplicity and numerous assumptions, which have in some instances led to criticism (eg, Pilkey *et al.*, 1993), the Bruun Rule works remarkably well in many settings (Morang and Parson, 2002). The use of the Bruun Rule may still be the valid step forward in the short term, as it gives an estimate of future recession values without requiring long-term monitoring of shoreline trends (cf. Stive and de Vriend, 1995).

In studying coastal erosion at Swanbourne Beach, the validity of assumption one (erosion of the upper beach due to profile translation) is relatively critical, as there is some evidence of beach-rock along this part of the coastline (I. Eliot, University of Western Australia, pers. comm., 2002). If this is the case then the calculations presented below are invalidated. However, in the absence of distribution data for the beach-rock a Bruun Rule analysis provides a useful measure of potential erosion.

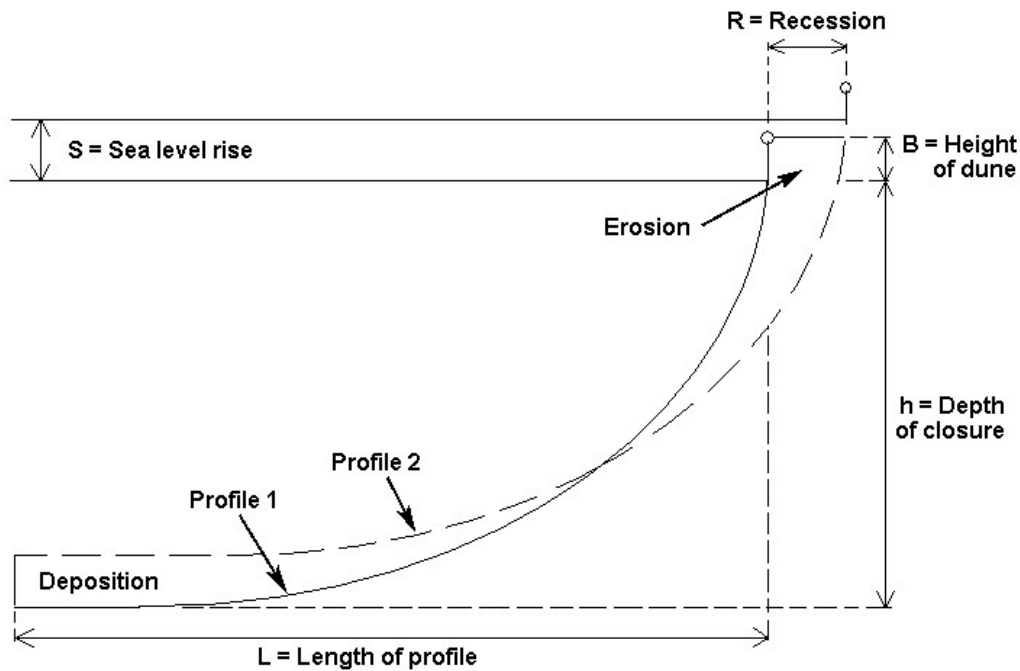


Figure 7.9: The net change in beach-profile position due to a rise in sea level, S , according to the Bruun model, resulting in a zone of offshore deposition and erosion of the upper beach, with an overall recession rate, R

Input variables

Sea level rise

Based on tide gauge data, the rate of global mean sea level rise during the 20th century is in the range 1.0 to 2.0 mm/yr (IPCC, 2001). As previously discussed, the local rate of relative sea level change may diverge from the global change due to a number of processes, including coastline subsidence or uplift. The tide record from Fremantle Harbour over the last 90 years shows an increasing sea level with a rate of approximately 1.1 mm/yr (Figure 7.10), which falls within the range of rates presented as global baseline over the past century (IPCC, 2001). Therefore, the sea level rise scenarios presented by the IPCC (2001) are considered to be appropriate for studying coastal erosion in the Perth region. These figures are 18 cm and 48 cm respectively.

Dune height

The heights of the dunes in the study area were measured directly from a digital elevation model (DEM) of the Perth region. The dune heights measured from three profiles in the Swanbourne area are 12.9 m, 15.4 m and 19.7 m for the north, central and southern profile, respectively.

Depth of closure

The depth of closure is the discontinuity in the offshore limit of a beach profile considered in coastal erosion studies. Bruun (1962) originally explained this discontinuity as the transition between nearshore sediments and deep-water sediments. Inherent in this division is the relative importance of sediment transport processes and how they change with depth and offshore distance (SCOR, 1991).

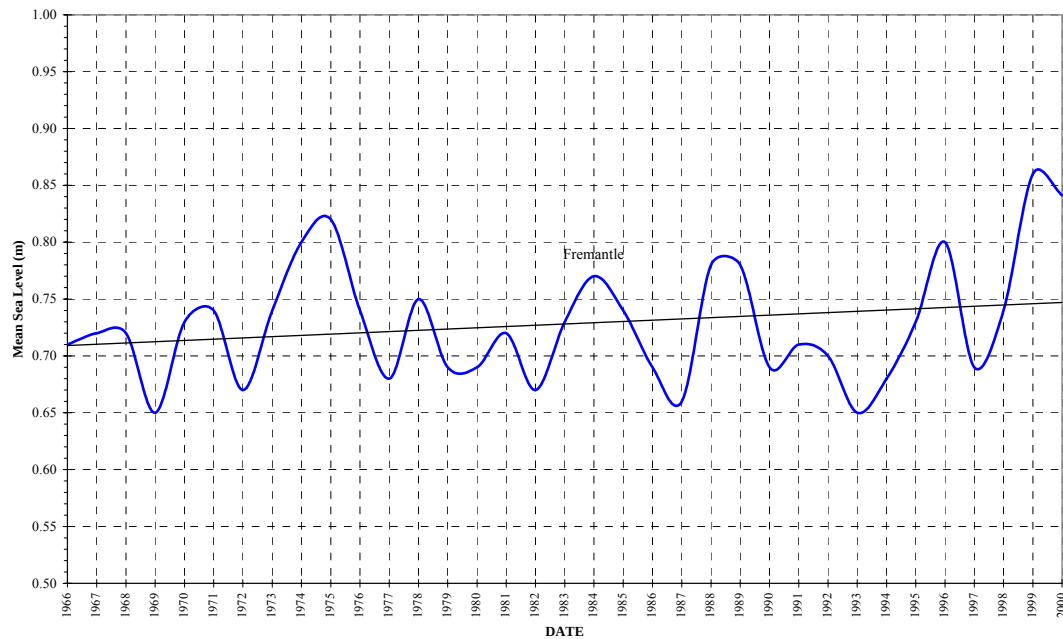


Figure 7.10: Long-term tide gauge record from Fremantle Harbour courtesy of the DPI. The average increase of 1.1 mm/year falls within the range of rates presented as global baseline over the past century (IPCC, 2001). Therefore, the sea level rise scenarios presented by the IPCC (2001) are considered to be appropriate for studying coastal erosion in the Perth region

The analysis procedures developed by Hallermeier (1981) relating wave and sediment conditions to profile zonation provide a satisfactory methodology for selecting the closure depth. Hallermeier (1981) defined the depth as being the maximum water depth for sand motion initiation by the annual median wave condition. The formula for calculating depth of closure (d) is:

$$d = (H - 0.3\sigma) T \left(\frac{g}{5000D} \right)^{0.5} \quad \text{Equation 7.3}$$

where H is the significant wave height, σ the standard deviation of significant height, T is the mean significant wave period, g is gravity, and D is the mean grain size.

The significant wave height and period utilised in closure depth calculation are shown in Table 7.1. The figures, provided by the Western Australia Department of Planning and Infrastructure, are averaged monthly measurements from the Cottesloe wave buoy (Figure 7.5), for the period between 1994 and 2001.

The grain size of the sediments that comprise the shoreface in the Perth area varies between gravel and coarse to fine sand (Semeniuk and Searle, 1985; Sanderson, 1992). Predominantly sands were moderately well sorted, with some material being well sorted or moderately sorted (Sanderson and Eliot, 1999); therefore for this purpose an average grain size of 0.35 mm (medium-grained sand) was used.

Following these estimates of wave climate and sediment size, the depth of closure for the Perth area is:

$$d = (0.921 - 0.3 \times 0.44) \times 10.997 \times (9.8 / (5000 \times 0.00035))^{0.5} \\ d = 20.5\text{m} \quad \text{Equation 7.4}$$

Table 7.1: Wave data measured at Cottesloe wave buoy

1994–2001 wave data for Cottesloe buoy	Significant wave height (m)	Significant wave period (sec)
Mean	0.921	10.997
Standard deviation	0.44	3.881

Length of profile

Once the depth of closure was determined it became possible to define beach profiles used for the calculation of potential coastal erosion scenarios. Three profiles from the Swanbourne beach area northwest of Perth CBD are shown in Figure 7.12. The profiles were constructed by combining elevation data from detailed bathymetry and a DEM. Figure 7.12 displays the lengths of the three profiles, which are 8.09 km, 8.96 km and 9.07 km.

Calculated erosion according to the Bruun Rule

In this study, the Bruun Rule is applied to three profiles in the Swanbourne area, north of the Perth CBD (Figures 7.5 and 7.12). As discussed previously, the depth of closure for the area is 20.5 m. The sea level rise scenarios upon which potential erosion is modelled are those of the IPCC (2001; 50 years: 18 cm, 100 years: 48 cm). The input variables determined from the three profiles are shown in Table 7.2. The potential coastal erosion at Swanbourne Beach over the next 50 and 100 years, as calculated using the Bruun Rule, is shown in Table 7.3. Figure 7.11 shows the approximate position of the coastline following the 100-year sea level rise scenario in Table 7.3.

Table 7.2: Input variables determined from the three profiles at Swanbourne beach

Variable	South profile	Central profile	North profile
B – Dune height	12.85 m	19.71 m	15.38 m
L – Profile length	9070 m	8960 m	8085 m

Table 7.3: Calculated potential coastal erosion for the Swanbourne area of Perth using the Bruun Rule

Scenario	South profile	Central profile	North profile
50 year	48.95 m	40.10 m	40.56 m
100 year	130.53 m	106.94 m	108.15 m

Impact on infrastructure

The zones within the Fremantle to Hillarys sector that are potentially prone to coastal erosion contain approximately 1,600 buildings and 70 km of roads. Of those buildings, approximately 700 are located in the ‘red’ zone, in which coastal erosion due to long-term sea level rise over the next century is considered likely (Figure 7.1). The quantitative modelling in the Swanbourne Beach area allows for an estimation of the number of these buildings and the length of road that is likely to be impacted by this erosion.

The total number of buildings within the Swanbourne Beach to Floreat Beach ‘red’ zones is 18, and there is 11 km of roads. This is relatively low compared to the majority of the study area, because these zones primarily cover the Campbell Barracks and parkland. Of that infrastructure, 3 buildings and 110 m of road is located within 110 m of the coastline, which is the amount that the coastline is likely to recede over the next century (see above). These buildings are beach facilities, designed to be close to the beach, and the roads are primarily access roads for these facilities. Consequently, these figures cannot be used as proportion estimates for the other zones; that is, 17% of the buildings within this area are likely to be affected by coastal erosion due to long-term sea level rise, but this is not going to be the case for the other zones that contain hundreds of buildings.



