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Tweed Shire
Coastal Hazards Assessment

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Tweed Shire

Coastal Hazards Assessment

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Title :	Tweed Shire Coastal Hazards Assessment
Author :	Dean Patterson
Synopsis :	*The Tweed Shire Coastal Hazards Assessment report presents a summary of the regional and local coastal processes operating on the Tweed coastline. The report presents the methodology and outcomes for the definition of coastal hazards affecting the study area coastline, including a detailed assessment of shoreline recession hazard for Kingscliff, determined from local knowledge, various survey data sources, analysis of photogrammetry data and numerical modelling. The Study provides definition of the erosion hazards using a risk-based approach providing for variability and uncertainty, particularly beach erosion and recession for the immediate, 2050 and 2100 timeframes, taking account of ENSO variability and projected future sea level rise.*

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EXECUTIVE SUMMARY

The Tweed Shire coastline forms part of the regional beach system that extends from the Clarence River to Moreton Bay (Figure 1-1) and the coastal processes affecting the beaches are inter-connected both spatially and temporally with those along the adjacent coastlines. This Tweed Shire Coastal Hazards Assessment provides a revision of coastal hazard extents defined for specific designated parts of the Tweed LGA coastal zone as shown in Figure 1-3. The assessment updates the Tweed Coastline Hazard Definition Study (WBM Oceanics Australia 2001) in relation to:

- Changes to the *Coastal Protection Act 1979* and new *Guidelines for Preparing Coastal Zone Management Plans* made by the NSW Government in 2010, which advocates a risk based approach to coastal hazards management;
- Adoption of sea level rise benchmarks for 2050 and 2100 by Council; and
- New and updated data on coastal processes and new analytical techniques for assessing coastal hazards.

Byron Shire which adjoins Tweed Shire to the south is preparing a CZMP for its beaches and estuaries. Accordingly, Tweed and Byron Shire Councils have adopted a collaborative approach to updating their respective coastline hazard assessments in order to apply consistent assessment techniques at a semi-regional scale.

Coastal processes (natural and human influenced) are the principle source of hazard in the coastal zone, and such hazards can generate significant risks to our use and development of coastal land and assets. The geologic framework of the coastline, waves and water levels interact to shape the morphology of beaches over various timescales, from days to many years. Coastal processes and their interactions that are outlined in this study include:

- **Regional Context** of geomorphology and coastline processes affecting the Tweed Shire shoreline, which includes the long term evolution and regional spatial behaviour of the coastal system within which the Tweed Coast beaches are located;
- **Waves and Storms**, and variability in the wave climate from large scale climatological patterns such as El Niño- La Niña over seasonal, inter-annual and decadal time scales;
- **Elevated Water Levels**, which includes tides, storm surge, wave set up and wave run-up;
- **Longshore and Cross-Shore Sediment Transport** driven by waves and currents;
- **Coastal Entrance Stability** and fluctuations of the adjacent shorelines;
- **Projected Sea Level Rise and Climate Change Impacts** and their interaction and impacts upon all of the coastal processes described above; and
- **Coastal Entrance Dynamics** and fluctuations of the adjacent shorelines.

Coastal hazards arise where coastal processes interact with our use and development of coastal land and assets, or where human development has impeded natural coastal processes. The major coastal hazards of note defined in this report include:

- **Beach Erosion**, relating to periods of intense storminess over seasons to years, and associated dune slope instability;

- **Long Term Recession**, relating to a long term sediment deficit and due to both prevailing sediment deficits and sea level rise in the future;
- **Coastal Inundation** associated with during high tides combined with storms, wave runup and sea level rise that may overtop coastal barriers and inundate low lying land adjacent to the lower estuaries of creeks or rivers; and
- **Coastal Entrance Instability** and effects on immediately adjacent shorelines.

Coastal Processes

The geological context and the wave and water level regime affecting the Tweed Shire coastal system are described in Chapter 2. The regional wave climate is a dominant component of coastal processes. The deep water wave climate of the northern NSW coast comprises a highly variable wind wave climate superimposed on a persistent long period moderate to high energy south easterly swell. Two dominant types of storm wave generation, east coast low and tropical cyclone, determine the prevailing extreme wave climate. Table 2-1 shows the extreme wave probabilities. Design storm tide (tide plus surge) water levels applicable in the Tweed-Byron region are given in Table 2-3.

Annual and medium term variability in the wave climate is observed in the Byron wave climate. Other researchers have found reasonable correlation between the Australian east coast wave climate and the El Niño Southern Oscillation (ENSO). Generally, there is an increase in the occurrence of tropical cyclones and east coast low cyclones, with a shift to a more easterly mean wave direction during the La Niña phase, while the El Niño phase is associated with more southerly waves. Substantial natural variability in the wave climate is observed to occur over longer periods (years and decades). Variability in wave height and direction that persists for years to decades may result in alternate cycles of erosion and accretion and potential rotation of the shoreline due to variability in the alongshore sediment movement and the direction of intense storm waves. The data suggests an extended La Niña pattern prior to 1977 followed by predominantly El Niño through to about 2009. There have been several La Niña years both within that time and strongly so during 2010-12.

Cyclone erosion events in the region have been recorded in the surveys at the Gold Coast and also are indicated in the photogrammetry data for Tweed Shire. The surveys indicate typical profile modification and bar formation limited to water depths of about 10m and up to about 13m in more extreme events. This corresponds well to the Hallermeier (1977) predicted depth of profile change in storm events. Storm bite volumes up to 250m^3/m have been identified but are more typically around 150-200m^3/m. The larger volume losses may occur during multiple storm events or where there is significant alongshore net sand loss in addition to the removal of sand to nearshore.

For the present hazard assessment study, both analysis of shoreline change data in the form of photogrammetry based on a series of aerial photos dating from 1947 to 2010 and shoreline change modelling have been used to assess the extents of erosion hazards. A new regional shoreline processes model has been developed, extending along both the Tweed and Byron Shire coastlines, based on the EVO-MOD software developed by BMT WBM. This provides for a comprehensive approach to wave propagation and includes provision for cross-shore storm erosion shoreline responses. Key aspects of the EVO-MOD model include linkage to the external wave model SWAN to define nearshore wave conditions in time series format by input of the deep water wave time series, a curvilinear baseline format such that complex and highly embayed coastlines may be represented and simulated reliably, cross-shore profile evolution responses to storm erosion and recovery in combination with the effects of alongshore transport gradients on shoreline changes and capability to respond to sea level changes.

In recognition that modelling is a tool for understanding long term recession, rather than an absolute outcome, the model results provide an estimation of likely impacts, which must be consistent and verifiable against the coastal processes and coastal geomorphology as described in the historical record (e.g. photogrammetry). Accordingly, careful analysis of photogrammetry data for long term beach trends was compared with model outputs as part of the model verification.

Previous analyses of longshore transport rates have been hampered by the lack of a reliably defined directional wave climate. As well, they have been undertaken in a somewhat piecemeal manner, being related to specific coastal management issues in particular areas. Average annual net longshore transport rates from various previous studies are summarised in Figure 2-22. The recent research on a regional scale and the present study show that there is a gradient in the net longshore sand transport rate from about 150,000-200,000m^3/yr at the Clarence River to about 550,000m^3/yr at the Gold Coast. Additionally, recent research shows that there is a net shoreward sand supply into the shore-face from the inner continental shelf of about 0.5-1.0m^3/m/yr, offsetting shoreline recession that would otherwise result from the longshore transport gradient.

The positive gradient in the longshore transport northward from the Clarence River to Point Danger of about 350,000-400,000m^3/year along 150km corresponds to an average loss of about 2.3-2.7m^3/m/yr, which would potentially lead to average shoreline recession for an active vertical zone of of about 0.15-0.18m/yr. However, it is likely that this is partially offset by a continuing shoreward sand supply to the beach system of at least 1m^3/m/year, reducing the average recession to less than 0.1m/yr. Further, the recession is not uniform along the coastline, being less immediately updrift (south) of headlands and greater downdrift (north).

Coastal Hazards

The beaches along the study region experience considerable fluctuation associated with storm erosion and variability due to changes in the prevailing wave conditions. As well, previous studies (e.g. WBM Oceanics Australia 2000; 2001) have established that there is a general regional trend of long term shoreline recession (refer Chapter 2). The conceptual pattern of shoreline variability and progressive long term change is illustrated in Figure 3-6.

Thus, the ‘immediate’ erosion hazard extent represents the zone that could be affected by erosion in the immediate near future (e.g. over the next few years) in the event of one or more major storm events while the 2050 and 2100 extents incorporate a landward shift in the immediate hazard line in response to the shoreline recession.

The erosion hazard extent is thus assessed by taking account of the combined factors of:

- Storm bite extent.
- Natural short to medium term variability of the shoreline.
- Projection to the future, with hazard definition at years 2050 and 2100,of:
    - o Any presently prevailing long term of shoreline recession, and

- o Shoreline recession caused directly by the effects of projected future climate change induced sea level rise.

Identification of prevailing long term trends may be difficult where variability is significant, if not dominant. For example, the shorelines immediately north of controlling headlands appear to show erosion-accretion variations in direct response to short to medium term (months to years) wave climate variability and associated gradients in the alongshore sand transport. The north-south aligned shorelines along the more exposed parts of the coast do not show such variability as they do not experience strong alongshore transport gradients with changing wave conditions.

The erosion hazards are thus determined and presented in terms of:

- The immediate erosion hazard which includes provision for the design storm bite with provision for the effects of wave climate variability over the next few years, determined on the basis of analysis of the available photogrammetry data for each location; and
- The future erosion hazards for which the immediate erosion hazard extent is projected to 2050 and 2100 respectively by incorporating the effects of underlying recession trends and sea level rise, with provision for uncertainties about those processes leading to hazard extent ranges from ‘minimum’ through ‘best estimate’ to ‘maximum’.

The definition of coastal hazards inherently involves uncertainty relating to not only how prevailing oceanic conditions will manifest in the future and how reliably their effects on the shoreline can be determined, but also the considerable unknown factors involved and limitations in the available measured data.

This hazard assessment investigation of the complex processes affecting the study region has been undertaken to define the nature and extent of coastal hazards to facilitate a management response and a reduction of associated risks including environmental degradation. While uncertainty, variability and technological limitations of the study are acknowledged, such uncertainties are not a reason to avoid quantification of the hazards. This is consistent with the Australian EPBC Act 1999 that states that “… lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation”.

The uncertainty and natural variability in coastal processes along the study region was recognised in the previous hazard definition assessments (WBM Oceanics Australia 2000; 2001). It was noted that adopting a best estimate (single line) approach inherently incorporates a possibility that the limit of erosion will either extend beyond the projected line or never reach it. The approach adopted has been to provide a band of feasible erosion extents, defined on hazard maps by lines representing the ‘best estimate’, ‘minimum’ and ‘maximum’ likely limits for the 2050 and 2100 planning periods. The ‘maximum’ and ‘minimum’ extents of the erosion hazard represent the range within which the erosion hazard is most likely to apply, as allowance for uncertainty inherent in the data interpretation and modelling, as well as other factors that are difficult to quantify reliably.

Provision for uncertainties associated with the immediate erosion hazard and projection of future shoreline recession are made on the basis of:

- Assessment of the immediate erosion hazard on the basis of the design storm bite provision in the context of the present erosion-accretion state of the beach and dune, in consideration also of variability patterns determined for each location on the basis of analysis of the photogrammetry data, as described in detail in Chapters 4 and 5;

- Assessment of the best estimate, as well as upper and lower limits of the prevailing underlying long term recession rates. For this assessment, these have been determined for each location on the basis of analysis of the photogrammetry data and consideration of regional trends, with generally ±20% adopted for the 'maximum' and 'minimum' recession distances relative to the best estimate except where local processes indicate other factors are more appropriate, as described in Chapters 4 and 5; and
- Adoption of modelled shoreline recession responses to sea level rise as the best estimate values, which are shown to correlate well with the Bruun Rule approach where effects of coastal headlands and structures are minor, with generally ±20% provisions applied to those best estimate distances to represent reasonable upper and lower limits, except where local circumstances indicate other factors are more appropriate, based on best practice engineering opinion as informed by the available evidence.

Long term recession rates at particular beaches are generally determined from analysis of volumetric and/or lineal movement trends derived from survey or photogrammetry data. Because the beaches along the study region are inter-connected, recession at each location should have consistency with the regional average pattern of behaviour, but will vary depending on location relative to headland controls and local shoreline alignment. Correlation with wave climate variability such as that associated with ENSO and/or IPO patterns has been attempted in order to gain better understanding of the timing and extent of the variability measured in the photogrammetry. As well, natural short to medium term variability has been assessed using time series shoreline response modelling in which the input wave information contains periods of equivalent variability.

Both the historical long term recession rates and provision for the variability have been incorporated into the assessment of future recession in combination with recession due to sea level rise. Where the long term recession is uncertain or masked by short term variability in the data, the regional recession trend based on the sediment budget is used as the basis for assessment, taking account of location relative to control structures. The model has been used to determine sea level rise responses (Figure 3-4) and compared with recession distances derived from Bruun Rule estimates in developing the adopted hazard extents.

The coastal processes and hazards for Kingscliff and Cudgen Creek are described in Chapter 4 and are intended to inform management planning and future decisions about how the coastline is managed. Provisions for expected storm bite and future recession lead to erosion hazards that extend into developed areas to varying distances within the Kingscliff township area but are accommodated by the dune and undeveloped hind-dune areas further north.

Coastal inundation hazards associated with elevated ocean levels and wave run-up, together with storm tide inundation within Cudgen Creek are described and mapped in Chapter 4.

The coastal hazards for other parts of Tweed Shire are described in Chapter 5. The erosion hazards extend into developed areas to varying distances in only some locations, particularly at Cabarita Beach, Casuarina and Fingal Head. Generally, future erosion to 2100 is expected to be accommodated by the dune and undeveloped hind-dune areas at other locations.

A brief summary of the key elements of the coastal hazards at each location is provided below. The coastal hazards are presented in the separate Appendix B volume of maps.

Kingscliff

The Kingscliff erosion hazards are based on the seawalls not being in place. This does not presume that they would be removed but rather is intended to provide Tweed Council with advice on where the erosion could extend should they be removed, depending on consideration in subsequent management planning. Broadly, future erosion to 2100 will be accommodated within the undeveloped dune and parkland area seaward of development infrastructure north from the Bowls Club, with the Kingscliff North Holiday Park likely to be affected after 2050. South from the Bowls Club, the potential erosion hazard impact on existing development depends on location and the planning time-frame. The hazard analysis indicates:

- Immediate storm erosion would extend into the seaward parts of the presently protected Bowls Club, Kingscliff Beach Holiday Park, Surf Club and adjacent park areas.
- The 2050 erosion hazard extent includes a large part of the Bowls Club, essentially all of the Kingscliff Beach Holiday Park and all areas seaward of Marine Parade to its south.
- By 2100, the erosion hazard extends to Marine Parade along the entire area south from approximately the intersection of Marine Parade and Kingscliff Street.
- The Kingscliff Beach Holiday Park and Faulks Park are vulnerable to potential wave inundation due to overtopping during major storm events, extending further landward with shoreline recession and sea level rise.
- Inundation by storm tide penetration may affect the eastern fringe of properties along the western shoreline of Cudgen Creek, the extent increasing with sea level rise.

Tweed Shire Coastline

- At Pottsville, development will not be affected by the erosion hazard to 2100, however the Pottsville South Holiday Park on the western shoreline of Mooball Creek is vulnerable to immediate and future storm tide inundation.
- At Hastings Point, development is unlikely to be affected by the erosion hazard to 2100, although there is a possibility that erosion may extend into the northern properties due to the effects of sea level rise by that time. The spit at the mouth of Cudgera Creek is vulnerable to erosion by entrance instability and wave overtopping.
- At Cabarita, the maximum 2050 year hazard line just reaches the seaward property boundary, while the best estimate and maximum limits extend into the properties to varying extents at 2100. All existing structures are landward of the best estimate 2050 year line except for the surf pavilion building. The projected 2100 year hazard zone extends substantially into the seaward properties.
- Further to the north along Bogangar - Casuarina, the 2050 year hazard zone does not extend into the seaward properties. The best estimate 2100 hazard extent is close to the seaward property boundaries, though generally slightly to the seaward side except adjacent to the southern end of Lorne Street where it encroaches into the properties. The maximum likely 2100 extent encroaches into the seaward parts of the properties along most of the developed length;

- At Fingal Head, the maximum likely 2050 hazard encroaches into the north-eastern parts of three allotments at the northern end of Marine Parade, affecting also the Fingal Rovers Surf Club and Fingal Head Holiday Park. The 2100 best estimate erosion hazard encroaches into eight residential allotments there and extends through the Surf Club and substantial parts of the Holiday Park. These hazard extents are highly dependent on the sea level rise component of recession, being assessed to be significantly greater here than that for the regional average because of its location immediately north of Fingal Head. There is considerable uncertainty about the projected amount of recession. Close monitoring of the future shoreline changes is important and strongly recommended for this location to provide continuing updated data for further erosion hazard assessments.

Sand drift by wind erosion is effectively controlled along the Tweed Shire beaches by fencing, access management and dune care activities.

1 INTRODUCTION

1.1 Background

The Tweed Shire coastline is located on the north coast of New South Wales and forms part of the broader coastal and beach system that extends from the Clarence River to Moreton Bay (Figure 1-1).

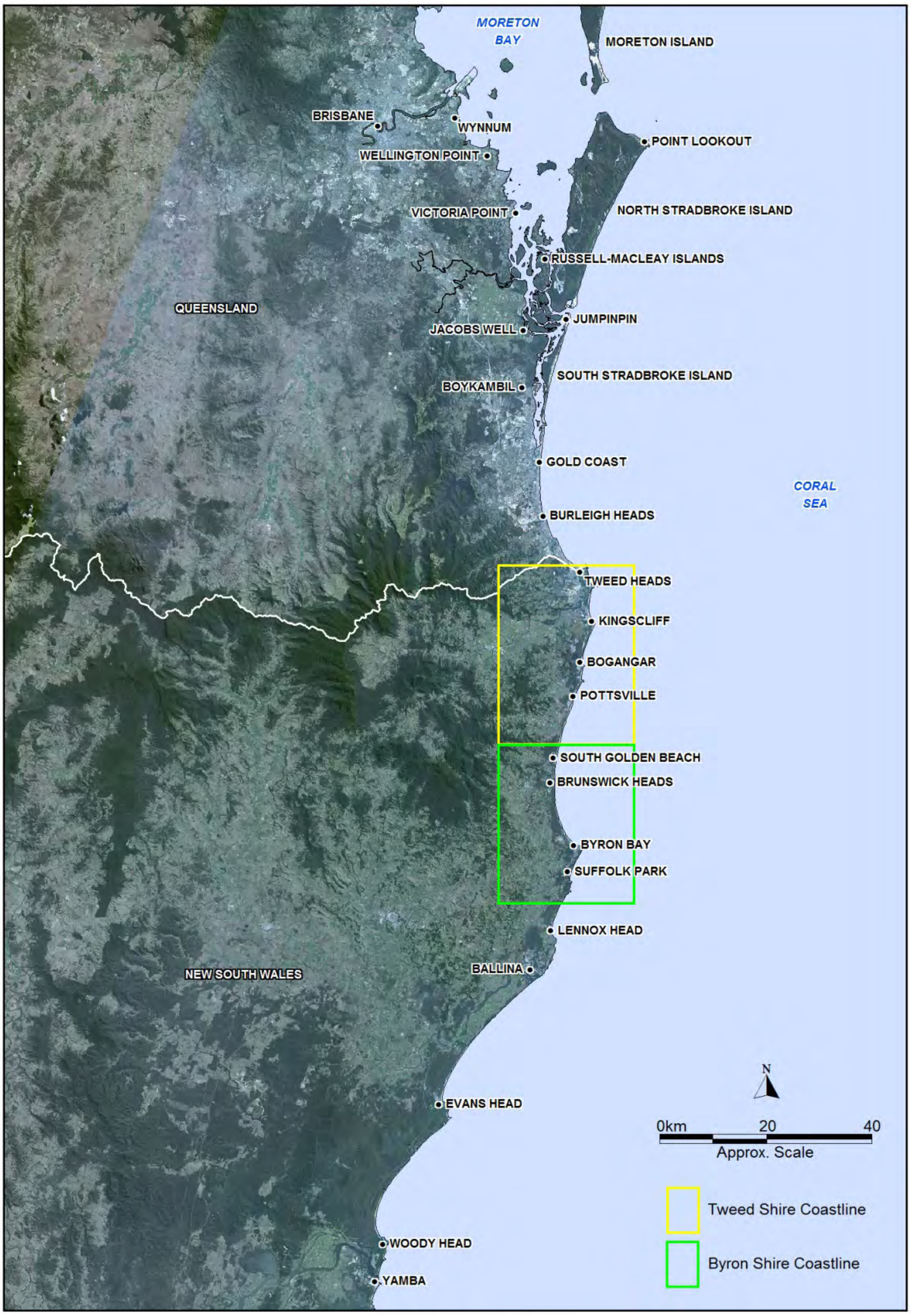


Figure 1-1 Regional coastline system – Clarence River to Moreton Bay

The Tweed coast (Figure 1-2) comprises extended sandy beaches between rocky headlands and nearshore reefs, the entrances to coastal estuaries at Pottsville (Mooball Creek), Hastings Point (Cudgera Creek), Kingscliff (Cudgen Creek) and the Tweed River. The beaches and coastal foreshore areas are key focal points for a wider range of recreational and social activities. Severe beach erosion has threatened development and assets in the past, particularly at Kingscliff.

Figure 1-2 Tweed Shire coastline

The Tweed Shire extent and study compartments are shown in Figure 1-3, extending from Pottsville in the south to Point Danger in the north. This study has reviewed and re-assessed the coastal hazards along parts of the Tweed Shire coastline within that zone, as specified by Council in the assessment scope. The previous Tweed Coastline Hazard Definition Study (WBM Oceanics Australia 2001) was completed on the basis of data and knowledge available to 1999. Since then, new projections for sea level rise have been adopted, changes to the *Coastal Protection Act 1979* have been made and new *Guidelines for Preparing Coastal Zone Management Plans* (OEH 2013) prepared. Further, additional coastal processes data have been collated, particularly updated photogrammetry, and new analytical techniques including modelling have become feasible through development of technical methodologies and acquisition of quality directional wave data on which those techniques may be based.

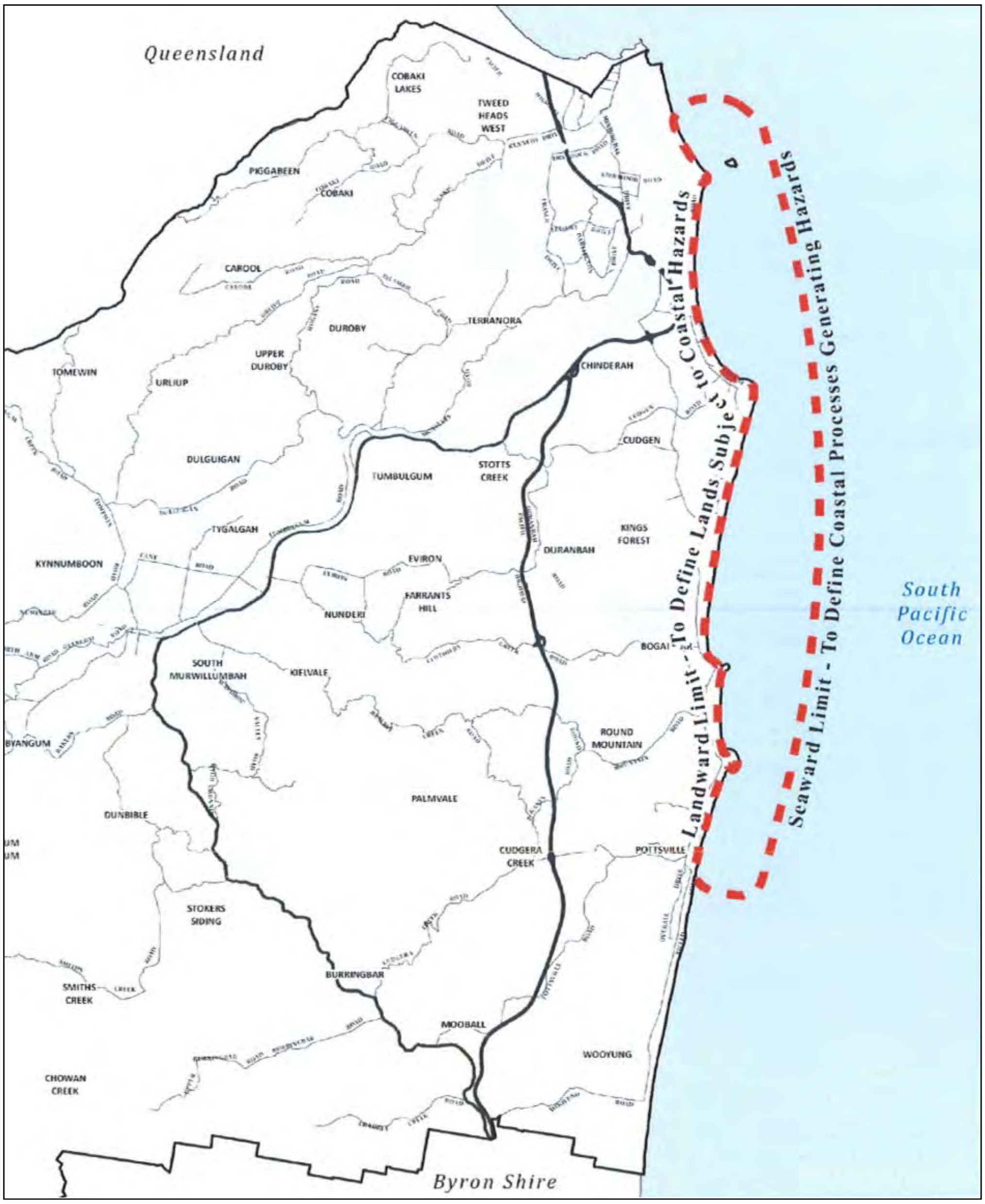


Figure 1-3 Tweed Shire coastal hazards assessment study area

This study represents an update of the previous hazard definition assessment, to take account of those factors. In particular, the study analyses the coastal processes affecting the Tweed Shire coastline from a range of spatial and temporal perspectives, establishing the broader regional context and, within that, a consistent local Tweed Coast context and detailed behaviour of each of the local study compartments.

Byron Shire which adjoins Tweed Shire to the south (Figure 1-1) is preparing a CZMP for its beaches and estuaries. Accordingly, Tweed and Byron Shire Councils have adopted a collaborative approach to updating their respective coastline hazard assessments in order to apply consistent assessment techniques at a semi-regional scale.

1.2 Context and Objectives of this Study

The Tweed Shire Coastal Hazards Assessment (November 2013) identifies the likely extent of coastal risks that may affect the Tweed coastline now and in the future (including sea level rise) and provides the technical basis for the Tweed Shire Coastal Zone Management Plan (CZMP) which is the framework for managing the risks from coastal hazards. As such, this hazards assessment represents a technical analysis of likely hazards while the management study and plan determines strategies and policies dealing with how those hazards are best managed, to meet the requirements of the *Coastal Protection Act, 1979* and associated *Guidelines for Preparing Coastal Zone Management Plans* (OEH 2013).

This report is an update assessment of the previous Coastline Hazard Definition Study (WBM Oceanics Australia 2001) and may be read in conjunction with that report. The assessment incorporates new data and analysis procedures, as well as a longer history of understanding how the coastal system behaves. The hazard extents are thus revised and represent an improved and more sound basis for management planning for the immediate, 2050 and 2100 planning periods.