Figure 7.11: Swanbourne Beach, southwestern Western Australia, showing the current position of the coastline and the potential coastline position given the recession calculated with the Bruun Rule

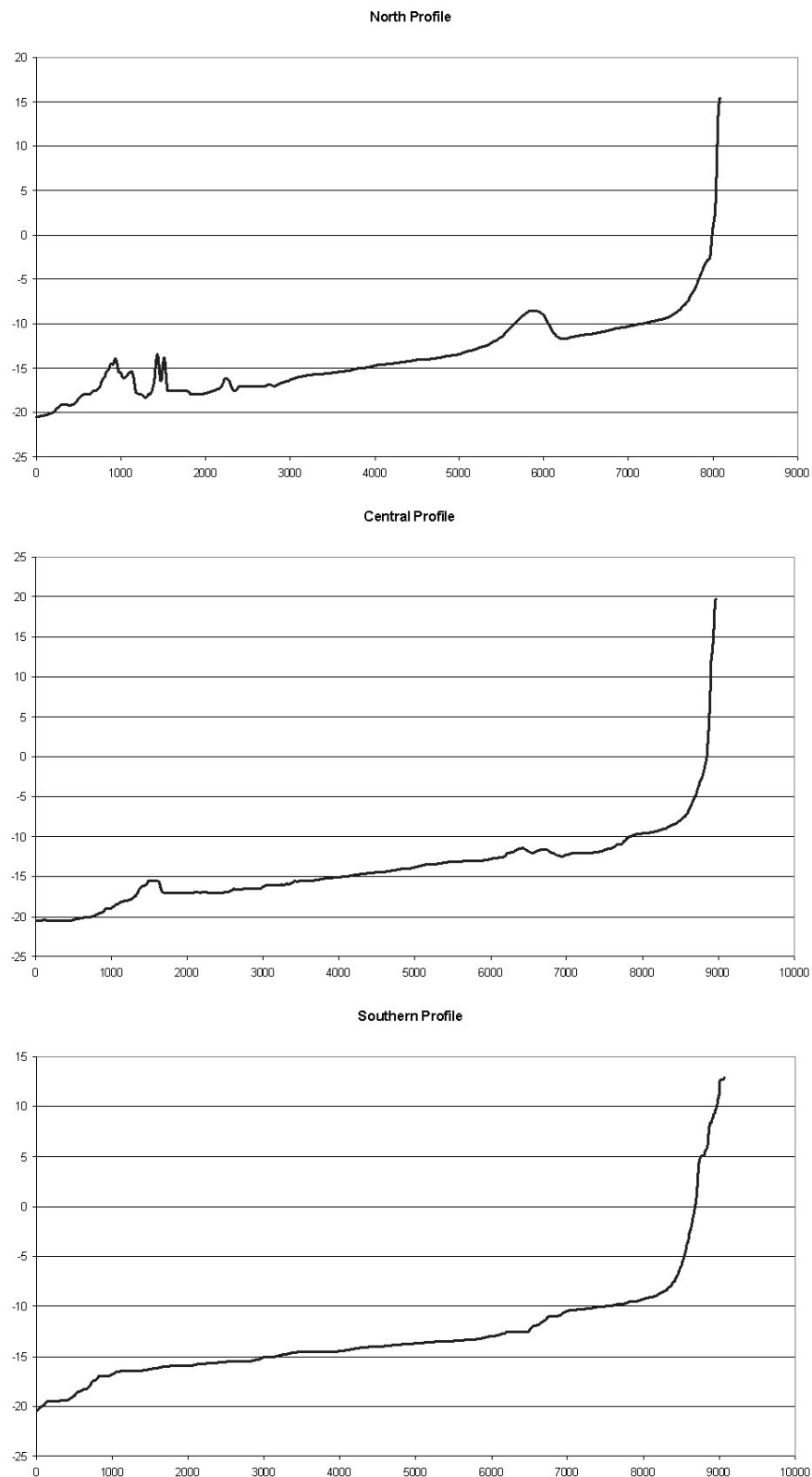


Figure 7.12: Beach profiles for Swanbourne beach, constructed by stitching together detailed bathymetry and a DEM. Vertical and horizontal axes in metres. Mean Sea Level and depth of closure are at approximately 0 m and 20.5 m, respectively

7.5 Mandurah to Fremantle

Geomorphology and sediment dynamics

This sector is characterised by a complex nearshore bathymetry and extensive but discrete cells of Holocene sediment accumulation. The nearshore/onshore geomorphology and bathymetry is dominated by a series of 330° trending Pleistocene ridges. These are termed, from west to east: the Five Fathom Bank Ridge, the Garden Island Ridge, and the Spearwood Ridge (Figure 7.13).

Holocene sediment accretion in this region has primarily been controlled by the interaction of the shelf wave climate and the complex ridge-and-depression bathymetry (Searle, 1984). Under the influence of the net northward littoral drift, there has been northward sediment transport along the exposed seaward face of the Garden Island Ridge (Figure 7.13). The Garden Island Ridge has therefore acted, and continues to function, as a perforate barrier, allowing a portion of the incident waves through gaps and passages into otherwise sheltered depressions. Waves passing through breaches in the ridge divert sediment from the transport pathway on the seaward side of the ridge, transporting it eastward into the adjacent depression to form lobate submarine banks (Searle *et al.*, 1988).

Discrete and significant bodies of Holocene sediment have developed across the submarine depression between the coastal mainland Spearwood Ridge and the offshore Garden Island Ridge, dividing it into a series of marine basins (including Cockburn Sound). This process has led to the shoreline progradation of the Rockingham/Becher cusped foreland (located 30 km south of Fremantle), and the deposition of the Success and Parmelia Banks (Figure 7.13; Kempin, 1953). In contrast, accretion in the depression between the Garden Island and Five Fathom Bank Ridges has been minimal (Searle and Semeniuk, 1985). It is interesting to note the depth of Madora Bay relative to Cockburn Sound in Figure 7.13. It is clear that Madora Bay is considerably shallower, which is likely to be a result of the net northward littoral drift depositing relatively more sediment in the more southerly basin.

Erosivity of the coastline

The environmental geology maps of this sector (Gozzard, 1983a; 1983b) show that the areas comprising Safety Bay Sand are the Rockingham/Becher Plain and Woodman Point (Figure 7.14; The Port/South Beach area was discussed in the Fremantle to Hillarys section). Erosion resistant limestone is preserved adjacent to the landward side of these sediment complexes, and comprises the remainder of the coast.

The upper surface of the limestone in the Rockingham/Becher Plain is reconstructed with microtremor data, as the coverage in this area is adequate (Figure 7.14). The coverage is not extensive enough to allow for a full reconstruction in a GIS environment, as with the Fremantle to Hillarys sector, but the results are sufficiently clear to allow for an assessment of erosivity without this step. There is a clear distinction between the estimates of top limestone on the Rockingham/Becher Plain, which are almost without exception below sea level, relative to the estimates directly to the east, in the vicinity of the Kwinana Town Centre, which are predominantly above sea level.

The SCPT that was undertaken in this area (Figure 7.14) also suggests the top of the limestone is well below sea level. The SCPT penetrated 33.05 m before terminating, and the height of the ground surface at this point is approximately 5 m, as estimated from a DEM. Therefore the top of the limestone is at or below approximately 28 m below sea level at this point. The estimate of top limestone at the nearest microtremor point (to the east) is -26.6 m AHD, which is further evidence of the robustness of reconstructing the upper limestone surface with microtremor measurements.

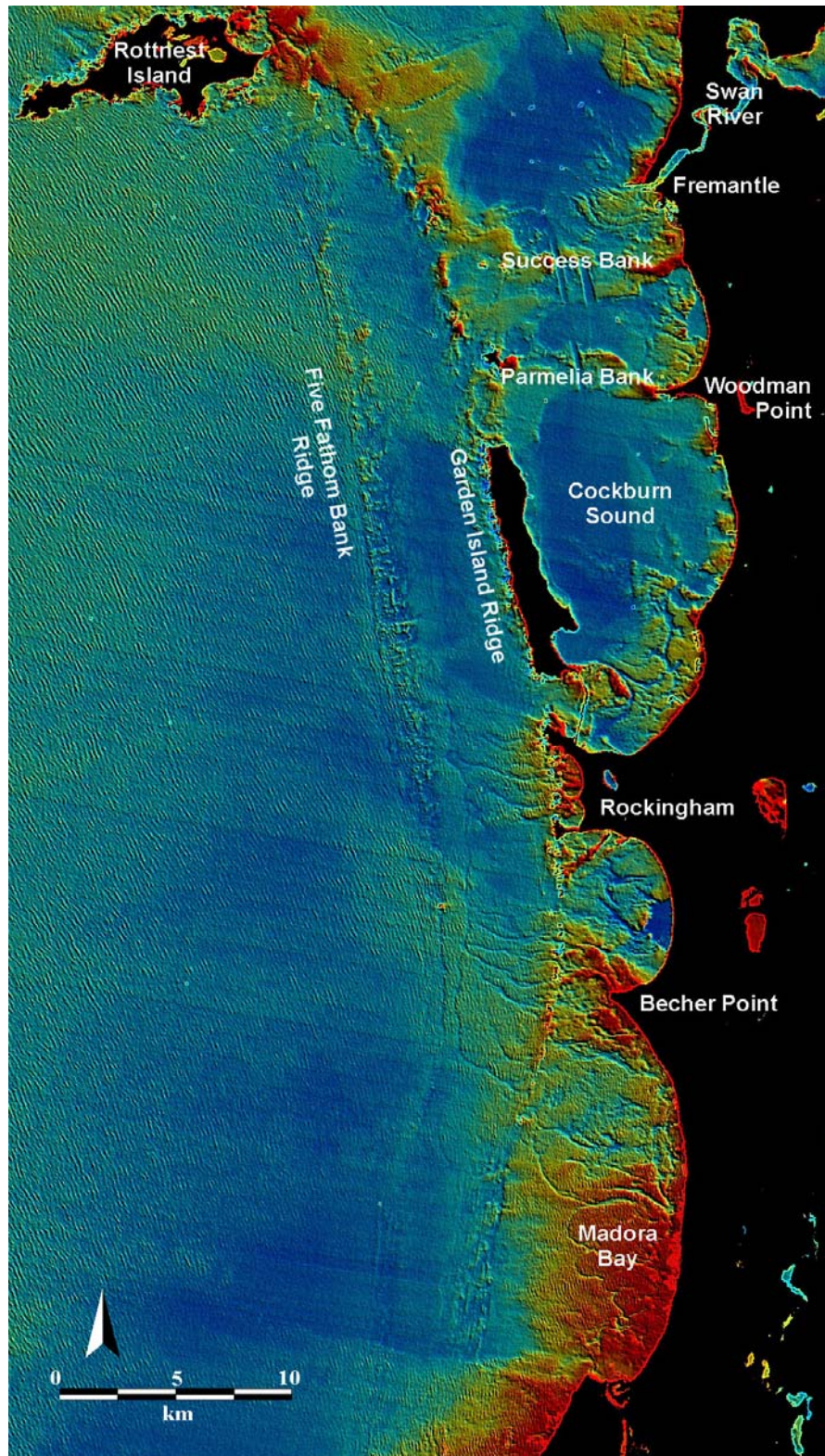


Figure 7.13: A Landsat image of the Mandurah to Fremantle sector, processed with the Geoscience Australia Shallow Water Image Mapping (SWIM) method to display bathymetry. The 'hot' and 'cool' colours indicate shallow and deep water respectively. Note the shallow (red) Madora Bay relative to the deep (blue) Cockburn Sound