1.2.1 Objectives of this Coastal Zone Hazards Study

The objectives for the Tweed Coastal Hazards Assessment are to:

- Describe the coastal processes occurring in the study area to a level of detail sufficient to inform decision making;
- Identify and map coastal erosion, recession and inundation hazard areas; and
- Identify in the form of suitable mapping the public and private properties and assets likely to be affected by coastal hazards at the immediate, 2050 and 2100 timeframes.

The key coastal hazards investigated for this report are:

- Beach erosion (due to storm processes and dune stability considerations);
- Shoreline recession, including future projection of the assessed historical trends together with recession due to future sea level rise at all beaches;
- Coastal inundation and wave overtopping during storms and including sea level rise; and
- Entrance shoreline fluctuations.

1.3 NSW Coastal Management Framework

Coastal management in New South Wales is guided by the *NSW Coastal Protection Act 1979*, NSW Coastal Policy (1997), *State Environment Planning Policy No. 71 – Coastal Protection, Guidelines for Preparing Coastal Zone Management Plans* (OEH 2013) and amendments to the *Coastal Protection Act, Local Government Act 1993 and Environmental Planning and Assessment Act 1979* relating to coastal protection. Other guidance for land use planning in the *Coastal Design Guidelines for NSW* (Coastal Council of NSW 2003).

With regard to provision for future sea level rise, Tweed Shire Council reconfirmed its commitment to the *Climate Change Strategic Planning Policy* that incorporates the DECCW (2009) sea level rise benchmarks of 0.4m and 0.9m relative to 1990 sea levels for 2050 and 2100 respectively.

A key change in the CZMP Guidelines is the direction to adopt a risk-based approach to coastal management, which incorporates the inherent uncertainty in hazards definition, and provides for prioritisation of management resources towards the greatest risks in the coastal zone. The CZMP Guidelines document the Principles for Coastal Management, as listed in Table 1-1. This hazard assessment study provides the technical basis for the CZMP.

Table 1-1 Coastal Management Principles

	Coastal Management Principles (DECCW, 2010)
Principle 1	Consider the objectives of the Coastal Protection Act 1979 and the goals, objectives and principles of the NSW Coastal Policy 1997
Principle 2	Optimise links between plans relating to the management of the coastal zone
Principle 3	Involve the community in decision-making and make coastal information publicly available
Principle 4	Base decisions on the best available information and reasonable practise; acknowledge the interrelationship between catchment, estuarine and coastal processes; adopt a continuous improvement management approach
Principle 5	The priority for public expenditure is public benefit; public expenditure should cost effectively achieve the best practical long-term outcomes
Principle 6	Adopt a risk management approach to managing risks to public safety and assets; adopt a risk management hierarchy involving avoiding risk where feasible and mitigation where risks cannot be reasonably avoided; adopt interim actions to manage high risks while long-term options are implemented
Principle 7	Adopt an adaptive risk management approach if risks are expected to increase over time, or to accommodate uncertainty in risk predictions
Principle 8	Maintain the condition of high value coastal ecosystems; rehabilitate priority degraded coastal ecosystems
Principle 9	Maintain and improve safe public access to beaches and headlands consistent with the goals of the NSW Coastal Policy
Principle 10	Support recreational activities consistent with the goals of the NSW Coastal Policy

1.4 Study Area Beaches

The Tweed Shire coastline study area (Figure 1-3) includes the following beaches:

- Pottsville and Mooball Creek;
- Hastings Point and Cudgera Creek;
- Cabarita Beach;

- Casuarina / Bogangar Beach;
- Kingscliff and Dreamtime Beaches; and
- Fingal Head Beach.

The coastal zone is defined as three nautical miles seaward of the mainland and one kilometre landward of the open coast high water mark. For the purposes of this report, the investigations consider the ocean and landward components of the coastal zone where this affects the extent of coastal hazards and their management.

1.5 Historical Data and Reports

The previous Tweed Shire Coastline Hazard Definition Study (WBM Oceanics Australia 2001) database has been incorporated and updated for this study to include:

- Previous technical reports (as referenced);
- Photogrammetric data from 1947 to 2010 provided by the Office of Environment and Heritage (OEH), extending the data base a further 11 years;
- Historical aerial photographs;
- Historical photographs;
- Wave time series data obtained from the Byron Waverider buoy directional records from 2000 to 2012, enhanced with filling of gaps based on Wave Watch III data;
- Aerial Laser Survey topographic data (provided by Council); and
- LiDAR bathymetric data (provided by OEH).

Geographical Information System (GIS) data sets for Tweed LGA were also utilised.

Site inspections and discussions with various people familiar with the behaviour of the beaches were also conducted for this study.

2 REGIONAL CONTEXT

2.1 Geology and Geomorphology

2.1.1 Geologic Context

The beach system of the study region (Figure 1-1) is the product of its geological history and the persistent influence over millennia during the late Quaternary period of the prevailing waves, currents and winds on the unconsolidated sediments of the continental shelf and coastal zone. The beaches and associated dunes, tidal inlets and nearshore active seabed areas are thus units within a larger geological framework, formed over timeframes commensurate with the processes involved, linked intimately to:

- Changes in relative level between land and sea through cycles of climate change, associated with those glacial and inter-glacial periods;
- Wind-generated waves and currents that transport unconsolidated sediments within coastal systems;
- Sources, supply and movement of sediments that comprise the sand that form the beaches; and
- Progressive evolutionary changes of the shorelines, dune barriers and active seabed areas.

The beaches as we see them today result from the morphological evolution of the continental shelf and coastline predominantly during the late Quaternary period covering two epochs, most notably:

- The late Pleistocene covering the last 120,000 years including the last ice age; and
- The Holocene covering the past 10,000 years of the most recent warmer post-glacial period.

While there are various interpretations of sea level changes over that time, Figure 2-1 illustrates the general pattern of cyclic variation associated with the glacial and inter-glacial periods over the past 350,000 years (Chappell 1983; Roy 2001).

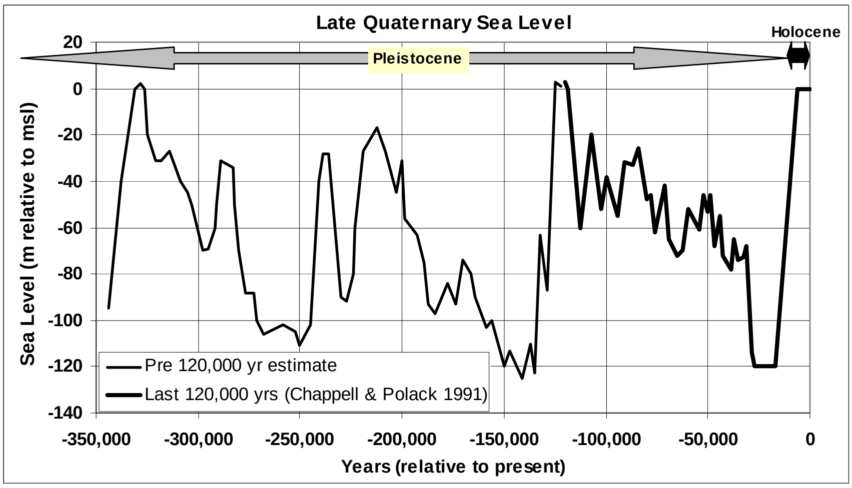
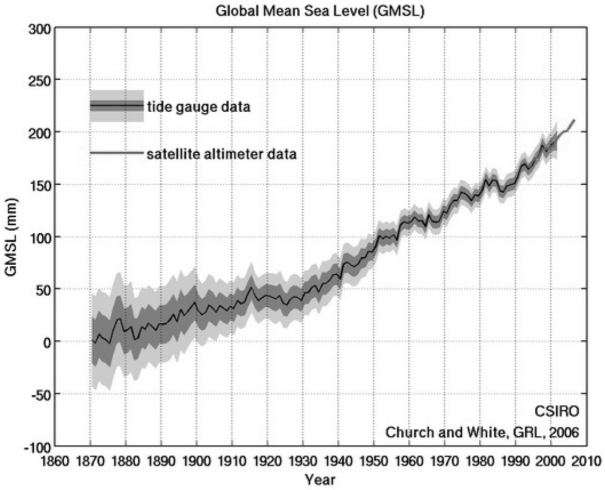


Figure 2-1 Late Quaternary sea level history

Over the Pleistocene-Holocene geological time-frame of the past 120,000 years, the sea level fell by about 120 metres, associated with the last glacial period, and subsequently rose to its present level

(Lambeck & Chappell 2001). The falling stage to about 20,000 years BP was gradual but not at a constant rate, with significant fluctuations superimposed on the downward trend. The post-glacial rising stage after 18,000 BP was relatively rapid (average about 10 mm/yr), reaching about 1-2m above PMSL at 6,000 to 7,000 years BP and subsequently falling to and remaining relatively stable at the present level since about 3,000 years BP (Chappell & Polach 1991; Sloss *et al* 2007). The more recent trend of sea level rise has been well documented, as illustrated in Figure 2-2 (Church and White 2006). There is clear evidence of contemporary climate change with global warming, most probably exacerbated by anthropogenic emissions of greenhouse gases, particularly carbon dioxide (IPCC 2007; Jansen *et al* 2007). Additionally, there is evidence of minor cyclic oscillations in the Pacific Ocean sea level, referred to as the so-called Inter-decadal Pacific Oscillation (IPO) Index (Goodwin 2005).



(source CSIRO, Church & White 2006)

Figure 2-2 Global sea level since 1870

While past sea level changes have shaped the coastal barriers and beach systems as we see them today, the present and projected future sea level rise will have impacts on the coastline that need to be understood and taken into account in the management of coastal developments. The modelling tool developed as part of this research is aimed at providing insights and quantitative information on coastal evolution in response to these sea level changes.

2.1.2 Geomorphologic Units

Broadly, the coastal system of significance to the proposed research includes the unconsolidated onshore and offshore sediments that have been deposited on and around the bedrock foundations of the continental shelf margin during the late Pleistocene period associated with large-scale changes in sea level and the prevailing waves. Roy (2001) distinguishes between the coastal sand deposits making up the dunes and beach system (barriers) and the deeper water areas extending across the continental shelf, with the seaward extent of the coastal sand barriers corresponding to the 'shore-face'. The toe of the shore-face abuts the more gently sloping inner continental shelf sand sheet, extending from the beach typically to around 20-25m water depth (Figure 2-3). References to the 'beach system' generally relate to the zone that includes the dune barrier, beach and shore-face.

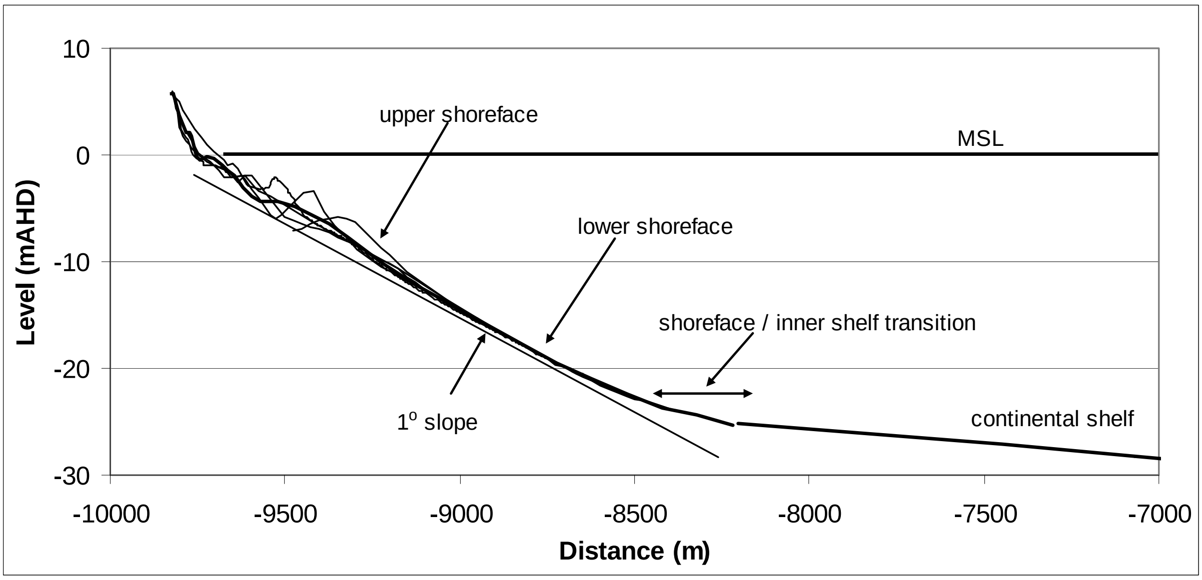


Figure 2-3 Typical beach and shore-face profile in study region

2.1.3 Coastal Barrier Evolution

2.1.3.1 Shoreward Sand Supply

Conceptual models have been presented (Roy and Thom 1981; Cowell *et al* 2000; Roy 2001) for the shoreward migration of sand during and subsequent to the sea level rise and cross-shelf transgression (Figure 2-4) and equivalent behaviour for falling sea level (regression) (Figure 2-5). Both transgressive and regressive reworking lead to net shoreward movement of the sand.

The sand that forms the beaches and dune systems is essentially all mature marine sand derived from the continental shelf, not contemporaneously derived fluvial sand (Roy and Crawford 1977; Roy and Thom 1981; Roy *et al* 1994). To the extent that the Clarence River is supplying sand to the coastal system (refer Section 2.4.1), Patterson (2013) provides evidence that it is predominantly marine sand that had previously filled the lower estuary outer basin during the Holocene sea level rise, displaced there by fluvial sediments. Shoreward transport of sand across the continental shelf accompanying the large changes in sea level during the Pleistocene has resulted in a considerable accumulation of sand in extensive dune barriers along the contemporary coastline of northern New South Wales and Southeast Queensland. There is a diversity of dune barrier types that reflects differences in the local coastal sediment budget (Roy 1998), with two readily identifiable sand dune barrier units in the study area, namely:

- Older Pleistocene inner barrier deposits, and
- Younger Holocene outer barrier dunes that abut un-conformably seaward of (or overlie in the case of Holocene transgressive wind drift) the Pleistocene system.

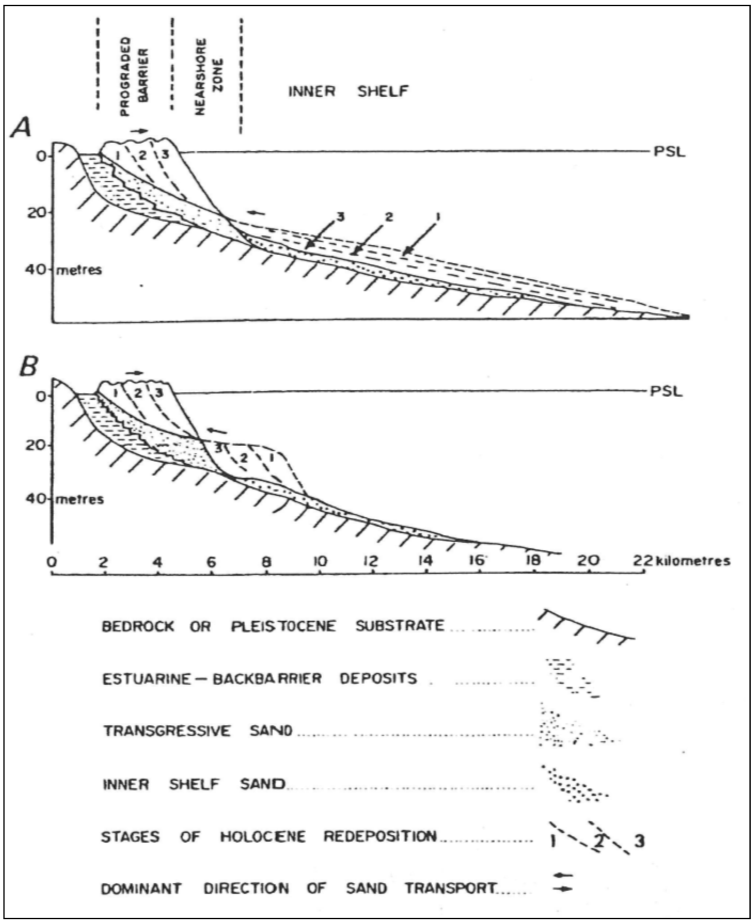


Figure 2-4 Conceptual dune barrier formation following sea level high-stand (Roy & Thom 1981)

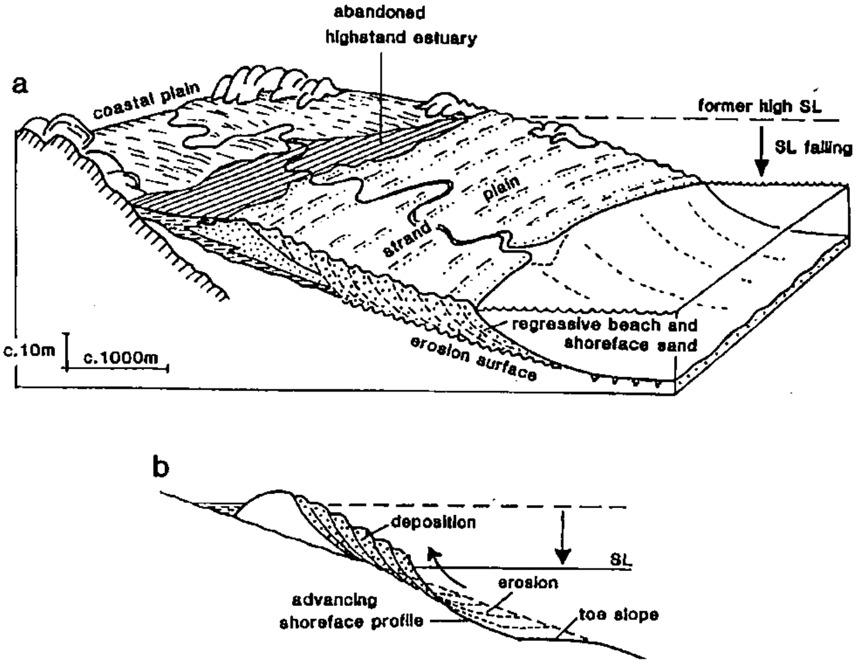


Figure 2-5 Falling Sea Level – Regressive Barrier Formation (Roy 2001)

The older, Pleistocene onshore sediments are, in the main, related to the sea level high attained 120,000 to 140,000 years ago (Thom *et al* 1978). Some of those dune barrier systems still show evidence of ridge and swale form, allowing former coastal alignment to be interpreted. Preserved

Pleistocene ridges are also evident along the Byron embayment north from Belongil Creek (Figure 2-6).

The active outer barrier beaches and dunes as we see them today were supplied with sand most recently following last post-glacial period (Thom 1984; Roy and Thom 1987; Stephens *et al* 1981). According to Thom (1984), it is likely that the coastline was subject to rapid accretion at 6,000 years BP, followed by a state of slow accretion to approximately 3,000-4,000 years B.P. The shoreward supply of sand onto the coast is thought to have diminished in late Holocene time, around 2,000 to 3,000 years before present (Thom 1975). Relative shoreline stability or slow recession has characterised the last 3,000 years.

Figure 2-6 Pleistocene dune barrier – Byron embayment (from PWD 1978)

While it is generally considered (Thom 1975; Thom 1984; Stephens *et al* 1981) that the most recent Holocene period of sand supply to the coast essentially ended about 3,000 years ago, it has been suggested (Roy *et al* 1997; Cowell *et al* 2000; Roy 2001; Goodwin 2005) that there remains a small but relatively significant shoreward supply of up to about 4m^3/m/year, at least in some parts of the coastline, that may completely or partially offset any progressive shoreline erosion that may otherwise result from alongshore gradients in longshore sand transport. Patterson (2013) utilised modelling of the coastline evolution processes involving both cross-shore and longshore sand transport in conjunction with the Pleistocene-Holocene sea level changes to suggest that there remains a net shoreward supply of sand to the beach system from the lower shore-face along most of the regional coastline between the Clarence River and the Gold Coast of about 1-2m^3/m/year.

2.1.3.2 Dune Formation

Sand accumulating on the sub-aerial beach area is transported landward by onshore winds to the back-beach area where the dunes form. Typically, the active back-beach dunes develop with a crest level of about 5m above sea level, with native dune vegetation of vital importance in their sustainable dynamic stability through cycles of storm event erosion and subsequent re-accretion over a temporal scale of years to decades. The study area presently has typically stable dune systems not vulnerable to landward losses of sand by wind erosion because of the abundant availability of suitable native dune plants. These plants thrive in this region due to the suitable climate and availability of nutrients, with various species evolved to perform different roles (Barr & McKenzie 1975). They include the primary sand trapping spinifex grass which has the remarkable ability to grow just above high water mark on the beach (see photo). Its resistance to salt and sand drift makes it the most important of species in stabilising these coastal dunes.

Foredune vegetation at Dreamtime Beach

Also playing key roles in stabilising the dune are other grasses (dune couch and blady grass), creepers (pigface, beach primrose and goatsfoot) and various shrubs and trees (acacia, coastal she-oak and coastal banksia) which have adapted to the wide range of coastal climatic conditions. For example, the coastal she-oak thrives in well-drained sandy soils, can withstand strong winds and salt blast and converts atmospheric nitrogen to a form used by the plant and improves the nitrogen content of the surrounding sand. Breakdown of the dune vegetation, or its inability to cope with factors involved in rapid shoreline recession and/or high rates of sand supply, may lead to migration of sand further inland. In the contemporary sense, this occurs only from the impacts of interference by man’s activities.

The distinction in the coastal barrier dune system is blurred in some areas where Holocene erosion into the Pleistocene barrier has occurred. In this case, the modern (Holocene) active dune is, in large part, the reworked Pleistocene barrier. However, this is merely an onshore manifestation of the process that has been the source of essentially all of the Holocene sands, the reworking of the older Pleistocene deposits across the continental shelf during and subsequent to the most recent post-glacial sea level transgression.

2.1.3.3 Northward Longshore Sand Transport

The Pleistocene-Holocene dune barriers increase in width and volume towards the north along the coastline north from the Clarence River to Fraser Island, indicating the importance of the northward wave-induced net longshore transport of sand along the coast associated with the predominantly southeast sector waves in the region. The inner nearshore shore-face sand unit, in the upper part of the profile from the shoreline to approximately 8-10m depth, indicates an almost continuous sediment pathway along the New South Wales and southern Queensland beaches.

The plan shape of the shoreline along the region reflects the dominant southeast swell conditions and northward net movement of beach sand. This manifests as a series of crenulate shaped embayments, more hooked at their southern ends and aligned more uniformly and relatively consistently at north-northeast (approx. 20°) at their northern ends.

While there is a narrow strip of active beach and dune Holocene sand along the entire coastline, Holocene dune barriers are largely missing along much of northern New South Wales. There, the narrow active beach system directly abuts older Pleistocene dune systems, generally interpreted as a sign of progressive sand loss by alongshore transport towards the north. The widely held view is that the entire length of the study area coastline is eroding as a result of a substantial gradient in the net longshore sand transport (PWD 1978; Stephens et al 1981; WBM Oceanics Australia 2000; 2001; 2003). This implies that Holocene barriers had developed in the southern parts of the study region and have since been removed by shoreline recession associated with the northward drift of sand.

Such a gradient in the net alongshore sand transport involves a progressive spatial change along the coastline in the longer term net longshore sand movement, resulting in an imbalance in the quantities of sand supplied to and transported away from parts of the beach system. This relates to the progressively varying interaction of the prevailing directional wave climate with the beach compartment alignments along the regional coastline, subject to the influence of the continental shelf bathymetry on wave propagation to the shoreline. Where net accretion of the shoreline has occurred, the longshore transport gradient must be negative (decreasing) in the northward direction and/or a shoreward supply of sand existed to overcome any longshore transport deficit. A change to net shoreline erosion there now requires positive (increasing) longshore transport gradient and/or substantial reduction in the shoreward supply at some time, leading to a change from net gain to net loss of sand.

The Holocene dune barrier north from Hastings Point into SE Queensland increases progressively in width and volume, with massive net shoreline accretion along the Gold Coast over the past ~6,000 years. Of significance, Roy (1975) notes that the extensive Holocene barrier in the Cudgen area (Figure 2-7) indicates a high rate of sand supply in the past. Thom *et al* (1978) suggest that 7,000 years BP sea level was somewhere between 10m and 15m below present and, at this sea level, Cook Island and Fingal Head were acting as littoral barriers along the coastline and the Tweed River would have exited to the sea via Wommin Lake. A sand barrier may have extended up from Cudgen Headland. In the same respect, Letitia Spit, because of the Fingal Head littoral barrier, would probably not be completely developed at that time. The attainment of present day sea levels approximately 6,000 years ago would have drowned these land bridges between existing outcrops of bedrock.

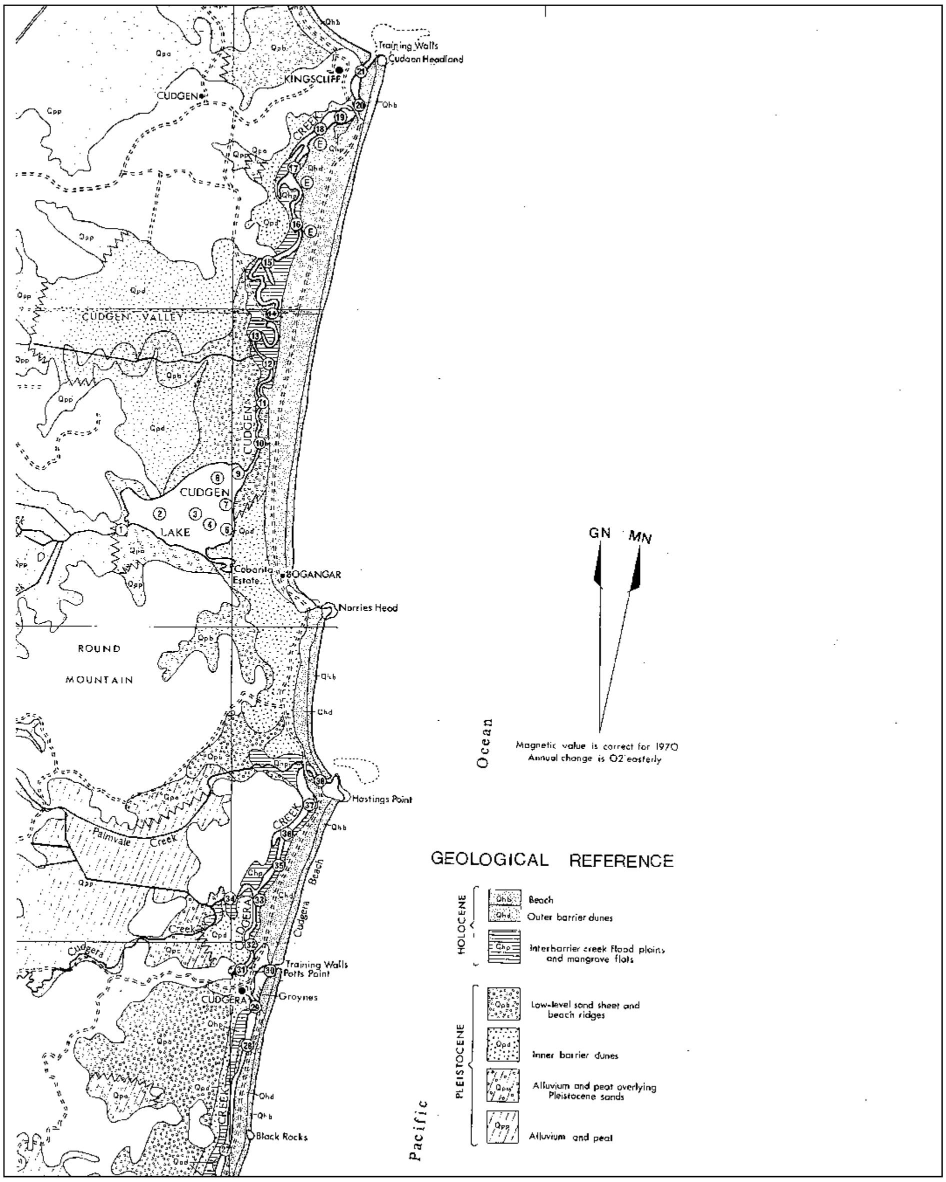


Figure 2-7 Dune barrier at Cudgen (from Roy 1975)

2.2 Regional Wave Climate

The regional wave climate is a dominant component of coastal processes. The deep water wave climate of the northern NSW coast comprises a highly variable wind wave climate superimposed on a persistent long period low to moderate energy swell predominantly from the southeast to east direction sectors. Typically, the swell may range up to 3-4m significant wave height with periods in the range 8 to 15 seconds. Prevailing wind waves are incident from a wider range of directions, predominantly the east to southeast sectors, consistent with the wind climate for the region, and range from small short period local 'sea' conditions to large storm and cyclone waves in excess of 6-7m significant wave height.