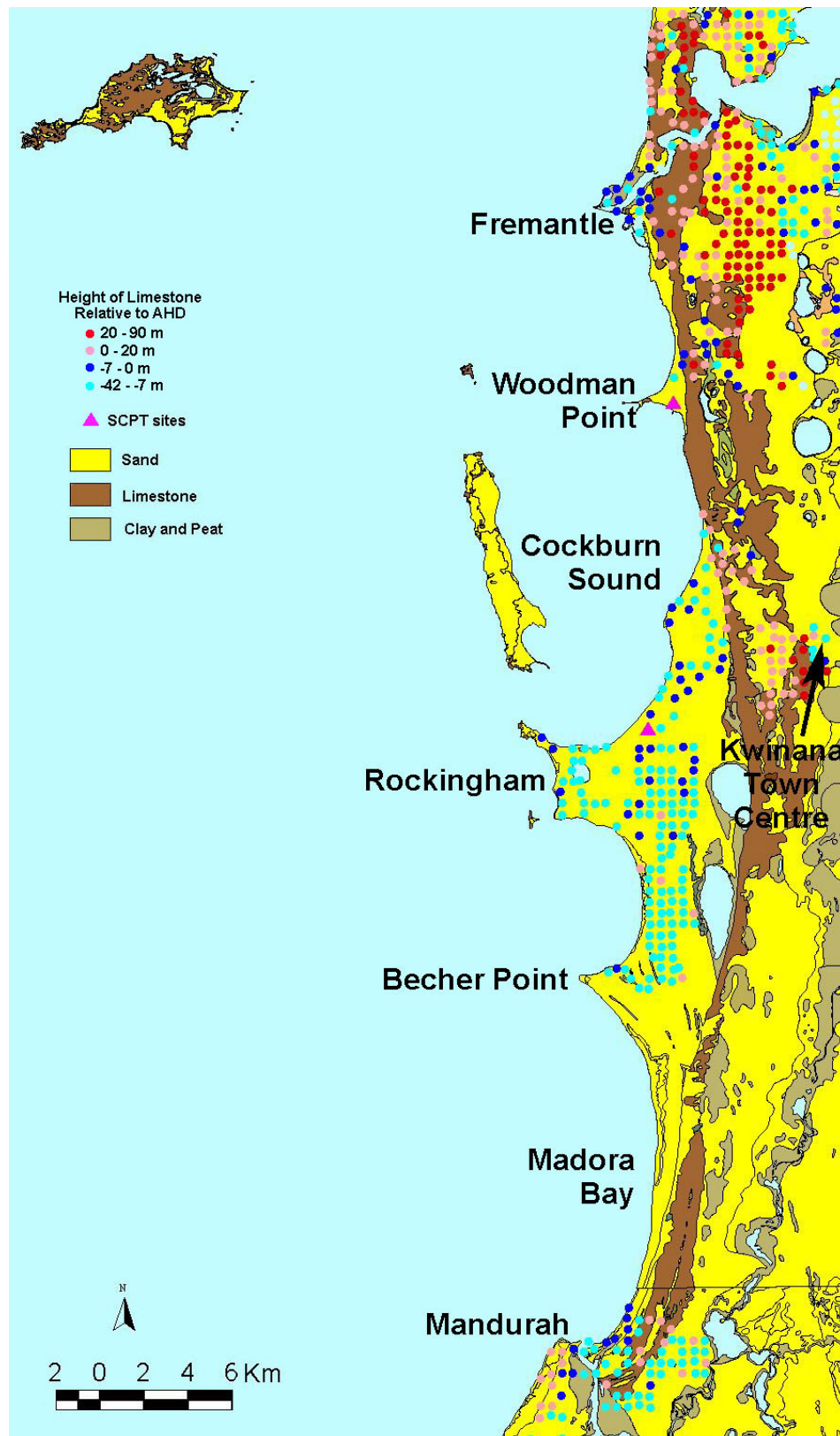


Figure 7.14: Height of top Tamala Limestone relative to Australian height datum, as estimated through microtremor tests, and spatial distribution of SCPTs in the Mandurah to Fremantle sector, overlain on the environmental geology of the area from Gozzard (1983a; 1983b)

There is a distinct lack of data with which the upper limestone can be reconstructed in the Woodman Point area. One SCPT was undertaken here (Figure 7.14), the results of which suggest the top of the limestone is below sea level. The SCPT penetrated 16.3 m before terminating, and height of the ground at this point is approximately 7.75 m, therefore the upper limestone surface is approximately 8.5 m below sea level.

Qualitative assessment of erosion hazard in susceptible areas

The Rockingham/Becher Plain comprises the majority of the Mandurah to Fremantle coast (Figure 7.13), and given the fact that the upper surface of the limestone under this plain appears to be below sea level it could be suggested that this area is susceptible to erosion over the next century. For the most part this is unlikely as this area has been the primary depositional province for the entire Swan Coastal Plain over the last 8,000 years (Figure 7.1). The most erosive province of the Swan coast is directly to the south (the Bunbury to Mandurah sector), therefore the net northward littoral drift will provide ample sediment to infill any accommodation space created by future sea level rise.

It is possible that there will be localised erosion of Becher Point in the foreseeable future (Figure 7.1). The fetch across Madora Bay is relatively significant, and will only be increased in the future due to the continued erosion of the Garden Island Ridge. A consequential increase in incident wave energy may result in minor erosion at Becher Point. This is supported by the palaeogeographic maps of Searle *et al.* (1988), which show some erosion occurring at the point in the present. However, any erosion should theoretically be replenished by sediment introduced by the net northward longshore drift, which has led to the rapid outbuilding of this part of the plain relative to the more northerly portion over the last 4,000 years (Searle *et al.*, 1988).

The upper surface of the limestone is also below sea level at Woodman Point but, as with the Rockingham/Becher Plain, the area is not likely to be susceptible to erosion over the next century. The area is sheltered by Garden Island and the Rockingham/Becher Plain, and therefore not exposed to significant incident wave energy. As with Becher Point, there is potential for localised erosion due to the fetch across Cockburn Sound, which is relatively deeper than Madora Bay and as such would allow for the development of larger waves (Figure 7.13). However, the Parmelia Bank/Woodman Point complex appears to be the primary loci of deposition after the Rockingham/Becher Plain and as such replenishment through longshore drift should be rapid.

Calculating erosion

Despite having detailed bathymetry in this sector, and the potential to use Cottesloe wave data, it is impossible to undertake a Bruun Rule analysis of this part of the coast for two reasons.

- The nearshore in this part of the sector is complicated by the presence of limestone ridges and reefs (Figure 7.13). The nearshore sediment–water interface cannot be remoulded by wave energy, and as such is unlikely to rise by an amount equal to the rise in sea level. Consequently, the third assumption outlined above is invalidated and the Bruun Rule cannot be used.
- A significant amount of sediment is introduced into this sector as a result of the net northward longshore drift. Therefore any accommodation space created by a rise in sea level may be infilled with sand from somewhere other than the upper beach. As such the volume eroded from the beach at any given profile is unlikely equal to the volume deposited, and the second assumption outlined above is invalidated.

Calculating the amount of potential erosion in this sector due to global warming related sea level rise over the next century should not be a priority, as erosion is not likely to be significant and there are no coastal behaviour models that can accommodate the complications outlined in the two points above.

Impact on infrastructure

The zones within this sector that are potentially prone to coastal erosion contain approximately 28,000 buildings and 641 km of roads. This is the largest amount of infrastructure in any of the sectors when

all zone types are considered. This is primarily due to the very large geographical extent of the Rockingham/Becher Plain, which is comprised of unconsolidated sand but hosts an extensive built environment. Of these buildings it is unlikely that any will be directly impacted by coastal erosion over the next century, due to this being a predominantly depositional environment and also because none is located within close proximity of the shoreline.

7.6 Bunbury to Mandurah

Geomorphology and sediment dynamics

Unlike the previously described sectors, the Bunbury to Mandurah sector is characterised by a simple offshore bathymetry, and a barrier dune system with associated lagoon onshore (Figure 7.15). This sector is also unique amongst those outlined in this report as it is oriented approximately north–south, but there are no well-developed offshore limestone ridges. Thus the west-facing shores are fully exposed to the wind, wave, and current regime of the Rottne Shelf.

Seaward of the shore, the sand-mantled shoreface slopes seaward to merge with the inner shelf plain about 1–2 km offshore in water depths of 12–15 m. Low-lying limestone pavement surfaces and discontinuous limestone ridges (1–2 m high) and beachrock slabs are exposed on the inner shelf, but they are not sufficiently prominent or continuous to influence sedimentation in this sector (Searle and Semeniuk, 1985).

The onshore area in this sector is dominated by a series of Tamala Limestone and Safety Bay Sand dune ridges trending approximately north–south, which form a topographic barrier between the main low-lying Swan Coastal Plain and the continental shelf. In depressions between the dune ridges there are elongate, shallow (usually less than 2 m deep) water bodies.

Harvey estuary, Peel Inlet and Lake Clifton occur in depressions between ridges of Tamala Limestone (Figure 7.15). Lake Preston and Leschenault Inlet occur between a dune ridge of Safety Bay Sand and the adjacent Tamala Limestone ridge (Figure 7.15; Searle and Semeniuk, 1985).

The sea level history for this sector (and the southernmost part of the Mandurah to Fremantle sector) is at variance with studies of accretionary sequences elsewhere along the Swan coast (Figure 7.16). Along the majority of the coast the sea level rose to a level approximately 2–2.5 m above the present level at the termination of the most recent glaciation, following which it gradually fell to the current level over the last 7,000 years. In contrast, sea level in this sector stayed approximately 2 m below the present level between 7,000 and 6,000 years ago, following which it rose dramatically by approximately 5 m. It stayed more than 3 m above the present sea level for over 1,000 years before dramatically dropping to the current level, at which it has stayed for the last 2,500 years (Semeniuk, 1985; Semeniuk and Semeniuk, 1991). This is likely to be a function of local tectonic forces (Semeniuk and Searle, 1986).

The combination of relatively simple geomorphology and relatively complex sea level curve for this sector has led to an interesting sediment budget history. The first stage involved deposition of lagoonal/estuarine sediment behind a coastal barrier approximately 2–3 km further offshore than present, when the sea level rose subsequent to the termination of the last glaciation. With still-stand conditions 2–3 m below present sea level, the dunes of Safety Bay Sand encroached eastward until their eastern edge reached approximately the position the eastern margin of the peninsula occupies today. The sea level rise over the following 500 years resulted in dramatic erosion of the seaward face of the barrier. The next phase of deposition took place with a still-stand approximately 3–4 m above the present level, when the coast prograded through deposition of beach and dune sediments on the western face of the barrier. The barrier system is currently migrating eastward, in association with the present marine incursion. Erosion and net northward sediment mobilisation are the major processes along the seaward edge of the barrier dune system today (Semeniuk, 1983; Semeniuk, 1985).

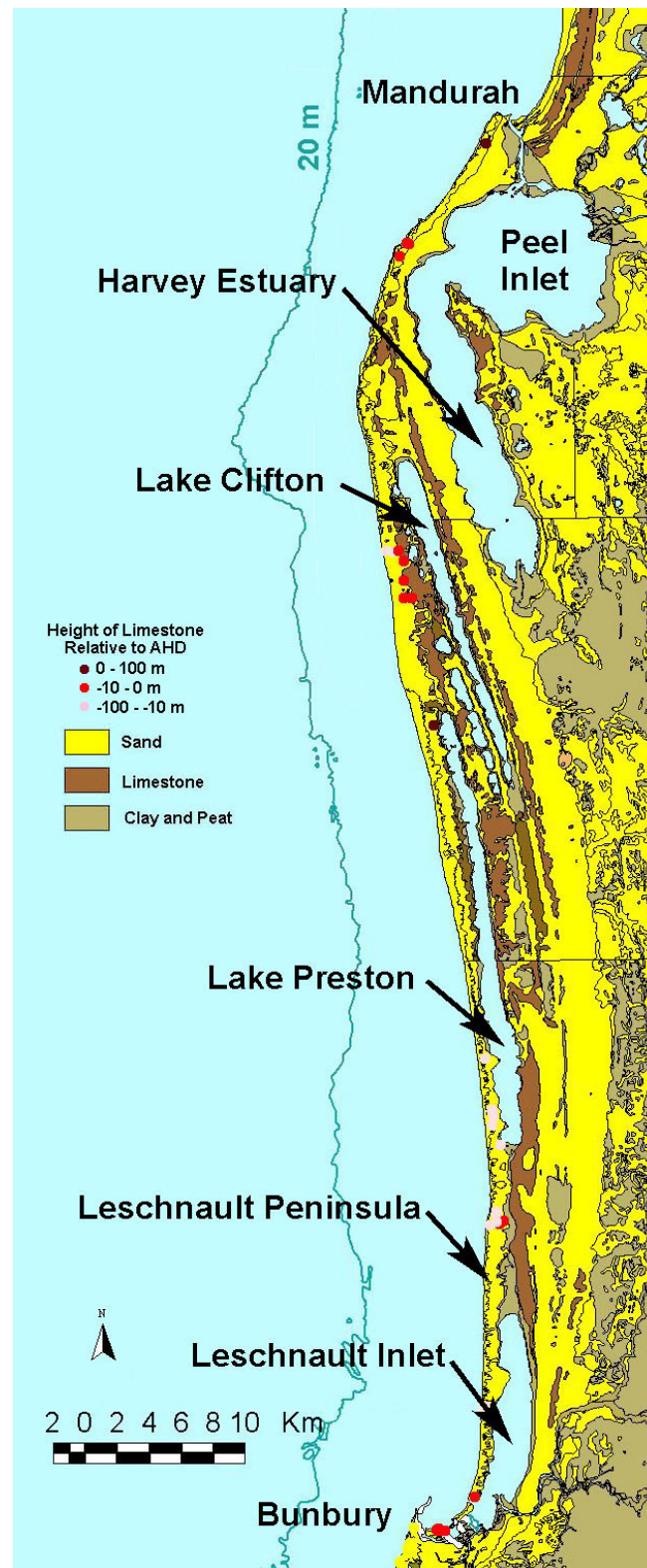


Figure 7.15: Height of top Tamala Limestone relative to Australian height datum, as measured in geotechnical boreholes in the Bunbury to Mandurah sector, overlain on the environmental geology of the area from Gozzard (1987)

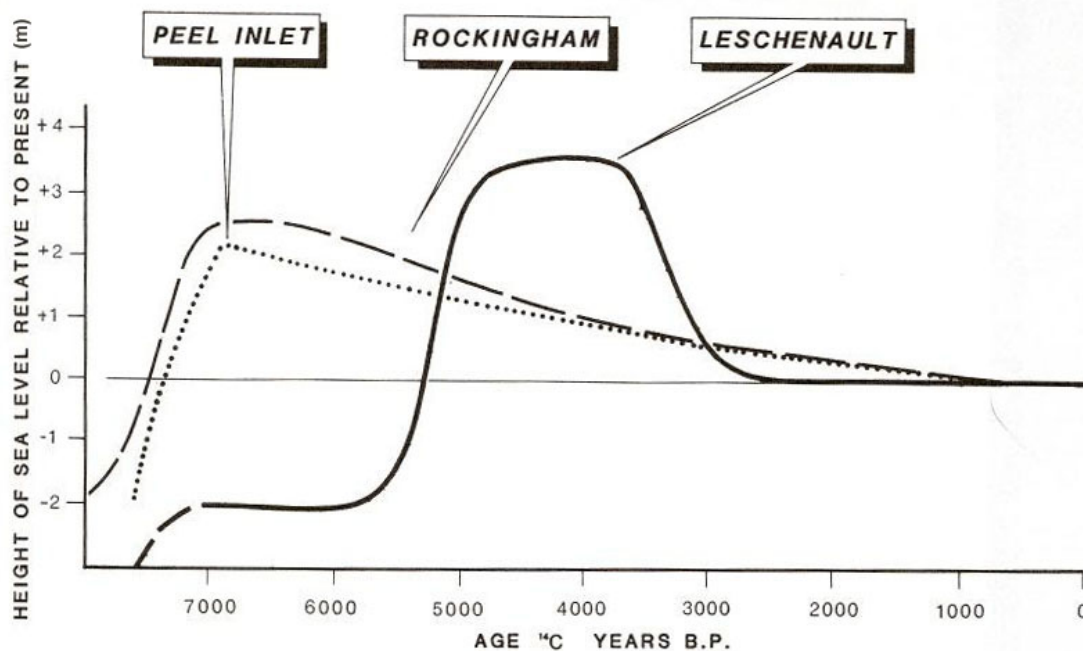


Figure 7.16: Sea level history curve for the Peel–Harvey estuary, the Rockingham–Becher area, and the Leschenault Peninsula (Semeniuk and Semeniuk, 1991)

Erosivity of the coastline

The environmental geology maps of this sector (Gozzard, 1987) show that Safety Bay Sand comprises a continuous strip adjacent to the coastline. Erosion-resistant limestone is predominantly preserved adjacent to the landward side of this unit, and only forms part of the coastline in the very northernmost part of the sector.

There is no SCPT data along this section of the Swan Coastal Plain, and microtremor data is confined to the region of the coast formed by, and on the landward side of, Tamala Limestone (Figure 7.17). The microtremor survey in this area shows the limestone is above sea level adjacent to the coast, but given this can be seen on the environmental geology map for the region, this data does not increase our understanding of erosion susceptibility for the area. Therefore geotechnical borehole descriptions from the DOE dataset were utilised in delineating the upper surface of the limestone throughout the majority of the sector. Of the boreholes drilled in the coastal units of this sector, 46 were found to give useful descriptions of lithology. The heights of lithological horizons relative to sea level were estimated by relating the drilled depth to DEM height at that point.

In the northern half of the sector the top limestone surface was encountered above sea level in only two of 13 holes (Figure 7.17). The northern of the two holes was drilled into an area of limestone, thus the upper surface is obviously above sea level. The height of the limestone in the southern of the two holes, according to the relationship between the DEM and drilling log, is approximately 30 cm above sea level. The average height of the upper limestone surface for all 13 holes in the northern part of the sector is approximately 4.8 m below sea level.

In the southern half of the sector the top limestone surface was not encountered above sea level in any of the holes (Figure 7.18). In 20 of the holes, the limestone is preserved more than 10 m below sea level. The average height of the upper limestone surface for all 33 holes in the southern part of the sector is approximately 13.3 m below sea level.

Qualitative assessment of erosion hazard in susceptible areas

Of the five sectors outlined in this report, the Bunbury to Mandurah sector is the most susceptible to coastal erosion over the next century (Figure 7.1). Almost the entire sector, with the exception of the northernmost component in which the shoreline is formed of Tamala Limestone, is likely to experience a degree of erosion before 2100. This erosion is primarily a function of this sector being towards the southern end of the net northward littoral transport path, the greater exposure to the incident wave and wind regime relative to the other sectors, and the preservation of limestone below sea level.

It is the northward longshore sediment transport induced by the sea breeze that accounts for the net littoral drift that occurs along this part of the coast (Masselink and Pattiaratchi, 1998). The Cape Naturaliste to Bunbury sector is a north-facing embayment. This orientation, perpendicular to the southerly sea breeze, means that a northward current cannot be established any further south than Bunbury. Therefore, very little sediment is introduced into this sector from the south. This sector is the southern part of the south to north littoral conveyor that operates along Swan coast, therefore it is a source area from which sediment that accumulates in other sectors is derived.

Previous research has suggested that the erosion currently occurring along this part of the coast is related to a marine incursion (Semeniuk, 1985). An accelerated sea level rise over the next century in association with global warming may increase the rate at which the coast is eroding. The environmental geology maps and boreholes drilled in this sector show that the upper surface of the Tamala Limestone is only above sea level on the eastern side of the northern Leschnault Peninsula (Figures 7.16–7.18). Safety Bay Sand comprises the majority of the peninsula; therefore the majority of the peninsula has the potential to be eroded. The outcome of continued erosion of the barrier system may be either that:

- the barrier is completely eroded, transforming Leschnault Inlet into an open embayment and Lake Preston into a semi-enclosed inlet; or,
- the barrier steps back through overwashing, infilling Leschnault Inlet and Lake Preston.

Calculating erosion

Calculating the erosion rate for this sector over the next century due to long-term sea level rise would be a valuable exercise but it is dependent on assembling a considerable amount of data that is not readily available. Correspondingly, the data to be collected are dependent on the model utilised.

If a Bruun-type model were to be used in calculating potential erosion then there are a number of considerations that must be taken into account. Firstly, and perhaps most importantly, wave data for this sector would have to be collected. The DPI currently manages four wave buoys that measure wave heights and periods. These are located offshore from Cape Naturaliste, Rottnest Island, Cottesloe, and Jurien (Figure 7.19). Cape Naturaliste is the closest of the buoys, and as such it might be expected that wave measurements from this station could be used. Unfortunately this buoy measures the offshore incident wave heights and periods. The energy in these incident waves will be attenuated as they cross the continental shelf, especially in this sector, as the shelf is over 50 km wide (Figure 7.1). Therefore this wave data could not be used in a Bruun Rule analysis in this sector, as it would give anomalously high estimates of closure depth, which would consequently produce overestimates of recession. A second consideration is the need for detailed bathymetry data from which profiles could be constructed. It is possible that this data exists but it was not available to the author at the time of analysis.

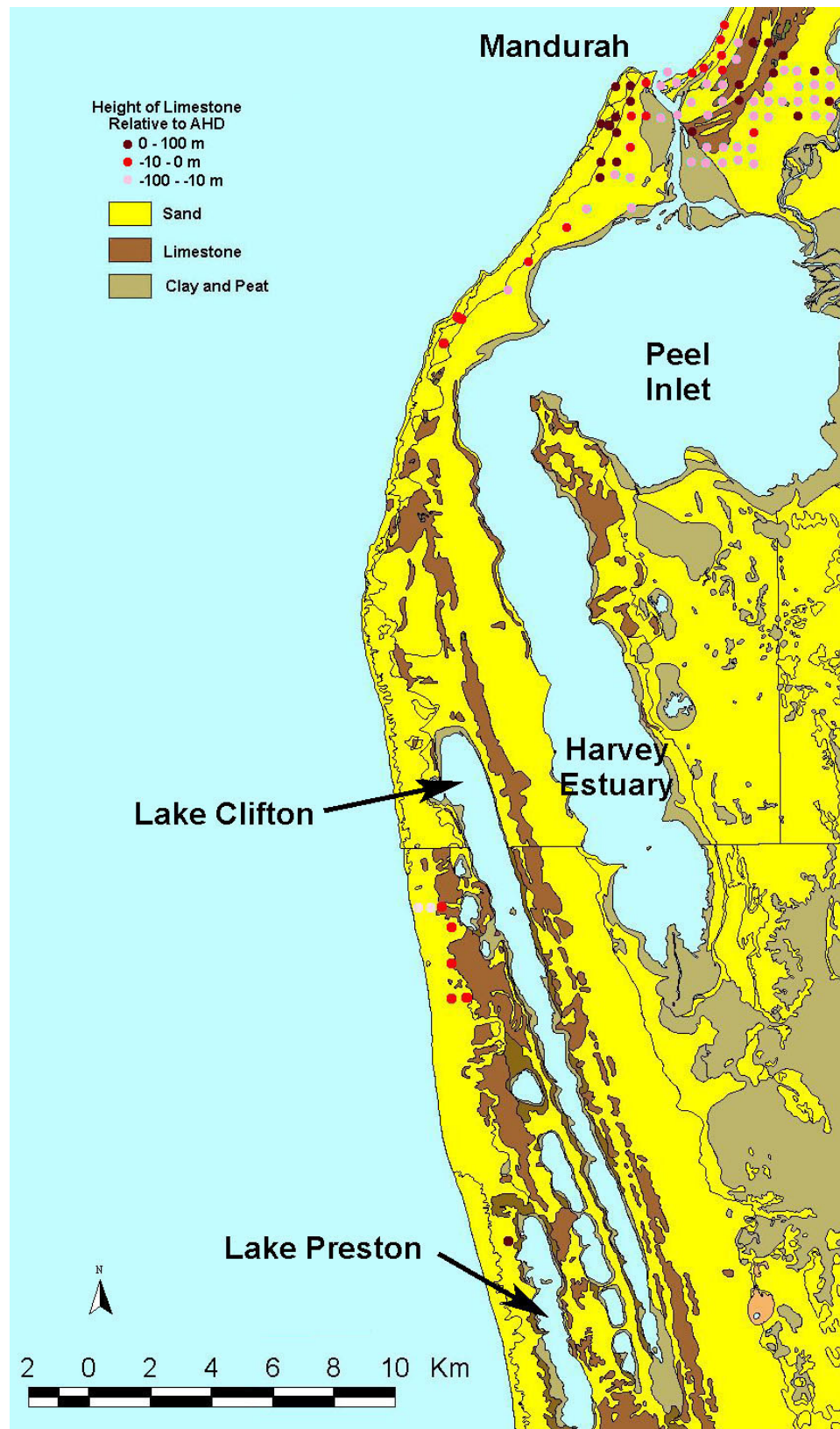


Figure 7.17: Height of top Tamala Limestone relative to Australian height datum, as measured in geotechnical boreholes and estimated through microtremor tests in the northern Bunbury to Mandurah sector, overlain on the environmental geology of the area from Gozzard (1987). Note the limestone is above sea level to the immediate south of Mandurah, and in a borehole near the northern end of Lake Preston