2.2.1 Storm Wave Generation Sources

The wave climate of the south east Australian coastline exhibits variability through the year due to the seasonal dominance of the major wave generation sources. While there is a predominance of the larger storm event waves from November to July, it is important to note that storm(s) of sufficient magnitude to cause erosion may occur at any time during the year.

The dominant wave generation sources include (Short and Trenaman 1992; Short 2007):

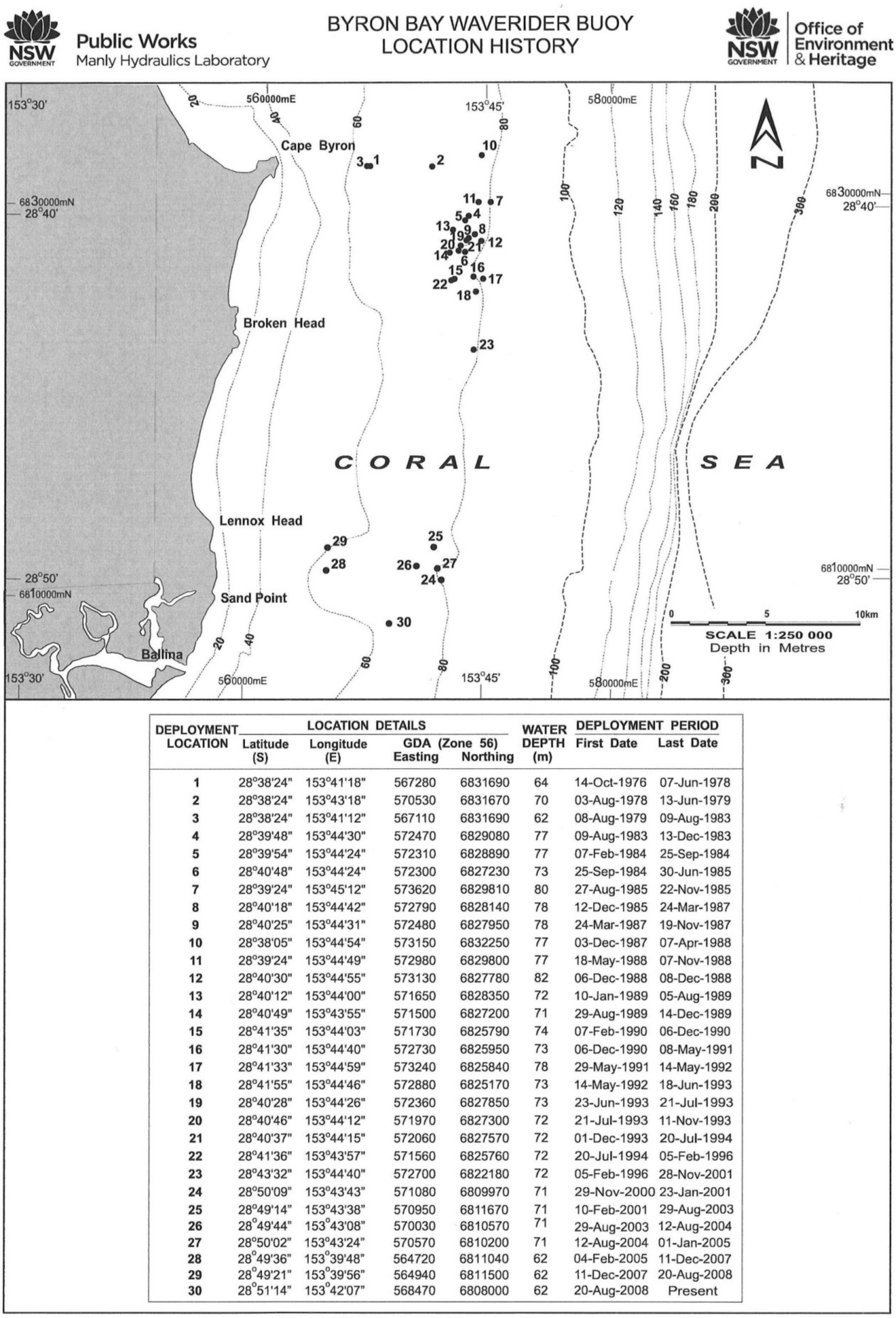
- Tropical cyclones (November to May), track towards the Tasman Sea (usually well offshore of the coast). These may generate large east-northeast to east-southeast waves at the Tweed coast.
- East coast cyclones commonly known as east coast lows (typically May, June and July), said to generate the strongest winds, heaviest rainfall and largest waves experienced on the NSW Coast. These small intense storms may form anywhere along the NSW coast, generating waves predominantly from south to south-east directions at the Tweed coast.
- Mid-latitude cyclones (occur throughout the year particularly March to September) form in the Southern Ocean and Tasman Sea and generate the predominant south easterly swell experienced along the coast. Mid-latitude cyclones form closer to the southern Australian continent in winter than summer, thus typically forming higher waves in winter.
- The subtropical anticyclone produces fine, warm weather on the NSW coast and, particularly during summer, may generate low to moderate southeast to northeast swells.
- Onshore sea breezes forming in summer on hot days (as the land heats faster than the ocean, causing hot air to rise over the land and cooler air from the ocean to move in to replace it), which when persistent over days may generate weak short period northeast to east wind waves.

2.2.2 Measured Regional Wave Climate

Wave data for Byron was provided for the study by MHL from the directional wave rider buoy moored in around 75-80 m water depth about 10 km offshore. The recorder location has been moved over the years in order to reduce the impacts of the East Australian Current on buoy stability and transmission/recorder failures that cause gaps in the data record. These gaps during storm events may lead to uncertain or inadequate statistical analysis of the extreme wave conditions derived from the available database. The recorder locations are documented in Figure 2-8. Directional wave data has been recorded only since late 1999, with complete annual directional data sets available from January 2000.

Other wave data sources utilised primarily to extend and fill gaps in the Byron database include deep water WaveWatch III (WWIII) global wave model information since 1992 and British Meteorological Office (BMO) wave model information for the period 1989 to 1995. These data were cross-referenced against published data from the Brisbane recorder, offshore from point lookout, although that information is known to be not sufficiently representative of prevailing conditions along the study region, particularly south of Cape Byron (Patterson 2007a).

Basic wave parameter statistics derived from the recorded Byron data for years 2000 to 2012 are presented in Figure 2-9 in terms of significant wave height and spectral peak wave period and in Figure 2-10 for wave direction.



Public Works
Manly Hydraulics Laboratory

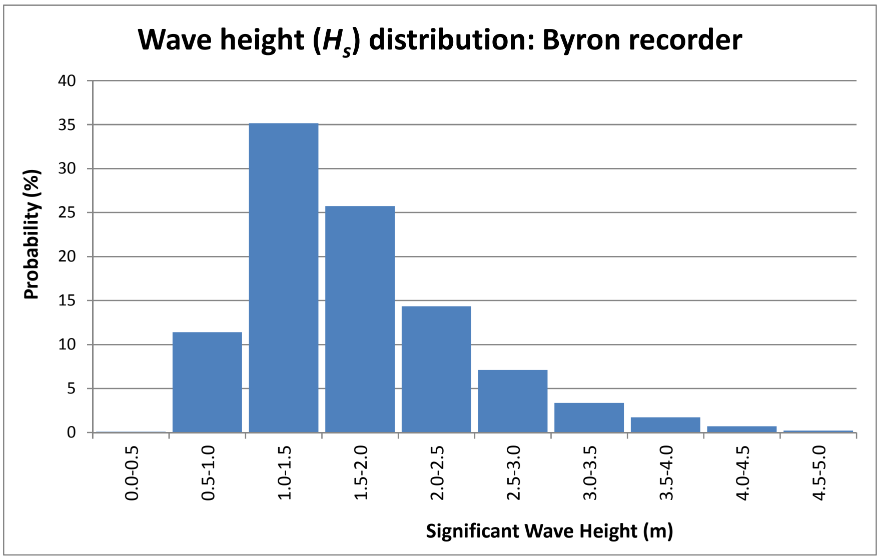
BYRON BAY WAVERIDER BUOY
LOCATION HISTORY

NSW GOVERNMENT
Office of Environment & Heritage

DEPLOYMENT LOCATION	LOCATION DETAILS Latitude (S)	Longitude (E)	GDA (Zone 56) Easting	Northing	WATER DEPTH (m)	DEPLOYMENT PERIOD First Date	Last Date
1	28°38'24"	153°41'18"	567280	6831690	64	14-Oct-1976	07-Jun-1978
2	28°38'24"	153°43'18"	570530	6831670	70	03-Aug-1978	13-Jun-1979
3	28°38'24"	153°41'12"	567110	6831690	62	08-Aug-1979	09-Aug-1983
4	28°39'48"	153°44'30"	572470	6829080	77	09-Aug-1983	13-Dec-1983
5	28°39'54"	153°44'24"	572310	6828890	77	07-Feb-1984	25-Sep-1984
6	28°40'48"	153°44'24"	572300	6827230	73	25-Sep-1984	30-Jun-1985
7	28°39'24"	153°45'12"	573620	6829810	80	27-Aug-1985	22-Nov-1985
8	28°40'18"	153°44'42"	572790	6828140	78	12-Dec-1985	24-Mar-1987
9	28°40'25"	153°44'31"	572480	6827950	78	24-Mar-1987	19-Nov-1987
10	28°38'05"	153°44'54"	573150	6832250	77	03-Dec-1987	07-Apr-1988
11	28°39'24"	153°44'49"	572980	6829800	77	18-May-1988	07-Nov-1988
12	28°40'30"	153°44'55"	573130	6827780	82	06-Dec-1988	08-Dec-1988
13	28°40'12"	153°44'00"	571650	6828350	72	10-Jan-1989	05-Aug-1989
14	28°40'49"	153°43'55"	571500	6827200	71	29-Aug-1989	14-Dec-1989
15	28°41'35"	153°44'03"	571730	6825790	74	07-Feb-1990	06-Dec-1990
16	28°41'30"	153°44'40"	572730	6825950	73	06-Dec-1990	08-May-1991
17	28°41'33"	153°44'59"	573240	6825840	78	29-May-1991	14-May-1992
18	28°41'55"	153°44'46"	572880	6825170	73	14-May-1992	18-Jun-1993
19	28°40'28"	153°44'26"	572360	6827850	73	23-Jun-1993	21-Jul-1993
20	28°40'46"	153°44'12"	571970	6827300	72	21-Jul-1993	11-Nov-1993
21	28°40'37"	153°44'15"	572060	6827570	72	01-Dec-1993	20-Jul-1994
22	28°41'36"	153°43'57"	571560	6825760	72	20-Jul-1994	05-Feb-1996
23	28°43'32"	153°44'40"	572700	6822180	72	05-Feb-1996	28-Nov-2001
24	28°50'09"	153°43'43"	571080	6809970	71	29-Nov-2000	23-Jan-2001
25	28°49'14"	153°43'38"	570950	6811670	71	10-Feb-2001	29-Aug-2003
26	28°49'44"	153°43'08"	570030	6810570	71	29-Aug-2003	12-Aug-2004
27	28°50'02"	153°43'24"	570570	6810200	71	12-Aug-2004	01-Jan-2005
28	28°49'36"	153°39'48"	564720	6811040	62	04-Feb-2005	11-Dec-2007
29	28°49'21"	153°39'56"	564940	6811500	62	11-Dec-2007	20-Aug-2008
30	28°51'14"	153°42'07"	568470	6808000	62	20-Aug-2008	Present

December 2011

Figure 2-8 Location history of the Byron Waverider Buoy (courtesy MHL)



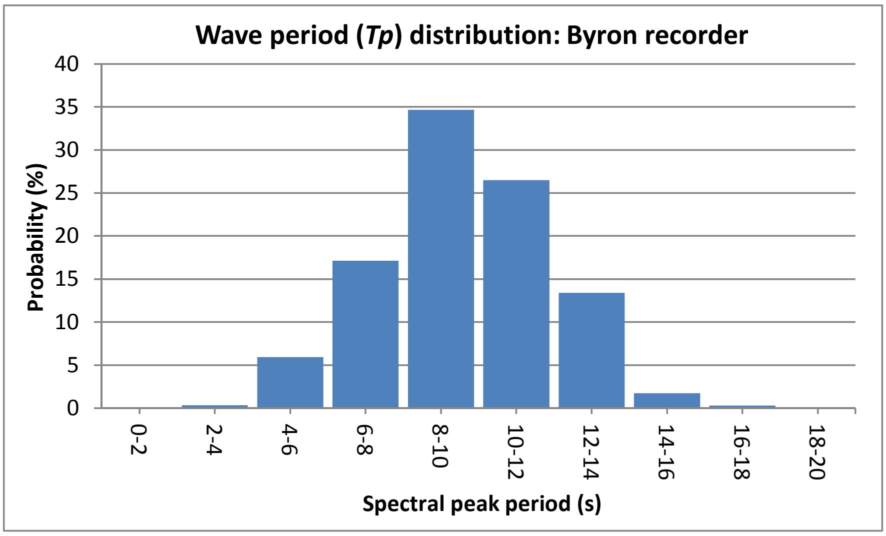


Figure 2-9 Occurrence probability of H_s (top) and T_p (bottom) at Byron recorder

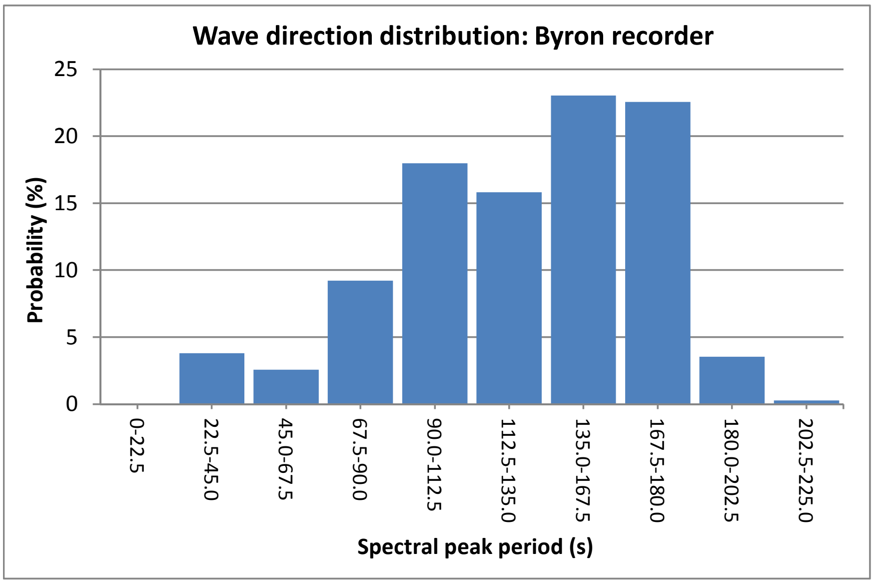


Figure 2-10 Occurrence probability of wave direction at Byron recorder

Figure 2-10 illustrates the predominance of southeast sector wave directions, showing that there is a relatively large proportion (approx. 26%) from directions south of southeast, in the range 157.5 to 202.5 degrees. Modal wave heights are 1.0-1.5m with spectral peak periods predominantly (~63%) in the range 8-12seconds.

The distribution of prevailing wave heights recorded at Byron is illustrated also in Figure 2-11, which shows their probability of exceedance calculated using the recorded data from January 2000 to July 2012. The median height is approximately 1.4m and 10%, 5% and 1% exceeded heights are 2.65m, 3.2m and 4m respectively.

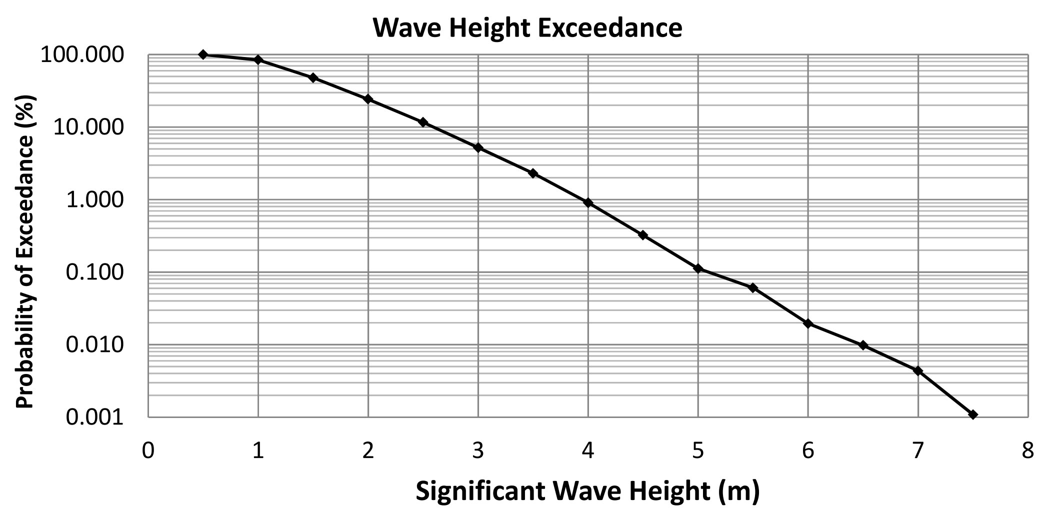


Figure 2-11 Exceedance probability of wave height at Byron recorder

2.2.3 Extreme Waves

Estimates of extreme deep water wave statistics have been calculated for the region from the set of peak storm wave height data collected by the Beach Protection Authority of Queensland over the period 1977 to 1999 (Allen and Callaghan 1999) for the recording site off Point Lookout, North Stradbroke Island. The two dominant types of storm wave, east coast low and tropical cyclone, were considered. Table 2-1 shows their extreme wave estimates, also including the results for 1 hour exceedances at Byron from Kulmar *et al* (2005) based on the Byron data 1976 to 2004 for comparison, showing close agreement for the more extreme conditions. The Allen and Callaghan (1999) analysis results are also shown graphically, as plotted in Figure 2-12.

Table 2-1 Extreme significant wave height estimates

Average Return Interval (years)	East Coast Lows Hs (m)	Tropical Cyclones Hs (m)	Combined Hs (Allen & Callaghan) (m)	Byron1 hr Hs Kulmar *et al* (2005) (m)
2	4.85	3.89	5.02	5.4
5	5.67	4.60	5.83	6.0
10	6.10	5.20	6.29	6.3
20	6.47	5.83	6.71	6.7
50	6.90	6.73	7.28	7.3
100	7.20	7.46	7.75	7.6

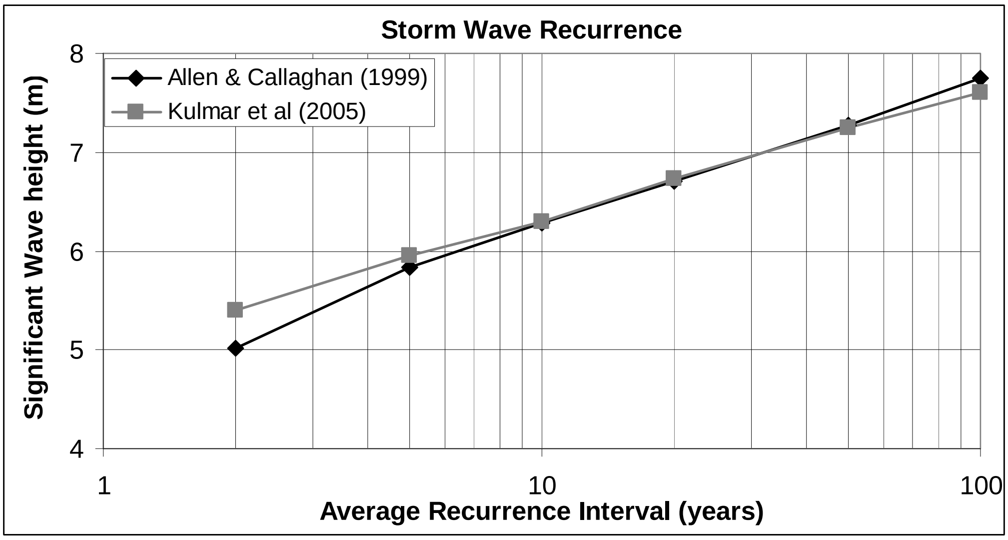


Figure 2-12 Storm wave recurrence intervals for the Byron - Gold Coast region

Storm waves from easterly trough lows and tropical cyclones may approach from the east-northeast to south-southeast. The largest storm waves are associated with tropical cyclones and extra-tropical east coast lows. Large southerly swells often result from intense low pressure systems off the New South Wales coast.

These extreme wave height statistics correlate quite well with the highest recorded significant wave height (H_s) of 7.64m on 21st May 2009 (Figure 2-13). In that event, the recorded H_s of 6m was exceeded for 37 hours, 6.5m for 8 hours and 7m for 2.4 hours.

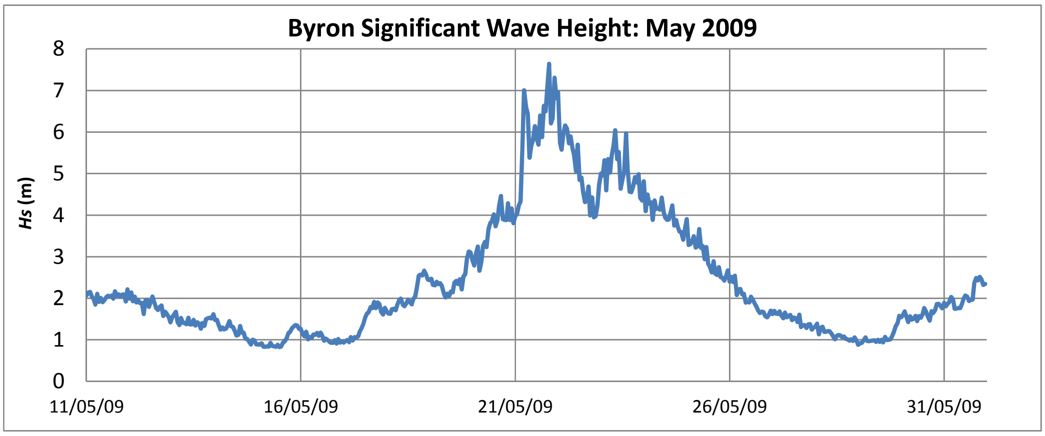


Figure 2-13 Storm wave recurrence intervals for the Byron - Gold Coast region

However, it must be noted that the Byron recorder is located on the continental shelf where there is some effect of the seabed on the longer waves (> approx. 10s period) in the form of refraction, bed friction attenuation and shoaling. The larger storm event waves typically have a spectral peak period of 10-13 seconds and will be thus affected, with refraction having the greatest effect. At Byron, easterly waves will be affected negligibly due to the water depth and bathymetry shape involved while (for example) a recorded large (e.g. 7.5m) southeast wave of 13s period will be reduced by about 2.5% by refraction from deep water to the recorder. That is, in this example, its initial height in deep water would be about 7.7m. More southerly waves would be reduced further by refraction, around 8-10% for a south-southeast deep water direction.

Further, the earlier recorder locations prior to 1996 were susceptible to Waverider buoy interference by the East Australian Current such that it pulled under during large waves, thus experiencing drop-out failures and lost data during storm events. Caution is therefore needed in interpreting the results of statistical analyses from the recorded data.

Thus, while some uncertainty exists about extreme wave statistics relevant to this region, a 100 year ARI deep water design wave height of 7.5m has been adopted, with an indication that it has a mean duration in the range 1 to 6 hours.

2.2.4 Nearshore Waves

Waves arriving in the nearshore zone have been transformed from offshore through refraction and bed friction attenuation using the spectral wave modelling package SWAN. The model was used to propagate waves from deep water to both the Byron wave recorder and all nearshore areas along the study region. This provided a basis for determination of:

- Wave height and direction transformation relationships to all sites; and
- Transformation of the recorded Byron wave data to an equivalent time series of equivalent deep water wave conditions for broader application to other parts of the regional coastal system.

SWAN is a wave refraction model that is used to simulate the formation and propagation of waves in deep, intermediate and finite depths. The SWAN model is able to simulate wave propagation in time and space with the following physical phenomena of interest to this study (Delft 2010):

- Wave shoaling and refraction, due to depth, bottom friction and bathymetric features;
- Wave frequency shifting due to non-stationary depth;
- Nonlinear wave-to-wave interactions (quadruplets and triads);
- Depth-induced breaking; and
- Wave-induced set up.

Bathymetric data for the study area derived from a collation of available Australian Hydrographic Charts, hydrosurvey data and Marine LiDAR were combined to produce a digital elevation model (DEM) of 20m grid cell size. A range of SWAN model grids were created from the DEM to provide a regional model of 500m spacing and several nested grid of finer (100m) resolution at the nearshore areas.

Typical nearshore transformation coefficients and wave refraction patterns along the study region are shown in Figure 2-14. These show:

- Maximum wave height coefficients for deep water wave directions in the range 50-100 degrees, the more north-easterly being for north-facing beaches at Kingscliff and Byron Bay while the east to east-southeast directions relate to the more exposed north-south aligned open coastline beaches; and
- Decreasing wave height coefficients for more southerly waves, particularly at those beaches in more sheltered areas immediately north of prominent headlands.

These effects are illustrated also in Figure 2-15 which shows relatively direct propagation of the east to north-east waves onto the shoreline (top figures) and zones of substantial wave height reduction along the sheltered beach areas north of headlands for the southeast to southerly sector waves (bottom figures).

Cape Byron has a profound effect at the shoreline along the coastline to its north on the more southerly waves, of particular significance for alongshore sand transport associated with large southerly swells generated by east coast lows off the NSW coast, as described by Patterson (2007). That effect may extend north to the Gold Coast and the Brisbane wave recorder (Figure 2-16).

The varying nature of wave propagation to the shoreline leads to quite different patterns of wave exposure and associated alongshore sand transport along the study region coastline. No particular wave condition results in uniform alongshore transport. The net transport rates at each location along the coast depend on the prevailing range of propagated nearshore waves that is unique to each location and will vary in response to variations in the incident deep water wave conditions.