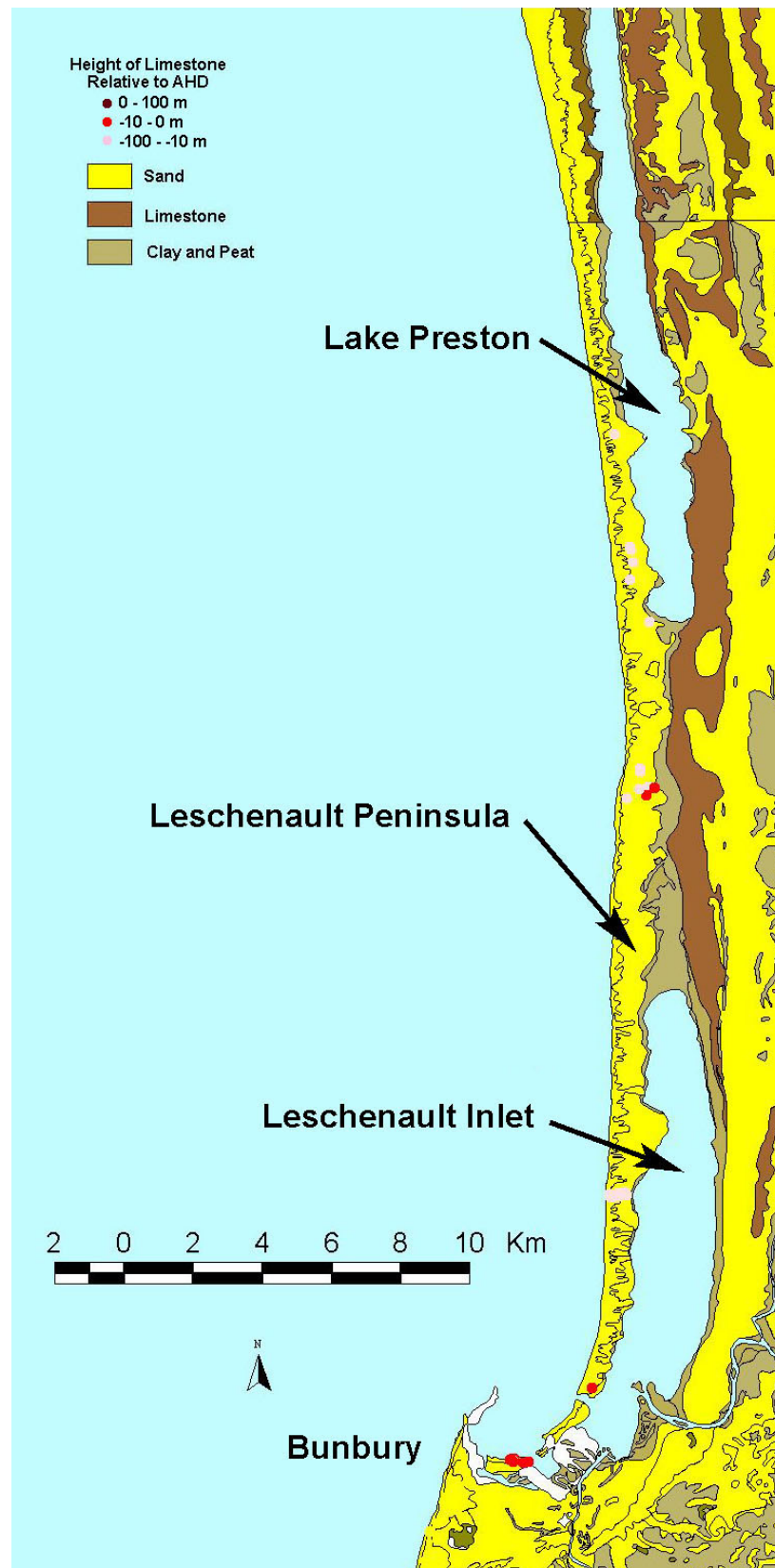


Figure 7.18: Height of top Tamala Limestone relative to Australian height datum, as measured in geotechnical boreholes in the southern Bunbury to Mandurah sector, overlain on the environmental geology of the area from Gozzard (1987). Note that the limestone is below sea level in all of the holes

Another consideration that would have to be taken into account in any Bruun-type analysis would be the volume of sediment that is transported out of the system by the net northward longshore drift. An inherent assumption of the Bruun Rule is that the material eroded from the upper beach is transported immediately into the offshore and deposited, such that the volume eroded is equal to the volume deposited (see above). This is clearly not the case for the Bunbury to Mandurah sector, as a considerable volume of sediment is taken out of the system and deposited further north, particularly in the Mandurah to Fremantle sector. This net volume loss would have to be taken into account, possibly through utilising the sediment budget equation of SCOR (1991). It should be noted that before applying this equation, which is simply an adaptation of the Bruun Rule, it is necessary to know the volume of sediment that is leaving or entering the system. This could be undertaken by following the example of Masselink and Pattariatchi (2001) in their study of sediment movements along Perth metropolitan beaches.

An alternative to using the Bruun Rule would be to apply the coastal behaviour model of Stive and de Vriend (1995). The complicating factor with this model is that it requires long-term measurements of shoreface morphology.

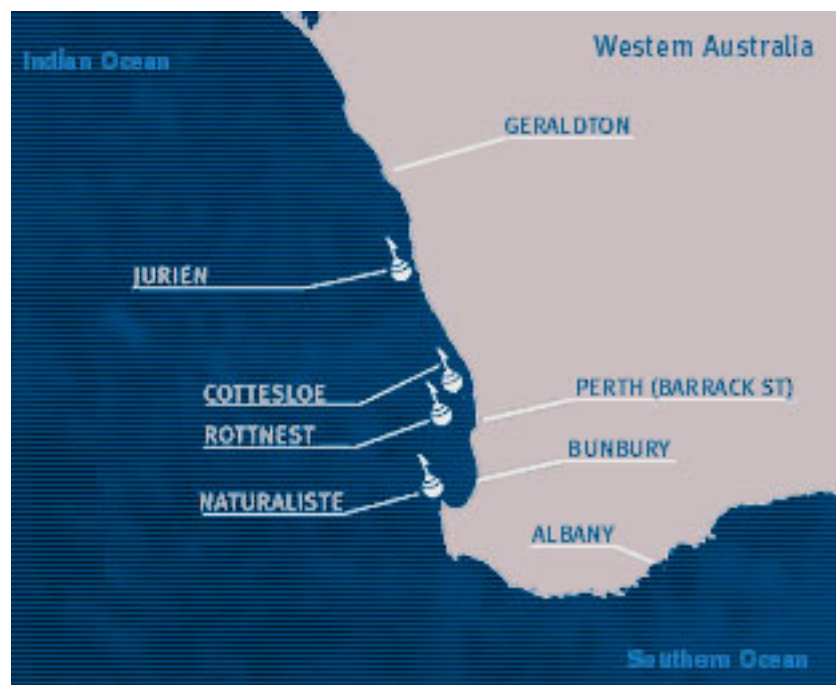


Figure 7.19: Location of wave buoys managed by the Western Australian Department for Planning and Infrastructure (http://www.coastaldata.transport.wa.gov.au/tides/real_time.html)

Impact on infrastructure

The zones within this sector that are potentially prone to coastal erosion contain approximately 400 buildings and 268 km of roads. This is relatively low, as much of the region has not been settled. Coastal erosion is likely to be high in this sector over the next century, therefore detailed quantitative modelling should be undertaken to determine the potential extent, which will allow for comment on the number of buildings and roads likely to be affected.

7.7 Hillarys to Yanchep

Geomorphology and sediment dynamics

The coast in this sector is characterised by a variety of features. The nearshore bathymetry has four well-defined largely submarine, 330° trending shore parallel Pleistocene limestone ridges (Figure

7.20). An unnamed ridge forms the architecture of the shore, and the other three ridges, termed Spearwood Ridge, Marmion Reef Ridge, and Staggie Reef Ridge, are located c. 2, 4 and 6 km from the shore respectively. In several locations subridges extend obliquely (trending 0–010°) across the main ridges. The subridges form discontinuous chains of submarine rock pinnacles and reefs commonly less prominent than the main ridges. The unnamed main ridge forms diffuse rocky coasts and pocket beaches interspersed with straight beached coasts backed by dune systems (Searle and Semeniuk, 1985).

Since the Pleistocene limestone ridge-and-depression topography first began to be inundated by rising post-glacial sea levels, it has been subjected to extensive but selective erosional modification. This has resulted in non-uniform retreat of the shoreline. As in the Mandurah to Fremantle sector, accretion has occurred in loci of wave-energy convergence in the comparatively sheltered inter-ridge depression between the shoreline ridge and the adjacent offshore ridge. The accretionary sites, however, are not prominent and have prograded only relatively small distances seaward. Sediment in these loci has again been derived from local benthic assemblages (principally the seagrass assemblage) and from the erosion of the Pleistocene ridges (Searle and Semeniuk, 1985).

Erosivity of the coastline

The environmental geology maps of this sector (Gozzard, 1982) show that Safety Bay Sand comprises the majority of the coastline (Figure 7.21). Erosion-resistant limestone is predominantly preserved adjacent to the landward side of this unit, and comprises very little of the coastline.

There is no microtremor or SCPT data along this section of the Swan Coastal Plain, therefore geotechnical borehole descriptions from the DOE dataset were utilised in delineating the upper surface of the limestone. Of the boreholes drilled in the coastal units of this sector, 34 were found to give useful descriptions of lithology. The heights of lithological horizons relative to sea level were estimated by relating the drilled depth to DEM height at that point. The top limestone surface was encountered below sea level in only two of the 34 holes. Limestone was encountered less than 2 m below sea level in these two holes. The average height of the upper limestone surface for all 34 holes is approximately 23.5 m above sea level.

Qualitative assessment of erosion hazard in susceptible areas

With the exception of the discrete region in the Alkimos area, marked by the two holes in which limestone appears to be below sea level, there does not appear to be any potential for erosion in the Hillarys to Yanchep sector (Figure 7.1). It is not considered worthwhile assessing the potential for erosion at this locality for two reasons:

- Heights of -1.8 m and -1.1 m for the top limestone in the two holes is well within the range of the uncertainty in the DEM, therefore it is possible the limestone actually exists above sea level at these localities.
- There is no infrastructure within 4 km of the coast at this locality.

Calculating erosion

Despite having detailed bathymetry in this sector, and the potential to use Cottesloe wave data, it is impossible to undertake a Bruun Rule analysis of this part of the coast for two reasons.