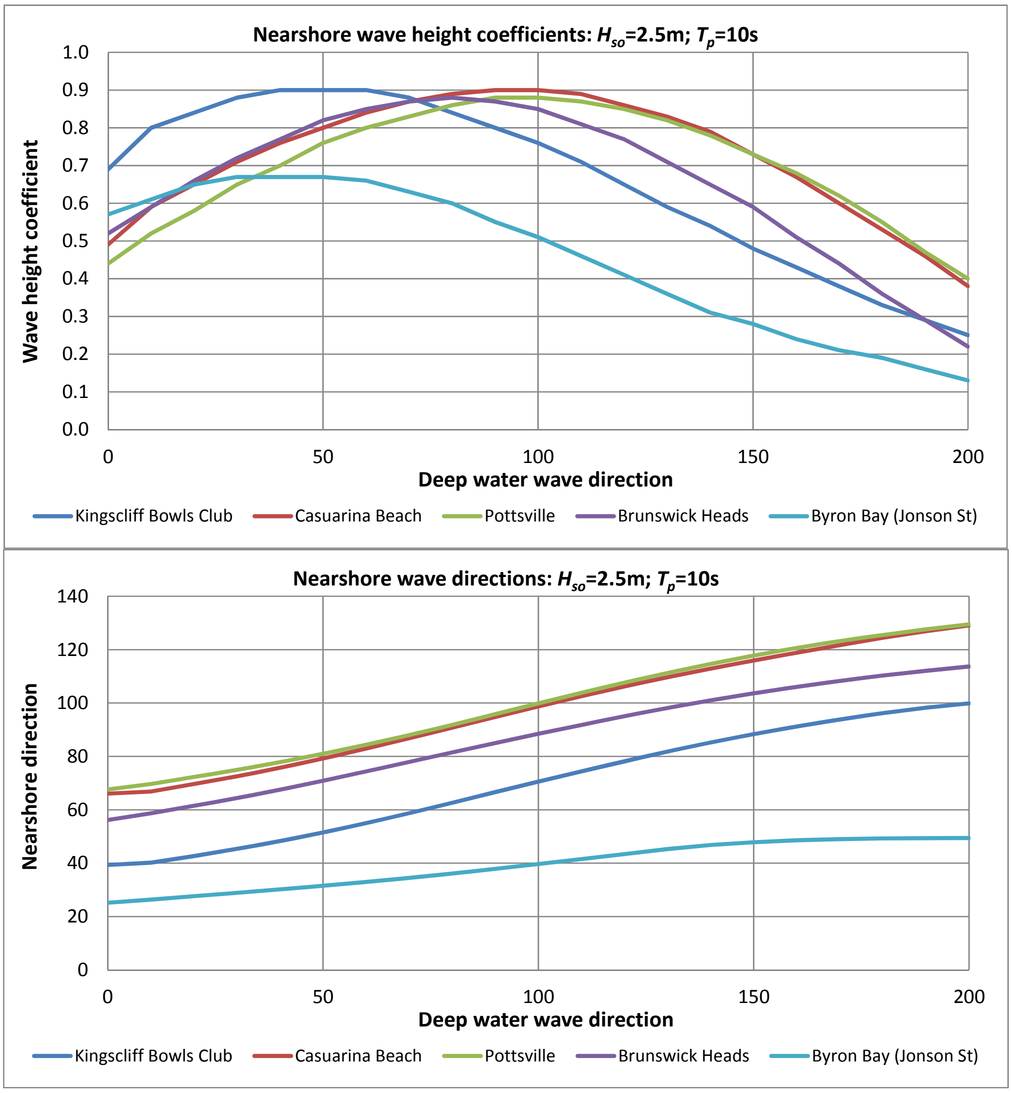


Figure 2-14 Typical nearshore wave height coefficients (top) and directions (bottom)

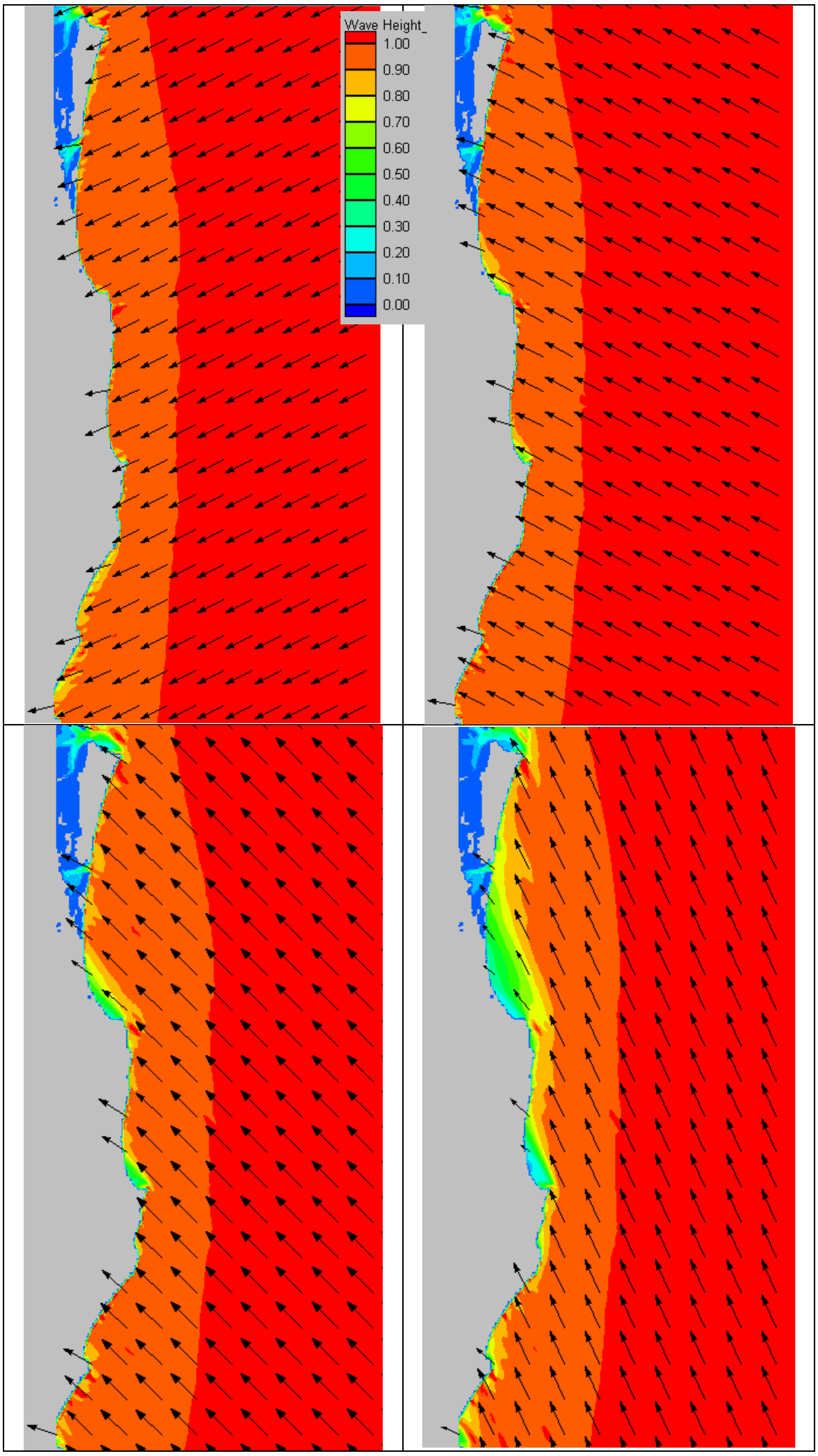


Figure 2-15 Typical wave refraction patterns along study region

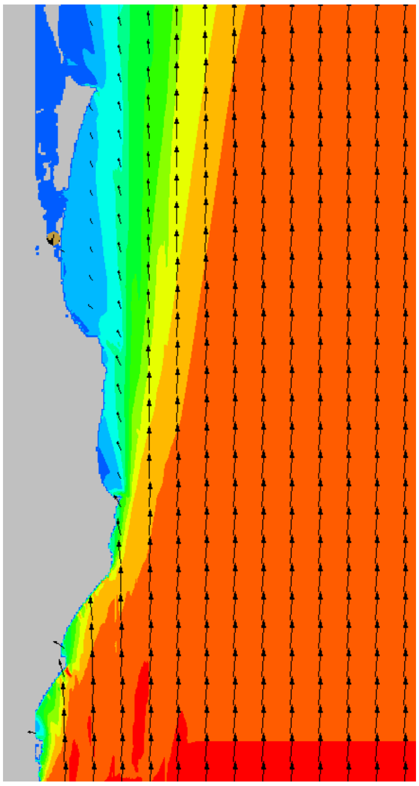


Figure 2-16 Wave refraction pattern for southerly swell

2.2.5 ENSO Variability of Wave Climate

2.2.5.1 Significance of Wave Climate Variability

In addition to the daily variability associated with passing weather systems, there are shifts in the wave climate (wave height, wave direction) between years and decades that relate substantially to the intensity and frequency of storms (affecting wave height) and storm generation sources (affecting wave direction). Such shifts in wave climate may manifest on the shoreline as variations in the direction and rate of alongshore sediment transport. This impact varies along the coastline from beach compartment to compartment and within each compartment depending on the shoreline alignment relative to incident wave direction, resulting in varying gradients in the longshore transport rates. More southerly waves cause increased sand transport along north-south aligned shorelines but are typically substantially attenuated by refraction and thus relate to decreased sand transport at the southern ends of coastline embayments. More easterly waves result in reduced sand transport at north-south aligned shorelines, even downcoast transport immediately south of embayment headlands, but increased sand transport at the southern ends of coastline embayments. These patterns of sand transport have substantial effects on shoreline accretion and erosion patterns within beach compartments and on variations in the alongshore transport of sand between compartments, including ‘slug’ like sand supply past headlands.

2.2.5.2 Wave Climate Correlation with ENSO

Annual and medium term variability in the wave climate is observed in the Byron wave data. Other researchers have found reasonable correlation between the Australian east coast wave climate and the El Niño Southern Oscillation (ENSO). Generally, there is an increase in the occurrence of tropical cyclones and east coast low cyclones during the La Niña phase (Goodwin 2005; Phinn and Hastings

1992; Hemer *et al* 2008, CSIRO 2007). Relating to these wave generation sources, the La Niña phase has been associated with more easterly wave directions (Short *et al* 2000; Goodwin 2005; Ranasinghe *et al* 2004). Mean wave power has also been found to be higher during the La Niña phase, likely due to the greater frequency / intensity of tropical and east coast cyclones which occur in addition to the predominant mid-latitude cyclones (e.g. refer Phinn and Hastings 1992; Ranasinghe *et al* 2004; You and Lord 2008). During the El Niño phase there are generally fewer tropical and east coast cyclones and mid-latitude cyclones (east coast lows) remain dominant, resulting in a more southerly mean wave direction (Ranasinghe *et al* 2004; Goodwin 2005).

Climate variability at decadal time scales (10-30 years) is also an intrinsic characteristic of the Australian regional climate (Power *et al.*, 1999). A period of extensive erosion and shoreline retreat over the 1950s and 1970s is well documented, since which time a relatively calmer period of beach recovery and lower storminess persisted to around 2007 (WBM 2003; Callaghan and Helman 2008). The high storm activity during the decade of the 1970s is typically associated with the greatest beach erosion extents in the historical record on NSW beaches (Forster *et al* 1975; Thom and Hall 1991; McLean and Shen 2006).

A notable component of the climate variability on decadal scales is found to be related to the Inter-decadal Pacific Oscillation (IPO) (Power *et al* 1999; Salinger *et al* 2001; Folland *et al* 2002). The sea surface temperature anomaly associated with the negative (or cool) phase of the IPO produces an increased frequency of east coast low pressure systems, higher rainfall and associated flood activity (Rakich *et al* 2008; Verdon *et al* 2004). Verdon *et al* (2004) demonstrated that the frequency of La Niña events is increased during the negative phase of the IPO. An increase in wave height and more frequent storms arriving from the east and east north east directions are expected during such periods, as evidenced in Figure 2-17 for the period 1950 to 1976 when tropical cyclone-related beach erosion was prevalent.

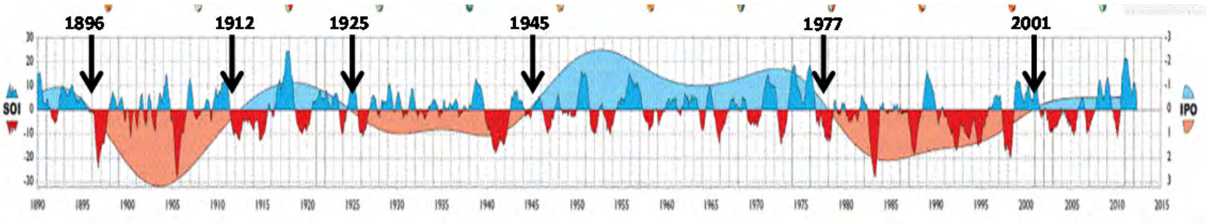


Figure 2-17 Correlated ENSO and IPO patterns since 1890

Figure from: http://www.longpaddock.qld.gov.au/products/australiasvariableclimate/index.html

Callaghan and Helman (2008) documented two centuries of weather records along the eastern Australian coastline and found that periods of extremes (storms and droughts) tend to occur in alternate phases that last for decades. Helman (2007; 2008) reported that major energy periods in the storm history of the east coast can be correlated with the negative (La Niña-like) phase of the IPO. While there is good correlation between ENSO and IPO and the storms that produce high waves, these climatic indicators alone are not adequate to describe or predict the extent of variability observed in the wave climate (height and direction), nor the shoreline response. The interrelationships between IPO, ENSO and other climatic drivers (e.g. Southern Annular Mode and Indian Ocean Dipole) and how they affect wave climate are not yet fully understood. Therefore, it is not currently possible to use such climatic indicators to reliably hindcast or forecast the NSW wave climate.

In order to relate wave climate variability to shoreline behaviour, Patterson (2013) derived an indicator of directional deep water wave energy related to the process of longshore sand transport at the beaches based on wave energy and energy-weighted mean wave direction parameters derived from the CERC equation for longshore sand transport. He derived deep water wave energy and direction parameters as:

Wave energy flux parameter = $g^{0.6} H_o^{2.4} T_p^{0.2}$ (m^3/s) (3.1)

Weighted mean direction = $\Sigma\,(g^{0.6} H_o^{2.4} T_p^{0.2}\,\mathrm{Dir}_o) / \Sigma\,(g^{0.6} H_o^{2.4} T_p^{0.2})$ (degrees) (3.2)

In applying these to this study, the recorded Byron data was back-refracted to equivalent deep water values based on SWAN wave model height and direction coefficients. The Byron data set was extended and data gaps filled using available global wave model information, yielding a continuous time series from January 1989 to July 2012. Plots of the time series values of the monthly mean energy and direction thus derived and the running 5-monthly means of those values are presented in Figure 2-18. The average value of the weighted mean direction over the period of data is 140.1 degrees. The average value of the wave energy parameter is 33.5m^3/s).

There are some distinct trends in the wave energy and weighted mean wave direction plots, namely:

- A distinct seasonal pattern with more southerly directions in winter and more easterly directions in summer;
- Phases of persistent high mean wave energy in 1999 and 2006, predominantly during winter months;
- Phases of more easterly summer directions during 1989 to 1994 and in 2009, the most extreme being in December 1993 to January 1994;
- Variable annual weighted mean direction around an average value of about 140 degrees, with a lower average values through 1989/1994, a progressive shift towards the east during 2004-2005 followed by a substantial change to the south-southeast between 2006 and 2008; and
- A combination of high monthly wave energy (up to 75m^3/s) and relatively more easterly (approx. 120 degrees) mean wave direction for March to June 2009.

The monthly SOI values for the corresponding period of wave data are shown in Figure 2-19. The mean SOI value for that period is close to zero (-0.6), suggesting that it could be reasonably representative of longer term conditions. Direct correlation between the SOI and these wave parameters is not clearly evident in the time-series format shown. However, there appears to be a tendency for high energy storm wave occurrences that can be related to ENSO patterns, consistent with previous research. For example:

- The period 2002-2003 shows a predominance of high energy southerly waves, as illustrated in Figure 2-20 (top), coinciding with El Niño in Figure 2-19; and
- The periods of early 2009 and 2011-12 display the La Niña wave pattern with occurrences of high energy waves from east to east-southeast (centre / bottom in Figure 2-20), correspond to La Niña phases of SOI in Figure 2-19.

Comprehensive analysis of these correlations is restricted by the relatively short duration of reliably recorded directional wave data. Nevertheless, it is most probable that substantial natural variability in the wave climate occurring over the longer term (years and decades) has significant consequent effects on shoreline behaviour. Southerly waves tend to cause higher rates of northward sand transport along the northern parts of embayments, including more headland bypassing, while having reduced energy and lower sand transport potential in the sheltered southern embayment areas. Easterly waves cause higher transport rates at the more east-west oriented shorelines towards the southern embayment areas but reduced transport (or downcoast transport) at the north-south oriented northern areas. These alongshore sand transport differentials and varying exposure to wave energy result in differences in erosion and accretion patterns along the coastline.

The prolonged predominantly La Niña phase from 1945 to 1977 is likely to have had a different prevailing wave climate and consequent pattern of shoreline behaviour to the predominantly El Niño phase that followed. Further, the more recent phases of La Niña in 2009 and 2011-12 appear to relate quite strongly to the storm wave occurrence pattern that would be expected.

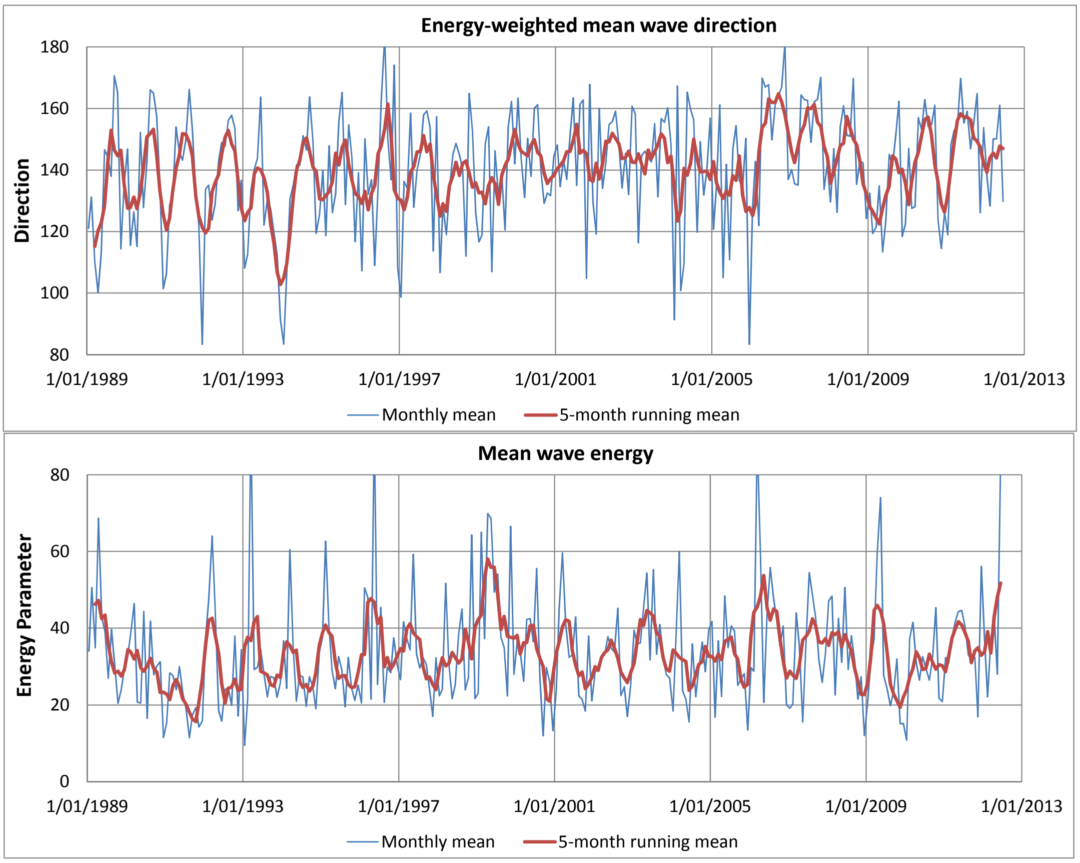


Figure 2-18 Monthly mean wave direction (top) and energy factor (bottom) since 1997

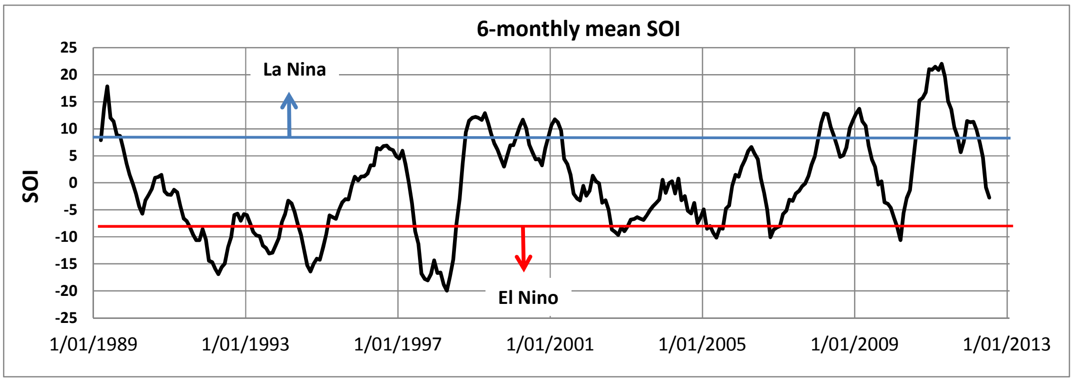


Figure 2-19 Monthly SOI since 1989

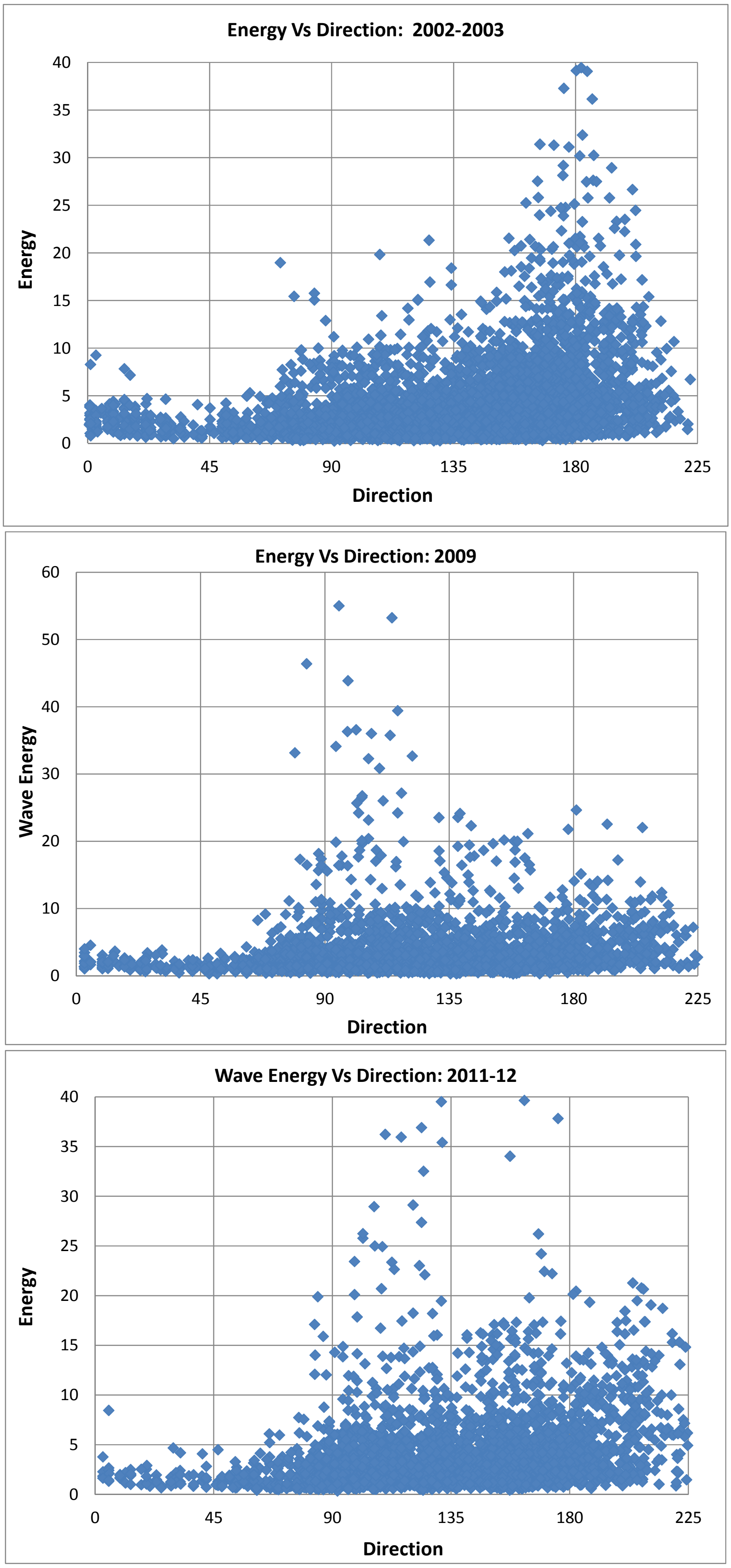


Figure 2-20 ENSO-related wave patterns: El Niño (top) and La Niña (centre / bottom)

2.3 Water Levels

In an open coastal situation, the components which contribute to elevated ocean water levels that influence beach erosion and potential foreshore overtopping and inundation during storms include:

- Astronomical tide;
- Storm surge, comprising the combined effects of:
  - Inverted barometric setup;
  - Wind setup;
- Wave setup; and
- Wave run-up.

The combined total ocean level of astronomical tide and storm surge is generally referred to as the storm tide. Sea level rise will also contribute to elevated ocean water levels in the future, and must be considered in any assessment of shoreline recession and inundation hazards.

2.3.1 Astronomical Tide

Forces caused by the gravitational attraction of the Moon, the Sun and the Earth result in the periodic level changes in large bodies of water. The vertical rise and fall resulting from these forces is called the astronomical tide. Tides of the NSW coastline are classified as semi diurnal with significant diurnal inequalities, with two high tides and two low tides per day that are generally at different levels (i.e. the two high tide levels are different in any one day).

Astronomical tides are well understood and can be predicted on the basis of their harmonic constituents. The variation of Mean High Water Springs along the NSW coast derived from the constituents (M2+S2) is illustrated in Figure 2-21, indicating only a slight increase of about 10cm along about 1,000km of coastline. This is reasonably consistent with the recent analysis by Manly Hydraulics Laboratory (2011) which indicates an increase of slightly more than 20cm in the total tidal range, defined by MHL in terms of (M2+S2+1.2*K1+1.2*O1), corresponding to 10cm increase in the total amplitude. The predicted tidal levels derived from constituents for the Tweed-Byron region are shown in Table 2-2. There is only about 3cm difference between MHWS there and at Fort Denison in Sydney.

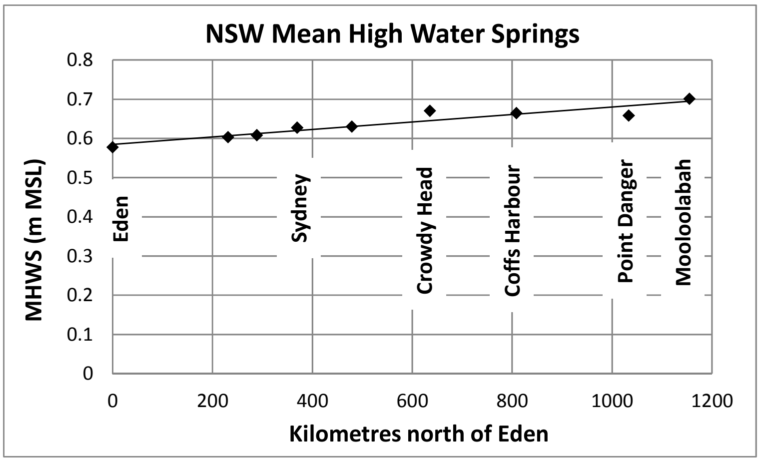


Figure 2-21 Mean High Water Springs variation along the NSW Coast

Table 2-2 Tidal statistics for Tweed-Byron region

Tidal Plane	m AHD
Highest Astronomical Tide (HAT)	Approx. 1.0 – 1.1
Mean High Water Springs (MHWS)	0.66
Mean High Water Neaps (MHWN)	0.37
Mean Sea Level (MSL)	0.0
Mean Low Water Neaps (MLWN)	-0.37
Mean Low Water Springs (MLWS)	-0.66
Lowest Astronomical Tide (LAT)	-1.0

Derived from tidal constituents: Source Australian National Tide Tables

2.3.2 Elevated Water Levels

2.3.2.1 Ocean Storm Tide Levels

DECCW (2010) presents average recurrence interval (ARI) water levels for use in coastal assessments in the Sydney region, with adjustment required for other parts of NSW depending on local conditions. The design storm tide (tide plus surge) water levels applicable in the Tweed-Byron region are given in Table 2-3. The levels in Table 2-3 compare reasonably well with those derived from other studies for the local Gold Coast region by James Cook University (1977) and McInnes *et al* (2000), as outlined in Table 2-4.

For 2050 and 2100 assessments, the ocean levels also include projected sea level rise from year 1990 at the previous NSW Government's benchmarks of 0.4 m and 0.9 m by 2050 and 2100 respectively. Note also that the levels in Table 2-3 account for the sea level rise of 0.06 m that has been recorded already between 1990 to 2010 (DECCW 2010). A small increase in storm surge heights (1–3cm) associated with future climate change has been projected by McInnes *et al* (2007).

Table 2-3 Design elevated water levels for Fort Denison (DECCW 2010)

ARI (years)	2010 (m AHD)	2050 (m AHD)	2100 (m AHD)
0.1	1.00	1.44	1.94
10	1.35	1.69	2.19
50	1.41	1.75	2.25
100	1.44	1.78	2.28

Table 2-4 Comparison of design storm tide levels from various studies

Recurrence Interval (years)	Fort Denison (DECCW 2010) (mAHD)	Gold Coast (JCU 1977) (mAHD)	Gold Coast Seaway (McInnes *et al* (2000) (mAHD)	
			Including setup	Excluding setup
Immediate to 20yr	1.00-1.38	1.24		
50	1.41	1.30	1.9±0.1	1.1-1.2
100	1.44	1.35	2.1±0.1	1.3-1.4

2.3.2.2 Wave Set Up

As waves approach a beach across the surfzone they cause changes in the mean water level which is associated with gradients in the radiation stress of the wave train (i.e., the pressure force in excess of hydrostatic pressure caused by the presence of waves). Once waves have broken, kinetic energy is released and the mean water level is raised, sometimes substantially above the still water level. Maximum setup occurs at the beach face. The amount of setup depends on wave height, wave steepness and beach slope.

Although wave setup along the open coast shoreline is reasonably well understood there is growing evidence that propagation of wave setup through estuary entrances is minimal. Measurements documented by Hanslow and Nielsen (1993) from the Brunswick River entrance (NSW north coast) indicated that even when waves were breaking across the entrance, measurements of mean water surface extending up-river for some 200 to 300m showed only a very small transfer of wave setup. The maximum wave setup within the entrance was found to be less than 3% of the offshore wave height.

However, wave setup contributions to elevated water levels in the ocean can affect estuaries or stormwater discharge outlets by acting to impede the outflow of water during flood events. That is, the hydraulic gradient between outflowing flood waters and the ocean may be reduced where ocean levels are high, exacerbating flooding upstream in the estuary or stormwater system.

Normally, wave setup is incorporated in the calculations of wave run-up, the key factor considered herein in terms of inundation related to wave effects.

2.3.2.3 Wave Run-up

Wave run-up is the vertical distance on the shore that the uprush of water from a breaking wave reaches above the local mean sea level. It is the wave run-up mechanism that governs the volume of water that overtops a coastal barrier, for example, dunes, seawalls and entrance berms. Wave run-up levels are dependent upon factors including wave height, wave period, storm surge, beach slope and permeability, the roughness of the foreshore area and wave regularity. Run-up is more severe on steeper slopes and impervious materials, which means that steep-sloped grouted rock seawalls will generate much higher run-up than gently sloped beaches.

Wave run-up is variable due to the irregular nature of waves and is commonly assumed to have a Rayleigh statistical distribution matching that of the prevailing waves.

For coastal inundation hazard definition, the potential for wave overtopping is an important consideration when determining the effectiveness of protection offered by existing dune barriers and seawalls, particularly with future sea level rise. Analyses of wave run-up levels and the associated potential for significant wave overtopping have been undertaken for each of the study beaches, including provision for sea level rise at 2050 and 2100, as reported in Section **3.6**.

2.3.2.4 Elevated Estuary Water Levels

Water levels within the lower estuaries of rivers and creeks may be elevated due to the effects of storm tide penetration, wave setup and the flow gradient through the entrance during flooding. There is uncertainty about the extent to which wave setup will propagate through river and creek entrances.

It is likely that, for relatively small creeks with shallow bars at their mouths, there will be a component of setup that increases the lower estuary water levels, though it will be significantly less than occurs along the adjacent beaches. As well, small creek systems respond more quickly to rainfall runoff from their catchments than larger river systems, with greater likelihood of high flood discharges coinciding with high waves and setup at their mouths during major storm events. For the purpose of this study, water levels within the lower estuary areas of the small creeks within the shire are taken to include the effects of some wave setup and the flood flow gradient.

2.4 Sediment Budget and Shoreline Change

2.4.1 Previous Studies

Shoreline changes and longshore sand transport processes along some of the beaches within the study region have been investigated in considerable detail over the past 30-40 years, including:

- Letitia Spit to Gold Coast beaches (Delft Hydraulics Laboratory 1970; Pattearson & Patterson 1983; Roelvink & Murray 1992; Hyder *et al* 1997, Patterson 1999);
- Byron Bay (PWD 1978; Patterson Britton Partners 2006);
- Byron Shire beaches (WBM Oceanics Australia 2000);
- Tweed Shire beaches (WBM Oceanics Australia 2001);
- Ballina Shire beaches (WBM Oceanics Australia 2003); and
- Woody Bay. Iluka (Moratti & Lord, 2000).

Of particular significance, there has been wide divergence of outcomes from those investigations with respect to assessment of:

- Short and longer term trends of shoreline change; and
- Rates of net longshore sand transport, gradients in longshore transport and their relationship to shoreline changes along the study area.

Waves approaching the shoreline from an oblique angle generate a current alongshore which, in conjunction with the wave action, transports sediment. Depending on the prevailing wave direction, the alongshore sediment transport may be directed either north or south along the coast. On the northern NSW and south-east Queensland beaches, the net alongshore sediment transport is directed to the north, due to the predominant south east wave climate relative to the general north to south orientation of the coastline.

Alongshore sediment transport (also commonly referred to as littoral drift) occurs predominantly in the mid to outer surfzone (or inner nearshore zone), diminishing in strength with distance offshore into deeper water. In some circumstances, winds and tides may contribute to longshore currents. During intense storm conditions, wind-induced currents may predominate outside of the surfzone. Longshore transport gradients are considered to be the dominant factor in the sand budget and shoreline changes. The geological interpretation supports this, based on variation in the width of the Holocene dune barrier.

The net regional longshore transport rate will be greater or lower than the average annual rate in any one year, or over years to decades depending upon the wave climate conditions. Wave climate may enhance or reduce the longshore transport rate due to slight shifts in wave direction and may affect the bypassing of sediment past headlands and reefs, which typically occurs during higher wave conditions.

The previous analyses of longshore transport rates have been hampered by the lack of a reliably defined directional wave climate. As well, they have been undertaken in a somewhat piecemeal manner, being related to specific coastal management issues. Average annual net longshore transport rates from various previous studies are summarised in Figure 2-22 (Delft Hydraulics Laboratory 1970; PWD 1978; Pattearson & Patterson 1983; WBM Oceanics Australia 2000; WBM Oceanics Australia 2003; Patterson Britton Partners 2006; Patterson 2007a; BMT WBM 2011; Patterson 2013). In addition, net longshore transport rates have been analysed as part of modelling undertaken for the present study, included in Figure 2-22 as BMT WBM (2013) (this study).

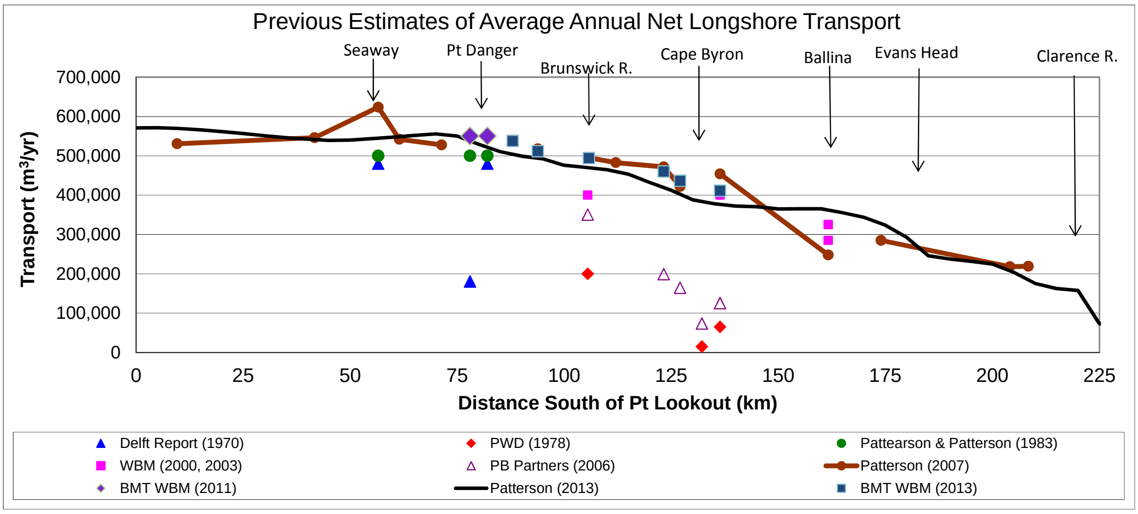


Figure 2-22 Historical estimates of the average annual net longshore sand transport rates

Only the analyses of Patterson (2007a; 2013) have adopted a regional approach to provide consistency along the entire coastline unit where it is known from the geological evolutionary history that there is a continuous alongshore transport of sand and shoreline change responses at particular beaches affect responses at adjacent beaches. Patterson (2007a) used a consistent and comprehensive analysis methodology involving detailed SWAN wave modelling and longshore sand transport calculations based on the wave data available to that time to show, for the first time, that the potential longshore transport rates vary from about 200,000m^3/yr at Iluka to 550,000m^3/yr at the Gold Coast. Patterson (2013) used shoreline modelling of the late Pleistocene-Holocene coastline evolution through to present day to indicate the same contemporary longshore transport pattern. He noted that such a transport rate at the Clarence River is contrary to the generally accepted understanding. His research included analysis of the net supply of sand from the lower river estuary and found agreement with the rate derived by Floyd and Druery (1976) from bar growth data of about 120,000m3/yr, additional to about 70,000m^3/yr being supplied from further south. Further, he concluded that this sand is predominantly marine sand previously accumulated in the lower estuary basin that is now being displaced by fluvial sediment currently depositing there.

The long term process of evolution tends to result in either dynamic balance or only gradual and progressive gradients in average net rates of both cross-shore and alongshore sand transport along the whole region. This has been demonstrated by Patterson (2013) who suggests a delicate balance between the contemporary longshore transport gradient and the residual shoreward sand supply.

The results of those analyses that have utilised a reasonable length of recorded directional wave data and adopted a consistent regional basis for determining wave transformation and sand transport rates show compellingly that there is a gradient in the net longshore sand transport rate from about 150,000-200,000m^3/yr at the Clarence River to about 550,000m^3/yr at the Gold Coast. This represents an average gradient of 350,000-400,000m^3/yr along about 150km, equivalent to 2.3-2.7m^3/m/yr.

This differs markedly from the earlier assessments of Delft Hydraulics Laboratory (1970); PWD (1978) and Patterson Britton Partners (2006). The Delft study has been shown subsequently to be erroneous (Pattearson & Patterson 1983; Roelvink and Murray 1992). Both it and the PWD studies were hindered by lack of any recorded directional wave data. The basis of the Patterson Britton Partners assessment is not clear but appears to be a modification of the PWD finding. Accordingly, the alongshore transport rates determined in each of those studies are considered to be not sufficiently reliable.

2.4.2 Cross-shore Sediment Transport

2.4.2.1 Storm Erosion

The study region beaches are exposed to large cyclonic ocean waves of H_s in excess of 7m. Cross-shore transport is dominated by exchanges of sand between the beach and the nearshore zone during storm events when large waves and elevated sea levels occur, causing sand to be eroded from the upper beach/dune system (often termed 'storm bite') and transported in an offshore direction, typically forming one or more shore-parallel sand bars in the nearshore zone. As the sand bars build up, wave energy dissipation within the surfzone increases and wave attack at the beach face reduces. During calmer weather, sand slowly moves onshore from the nearshore bars to the beach forming a wave-built berm under the action of swell waves. From the berm, wind blows sand to form incipient dunes and foredunes.

The severity of wave attack at the dune is dependent on wave height, elevated water level (the combination of tide, storm surge and wave setup) and preceding beach condition (i.e. if the beach is accreted or eroded prior to the storm). In addition, depending upon the orientation of the coastline relative to the direction of the incoming storm, the beach may either experience unimpeded wave power and severe erosion, or may be shadowed and protected from incoming wave energy.

Typically, the cross-shore exchange of sand from the upper beach/dune area to the nearshore profile does not represent a net loss or gain of sand from the overall active beach system. While it may take several years, the sand eroded in the short-term during severe storms is typically returned to the beach and dune by the persistent action of swell waves and wind, such that there is dynamic stability over the longer term. In addition, for stable embayments, the longshore transport into and out of the compartment is equal over the long term, enabling an overall balance in the cycle of storm erosion and recovery.

No survey measurements of the nearshore profiles that identify the nature and extent of storm event erosion have been undertaken for the majority of the study region beaches. However, comprehensive survey monitoring has been undertaken along the Gold Coast and northern Tweed Shire beaches, extending seaward from behind the dune to water depths around 18-25m, providing a good understanding of storm erosion in the broader region. The surveys measured the nature and extent of storm erosion in 1967, the most extreme surveyed cyclone season erosion monitored to date, and the subsequent recovery, as illustrated in Figure 2-23. Two shore-parallel storm profile bars were formed during the erosion process that culminated in June 1967 and was surveyed in July 1967. Profile modification is evident to a depth of about 13m.

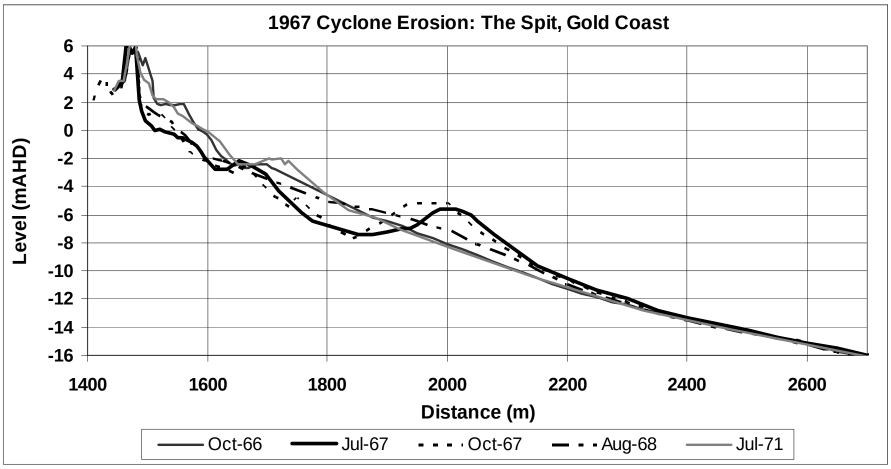


Figure 2-23 Profile response to cyclone erosion at Gold Coast in 1967

Other cyclone erosion events have been recorded in the surveys, for example the series of events that affected the area in 1988, as illustrated in Figure 2-24. This indicates more typical profile modification and bar formation limited to water depths of about 8-10m. This corresponds well to the Hallermeier (1977) depth of typical annual profile change, calculated for the Gold Coast wave climate to be about 9-10m. This prediction method for more severe storm events over a time frame of 50 to 100 years indicates a potentially greater depth of about 13m, consistent with that measured in 1967.

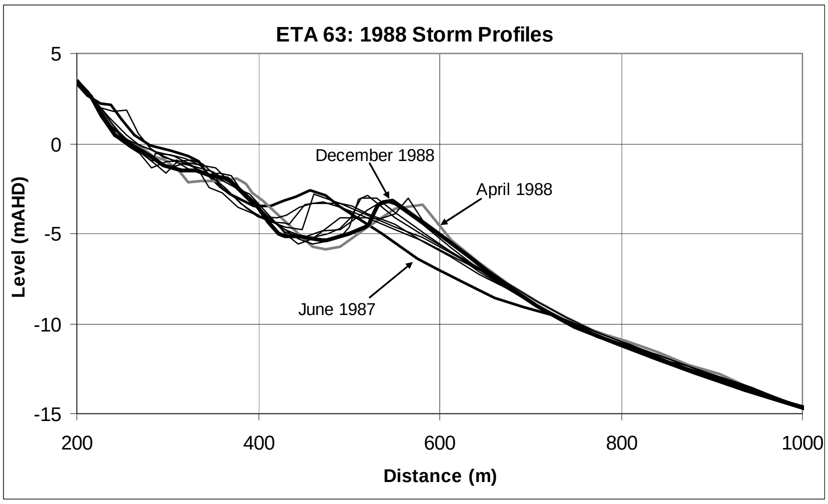


Figure 2-24 Profile response and bar migration associated with storm events in 1988

Storm bite volumes have been determined along many NSW beaches in terms of the loss of sand from above mean sea level (AHD) indicated in the photogrammetry. Storm bite volumes up to 250m^3/m have been identified but are more typically around 150-200m^3/m. The larger volume losses may occur during multiple storm events or where there is significant alongshore net sand loss in addition to the removal of sand to nearshore. The available updated photogrammetry is used in the present study to assess and confirm the appropriate storm bite provision for each beach.

2.4.2.2 Net Shore-face Supply to the Beach System

While a gradient in the longshore transport rates indicates progressive contemporary shoreline erosion, Roy (2001), Cowell *et al* (2000), Goodwin (2005) and Patterson (2013) suggest that there may remain a significant shoreward sand supply from the continental shelf that could be sufficient to at least partially offset the alongshore transport gradient and associated shoreline recession (Figure 2-25). Thus, any such recession may be significantly less than would otherwise result from the alongshore sand deficit alone. A shoreward supply of this nature and rate has not been proven, but would be necessary to reconcile the difference between the regional shoreline recession rates expected in consideration of the alongshore transport gradient and the relatively low rates of regional recession evidenced in the photogrammetry (refer Chapters 4 and 5).

Patterson (2013) shows that the shoreward supply is likely to vary across the shore-face from about 0.5-1.0m^3/m/yr at the lower shore-face to rates varying up to about 2-5m^3/m/yr at 10m depth, depending on location. While the lower shore-face supply is persistent and consistent along the coast, the higher rates at shallower depth are due to the effect of shoreline recession in inducing an additional shoreward supply at the upper shore-face, with a lag in the response time of the lower shore-face profile adjustment. This indicates a delicate natural balance between alongshore transport gradients, relatively small shoreward sand supply and shoreline change. For example, an average supply of 1-2m^3/m/yr along the 150km coastline from the Clarence River to Point Danger would offset 150,000-300,000m^3/yr of the 350,000-400,000m^3/yr gradient in the longshore transport gradient. This is most probably a significant component of the explanation for the relatively low rates of regional shoreline recession identified to date in the photogrammetry data.

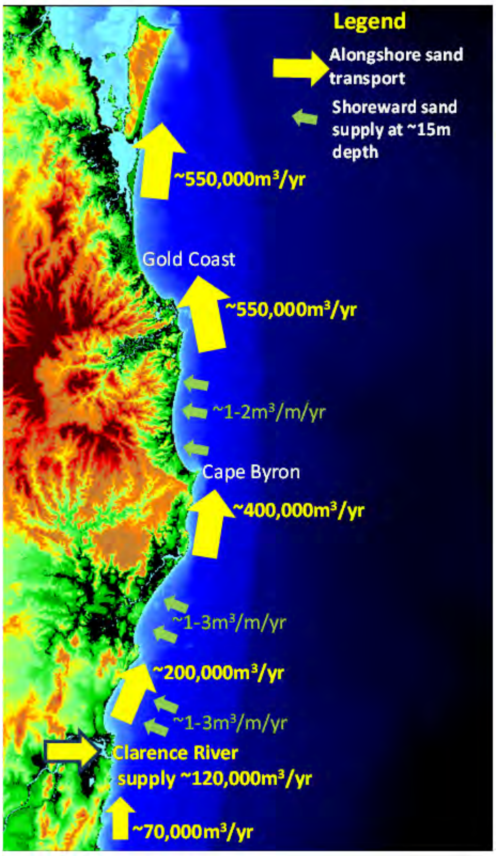


Figure 2-25 Regional sand transport regime

2.4.3 New Modelling of Contemporary Shoreline Processes

Regional coastline modelling based on reliable directional wave data, comprehensive wave propagation analysis and established longshore sand transport calculation methods (eg. CERC 1984; Kamphuis 1991) can provide useful information on the alongshore sand transport rates and gradients and the associated shoreline change processes. For the present hazard assessment study, a new shoreline processes model has been developed based on the EVO-MOD software developed by BMT WBM. This is quite separate and independent of the work of Patterson (2013) and is based on a more comprehensive approach to wave propagation and includes provision for cross-shore storm erosion shoreline responses. Key aspects of the EVO-MOD model include:

- Incorporation of the external wave model SWAN which is used to generate a set of comprehensive wave transformation tables used to define nearshore wave conditions in time series format by input of the deep water wave time series;
- Curvilinear baseline from which the shoreline definition grid points are defined such that, in combination with the external SWAN wave model, complex and highly embayed coastlines may be represented and simulated reliably;
- Incorporation of cross-shore profile evolution responses to storm erosion and recovery in combination with the effects of alongshore transport gradients on shoreline changes;
- A cross-shore profile structure in which the evolving surfzone profile is founded on an underlying profile of slope equivalent to that of the shore-face, which may be set consistent with that appropriate for Bruun Rule response to sea level change; and
- Capability to respond to both sea level changes, at short time-scales (tides; storm tides over hours to days/weeks) and longer time-scales (sea level rise over decades to centuries).

The model profile schematisation is illustrated in Figure 2-26.

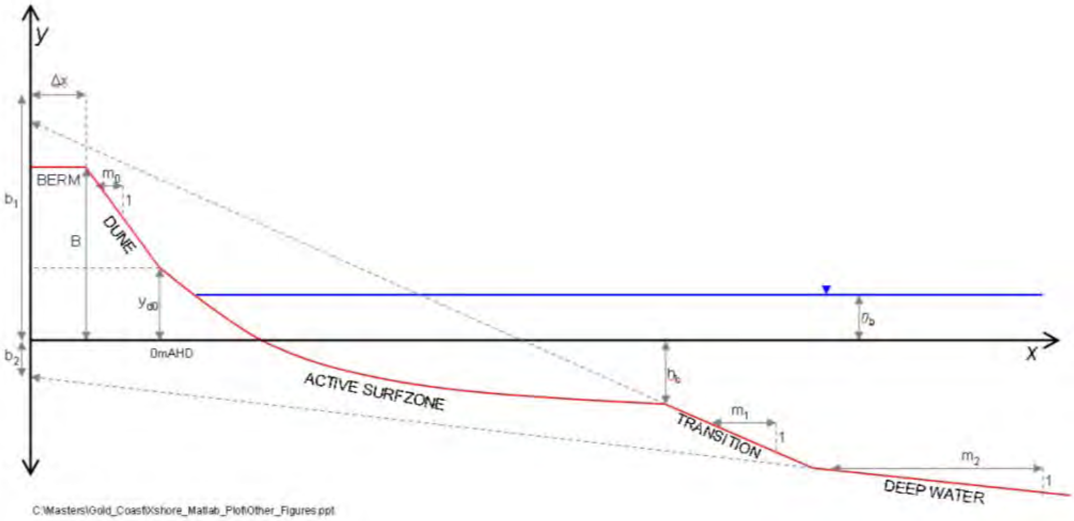


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Figure 2-26 EVO-MOD schematisation of the beach and nearshore profile

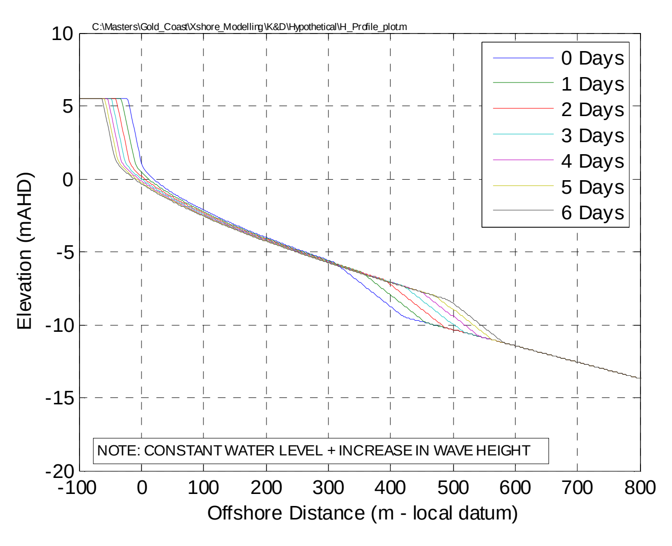


Figure 2-27 EVO-MOD time-dependent profile evolution with changing wave height

The EVO-MOD model has been established for the sub-regional extent of coastline from near the southern Byron Shire boundary on Seven Mile Beach to the northern boundary of Tweed Shire at Point Danger, as illustrated in Figure 2-28. The shoreline shape and structural controls including headlands, groynes, training walls and seawalls have been established in the model to match the geometry derived from charts, aerial photographs and survey data.

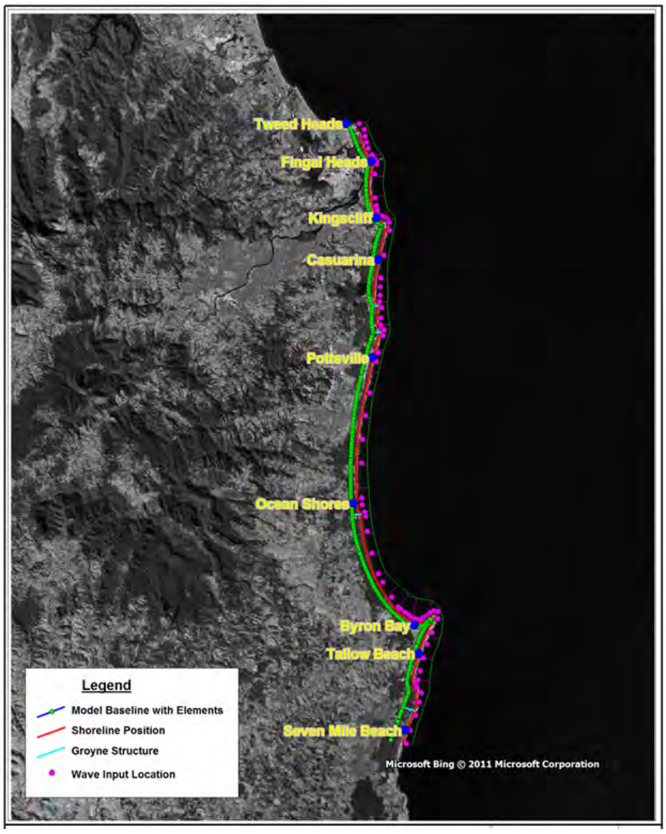


Figure 2-28 EVO-MOD model extent and baseline grid schematisation

The southern boundary condition is set to a constant annual average net longshore sand transport rate calculated initially for the input wave time series with fixed shoreline alignment corresponding to that derived from the measured marine Lidar bathymetry data. This confirms that the average annual net transport to be applied into the southern boundary of the model should be approximately 400,000m^3/yr. The daily variability of the longshore transport there is illustrated in Figure 2-29.