- The nearshore in this part of the sector is complicated by the presence of limestone ridges and reefs (Figure 7.20). The nearshore sediment-water interface cannot be remoulded by wave energy, and as such is unlikely to rise by an amount equal to the rise in sea level. Consequently, the third assumption of the Bruun Rule is invalidated and it cannot be used.
- The upper surface of the limestone is above sea level for the most part. Thus the upper beach cannot be eroded due to the landward translation of the profile and the first Bruun Rule assumption is invalidated.

Calculating the amount of potential erosion in this sector due to global warming related sea level rise over the next century should not be a priority, as the coastline does not appear to be susceptible to erosion, there is no infrastructure along this part of the coast, and there are no coastal behaviour models that can accommodate the complications outlined in the two points above.

Impact on infrastructure

As previously stated, there is no infrastructure at risk from coastal erosion due to long-term sea level rise in this sector.

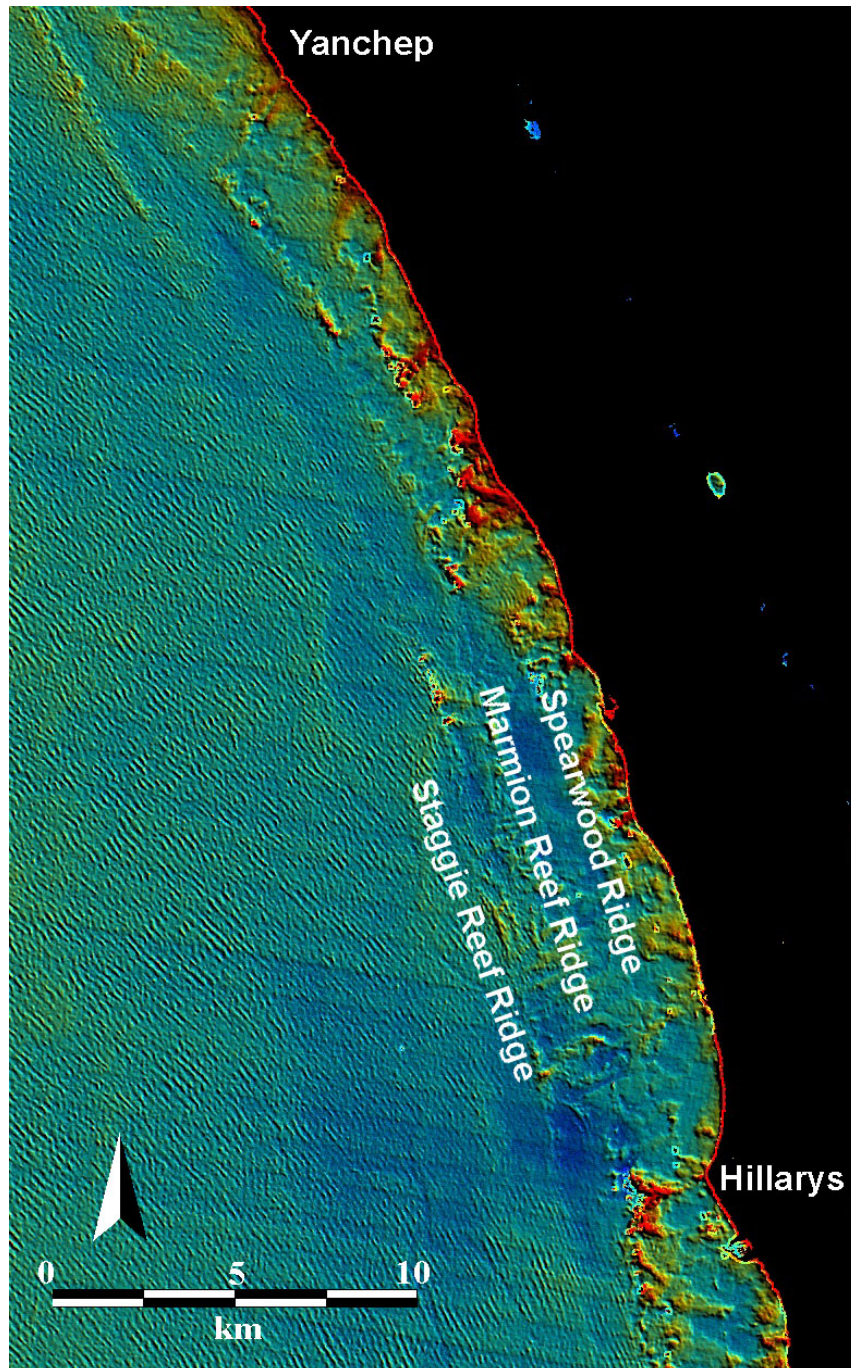


Figure 7.20: A Landsat image of the Hillarys to Yanchep sector, processed with the GA Shallow Water Image Mapping (SWIM) method to display bathymetry. The ‘hot’ and ‘cool’ colours indicate shallow and deep water respectively

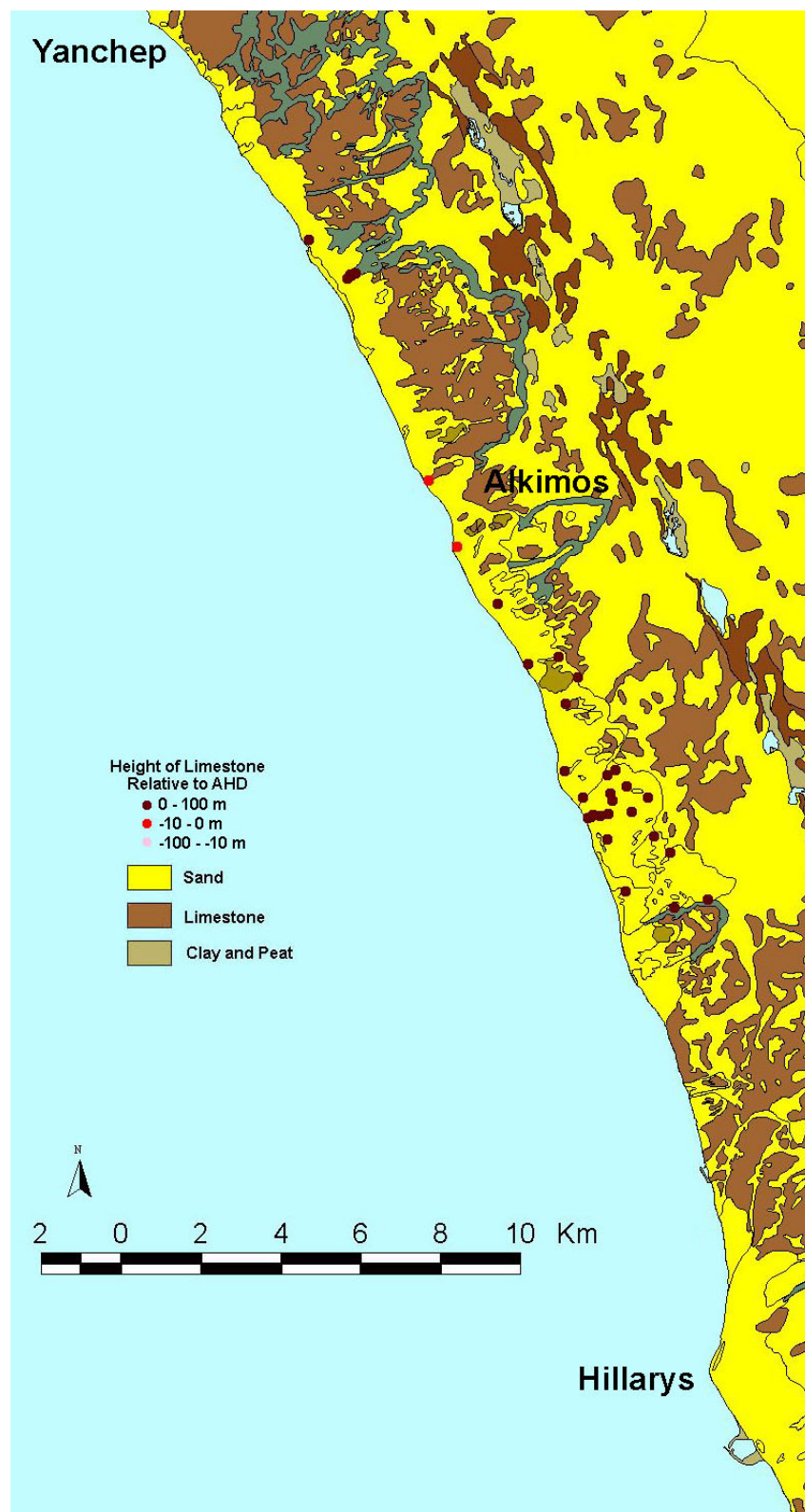


Figure 7.21: Height of top Tamala Limestone relative to Australian height datum, as measured in geotechnical boreholes in the Hillarys to Yanchep sector, overlain on the environmental geology of the area from Gozzard (1982). Note that the limestone is preserved below sea level in only two boreholes, in the Alkimos area

7.8 Cape Naturaliste to Bunbury

Geomorphology and sediment dynamics

Geographe Bay, which comprises the Cape Naturaliste to Bunbury sector, is a broad, 100 km wide, north-facing embayment at the southern end of the Rottne Shelf. This sector is characterised by a simple offshore bathymetry, a lowland onshore, and Holocene sedimentation confined to an onshore beachridge/strandplain to nearshore sand sheet deposits (Figure 7.22). The coastal hinterland and seafloor of this sector slope gently northward to depths of 12–15 m where the embayment floor opens out onto the inner Rottne Shelf. A narrow band (average 500 m wide) of Holocene beachridges that young towards the present shore is developed behind the contemporary coastline. Offshore the gently sloping shore of the bay is a sand sheet, vegetated by dense sea grass meadows (Searle and Semeniuk, 1985).

In the long-term (past 5,000 years) sediment accretion in this sector has resulted in this sector has resulted in an average progradation of approximately 500 m. The accumulated sediment is derived from the erosion of Pleistocene coastal deposits and *in situ* accumulation of carbonates from benthic communities, both the seagrass community and organisms inhabiting adjacent bare sand (Searle and Semeniuk, 1985). Under prevailing conditions, refracted westerly swell and longer period wind waves impinge on the entire shoreline of this sector. Sediment tends to be transported shoreward from scours and bars. The refracted westerly waves induce a slight littoral movement eastward, which is reversed by winter storms (Searle and Semeniuk, 1985).