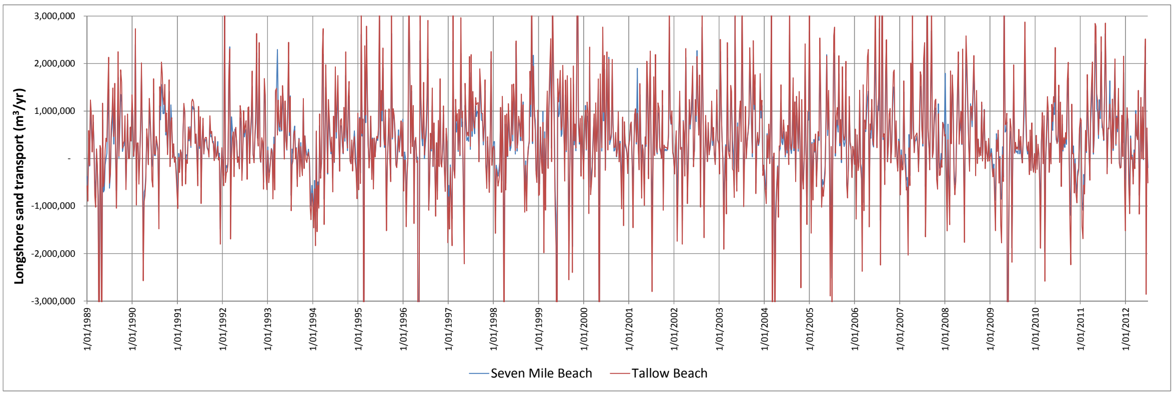


Figure 2-29 Calculated longshore transport at Seven Mile Beach and Tallow Beach

The model software and its application have been validated in development testing of sediment transport and profile evolution processes as well as responses to structure controls. The SWAN wave model that provides wave input data has been thoroughly validated in previous studies (BMT WBM 2011; BMT WBM 2012). The EVO-MOD system has been applied and validated to shoreline modelling along the Gold Coast for Gold Coast City Council (BMT WBM 2012).

The model is a tool to assist primarily in understanding relative long term recession patterns and to determine the impacts of sea level rise for this coastline with headland controls and relatively strong alongshore sand transport, rather than being accurate in absolute terms. To serve its purpose, the model has thus been established with sand transport and shoreline recession patterns that match reasonably the known behaviour, as described in the historical record (e.g. photogrammetry and independent analyses). However, it has not been refined to the extent that it caters for the effects of (for example) the minor sea level rise that has occurred in the past or any longer term (centuries to millennia) trends of change in the sediment budget regime. With respect to the latter, Patterson (2013) identified that there is a trend of progressive reduction in the net northward alongshore transport into the coastal compartment at the southern boundary of the model.

The new regional model has thus been validated by confirming that it produces regional shoreline recession at rates consistent with those derived from available measured data, in this case the photogrammetry analyses along the Tweed-Byron region, over a long 'warm-up' period of 1,000 years. The prevailing wave climate is represented by looping the available time series directional data collated from the recorded and global wave model information for the period 1989 to 2011 over that simulation period.

The photogrammetry analyses undertaken previously (WBM Oceanics Australia 2000; 2001; 2003) and in this study indicate a regional average shoreline recession rate of about 0.05-0.1m/yr, corresponding to an average sand loss of about 0.75-1.5m^3/m/yr. It has been found in the model simulations that:

- The annual average net longshore transport rate predicted by the model increases from 400,000m^3/yr at the southern boundary to approximately 550,000m^3/yr at Point Danger.

- Thus, a shoreward sand supply from the shore-face of about 150,000m^3/yr (2.1m^3/m/yr) of shoreward sand supply along the model length would yield a stable shoreline. A shoreward supply from the shore-face of 1.0m^3/m/yr, as suggested by Patterson (2013), would lead to an average deficit of 1.1m^3/m/yr, corresponding to approximately 0.075m/yr recession. This varies depending on location relative to headland controls, at rates consistent with those indicated by both the previous photogrammetry analyses and Patterson (2013).
- The modelled littoral zone longshore transport capacity through the Byron Embayment is less than the regional transport rate into and out of the embayment. This is because such models do not represent the complex 2-dimensional processes of cross-embayment transport. This is consistent with the modelling of Patterson (2010b). This cross-embayment component has been simulated by extracting some of the longshore supply immediately north of Cape Byron and distributing it along the Byron Embayment shoreline. The rate of cross-embayment transport has been found in the model to be about 200,000m^3/yr (approximately 50% of the total) to achieve balance between the littoral zone transport and shoreline stability, consistent also with the modelling of Patterson (2010b).
- At the Kingscliff embayment, an equivalent though less significant cross-embayment sand transport occurs through the zone from Sutherland Point to around the Cudgen Headland Surf Club area (refer Chapter 4 for a description of the sand transport processes there). There however, the model does force the sand transport through that zone, with considerable shoreline variability. While that variability is consistent with the observed and measured behaviour, the model cannot be expected to reproduce the processes accurately.

Based on the above, the model has been established with an average net shoreward sand supply of 1m^3/m/yr, corresponding to about 70,000m^3/yr along its length.

3 COASTAL HAZARDS ASSESSMENT: ISSUES AND METHODOLOGY

3.1 Coastal Hazard Components

Coastal hazards for Tweed Shire were assessed previously in 2001 (WBM Oceanics Australia 2001) and provide the basis for the existing erosion hazards and management plan provisions. The coastal hazards being updated in the present re-assessment relate to:

1. Beach erosion: The storm bite allowance that determines extent of retreat of the dune scarp during a major storm event or series of storms;
2. Shoreline recession: The underlying long term change in the position of the shoreline due to the prevailing coastal processes as well as the effects of sea level rise;
3. Coastal entrance instability: Entrance dynamics affecting shoreline stability at the untrained mouth of Cudgera Creek; and
4. Coastal inundation: Determination of the zones affected by elevated ocean levels and wave run-up processes, incorporating the effects of climate change induced sea level rise.

Updated knowledge of the extent of these hazards is based on a range of additional data, predominantly updated photogrammetry information on beach/dune changes now covering the period 1947 to 2010, and assessment methodologies consistent with improved understanding of the coastal system dynamics and responses to prevailing conditions, including modelling as appropriate.

3.2 Climate Change

3.2.1 Sea Level Rise

Both Byron and Tweed Shire Councils have adopted a sea level rise policy for planning purposes that is consistent with the previous Sea Level Rise Policy Statement (DECCW 2009a) that provides for an increase in mean sea level above 1990 levels of 0.4 m by 2050 and 0.9 m by 2100. The Office of Environment and Heritage (OEH) has advised that an estimated sea level rise of 0.06 m between 1990 and present should also be considered in coastal assessments. The sea level rise provisions adopted for this study are thus 0.34m by 2050 and 0.84m by 2100.

3.2.2 Wave Climate Changes

McInnes *et al.* (2007) investigated future wave heights (average and storm waves) and future wave directions due to climate change for Batemans Bay and Wooli Wooli Estuary. For Batemans Bay, McInnes *et al.* (2007) suggested a potential increase in storm wave heights of 32%, or decrease by 6% by 2070. Batemans Bay is relatively closer to Mid-latitude cyclones, which generate the dominant swell and storm waves along southern and central NSW. Therefore, use of the Batemans Bay projections for northern NSW is likely to give an over estimate of future storm waves. Projections for Wooli are inconclusive, with a potential decrease (-15%) or increase (+9%) by 2070. Projections for changes to swell wave height from the dominant SSE direction were similar for Batemans Bay and Wooli, but inconclusive (-8 to +8 %). Projections for changes to swell wave direction given by McInnes *et al.* (2007) suggested a shift of up to 3.3° more easterly at Wooli, and 3.8° more southerly at Batemans Bay.

The historical variability of wave climate over the past 60 years most likely reflects the range of possible conditions over the next century. The resolution of the climate change models (CCM2 and CCM3) used to derive the predictions for both studies is not sufficiently fine scaled to replicate all of the climatic systems important to the NSW coast. Most notably, the models cannot fully simulate the occurrence of east coast low weather systems that are responsible for extreme waves in NSW.

An increase in storm wave heights or shifts in average wave direction are considerations for future hazard extents at 2050 and 2100. Wave height and directional change during storms has largely been encapsulated by the approach taken to determining beach erosion hazard extents. Sensitivity testing of the variability of wave conditions has been included in the assessments for this study. This has been based on consideration of sustained periods of El Niño and La Niña phases to determine impacts upon regional longshore sediment transport rates and the variability of likely future shoreline recession trends. Additionally, a conservative determination of maximum likely storm wave heights has been adopted in the inundation assessments.

3.2.3 Storm Surge Impacts

Storm surge comprises the barometric pressure and wind set up components that, when added to the astronomical tidal level and wave set up, comprise elevated water levels at the shoreline during a storm. Elevated water levels may increase the severity of coastal erosion by moving the wave impact and swash zone further up the beach face. Elevated water levels may also result in inundation of low lying land where this is connected to the ocean through the entrance of a coastal stream or lagoon.

In the absence of regionally specific information, predictions for the likely change in storm surge due to climate change provided by McInnes *et al.* (2007) have been used in assessing future elevated water level events under a worst case or ‘rare’ scenario, in addition to projected sea level rise and wave set up change due to climate change impacts on wave height (as given above), for the coastal inundation hazard.

3.3 Beach Erosion (Storm Bite)

3.3.1 Erosion Processes

During severe storms or a series of storms in succession, increased wave heights and elevated water levels results in wave attack of the beach berm and foredune region. Storm events generate high rates of transport of sand both:

- Offshore, with sand eroded from the beach face and transported to the nearshore seabed to form a sand bar roughly parallel to the shoreline; and
- Alongshore (i.e., along the beach) either upcoast or downcoast depending on wave direction, with gradients in the transport rates leading to erosion or accretion.

The result is erosion on the beach face and dune that may pose a hazard to back beach land and assets. The short term storm related cross shore sand transport and longshore drift occur simultaneously, the latter commonly leading to a significant shoreline erosion component immediately downdrift of headlands in cases where the sand supply into the beach compartment is less than the transport away to the north. Their effects are additive, although the beach itself (above mean sea level) will be observed to erode predominantly during storm events.

The extent of storm erosion that will occur under the same set of water level and wave conditions may vary. This is because the volume of erosion relates also to:

- The occurrence, location and strength of rip current cells, which promote seaward transport of sediment and may allow larger waves access to the beach face, resulting in further localised beach erosion;
- The state of the beach (eroded / accreted both on land and underwater) immediately prior to the storm; and
- Adjacent headlands or coastal structures that can modify local wave conditions and the supply of sand during the storm event.

On average, stable beaches exhibit a form of dynamic equilibrium. Following periods of large-scale short term erosion, the beach will tend to restore itself over time to an average or accreted state during favourable wave conditions. This recovery involves the shoreward return of sand from nearshore and/or, where the erosion resulted from alongshore losses, a sand supply from updrift that exceeds the transport away, commonly associated with headland bypassing processes.

On beaches that are in long term 'dynamic equilibrium', the amount of sand that returns to the beach is equal to the amount eroded during the storm. However, at beaches experiencing long term recession, not all the sand eroded may be returned and the eroded dune escarpment will move landward on average over time.

3.3.2 Storm Bite Assessment

Photogrammetric data provides information on changes to beach volume and the position of dunes over time. While inaccuracies can be common in older dates of photogrammetric data, all dates of photogrammetry were found to be accurate for analyses in this study. Photogrammetry provides data on changes above mean sea level, therefore consideration of longer term trends is based primarily on movements of the upper beach/dune system. However, the photographs present individual ‘snap-shots’ that describe beach state at one particular time. Knowledge of the timing and intensity of major historical storm erosion events is taken into account in interpreting the available data.

The photogrammetric data has been processed to calculate beach / dune volumes for each profile cross-section, and both average and cumulative volumes along representative sections of shoreline analysed. The envelope of volumetric variability in the photogrammetric data over a period of several years or decades may provide a measure of the potential storm bite volume even where the data does not relate to any particular storm event, provided any long term trends are taken into account. This takes account of both storm erosion and short term (months to years) variability due to alongshore fluctuations. As well, the horizontal distances to several specified level contour positions have been determined to indicate beach width variability and any movements of the dune face. For this study, distances to the +1.5m, +2.5m and +4m contours have been analysed, with movements in the +4m contour indicating any progressive shift over the long term in the extent of storm erosion, also an indicator of long term recession.

Review of photogrammetric processing methods by Hanslow (2007) concluded that both the horizontal movement of a selected dune contour position and the sub-aerial beach volume calculation have statistical significance to be appropriate for use in hazard assessments. Both of these methods have advantages and disadvantages. Both the sub-aerial beach volume data (cumulative block volumes, individual profile volumes) and dune contour position movements have been used to assess beach erosion potentials, as well as historical long term shoreline trends.

The results obtained in this way are compared with experience elsewhere along the NSW coastline, where design storm bite volumes above AHD at fully exposed ocean beaches are generally in the range 150-250m^3/m, most commonly about 200m^3/m for reasonably accreted pre-storm beach situations. As adopted in the previous hazard definition studies for the region (WBM Oceanics Australia 2000; WBM Oceanics Australia 2001), unless the photogrammetry shows a clearly different result, the adopted minimum storm bite volume is 200m^3/m, reduced where the beach is already eroded due to previous storm events and/or at sheltered beaches with lower wave attack or where bedrock will limit erosion.

The erosion distance depends on the height of the dune affected. Typically, the foredune has a height of about 4-5m (AHD), rising in many places to higher main dune levels. Typically, where the average dune height is about 5m, a storm bite of 200m^3/m will correspond to about 40m recession. Higher dunes will erode less distance.

Each location is analysed on an individual basis. Generally, an attempt has been made to establish only one storm bite component for each location, based on the most recent accreted beach condition (typically 2007). Where uncertainty exists, it is feasible to adopt a range of values that may be incorporated into the probability spectrum in determining the erosion hazard lines.

3.4 Long Term Recession

3.4.1 Assessment Approach and Issues

The erosion hazard extents for the immediate, 2050 and 2100 planning times are based on the contemporary behaviour and forward projections of historical shoreline behaviour derived from the available data, together with analysis using either conventional coastal engineering methods or modelling of shoreline responses to sea level rise (SLR) and other likely climate change factors. The past behaviour comprises:

- Long term trends of shoreline change that relate to the geological evolution of the coastline regionally and will persist into the future;
- Short term storm erosion that will continue to affect the beaches much as it has to date;
- Short to medium term variability associated with variations in wave climate regime;
- Minor shoreline recession associated with the relatively slight sea level rise that has occurred over recent decades; and
- Anthropogenic influences such as coastal structures or sand mining interference with the beach/dune system.

Long term recession relates to the persistent and progressive existing trends of shoreline change that may be projected with reasonable confidence to the future. This needs to include also the projected progressive recession associated with future sea level rise. Superimposed on those trends are the reasonably well-defined cyclical effects of storm erosion and subsequent beach recovery.

However, additionally, there will be fluctuations and trends that are not readily assessed, associated with variability in the prevailing wave climate. This requires an assessment approach that caters for the uncertainties involved.

3.4.2 Considerations and Uncertainties

Beaches can be subject to longer term trends of erosion or accretion associated with the gradual net removal or addition of sand to the active nearshore profile. Such long term trends may be extrapolated to the future in determining the erosion hazard extent. Long term recession is frequently associated with an alongshore sediment transport gradient, where the average net supply of sediment into a beach compartment is less than that transported out. On natural beaches, strong local transport gradients are commonly associated with man-made coastal structures such as river entrance breakwaters that, when introduced to the coastline, interrupt the net longshore transport of sediment.

Shorelines experiencing progressive long term recession associated with natural longshore transport gradients must be considered in the context that the contemporary behaviour is the product of past evolutionary processes, including responses to prevailing wave climate conditions over about 6,000 years of approximately constant sea level. There may be short to medium term shoreline variability superimposed on a longer term trend, associated with storm erosion (days) and/or wave climate variability (months to decades). It may be difficult to identify and separate those processes. It is important that interpreted variability and persistent trends are consistent with the longer geological evolution context in order to have confidence in projections of future behaviour. In most cases, it would be unusual that a shoreline is experiencing a strong natural trend of recession or accretion unless there are circumstances of sand loss or supply that can be identified readily.

Extrapolation to the long term of trends that are part of cyclical variability will lead to inappropriate erosion hazard extents. Nevertheless, the variability needs to be taken into account in addition to the underlying progressive trend in defining the erosion hazard extent.

Beaches experiencing progressive long term recession due to net sand loss are often characterised by a prominent back beach dune escarpment which moves landward over time during subsequent storm events, without recovering fully to the pre-storm condition before the next major erosion occurs. While the active beach system extends from the dune seaward to water depths of at least 15-20 metres, the zone down to about 10 metres is the most active and responsive while evolution of the deeper parts occurs over progressively longer time scales. Thus, shoreline changes associated with alongshore transport gradients are concentrated initially in the upper 'littoral' zone subsequently become redistributed across the lower shore-face region over time.

Sea level rise (SLR) will cause recession of the shoreline by inundation of the foreshore together with some beach, dune and nearshore profile modification. In this case, it is recognised that most beaches develop a predominant long term average shape in response to varying wave conditions and balance between offshore sand transport during storm events and subsequent beach recovery with shoreward sand movement. This is commonly referred to as the 'equilibrium' profile, recognising that it is a condition that is rarely, if ever, achieved and most probably does not relate to any particular wave condition. Nevertheless, the 'equilibrium' shape to the profile is generally maintained relative to sea level, subject to the increasing response time scale with water depth. The 'Bruun Rule' is based on that concept, as discussed in Section 3.4.4. As well, modelling of sea level rise impacts also depend on adoption of an equilibrium profile refer Section 2.4.3 and Section 3.4.4.2. Uncertainties and limitations of both the Bruun Rule and the modelling relate to how the equilibrium profile is represented. While best estimates are determined, the uncertainties are provided for by adopting likely upper and lower limits to provide a range of potential outcomes within a risk-based approach.

3.4.3 Analysis of Historical Shoreline Recession

Historical shoreline recession trends may be identified most readily in the photogrammetry data in terms of either:

- Persistent progressive changes in the volume of sand contained in the beach/dune system; and/or
- Persistent and progressive changes in the position of the dune scarp.

Beaches experiencing long term recession are characterised by a persistent trend of reduction in the average sand volume and, often, a prominent back beach escarpment which moves landward over time. Net sand losses generally affect the nearshore area initially, typically due to alongshore gradients in the longshore sand transport rates. When the nearshore area has been depleted of sand progressively by longshore sand losses, the storm cut into the beach and dune will be unusually high and extend further landward than previously. In such a case, the beach will not recover to its former state.

Longshore sand losses create an overall net depletion of the active beach profile as retreat of the dune face, beach and nearshore profile down to a depth of about 10 metres, the typical limiting depth of longshore sand transport along the open coast. Thus, for a profile with dune height of 5 metres, only approximately one-third of the total volumetric sand loss occurs above mean sea level. This is an important factor in interpreting photogrammetric and survey data that only covers the upper beach/dune area.

It is feasible to identify such sand losses and thus the shoreline recession by analysis of the longshore sand transport rates. However, the database of recorded directional waves is limited and this approach is useful only where there is a significant transport gradient, typically along an extended coastline such as the regional context, as shown in Figure 2-19. This shows a substantial positive gradient in the longshore transport northward from the Clarence River to Point Danger of about 350,000-400,000m^3/yr along 150km, corresponding to an average of about 2.3-2.7m^3/m/yr. This would potentially lead to average shoreline recession for an active vertical zone of 15m (dune height of 5m to a littoral zone depth of 10m) of 0.15-0.18m/yr. However, it is likely that this is offset by some continuing shoreward sand supply to the beach system of at least 1m^3/m/yr (Patterson 2013), reducing the average recession to less than 0.1m/yr. Further, the recession is not uniform along the coastline, being less immediately updrift (south) of headlands and greater downdrift (north).

Accordingly, long term recession rates at particular beaches are generally determined from analysis of volumetric and/or lineal movement trends derived from survey or photogrammetry data. Shoreline recession trends within the study region derived in that manner should be reasonably consistent with the regional average, but will vary depending on location relative to headland controls.

However, short to medium term variability due to wave climate variability may mask such a trend in data that is of insufficient length to isolate and identify the two processes. This is evident along the study region, most particularly in the embayment areas north of major headlands. In those cases, the underlying trend of change that could be extrapolated to the future may be difficult to quantify and needs to be interpreted in light of the patterns evident in the measured photogrammetry data and the best available knowledge of the prevailing wave conditions, to gain an understanding of the timing and extent of such variability. As well, natural short to medium term variability may be assessed using shoreline response modelling for the period of the input wave information.

Both the historical long term recession rates and provision for the variability must be incorporated into the assessment of long term recession in the future in combination with recession due to sea level rise, as outlined below.

3.4.4 Sea Level Rise Impacts

3.4.4.1 Equilibrium Profile (Bruun Rule) Concept

The study region beaches have evolved with mean sea level relatively constant at or near the present level over about 6,000 years to a condition of cross-shore dynamic equilibrium. That is, the profile shape across the beach/dune and nearshore areas to the lower shore-face has an equilibrium form about which cross-shore storm erosion and accretion seabed changes fluctuate. In principle, that equilibrium shape tends to be maintained relative to sea level as the sea level changes. This two-dimensional concept is demonstrated by the Bruun Rule, in Figure 3-1.

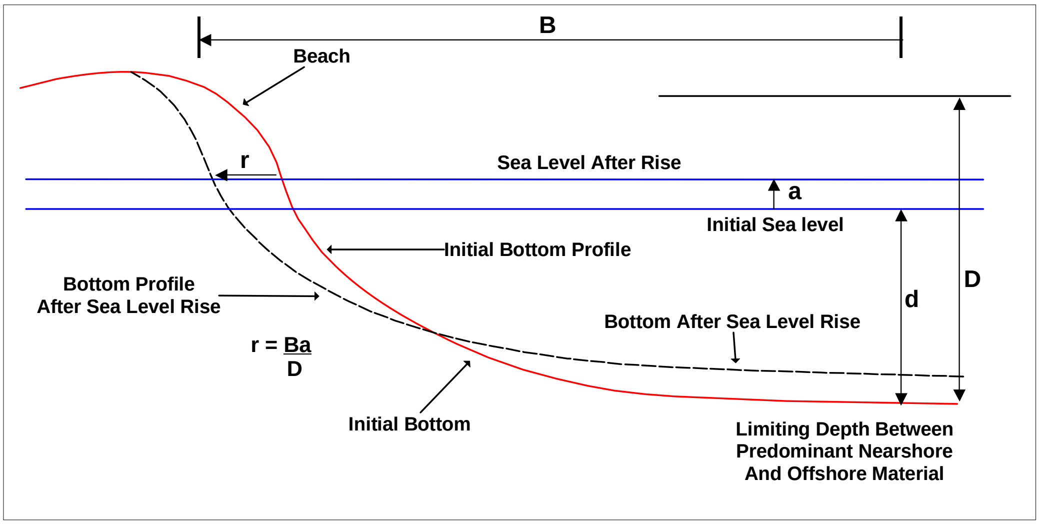


Figure 3-1 Bruun (1962) Concept of Recession due to Sea Level Rise

As the sea level rises, wave, tide and wind processes are occurring at a higher position at the beach face, with the beach and dune evolving to a more landward position to return to equilibrium with the new sea level. There is an upward and landward translation of the profile that is in equilibrium with the prevailing conditions at the new sea level position. Bruun (1962) has shown that the shoreline recession (r) may be estimated as Ba/D (as defined in Figure 3-1), where B/D represents the slope factor and the predicted recession is the slope factor times the sea level rise.

Application of this ‘standard’ simplified Bruun Rule has been highly contested within the coastal science community (e.g. Ranasinghe *et al*., 2007), often relating to the depth of closure to which the equilibrium shape is maintained. The depth of closure is generally adopted as the depth limit at which there is little or no potential for significant cross-shore exchanges of sand, but there has been conjecture surrounding what this depth may be. The DECCW (2010) *Coastal Risk Management Guide: Incorporating sea level rise benchmarks in coastal risk assessments* indicate the appropriate calculation of the depth of closure term required with the Bruun equation as follows: "*when using the 'Bruun Rule', use of the lower limit of profile closure (seaward limit of the Shoal Zone) as prescribed by Hallermeier (1981) is recommended in the absence of readily available information on active profile slopes at a location under consideration*". It has also been common practice along the NSW coastline to adopt generic active profile slope factors from the closure depth to the dune crest (Figure 3-2) in the range of 1:50 to 1:100. However, because of the intra-regional variability in slope that exists across the offshore NSW shelf, more rigorous site-specific analysis is recommended to justify the use of a selected active profile slope.

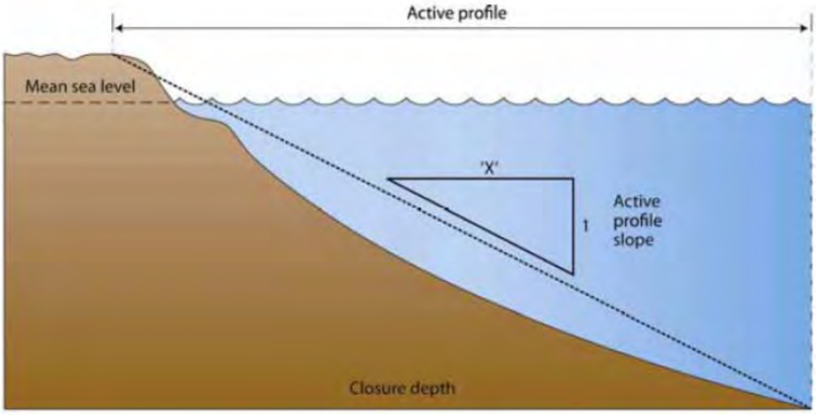


Figure 3-2 Idealised schematic of the active profile slope applicable in the 'Bruun Rule' (from DECCW, 2010)

Patterson (2012; 2013) has identified that the time-scale of profile response, the time required for the profile to achieve equilibrium, increases with depth and needs to be considered in determining closure depth. Nicholls *et al* (1998) and Cowell *et al* (2000) both refer to the closure depth in terms of the time scale considered. That is, they note that profile 'closure' occurs at greater depth as the time scale increases. Nicholls *et al* adopt a version of the Hallermeier (1977; 1981) relationship for depth of closure of the form:

$$d_{l,t} = 2.28H_{e,t} - 68.5(H_{e,t}^2 / gT_{e,t}^2) \qquad (1)$$

Where $d_{l,t}$ = the predicted depth of closure over *t* years, referenced to Mean Low Water; $H_{e,t}$ = non-breaking significant wave height exceeded 12 hours per *t* years; and $T_{e,t}$ = associated wave period.

On that basis, the depth of closure to cater for sea level rise over a planning period of 100 years will be greater than that adopted for shorter durations. Typical parameter values derived for the study region wave climate suggest a longer term (approx. 100 years) depth of closure in the range 15-16m. However, this does not provide for the concept of accumulation at the lower part of the equilibrium profile translation to balance upper profile erosion, on which the Bruun Rule is based. Nevertheless, use of the Hallermeier (1981) limiting depth (d_i) of significant net cross-shore sand transport is not recommended. This is given as $H_{sm}T_{sm}(g/5000d_{50})^{0.5}$, where subscript *m* denotes the long term median values and T_s is the significant wave period and d_{50} is the median grain size in metres. The recorded wave data indicates approximate values H_{sm}=1.35m and T_{sm}=9s, yielding a limiting depth (d_i) of about 36m. This corresponds to a depth of very long term profile response (centuries to millennia) and has no direct relationship to vertical profile change at a time scale of (approximately) 100 years.

Conceptually, it is appropriate to adopt a depth in the range zone h_L to h_i, as prescribed by Hallermeier (1977; 1981). These represent the seaward limit of regular vertical profile changes and the seaward limit of significant net cross-shore sand transport respectively. Within that range, the limitation imposed by the time-scale of profile response needs to be considered. Wright (1995) notes that there should be a thinning of the accretion in the vicinity of the closure depth and suggests an effective closure depth somewhere between h_L and h_i but does not pursue a specific choice of depth. Cowell et al (2006) deal with this in a probabilistic manner in which it is accepted that the toe of the profile may experience deposition in the range of 'full accommodation' (lower profile fully filled) or 'full dilation' (zero filling at the toe) with assigned probability. As such, the range of sea level rise recession distances derived with their methodology are expected to correspond to those equivalent to the *Bruun Rule* over the range of Hallermeier closure depths from h_L to h_i.

Further, BMT WBM emphasises that any application of the Bruun Rule must incorporate a reliable representation of the equilibrium shore-face profile shape, not affected by the transition to the inner continental shelf that commonly is evident beyond a depth of about 20-25m. Figure 3-3 illustrates the effective Bruun Rule slope factor that applies to typical exposed coastline parts of northern NSW and SE Queensland, being approximately 45:1 for a 5m dune height. The slope factor would be somewhat less for higher dunes, for example about 35:1 for 10m dunes and 40:1 for 8m dunes.

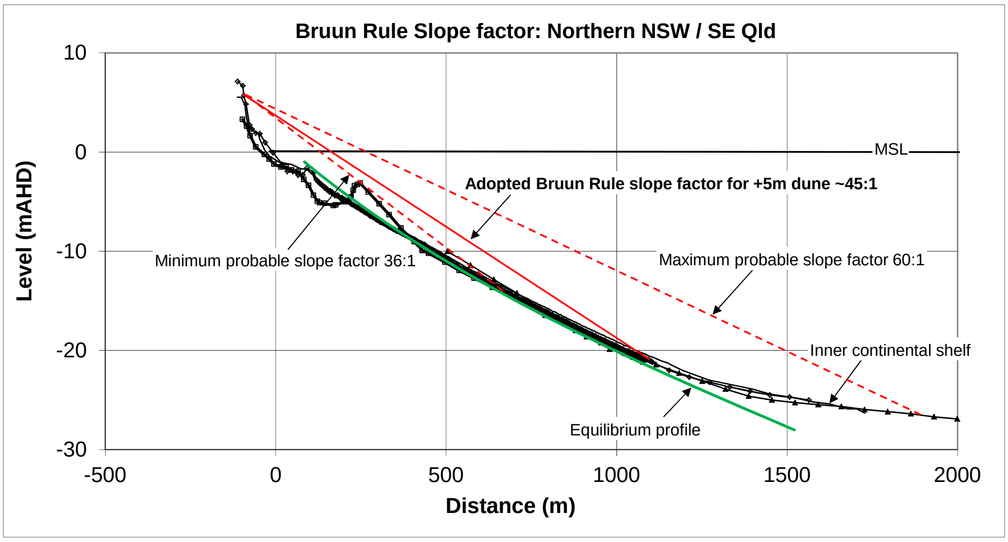


Figure 3-3 Bruun Rule slope factor for northern NSW and SE Queensland

The previous erosion hazard assessment (WBM Oceanics Australia 2000) adopted a generic Bruun Rule slope factor of 50:1 for shoreline recession. For this assessment, a best estimate factor of 45:1 is adopted based on available data for the study region. To allow for the uncertainties involved in determining projected future sea level rise impacts on the shoreline, lower and upper limits of potential recession are set by applying variation of -20% to +30% to the best estimate factor; that is, a range of approximately 36:1 to 60:1 for 5m high dunes. Those limits are considered reasonable on the basis of their fit with the profile shape, as illustrated in Figure 3-3.

Thus, considering the adopted future sea level rise levels of 0.34m and 0.84m at 2050 and 2100 respectively, the Bruun Rule approach would yield recession provisions for 5m high dunes shown in

Table 3-1. While the photogrammetry shows that 5m is the typical active dune height for the beaches of northern NSW and SE Queensland, where the recession would extend into higher hind-dune areas, those provisions need to be factored down proportionally, as outlined above.

Table 3-1 Bruun Rule shoreline recession provisions for 5m dunes

	2050	2100
Minimum	12m	30m
Best Estimate	15m	38m
Maximum	20m	50m

Further, it must be recognised that the Bruun Rule does not provide for longshore processes in which the headlands and other control structures provide stability and reduced recession on their updrift (southern) side and exacerbated downdrift recession to their north. For the assessments at each individual location in this study, an allowance for those effects is incorporated, with guidance provided by modelling that caters for both longshore and cross-shore profile adjustment processes.

3.4.4.2 Shoreline Evolution Modelling of Sea Level Rise Effects

BMT WBM utilises shoreline evolution modelling as a means of analysing the complex interactions of both longshore and cross-shore processes that will affect the shoreline in the future as the sea level rises (Patterson 2009; Patterson 2010a; Patterson 2013; Huxley *et al* 2010; BMT WBM 2012). The modelling undertaken for this study using the EVO-MOD system internally calculates shoreline movements and cross-shore profile evolution in response to both alongshore and cross shore sediment transport, driven by wave time series. It thus incorporates responses to storm erosion and subsequent recovery. The model includes the effects of coastal structures such as headlands, groynes and seawalls where they are present in the natural coastline. This model is particularly effective at a regional scale as it is able to model multiple beach units along long coastlines. The modelling also will simulate the longshore responses in the absence of SLR or other cross-shore effects, and also will simulate the cross-shore responses in the absence of significant net longshore sand transport. As such, this model is a significant advance from the Bruun Rule (1962) for analysis of sea level rise impacts as it is able to account for the three dimensional nature of the coastline including the headland/groyne effects initiated by the shoreline retreat.

Sea level rise impacts on shoreline recession are inherently simulated through maintenance of the equilibrium profile condition relative to sea level as it rises. The active upper profile continues to respond to the alongshore processes and short term profile evolution relative to the changing prevailing sea level. The underlying profile slope below the transition slope (Figure 2-26) also affects how the profile progressively recedes, a flatter slope leading to greater recession, although conceptually it does not correlate with the Bruun slope factor. That slope corresponds to the lower shore-face profile shape and is typically about 1:50 to 1:60 in the study region. The more conservative flatter slope of 1:60 has been adopted for the present modelling. There are clearly uncertainties and limitations involved, however it is considered that the model approach is more thorough than the Bruun Rule in dynamically linking the profile response with the alongshore response processes.

The incremental impacts of sea level rise are simulated by testing the model for both existing and rising sea level and deriving the differences in shoreline position at 2050 and 2100 respectively. The model result is shown in Figure 3-4 This indicates a general average recession at 2100 of about 35-40m, reasonably consistent with the best estimate Bruun Rule provision in Table 3-1, but with significant alongshore variation involving larger recession distances (60-80m) immediately north of headlands and less (15-20m) immediately south. This has been shown (Patterson 2009; 2010; 2013) to result from re-activation of the 'groyne' effect of both natural headlands and anthropogenic coastal structures associated with the tendency for shoreline recession in combination with significant net alongshore sand transport, as illustrated in Figure 3-5.

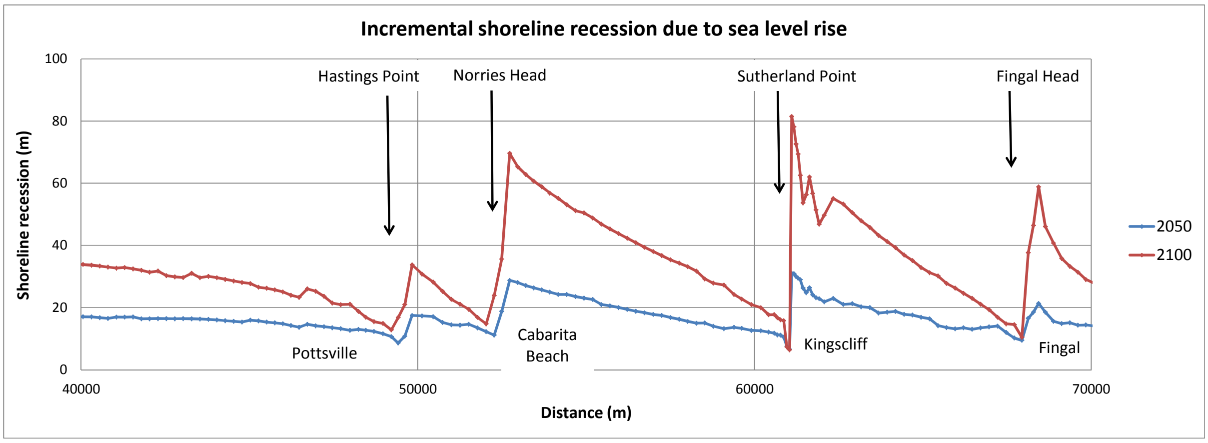


Figure 3-4 Modelled incremental recession due to sea level rise

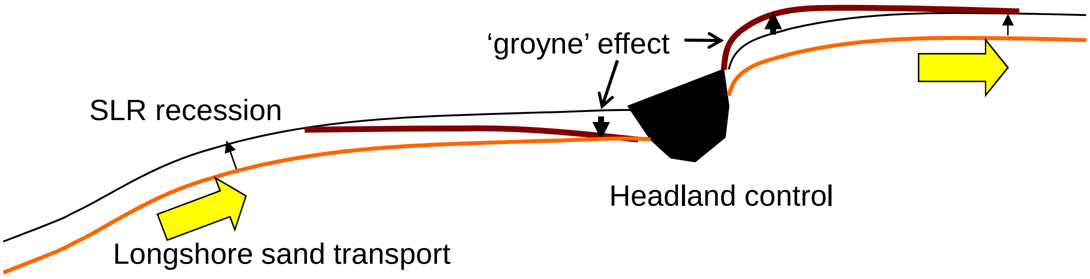


Figure 3-5 Conceptual 'groyne' effect of headlands on shoreline change due to sea level rise

The model result is therefore adopted as the more comprehensive best estimate of recession due to sea level rise for hazard assessment purposes at each part of this coastline, in lieu of the Bruun Rule result. However, allowance for the uncertainties involved in determining projected future sea level rise impacts on the shoreline is made with lower and upper limits of potential recession set by applying variation generally of -20% to +20% to the best estimate recession distances from the model, except where local circumstances or uncertainties suggest higher factors should be applied.

3.5 Erosion / Recession Hazard Definition

3.5.1 Erosion Hazard Assessment Approach

The beaches along the study region experience considerable short term (days; weeks; months; years) fluctuation and short to medium term (years) variability due to changes in the prevailing wave and water level conditions, including storm events and shifts in the predominant wave direction. Additionally, previous studies (e.g. WBM Oceanics Australia 2000; 2001) have established that there is a general regional trend of long term shoreline recession, as discussed in Chapter 2.

The conceptual pattern of shoreline variability and progressive long term change is illustrated in Figure 3-6. It can be seen that there may be periods of sustained shoreline accretion despite the longer term erosion trend. Correspondingly, there may be periods of recession at greater than the longer term trend rate. The short to medium term fluctuations may thus mask the longer term trend and care must be taken in interpreting shoreline change data, particularly over limited time periods.

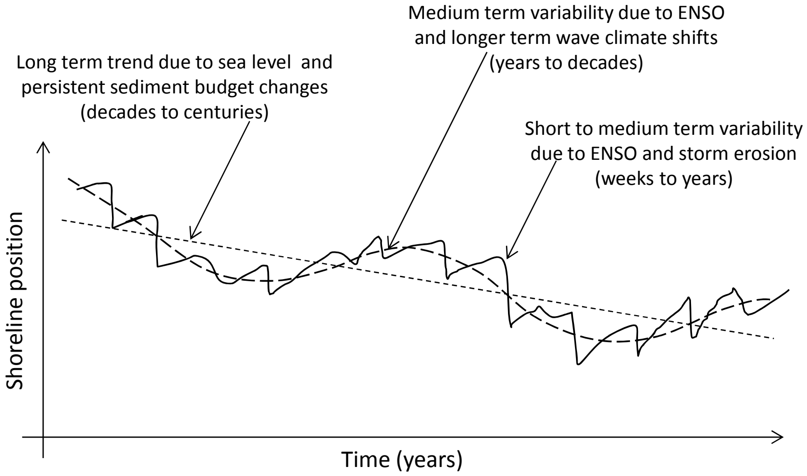


Figure 3-6 Conceptual shoreline variability

Thus, the 'immediate' erosion hazard extent represents the zone that could be affected by erosion in the immediate near future (e.g. over the next few years) in the event of one or more major storm events while the 2050 and 2100 extents incorporate a landward shift in the immediate hazard line in response to the recession provisions. The hazard extents determined are intended to inform management planning and future decisions about how the coastline is managed.

The erosion hazard extent is thus assessed by taking account of the combined factors of:

- Storm bite extent.
- Natural short to medium term variability of the shoreline.
- Projection to the future, with hazard definition at years 2050 and 2100,of:
  - Any presently prevailing long term shoreline recession; and
  - Shoreline recession caused directly by the effects of projected future climate change induced sea level rise.

This is illustrated conceptually in Figure 3-7.

Figure 3-7 Conceptual schematic of erosion hazard areas (from DECCW 2010)

It is difficult to assess how variability in the prevailing wave climate has manifest in terms of the existing shoreline state and will affect future shoreline changes. As illustrated conceptually in Figure 3-6 and identified in the photogrammetry analyses described and discussed in Chapter 4 and Chapter 5, that variability may be significant, if not dominant, compared to the underlying long term trends at some locations. For example, the shorelines immediately north of controlling headlands appear to show erosion-accretion variations in direct response to wave climate variability and associated significant gradients in the alongshore sand transport. The SOI record indicates predominantly La Niña conditions from about 1945 to 1977 and El Niño dominance from 1977 to around 2006-2009, after which a phase of La Niña has been again evident. Whether or not that marks another phase of protracted La Niña is unknown but has a major influence on how the shoreline might behave over the next few decades and possibly longer.

The north-south aligned shorelines along the more exposed parts of the coast do not show such variability as they do not experience strong alongshore transport gradients with changing wave conditions.

It has been adopted that allowance for variability be incorporated in the erosion hazard lines by provisions such that:

1. The immediate erosion hazard should provide for potential short to medium term variability associated with variable wave climate patterns over the next few years, in addition to the calculated ‘design’ storm bite component, consistent with the adopted time frames for coastal planning.
2. The storm bite component considers the variable state of erosion or accretion of the beach and dune from which the design storm erosion volume is eroded, taking account also of the maximum extent of erosion that has occurred in the past.
3. Future erosion hazard extents are determined as landward recession movements of the immediate erosion hazard extent to provide for the effects of sea level rise, incorporating a range of recession distances that account reasonably also for the uncertainties involved in the analysis procedures.

3.5.2 Erosion Hazard Assessment Uncertainty

The definition of coastal hazards inherently involves uncertainty relating to not only how prevailing oceanic conditions will manifest in the future and how reliably their effects on the shoreline can be determined, but also the considerable unknown factors involved with climate change. There are uncertainties surrounding climate change projections, the timeframes over which this change may occur and how climate change may affect the environment. Irrespective of climate change, the episodic nature and unpredictability of coastal hazards have always presented a challenge to planners and managers. There is limited measured data on coastal processes (e.g. historical shoreline change, wave climate, water levels and response to these variables) and there are many different ways to assess the shoreline responses, which add to the uncertainty in estimating coastal hazards.

This hazard assessment investigation of the complex processes affecting the study region has been undertaken to define the nature and extent of coastal hazards to facilitate a management response and a reduction of associated risks including environmental degradation. While uncertainty, variability and technological limitations of the study are acknowledged, such uncertainties are not a reason to avoid quantification of the hazards. This is consistent with the Australian EPBC Act 1999 that states that "… lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation".

The uncertainty and natural variability in coastal processes along the study region was recognised in the previous hazard definition assessments (WBM Oceanics Australia 2000; 2001). It was noted that adopting a best estimate (single line) approach inherently incorporates a possibility that the limit of erosion will either extend beyond the projected line or never reach it.

The approach adopted has been to provide a band of feasible erosion extents, in order to illustrate the variable probability associated with erosion reaching certain limits within each planning period. The upper (landward) limits of the band represented an erosion extent that had a low likelihood of being reached. Conversely the seaward boundary of the band represented the minimum distance considered appropriate for planning purposes and, by definition, erosion has a high likelihood of reaching that line within the specific planning period.

The erosion hazards are thus determined and presented in terms of:

- The immediate erosion hazard which includes provision for the design storm bite with provision for the effects of wave climate variability over the next few years.
- The 2050 and 2100 year erosion hazards for which the immediate erosion hazard extent is carried forward to 2050 and 2100 respectively to incorporate the effects of underlying recession trends and sea level rise, with provision for uncertainties about those processes leading to hazard extent ranges from 'minimum' through 'best estimate' to 'maximum'.

Combining the long term recession due to sea level rise and underlying recession trends with the immediate beach erosion hazard determined in this manner ensures that wave climate variability, long term permanent change and the uncertainties involved are captured within the hazard extents. Provisions for uncertainties associated with projection of future shoreline recession to determine likely range of the hazard extents are made on the basis of:

- Assessment of the immediate erosion hazard on the basis of the design storm bite provision in the context of the present erosion-accretion state of the beach and dune, in consideration also of variability patterns determined for each location on the basis of analysis of the photogrammetry data, as described in detail in Chapters 4 and 5.

- Assessment of the best estimate, as well as and upper and lower limits of the prevailing underlying long term recession rates, determined for each location on the basis of analysis of the photogrammetry data and consideration of regional trends, as described in Chapters 4 and 5.
- Adoption of modelled shoreline recession responses to sea level rise as the best estimate values, which are shown to correlate well with the Bruun Rule approach where effects of coastal headlands and structures are minor, with ±20% provisions applied to those best estimate distances to represent reasonable upper and lower limits, based on best practice engineering opinion as informed by the available evidence.

The available understanding of coastal processes and climate change and the potential for hazards impacts will continue to improve in the future, allowing for improvements in determination of likelihood or probabilities in the future. Continued expansion of the data base and improved assessment methods will assist in refining the coastal hazard risk assessments in the future.

3.6 Coastal Inundation

The coastal inundation hazard comprises the overtopping of coastal barriers, such as dunes and seawalls, by oceanic waters and waves, and the inundation of estuary foreshores, lake and lagoon foreshores (closed or open) and low lying back beach areas hydraulically connected to the ocean due to elevated ocean water levels during a storm. Sea level rise will also contribute to elevated ocean water levels in the future, and must be considered in any assessment of inundation hazard.

Coastal inundation is characterised by two processes:

- A “quasi-static” component, which includes the effects of elevated water levels due to astronomical tide, inverted barometric setup and wind setup (storm surge) and wave setup; and
- A “dynamic” component, which includes the effects of wave run-up and wave overtopping caused by the direct impact of waves on coastal dunes and structures.

The components comprising elevated water levels (ie, astronomical tide, inverted barometric setup and wind setup (storm surge), wave setup and wave run-up) are detailed in Section 2.2.5.

3.6.1 Elevated Ocean Levels

The design ocean water levels listed in Table 2-3 are adopted for this assessment of potential inundation. They include the “quasi-static” components of astronomical tide plus storm surge, including barometric pressure set up and wind set up.

Generally, wave set up at the inner edge of the surfzone may be estimated at approximately 15% of the nearshore breaking significant wave height (H_{sb}). Neilsen and Hanslow (1991) define the setup in terms of the intersection of the hydrostatic still water level with the beach face in the swash zone, where the setup as thus defined may reach about 40% of the breaking root mean square wave height (H_{rms}) (about 28% H_{sb}).

3.6.2 Design Wave Conditions

The nearshore wave conditions vary with location along the coastline due to the differences in propagation from deep water. Detailed SWAN wave modelling has been used to determine the nearshore design wave heights in about 10m water depth for each location, taking into account refraction, shoaling and bed friction attenuation. The design wave heights for each location are described in Chapters 4 and 5. These are based on an adopted 1 in 100 year storm event deep water significant wave height of 7.5m with likely mean duration in the range 1 to 6 hours, consistent with the statistical data described in Section 2.2.3. That condition has reasonably high likelihood of coinciding with the peak of the storm tide as both generally occur at the peak of the storm.

Breaking wave conditions are calculated by simple analytical refraction/shoaling procedures from the nearshore SWAN model output locations to the break point. These are used in the wave setup and run-up calculations.

3.6.3 Wave Run-up and Overtopping

The "dynamic" component of coastal inundation results from the combination of waves at the shoreline on top of any "quasi static" elevated ocean water level. This is generally referred to as wave run-up. Where the crest height of a shoreline structure or dune is less than the wave run-up level, waves will overtop the shoreline and cause inundation. The wave run-up water level may not present a hazard unless the run-up is overtopping coastal barriers at a rate or volume that would cause a significant impact to people or land and assets behind. For this reason, wave overtopping capacity is considered in addition to the wave run up levels. Because of the variability of wave heights, the assessment of inundation due to run-up processes has been based on the 2% run-up levels ($R_{u2\%}$), considering a 100 year ARI still water level and 100 year ARI incident significant wave height.

Elevated ocean levels associated with storm surges may be of many hours duration while the peak astronomical tide level occurs over about an hour. Thus, elevated storm tide levels may exist at or near their peak levels for a maximum duration of about 1 hour around the high tide. As such, for typical wave periods of 10-12 seconds during severe storms, about 300-360 waves will occur, of which the 2% exceedance involves about 6 or 7 individual waves. The severity of the inundation will depend on the extent to which the run-up level exceeds the crest level of the dune or coastal barrier.

Wave run-up levels and subsequent overtopping depends, amongst other things, on:

- Hydraulic parameters such as: ocean water level, wave height, wave period, wave direction, water depth; and
- Foreshore factors such as roughness and porosity, slope and dune/barrier crest levels.

The procedure for calculation of potential run-up levels differs somewhat for natural beaches/dunes and coastal structures such as seawalls. Both require determination of the local design wave parameters through propagation of the offshore design wave to nearshore, accounting for refraction and shoaling as appropriate. For dune run-up, the break point conditions are used in conjunction with the average surfzone slope. For seawalls, the water depth and wave condition (typically depth limited) near the toe of the structure are used. Allowances for sea level rise at 2050 and 2100 (0.40 and 0.90m respectively relative to 1990) are incorporated as appropriate. The run-up levels derived from the above equation is added to the still water levels.

A number of relationships for run-up and overtopping have been applied, depending on the nature of the coastline at each location. For a sandy beach with natural dune, the 2% run-up level ($R_{2\%}$) may bederived based on the findings of Nielsen and Hanslow (1991), who indicate:

$$R_{2\%} = 0.58 \tan \beta \sqrt{H_o{}'_{rms} L_o} \sqrt{\ln(50)}$$

Where
tanβ = average slope across the surfzone, commonly also the slope of the beach face, with minimum value 0.1;
$H_o{}'_{rms}$ = equivalent deep water RMS wave height

$$Lo = \frac{gT^2}{2\pi}$$

T = wave period

It is noted that the run-up is directly proportional to wave period and thus sensitive to the value used. While Nielsen and Hanslow suggest the average wave period (generally T_z) be used, it is understood (Nielsen pers. comm.) that a substantial part of their data was based on counting waves propagating through the surfzone. This is known to miss the smaller waves and provide a period estimate closer to the significant period (T_s) or spectral peak period (T_p) (Patterson 1985). For the assessments in this study, the T_p values are used to ensure conservative results.

3.6.4 Creek Estuary Inundation

Elevated ocean levels during storm events will propagate into lower estuary areas, with potential inundation of the adjacent land. Components of elevated ocean levels that may affect estuaries in this way may include:

- The storm tide (tide plus surge); and
- Wave set-up

While it is generally recognised that wave set-up does not propagate through fully trained entrances with deep water channels, there is uncertainty about the degree to which set-up at untrained entrances with shallow bars where wave breaking extends across the estuary mouth. It is understood that any such set-up would be less than that on the adjacent beaches, however the extent to which it needs to be provided for is not able to be defined reliably.

Additionally, elevated lower estuary levels may occur as a result of stream flow discharge through the mouth, associated with the flow gradient through the entrance. This may be substantial at entrances with shallow bars and constricted flow channels.

For the purpose of assessing the inundation hazard within the lower estuary areas of creeks within Tweed Shire, elevated water level provisions added to the adopted design nearshore storm tide level are taken to be:

- A limited wave set-up component of 10% of the local 100 year design significant wave height; and
- A general lower estuary water level increment of 0.4m, based on the flood flow gradient calculated to be associated with an adopted flow velocity of 1.5-2m/s applied along the creek entrance channel.

This flood flow gradient component is adopted for each of the estuaries considered as a reasonable approximate provision. However, each estuary will behave uniquely in response to specific event-based circumstances. Nevertheless, the inundation levels thus derived and applied to the estuary inundation mapping in Chapters 4 and 5 are reasonably consistent with those utilised as downstream tailwater levels for flood assessments in the region, although tailored to local wave conditions. For example, BMTWBM (2010) reviewed various independent studies (Lawson & Treloar 1994; WBM 2000; CSIRO 2000; Cardno 2004; SMEC 2007) that determined 100 year ARI design ocean levels for flood investigations in the region in the range 1.9m to 2.17m (AHD). The mean value of those levels is 2.04m (AHD). Further, recorded water level data for the Cudgen Creek flood event of 2005 (refer Figure 5-8 of that report) indicates a flood flow gradient of about 0.4m between Kingscliff recorder located on the training walls and the ocean.

3.7 Coastal Entrance Instability

Untrained entrances to coastal streams or lagoons are subject to variability in both their location along the coastline and the adjacent shoreline shape. They may migrate along the beach from time to time depending on prevailing alongshore sand transport and/or stormwater discharge behaviour. The entrances may tend to close during extended periods of low rainfall and re-open by natural scour in high runoff events. These movements may affect the adjacent beaches and assets.

Assessment of the behaviour of the coastal entrances in the study region is based on review of aerial photography and historical knowledge. Each entrance has its own characteristics and is assessed independently.

3.8 Dune Stability & Reduced Foundation Capacity

Immediately following storm erosion events on sand beaches, a near vertical erosion scarp of substantial height can be left in the dune or beach ridge. A zone of reduced foundation capacity can exist on the landward side of sand escarpments. This can impact on structures founded on sand within this zone and the sand escarpments pose a hazard associated with sudden collapse. Following such storm events, inspection of sand scarps should be undertaken to assess the need for restricting public access and the impact on structures.