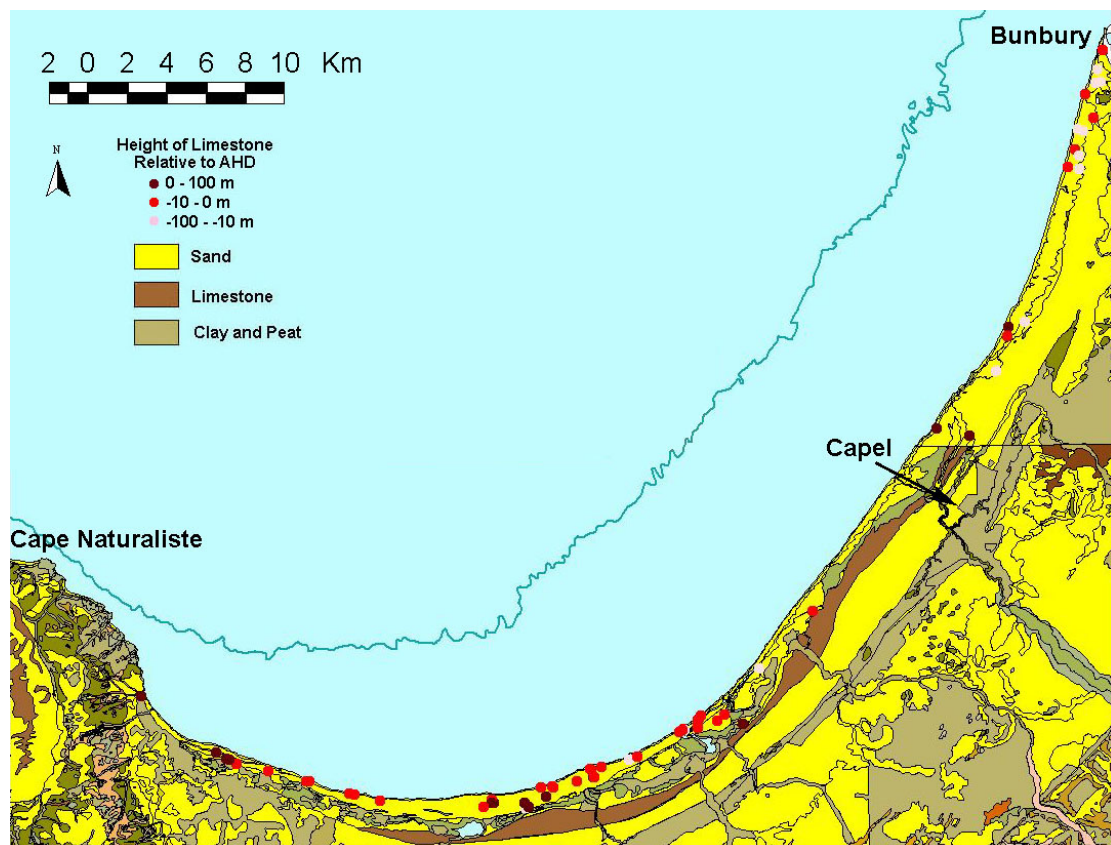


Figure 7.22: Height of top Tamala Limestone relative to Australian height datum, as measured in geotechnical boreholes in the Cape Naturaliste to Bunbury sector, overlain on the environmental geology of the area

Erosivity of the coastline

The Safety Bay Sand comprises the entirety of the coastline in this sector (Figure 7.22; Searle and Semeniuk, 1985). This sand is flanked on the landward side by either Tamala Limestone or muds of the Guilford Formation.

There is no microtremor or SCPT data along this section of the Swan Coastal Plain, therefore geotechnical borehole descriptions from the DOE dataset were utilised in delineating the upper surface of the limestone. Of the boreholes drilled in the coastal units of this sector, 69 were found to give useful descriptions of lithology (Figure 7.22). The heights of lithological horizons relative to sea level were estimated by relating the drilled depth to DEM height at that point.

The top limestone surface was encountered above sea level in approximately 20% of the holes. This suggests that the majority of the coastline in this sector is likely to be susceptible to erosion over the next century due to long-term sea level rise. The average height of the upper limestone surface for all 69 holes is approximately 5.5 m below sea level.

Qualitative assessment of erosion hazard in susceptible areas

The coastline appears to be susceptible to erosion along almost the entire length of this sector (Figure 7.1). A lack of differentiation between those areas that are prone to erosion and those areas that are not makes qualitative assessment unnecessary for the most part. Two holes in the vicinity of the township of Capel record the top limestone as above sea level, therefore it may be suggested that this section of coast is somewhat less susceptible to erosion (Figure 7.22). However, the heights recorded by these holes are 1.4 m and 12 cm above sea level, which is not significant enough to differentiate this stretch of coast as disparate from the remainder of the sector.

Calculating erosion

The coastline of the Cape Naturaliste to Bunbury sector appears to satisfy the three primary conditions upon which the Bruun Rule is dependent:

- Any erosion resistant lithologies in the onshore are below sea level so the upper beach can be eroded due to the landward translation of the profile.
- There is no significant littoral drift in this sector so the material eroded from the upper beach is likely to be equally to the amount deposited in the offshore.
- There are no reefs in the nearshore so the sediment–water interface can be remoulded by wave processes, maintaining a constant water depth in the offshore.

Along with the Swanbourne Beach area, the beaches in this sector comprise the best opportunity to estimate erosion rates using the simple but effective Bruun Rule. Unfortunately, the lack of wave data for the sector prevents this analysis being undertaken. As with the Bunbury to Mandurah sector, Cape Naturaliste is the closest of the wave buoys (Figure 7.19). This buoy measures the offshore incident wave heights and periods. The energy in these incident waves is attenuated as they are refracted around Cape Naturaliste and they cross the continental shelf. Therefore this wave data could not be used in a Bruun Rule analysis in this sector, as it would give anomalously high estimates of closure depth, which would consequently produce overestimates of recession. A second consideration is the need for detailed bathymetry data from which profiles could be constructed. It is possible that this data exists but it was not available to the author at the time of analysis.

Impact on infrastructure

The zones within this sector that are potentially prone to coastal erosion contain approximately 2,900 buildings and 213 km of roads. Of those buildings, approximately 2,000 are located in the ‘red’ zone, in which coastal erosion due to long-term sea level rise over the next century is considered likely (Figure 7.1). As a consequence of this relatively significant volume of infrastructure, this sector should be the primary focus in detailed quantitative coastal erosion modelling in southern Western Australia.

At the very least, Bruun Rule estimates should be undertaken to determine the potential extent of erosion, which will allow for comment on the number of buildings and roads that may be affected.

7.9 Impact of Coastal Erosion Due to Long-term Sea Level Rise

Although the adoption of statutory planning schemes in a number of states over the last 5–10 years indicates a change in the local planning environment to one in which sea level rise is taken into account, the current process for assessing potential erosion is still inconsistent between the states. The coastal management strategies of Queensland, New South Wales and South Australia require a Bruun Rule calculation to be incorporated into coastal planning, whereas Tasmania has no planning requirements. Victoria is in the process of undertaking more focussed regional studies (Walsh *et al.*, 2004). The Western Australian Coastal Statement of Planning Policy (Coastal SPP) includes a schedule on the calculation of setbacks, which takes into account sea level rise. The sea level rise component has been derived from IPCC (2001) and is taken to be 38 cm, translating into a setback of 38 m by the Bruun Rule (Walsh *et al.* 2004).

The figures presented in the Bruun Rule analysis in the Fremantle to Hillarys section (approximately 1 m per year over the next 100 years) indicate that the use of 38 m as a guide for planning setbacks due to sea level rise may be a gross underestimation for the Swanbourne Beach area. Assuming the figure of 38 m relates to the potential recession over the next century, the calculations presented in this study indicate that erosion may be 2.5 times that currently used in planning (Jones and Hayne, 2002). Despite this underestimation, the potential impact on the Swanbourne Beach area is likely to be minimal, as very little infrastructure is located within 100 m of the shoreline at this locality (Figure 7.11). Given the Port/South Beach area appears to be most vulnerable of the hazardous regions in this sector presented in Figure 7.8, it is likely that erosion rates would be similar to, or greater than, rates at Swanbourne Beach. If this were the case, then the impact would be much greater than experienced at Swanbourne Beach, as there is considerably more infrastructure at the southerly location (Figure 7.8).

Response to coastal erosion

Modelling of potential recession within the susceptible zones outlined in this report will allow for the relevant planning agencies to respond to future coastal erosion. These agencies have two primary options in responding to potential erosion, they may choose to do nothing or do something. If they choose to act, then there are three generic responses:

- planned retreat (eg, building setbacks);
- accommodation (of sea level rise, by means such as raising buildings on pilings above the increased flood elevations); and
- protection (Nicholls *et al.*, 1995). Protection of coastal land is traditionally achieved through either building seawalls or placement of sand to increase the size of the beach (usually by pumping from offshore) and so counteracting erosion, commonly described as ‘beach nourishment’.

Decisions regarding the appropriate mitigation measures for the Perth coast are beyond the scope of this report, as such judgments should be made by coastal engineers with knowledge of the local conditions and relevant resource structures that will fund the measures.

Consideration of increased storminess

A potential issue that relates to climate change, but is beyond the scope of this report, is that long-term sea level rise is not the only driving factor of shoreline change. Sources of potential hazard to the coast other than sea level rise, such as changes in the wave climate or an increase in storminess, are not considered in detail here. It is suggested that global warming and the associated higher sea surface temperatures may lead to a more ‘stormy’ climate (Henderson-Sellers *et al.*, 1998; IPCC, 2001). While increased ‘storminess’ will also affect levels of coastal erosion such influences are not considered in this study. The estimates of future erosion rates presented in this study, therefore, may be considered an underestimate of potential shoreline change through their absence.

Attempting to quantify erosion resulting from storms requires storm-surge modelling, using software packages such as SBEACH (developed by the US Army Corps of Engineers). The application of storm-surge models in association with long-term coastal erosion estimates is invaluable. For example, storm-surge models may indicate that X number of buildings in the Swanbourne Beach area will be inundated by a 100-year storm. If the same modelling is undertaken with a shoreline that has receded approximately 110 m and a sea level that is 48 cm higher than it is presently, particularly in a stormier climate, then the impact of the storm will be much greater. This suggests that detailed modelling of coastal erosion due to long-term sea level rise should be undertaken as a primary step in understanding coastal behaviour over the next century, subsequent to which storm-surge modelling will reveal a more accurate picture of effects on infrastructure within that timeframe.

Further research

An advance on the Bruun Rule that may be applied to sections of the Swan coast is the vector-based Bruun–GIS model, which is based on work undertaken by Bruun and describes the full implementation of the Bruun Rule in a GIS (Hennecke and Cowell, 2000). The Bruun–GIS model may be applied to areas such as Swanbourne Beach, although it is likely that this will give similar results to the conventional Bruun analysis presented above, which suggested erosion rates may be approximately 1 m per year over the next century due to sea level rise.

Attempting to quantify the amount of potential erosion over the next century at many localities along the Swan coast is problematic due to inadequacies inherent in available models, complications in the local geomorphology, and the influence of engineering works. Of the areas identified as being susceptible to coastal erosion in the Fremantle to Hillarys sector, estimating future recession rates would be complicated in the Port/South Beach and Pinaroo Point areas relative to the Swanbourne area. The southern locality is heavily influenced by the engineering works at Fremantle Harbour and the Swan River outlet, and the northern locality is bordered by extensive submerged reefs that would invalidate any modelling (Figure 7.1). A more detailed investigation of these areas is required in the future, to more accurately delineate the areas and infrastructure at risk.

Of the remaining sectors, future research into potential coastal erosion should be focussed on the Cape Naturaliste to Bunbury sector and the Bunbury to Mandurah sector. Undertaking recession estimate calculations in the former are more feasible given the current state of coastal behaviour models and any future erosion due to sea level rise will likely affect relatively more infrastructure in this area. In contrast, the latter sector is more likely to be heavily damaged by erosion over the next century, but modelling potential rates is complicated by a lack of data in the context of current models.

The difference between the figure presented in the Western Australian Coastal SPP and the calculations presented above highlights the need for site-specific investigations for determining potential coastal erosion. This approach has been adopted in Queensland, New South Wales and Victoria, but Tasmania and Western Australia are still to factor it into statutory planning schemes. A first-order assessment in any planning process should involve a Bruun Rule analysis at the very least. Given the resources (eg, time, money, expertise), it is also recommended that a more process-oriented analysis of sediment budgets be undertaken, as this will incorporate local factors, which can greatly influence the potential extent of erosion.

7.10 Conclusions

- It is highly likely that coastal erosion will have a significant impact on coasts around the globe, including Australian coasts, over the next century.
- Three sections of the Fremantle to Hillarys sector appear to be susceptible to coastal erosion: Port/South Beach; Swanbourne to Floreat Beach; and the Pinaroo Point area. The hazard decreases from south to north, primarily due to the northward net longshore drift.

- Given a sea level rise of 18 cm over the next 50 years, and 48 cm over the next 100 years, Swanbourne beach is likely to erode approximately 40–50 m and 100–130 m respectively. These figures are approximately 2.5 times the value currently used in planning in WA.
- The impact of modelled recession at Swanbourne Beach is not significant due to a lack of overlying infrastructure. Similar erosion at the other vulnerable localities would have a much greater impact.
- The majority of the Mandurah to Fremantle sector does not appear to be susceptible to coastal erosion over the next century, despite the fact that the Tamala Limestone is preserved below sea level across the majority of the area. This is due to the fact that this sector has been the primary depositional province for the Swan coast over the last 8,000 years.
- The Bunbury to Mandurah sector is the section of Swan coast that appears to be most susceptible to coastal erosion over the next century. This is because the Tamala Limestone is preserved below sea level, this sector is not well sheltered from offshore swell, and this location is at the southern end of the net northward littoral conveyor that operates along the Swan coast.
- The Hillarys to Yanchep sector does not appear to be susceptible to erosion over the next century as Tamala Limestone is preserved above sea level along the majority of the coast, and the beaches are well sheltered by three lines of offshore reefs.
- The Cape Naturaliste to Bunbury sector may be affected by coastal erosion associated with long-term sea level rise.
- A Bruun Rule calculation should be undertaken as a preliminary methodology in planning for coastal recession due to sea level rise. Future research should be focussed on the Bunbury to Mandurah sector, the Cape Naturaliste to Bunbury sector, and the Port/South beach area of Fremantle.
- The two significant problems that must be overcome before more modelling can be undertaken in the region are: a lack of data (particularly sector-specific wave data and more detailed subsurface data); and a lack of sophistication in current models that do not allow for calculation in areas where the nearshore/offshore includes competent substrate.

7.11 References

- Abbs, D.J. and Physick, W.L. (1992) 'Sea-breeze observations and modelling: A review', *Australian Meteorological Magazine*, 41:9–19.
- Bird, E.F.C. (1996) 'Coastal erosion and sea-level rise', in Milliman, J.D. and Haq, B.U. (editors) *Sea-level Rise and Coastal Subsidence*, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 84–104.
- Bruun, P. (1988) 'The Bruun Rule of erosion by sea-level rise', *Journal of Coastal Research*, 4:627–48.
- Bruun, P. (1962) 'Sea-level rise as a cause of shore erosion', *Journal of the Waterways and Harbours Division, American Society Civil Engineers*, 88:117–30.
- Bureau of Meteorology (1969) *The Climate of Perth, Western Australia*, Australian Government Printing, Tasmania.
- Carrigy, M.A. and Fairbridge, R.W. (1954) 'Recent sedimentation, physiography and structure of the continental shelves of Western Australia', *Journal of the Royal Society of Western Australia*, 38:65–95.
- Clarke, D.J. and Eliot, I.G. (1983) 'Mean sea-level and beach-width variation at Scarborough, Western Australia', *Marine Geology*, 51:251–67.
- Clarke, E.deC. (1926) 'The geology and physiography of the neighbourhood of Perth Western Australia', *Handbook of the Australian Association for the Advancement of Science*, Perth, pp. 23–30.
- Collins, L.B. (1983) 'Post-glacial sediments and history, southern Rottnest Shelf, Western Australia', PhD Thesis, Department of Geology, The University of Western Australia.

- Gentilli, J. (1971) 'Climate of Australia and New Zealand', in Landsberg, H.E. (editor) *World Survey of Climatology*, Volume 13, pp. 108–114, Elsevier, Amsterdam.
- Gozzard, J.R. (1987) *Lake Clifton–Hamel Sheet 2032 II and part 2032 III*, Environmental Geology Series, Geological Survey of Western Australia.
- Gozzard, J.R. (1986) *Perth, Sheet 2034 II and part 2034 III and 2134 III*, Perth Metropolitan Region Environmental Geology Series, Geological Survey of Western Australia.
- Gozzard, J.R. (1983a) *Fremantle Part Sheets 2033 I and 2034 IV*, Perth Metropolitan Region Environmental Geology Series, Geological Survey of Western Australia.
- Gozzard, J.R. (1983b) *Rockingham Part Sheets 2033 III and 2033 II*, Perth Metropolitan Region Environmental Geology Series, Geological Survey of Western Australia.
- Gozzard, J.R. (1982) *Yanchep Sheet 2034 IV*, Perth Metropolitan Region Environmental Geology Series, Geological Survey of Western Australia.
- Hallermeier, R.J. (1981) 'A profile zonation for seasonal sand beaches from wave climate', *Coastal Engineering*, 4:253–77.
- Hegge, B. (1994) 'Low-energy sandy beaches of southwestern Australia: two-dimensional morphology, sediments and dynamics', PhD Thesis, Department of Geography, The University of Western Australia.
- Henderson-Sellers, A., Zhang, H., Berz, G., Emanuel, K., Gray, W., Landsea, C., Holland, G., Lighthill, J., Shieh, S-L., Webster, P., and McGuffie, K. (1998) 'Tropical cyclones and global climate change: a post-IPCC assessment', *Bulletin of the American Meteorological Society*, 79(1):19–38.
- Hennecke, W. and Cowell, P.J. (2000) 'GIS modelling of impacts of an accelerated rate of sea-level rise on coastal inlets and deeply embayed shorelines', *Environmental Geosciences*, 7:137–48.
- H. John Heinz III Centre for Science Economics and the Environment (2000) *Evaluation of Erosion Hazards – Contract EMW-97-CO-0375*, Federal Emergency Management Agency (FEMA), USA.
- Hounam, C.E. (1945) 'The sea breeze in Perth', *Weather Developments and Research Bulletin*, 3:20–55.
- Hsu, S.A. (1988) *Coastal Meteorology*, Academic Press, New York.
- Institution of Engineers (2000) *Research Priorities for Coastal and Ocean Engineering*, National Committee on Coastal and Ocean Engineering, Canberra, Australia.
- Intergovernmental Panel on Climate Change (IPCC) (2001) *Climate Change 2001: Impacts, Adaptions and Vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge and New York.
- Intergovernmental Panel on Climate Change (1996) *Climate Change 1995, The Science of Climate Change*, Cambridge University Press, Cambridge.
- Jones, A.T. and Hayne, M. (2002) 'Modelling coastal erosion at Perth due to long-term sea level rise', *Proceedings of Australia's National Coastal Conference (Coast to Coast) – Source to Sea*, Tweed Heads, pp. 225–28.
- Jones, A.T. and Hayne, M. (2003) 'Assessing the vulnerability of the Perth Coastal System to coastal erosion through GIS' in Woodroffe, C.D and Furness, F.A. (editors.) *Coastal GIS 2003: an integrated approach to Australian coastal issues*, University of Wollongong, Wollongong Papers on Maritime Policy, 14:303–316.
- Kempin, E.T. (1953) 'Beach sand movements at Cottesloe, Western Australia', *Journal of the Royal Society of Western Australia*, 37:35–58.
- Lemm, A. (1996) 'Offshore wave climate, Perth, Western Australia', BEng (Hons) Thesis, Centre for Water Research, The University of Western Australia.
- Masselink, G. and Pattiaratchi, C.B. (2001) 'Seasonal changes in beach morphology along the sheltered coastline of Perth', Western Australia, *Marine Geology*, 172:243–63.
- Masselink, G. and Pattiaratchi, C.B. (1998) 'The effect of sea breeze on beach morphology, surf zone hydrodynamics and sediment resuspension', *Marine Geology*, 146:115–35.

- Morang, A. and Parson, L. (2002) 'Coastal morphodynamics', in Morang, A. (editor) *Part IV, Coastal Geology, Chapter IV-3. Engineer Manual 1110-2-1100*, US Army Corps of Engineers, Washington, DC.
- Nerem, R.S., Haines, B.J., Hendricks, H., Minster, J.F., Mitchum, G.T., and White, W.B. (1997) 'Improved determination of global mean sea level variations using TOPEX/POSEIDON altimeter data', *Geophysical Research Letters*, 24:1331–34.
- Nicholls, R.J., Leatherman, S.P., Dennis, K.C. and Volonté, C.R. (1995) 'Impacts and responses to sea-level rise: qualitative and quantitative assessments', *Journal of Coastal Research*, SI 14:26–43.
- Passmore, J.R. (1967) 'The geology, hydrology, and contamination of shallow water aquifers in the Rockingham district, Western Australia', PhD Thesis, The University of Western Australia.
- Pattiaratchi, C., Hegge, B., Gould, J. and Eliot, I. (1997) 'Impact of sea breeze activity on nearshore and foreshore processes in south-western Australia', *Continental Shelf Research*, 17:1539–60.
- Pilkey, O.H., Young, R.S., Riggs, S.R., Smith, A.W.S., Wu, H., and Pilkey, W.D. (1993) 'The concept of shoreface profile of equilibrium: a critical review', *Journal of Coastal Research*, 9(1):255–78.
- Playford, P.E., Cockbain, A.E. and Low, G.H. (1976) 'Geology of the Perth Basin, Western Australia', *Geological Society of Western Australia Bulletin*, 124.
- Playford, P.E. and Low, G.H. (1972) 'Definitions of some new and revised rock units in the Perth Basin', *Western Australia Geological Survey Annual Report*, 1971:44–46.
- Sanderson, P.G. (1992) 'A longshore compartmentalisation and distribution of beach sediments on the central coast of Western Australia', BSc (Hons) Thesis, Department of Geography, The University of Western Australia.
- Sanderson, P.G. and Eliot, I. (1999) 'Compartmentalisation of beachface sediments along the southwestern coast of Australia', *Marine Geology*, 162:145–64.
- Scientific Committee on Ocean Research (SCOR) Working Group 89 (1991) 'The response of beaches to sea-level changes: a review of predictive models', *Journal of Coastal Research*, 7:895–921.
- Searle, D.J. (1984) 'A sedimentation model of the Cape Bouvard to Trigg Island sector of the Rottneest Shelf, Western Australia', PhD Thesis, The University of Western Australia.
- Searle, D.J. and Semeniuk, V. (1985) 'The natural sectors of the inner Rottneest Shelf coast adjoining the Swan Coastal Plain', *Journal of the Royal Society of Western Australia*, 67:116–36.
- Searle, D.J., Semeniuk, V. and Woods, P.J. (1988) 'Geomorphology, stratigraphy and Holocene history of the Rockingham-Becher Plain, South-western Australia', *Journal of the Royal Society of Western Australia*, 70(4):89–109.
- Semeniuk, V. (1985) 'The age structure of a Holocene barrier dune system and its implications for sea level history reconstructions in southwestern Australia', *Marine Geology*, 67:197–212.
- Semeniuk, V. (1983) 'The Quaternary stratigraphy and geological history of the Australind-Leschenault Inlet area', *Journal of the Royal Society of Western Australia*, 66:71–83.
- Semeniuk, V. and Searle, D.J. (1986) 'Variability of Holocene sealevel history along the southwestern coast of Australia – evidence for the effect of significant local tectonism', *Marine Geology*, 72:47–58.
- Semeniuk, V. and Searle, D.J. (1985) 'The Becher Sand, a new stratigraphic unit for the Holocene of the Perth Basin', *Journal of the Royal Society of Western Australia*, 67:109–15.
- Semeniuk, V. and Semeniuk, C.A. (1991) 'Radiocarbon ages of some coastal landforms in the Peel-Harvey estuary, south-western Australia', *Journal of the Royal Society of Western Australia*, 73(3):61–71.
- Silvester, R. (1961) 'Beach erosion at Cottesloe, Western Australia', *Civil Engineering Transactions*, 3:27–33.
- Simpson, J.E. (1994) *Sea Breeze and Local Wind*, Cambridge University Press, Cambridge.
- Steedman, R.K. (1977) *Mullaloo Marine: a report on oceanography and marine environment*, Shire of Waneroo, Western Australia.
- Stive, M.J.F. and de Vriend, H.J. (1995) 'Modelling shoreface profile evolution', *Marine Geology*, 126:235–48.

Walsh, K.J.E., Betts, H., Church, J., Pittock, A.B., McInnes, K.L., Jackett, D.R. and McDougall, T.J. (2004) 'Using sea level rise projections for urban planning in Australia', *Journal of Coastal Research*, 20:586–98.