Over time the near vertical erosion scarp will slump through a zone of slope adjustment to the natural angle of repose of the sand (approx. 1.5 Horizontal to 1.0 Vertical). Nielsen *et al.* (1992) outlined the zones within and behind the erosion escarpment on a dune face that are expected to slump or become unstable following a storm erosion event (see Figure 3-8), namely:

- *Zone of Slope Adjustment:* the area landward of the vertical erosion escarpment crest that may be expected to collapse after the storm event; and
- *Zone of Reduced Foundation Capacity:* the area landward of the zone of slope adjustment that is unstable being in proximity to the storm erosion and dune slumping.

Amongst other factors, the width of the zone of reduced foundation capacity behind the top of an erosion escarpment is dependent upon the angle of repose of the dune sand and the height of the dune above mean sea level (refer Figure 3-8). Table 3-2 provides an indicative guide to the width of the zone of reduced foundation capacity measured landward from the top of the erosion escarpment for various dune heights.

The defined zones should be added to the immediate, 2050 and 2100 year beach erosion hazard (i.e. taken to occur in a landward direction from the edge of the beach erosion extent). Climate change is not expected to modify soil stability, and thus the hazard extents remain relevant at the 2050 and 2100 year planning period.

The allowances in Table 3-2 are provided for indicative planning purposes only and have not been included in hazard definition maps. The presence of bedrock will modify the likely foundation capacity extents. The allowances in Table 3-2 assume a dunal system made up entirely of homogeneous sands (with an assumed angle of repose of 35 degrees) and makes no allowance for the presence of more structurally competent stratums, for example indurated sands and bedrock, nor do these allowances take account of water table gradients that may be present within the dunal system. Expert geotechnical engineering assessment is recommended to establish the structural stability of foundations located (or likely to be located) within the zone of reduced foundation capacity on a case by case basis.

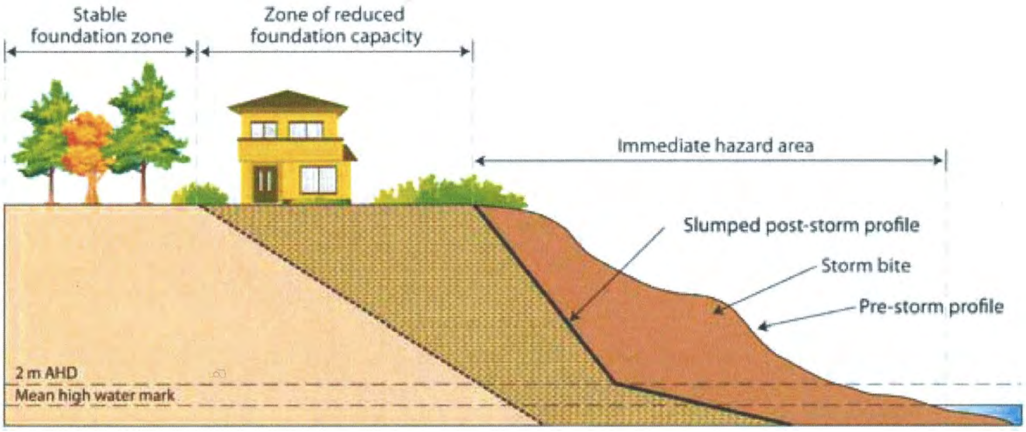


Figure 3-8 Design profile and zones of instability for storm erosion (from DECCW 2010; after Nielsen *et al* 1992)

Table 3-2 Width of zone of reduced foundation capacity

RL of Dunal System (m AHD) [1]	Indicative width of Zone of Reduced Foundation Capacity (m) [2]
4	9.3
5	10.7
6	12.2
7	13.6
8	15.0
9	16.4
10	17.9

1 Assumed that surface of dunal system is approximately level (see Figure 3-8).
2 Distance measured landward from the top of the erosion escarpment following slope readjustment (see Figure 3-8).

Following storm events where dune erosion has occurred, inspection of sand scarps in popular recreational beach areas should be undertaken to assess both the need for restricting public access and structural instability. The stability of existing and new building foundations in the vicinity of any erosion scarp will need to be assessed or designed by a qualified geotechnical engineer.

3.9 Sand Drift

Sand drift occurs when sand is transported from the beach by wind action. As the surface sand in the upper beach areas dry it can be moved by persistent day-to-day winds. All sandy beaches experience sand drift to a certain extent and, during periods of strong winds, substantial volumes of sand can be moved. On natural beaches, sand drift by onshore winds is the primary mechanism for rebuilding the dune system following storm erosion. This occurs where the dune vegetation is able to trap the sand.

Sand blown inland can cause a range of hazards including:

- A permanent loss to the beach system; and
- A nuisance for coastal developments.

If sand is blown inland out of the zone of active beach fluctuations it becomes a permanent loss to the beach system. Dune systems act as reservoirs and supply sand to the nearshore areas during periods of erosion. If sand is lost inland from this system, the volume of sand available to supply the erosion demand is less and therefore the shoreline recession is greater. A long term loss as a result of sand drift therefore effects the overall sediment budget and can contribute to shoreline recession.

Dune vegetation plays an important role in minimising sand drift by acting to trap any wind-blown sand. This trapping action helps to build up the dune and keep the sand within the active beach system. Sand drift is usually initiated by the degeneration or destruction of dune vegetation. Once initiated, it can often lead to the irreversible generation of blow outs which concentrate the wind velocities and cause more sand to drift. A common cause of dune vegetation destruction is uncontrolled pedestrian and vehicular traffic.

Areas of the Shire affected by sand mining have been stabilised with vegetation. There are no areas that experience sand drift problems not controlled by dune management practices based on vegetation and fencing. Local community Dune Care groups play an important role in management of the dunes to prevent sand drift problems.

4 KINGSCLIFF COASTAL HAZARDS ASSESSMENT

4.1 Context

Regionally, the Kingscliff to Dreamtime Beach embayment is part of a long coastal unit that experiences a continuous longshore transport of sand extending from around the Clarence River in the south to Moreton Bay in the north. This coastal unit has a series of major controlling headlands past which the sand is moved by the prevailing waves. Cape Byron is the most prominent of these headlands and has a major influence on both wave propagation to the beaches to its north and longshore sand transport processes. Sutherland Point is less prominent but also has significant effect on sand transport and shoreline responses at Kingscliff, particularly in controlling the nature and rates of headland bypassing supply of sand into the embayment. The shoreline processes along the Kingscliff / Dreamtime Beach embayment are thus uniquely dependent on how the headland controls interact with the prevailing deep water wave climate. The shoreline behaviour is thus sensitive to variability of the deep water wave conditions at both short (days to weeks) and longer term (months; years; decades) time-scales.

4.2 Conceptual Coastal Processes

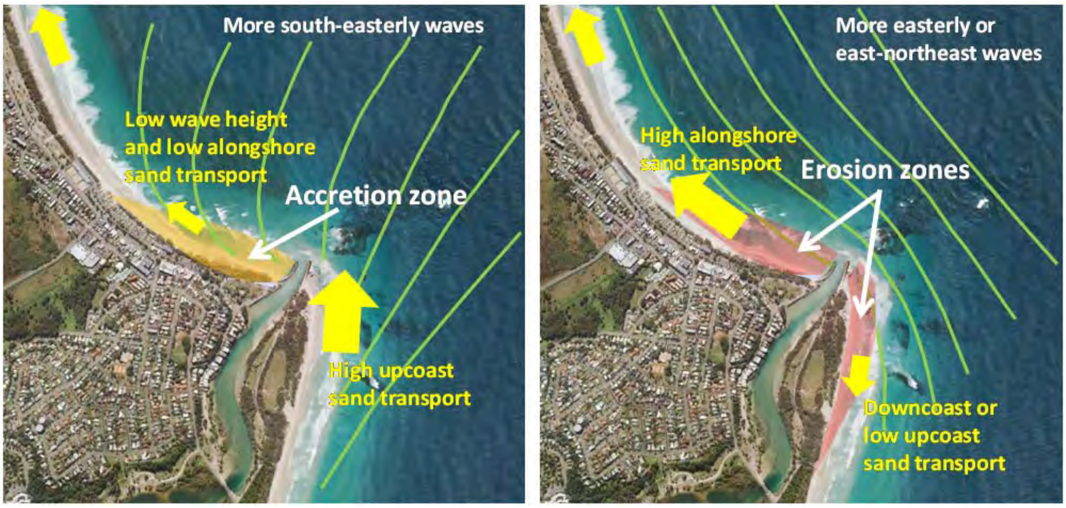
The available evidence (refer Figure 4-1) suggests that sand transport past Sutherland Point through the Kingscliff area occurs as both:

- A littoral zone transport predominantly within the surfzone driven by breaking waves and currents induced by wave radiation stresses; and
- A form of cross-embayment transport along nearshore spits and bars that are highly variable in their form and location.

Figure 4-1 Sand transport pattern past Sutherland Point to Kingscliff

The proportion of sand that follows the littoral zone and the proportion that moves across the embayment will vary with varying wave and sand transport conditions. There is lower total transport but a higher proportion within the littoral zone under lower wave energy conditions while larger waves transport a greater proportion across the embayment. Thus, the supply of sand to the embayment and the predominant path that it takes are quite variable and highly dependent on the prevailing wave conditions. Persistent El Niño conditions are likely to result in increased sand bypassing of

Sutherland Point but reduced littoral transport at Kingscliff, resulting in a tendency for shoreline accretion there. La Niña conditions reduce headland bypassing but increase littoral transport at Kingscliff and thus cause shoreline recession. These trends are illustrated conceptually in Figure 4-2.



El Niño La Niña

Figure 4-2 Conceptual responses to ENSO wave climate variation at Kingscliff

It is recognised that there has been some historical sea level rise, at a rate of about 1.5-2.0mm/yr, that would have affected the shoreline during the past century (and earlier). For example, if a factor of 50 to 1 were adopted as the ratio of shoreline recession to sea level rise based on typical Bruun Rule assumptions, a persistent shoreline recession of about 0.08-0.1m/yr would be expected to be occurring, even in the absence of any additional climate change impacts or other influences. Where there is evidence of short to medium term shoreline advance (eg. over years to decades), the magnitude and time-scale of variability must be such as to overcome that underlying trend. Conversely, measured persistent recession would be at least in part attributable to that process.

While there is insufficient knowledge to be definitive about these processes, Patterson (2013) utilised geological time-scale modelling incorporating combined longshore and cross-shore processes associated with the late Quaternary sea level change over the past 120,000 years to suggest an average net recession at Kingscliff of about 0.1-0.2m/yr over the past 1,000 years.

Thus, conceptually, the shoreline is responding to several interacting influences, each at different time-scales as illustrated in Figure 3-6. Because of the unique location of the embayment within the regional context, the short to medium term variability masks the long term trend when considered at time-scales of only decades or less. Only a data set of century time-scale would begin to reveal the underlying trend.

Other factors that conceptually will influence the behaviour of the shoreline along the embayment include:

- Underlying bedrock that may restrict shoreline recession or otherwise affect sand transport processes; and
- Anthropogenic interference with natural processes that may affect the system locally and/or at adjacent parts of the shoreline that may extend up to kilometres updrift or downdrift.

4.3 Historical Shoreline Behaviour

4.3.1 Impacts of Cudgen Creek Training Walls

Aerial photo evidence is available that shows that training of Cudgen Creek in about 1967 for flood mitigation purposes has had a significant impact on the local shoreline behaviour. The entrance stabilisation works have also provided limited improvement in navigation for small vessels. However, given the strong littoral sand transport past the entrance and relatively small tidal prism of Cudgen Creek, navigation will always be restricted and inherently dangerous. Figure 4-3 and the aerial photo sequence in Figure 4-4 illustrate the changes that have occurred since 1944 in which:

- The training walls have intercepted part of the sand movement around Sutherland Point and forced it to be transported around the ends of the walls in moving into the Kingscliff embayment.
- The walls have stabilised the creek location and prevented meandering of the mouth along Kingscliff beach.
- The training walls have altered the wave propagation behaviour to their immediate west, blocking those waves that would otherwise have passed over the mouth shoals there.
- The shoreline to the immediate west of the walls has adapted over a period of decades to the new regime of wave incidence and sand transport, developing a new dynamic equilibrium crenulated shape in the lee of the walls.
- The pattern of headland/training wall bypassing has become more 'slug' like, occurring in stronger but somewhat less frequent pulses that depend on wave incidence from the south to southeast sector. This would be consistent with the alignment of the foreshore at Sutherland Point becoming more prominent headland control as a result of the training works.
- The shoreline and nearshore bathymetry between the creek and approximately the Bowls Club are subject to considerable variability in response to varying prevailing wave conditions and sand supply into the embayment past Sutherland Point.

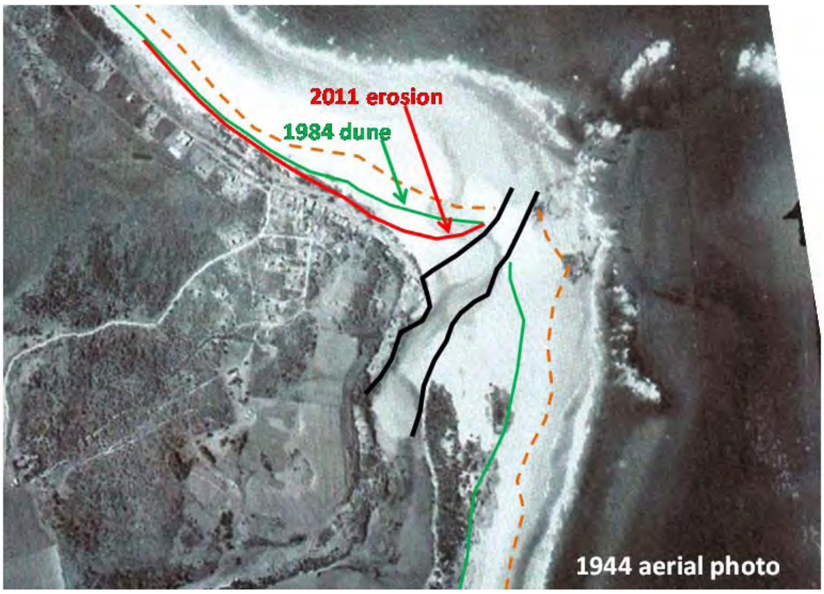


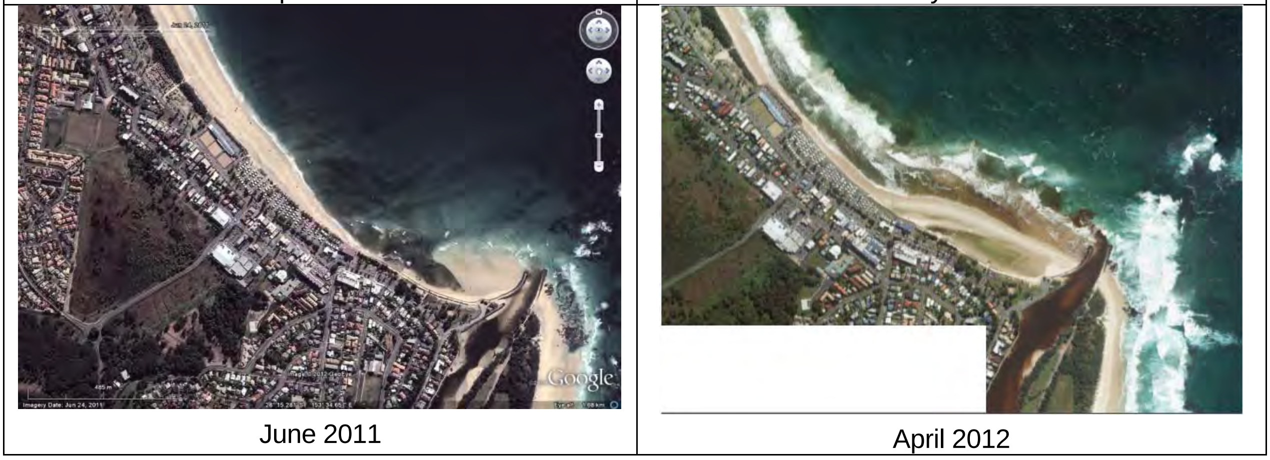
Figure 4-3 Shoreline changes at Kingscliff since 1944

May 2003

June 2008

April 2009

May 2010



June 2011

April 2012

Figure 4-4 Recent satellite images: Kingscliff 2003 to 2012 (source: Google; TSC)

Overall, the creek training works have provided stability to Kingscliff Beach between the creek and the Surf Club by removing the erosive potential of channel meandering along the beach while both changing its alignment to a more accreted position. Correspondingly, they have altered its behaviour in a way that has increased variability in sediment supply and local alongshore transport, leading to shoreline position variation from wide beach conditions to erosion where infrastructure is threatened and has been temporarily protected by seawall works (refer Figure 4-4 and Figure 4-5).

Patterson Britton Partners (1998) have determined that there is a new regime of sand influx to the creek estuary in which:

- The coastal sand shoals downstream of the road bridge appear to be dynamically stable;
- The bridge is the limit of flood tide transport of sand;

- There is no significant supply of sand from upstream of the bridge;
- Northeast sector waves can force sand directly into the entrance and cause heavy shoaling; and
- Flood event flows can flush the entrance shoals out to the beach system.

WBM (2006) investigated hydrodynamic processes of Cudgen Creek and concluded that the road bridge crossing upgrade proposed at that time would result in only negligible changes to flood and tide hydraulics. Accordingly, its effects on the sedimentation dynamics within the lower estuary as described by Patterson Britton Partners (1998) would be negligible, with imperceptible impacts on the erosion processes of Kingscliff Beach.

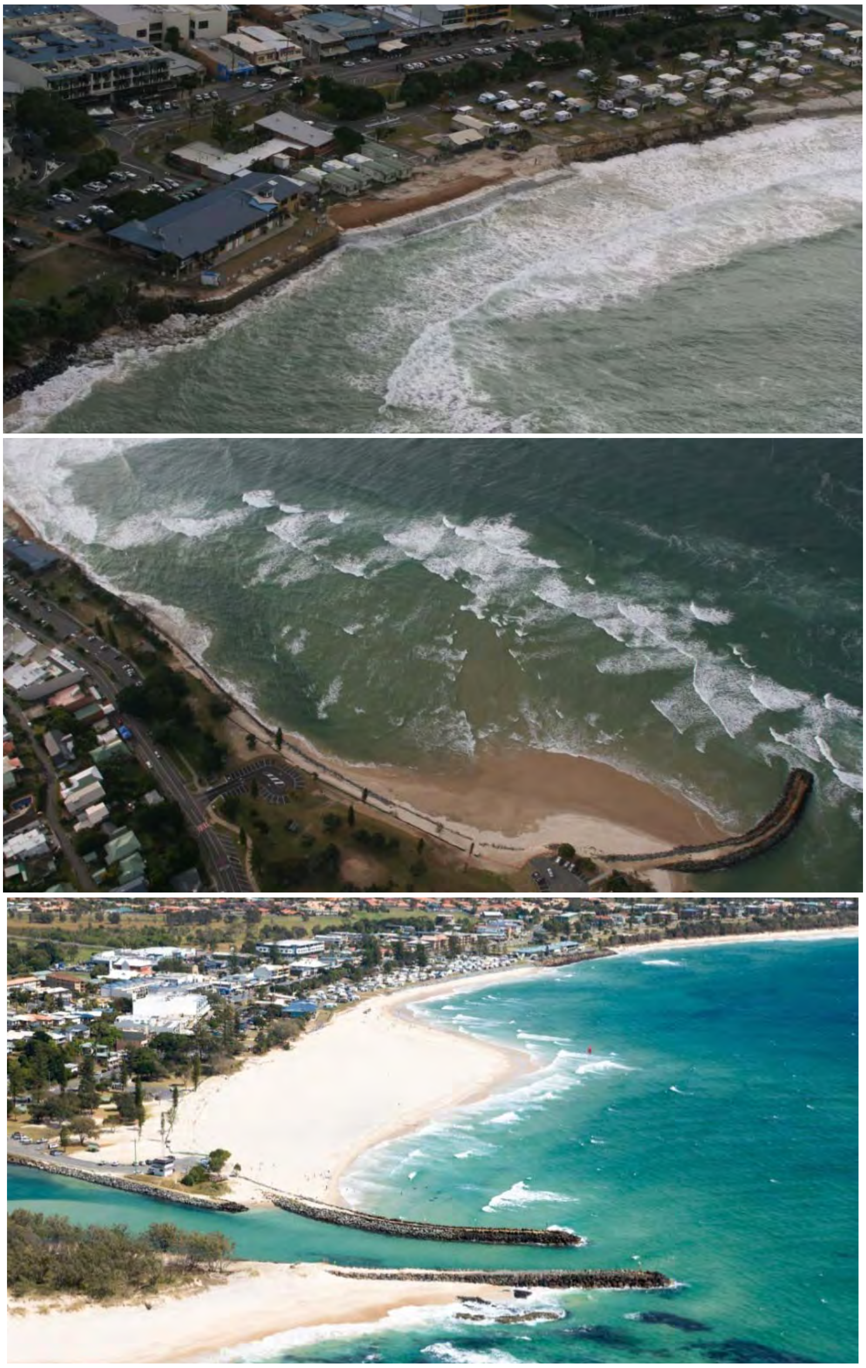


Figure 4-5 Kingscliff erosion in August 2011 (top; mid) and recovery to 2012 (bottom)

Analysis of the historical photogrammetry data, as described below, provides a basis for determining the nature and rates of historical shoreline change and patterns of behaviour that have occurred in response to natural processes including wave climate variability and the effects of the creek training works. With future climate change, the Kingscliff embayment shoreline will continue to evolve over the medium to long term in response to cross-shore and alongshore processes affected by sea level rise that may be assessed by modelling. These are used to assess prevailing and future shoreline trends for definition of potential erosion hazards.

4.3.2 Analysis of Photogrammetry Data

Photogrammetry analysis of aerial photographs has been used to determine the profile shapes, beach/dune volumes and dune scarp positions over the period 1947 to 2010 to assess the long term trend of behaviour of the shoreline. This extends the previous analyses undertaken for the Tweed Shire Coastline Hazard Definition Study (WBM Oceanics Australia 2001), with additional photogrammetry for the years 2004, 2007 and 2010.

It should be noted that the photogrammetry record identifies the dune and beach profile shapes on particular historical dates and these represent different stages in the cycles of storm erosion and beach/dune recovery, depending on their timing relative to major storm events. It is known that severe erosion of the beaches of northern NSW and SE Queensland occurred during 1967 and 1974 and that Kingscliff experienced severe recent erosion over the period 2010-2011. Care must be taken in interpreting the profiles, shoreline positions and beach volume changes around those times to account for the loss of sand from the beach to nearshore. Further, the older dates of photography (1940s and 1950s) are typically of lower quality in terms of their quantitative accuracy for photogrammetric analysis, both horizontally and vertically.

The photogrammetry data is presented in separate blocks along the shoreline. The data has been analysed for the present study in a series of representative zones, as shown in Figure 4-6. Typical beach/dune profiles showing the history of change from 1947 to 2010 are presented in Appendix A, Figure A- 2 to Figure A- 10.

These illustrate:

- Areas where sand mining has altered the natural dune topography, generally removing former higher main dunes and re-forming the dune profile to suit parkland or other amenity purposes;
- The pattern of foredune erosion and re-accretion seaward of the main dune where a dominant dune scarp exists, most commonly formed in the 1974 erosion event;
- Major modification of the beach/dune along Zone 12 where formerly the meander behaviour of Cudgen Creek affected the shoreline; and
- Typical main dune heights of 7-8m (AHD) along the central and northern part of the embayment (zones 1 to 5, reducing to generally 5-6m along zones 6-11. In the southern area (zone 12), dune heights are typically less than 4m.

Additional analysis of the data for this assessment has been undertaken in terms of changes in cross-shore position of three adopted contour levels, namely RL+1.5m, RL+2.5m and RL+4.0m (AHD), as an indicator of movements of the beach shoreline, foredune toe and dune face respectively. While the shoreline position is highly variable, movement of the dune face is slow and represents a reasonable measure of longer term trends. As well, beach dune profile volumes have been calculated and changes in volume since the first date of photography determined. The results presented are the averages within each zone of the respective:

- Distances from the baseline of the photogrammetry for each profile.
- Volume changes above RL0m (AHD) seaward of a fixed position for each profile, chosen to represent the whole beach and dune while limiting potential error due to inaccuracies in the hind-dune area.
- The trends of dune scarp and beach contour distances and corresponding volume changes derived from the analyses are presented in Appendix A, Figure A- 11 to Figure A- 13.

Figure 4-6 Locations of photogrammetry analysis zones

The photogrammetry indicates a significant initial volume reduction and shoreline recession through to about 1980 in some southern locations (zones 8 to 11) while other central parts of the beach (zones 3 to 6) show significant increase in volume over the same period. Since 1980, the beach system generally has experienced relative stability, subject to variability associated with storm events and prevailing wave variability. The more recent 2010 beach/dune condition at Kingscliff (zones 9 to 12) has been affected by substantial erosion over 2009-2011.

The movements of the dune scarp (defined at RL+4m AHD) are much less significant. There does not appear to be an evident progressive trend of recession. In the Dreamtime Beach area the scarp has moved seaward with development of a new foredune in front of the main dune. Generally, 1974 marks the most landward extent of erosion and minimum beach/dune volume. However, the 2010 erosion appears to be the worst case in the most northern Dreamtime Beach zones 1 to 3, immediately south of Fingal Head. This is surprising, given the expected relative stability to the south of the controlling headland. It is likely that the prevailing La Niña wave conditions led to temporary southward sand movement from that area and recovery there is expected.

These trends of change may be related to the ENSO pattern of predominant La Niña from 1945 to 1977 followed by predominant El Niño to about 2008. For example, the data shows that Kingscliff south (zone 12) has fluctuated substantially in position and volume, with a general trend of accretion after about 1980, followed in 2010 by substantial short term volume loss and shoreline erosion. The recent erosion appears to relate to a return to La Niña conditions.

These patterns of variability mask any ongoing progressive underlying trend of shoreline change, making it not feasible to determine with confidence a long term trend that may be projected to the future on the basis of the photogrammetry data alone. The present understanding of the processes occurring is that the beach experiences cycles of naturally varying sand supply causing beach erosion and accretion. A progressive underlying long term net trend of sand loss from the embayment on which such cycles may be superimposed would be expected on the basis of the regional gradient in the alongshore sand transport, at a rate dependent on the extent to which a shoreward sand supply offsets that gradient. For this assessment, it is accepted that there is an underlying long term net trend of recession at a regional average rate of up to about 0.05 to 0.1m/year, depending on location. Assessment of the measured photogrammetry data is made in that context in order to identify patterns and time-scales of variability that may then be considered in determining immediate and future erosion hazard extents.

4.4 Assessment of Kingscliff Coastal Hazards

4.4.1 Coastal Hazards Affecting Kingscliff

The Kingscliff coastline and land adjacent to Cudgen Creek are affected by a range of coastal hazards that will become potentially more acute or extensive in the future with climate change induced sea level rise. These have been assessed and mapped as described in the following sections of this report and the relevant appendices. They include:

- The erosion hazard, including components of immediate storm erosion, shoreline variability and future shoreline recession;
- Coastal inundation associated with ocean wave run-up and overtopping of the dune barrier;
- Estuary inundation within Cudgen Creek associated with elevated ocean storm tide levels;
- Tidal inundation of the Cudgen Creek shoreline; and

- Dune zones of reduced foundation capacity.

Entrance instability at Cudgen Creek has been overcome by training wall works. Potential sand drift hazards have been controlled by comprehensive dune management to protect native dune vegetation and to prevent wind erosion.

4.4.2 Erosion Hazard Strategy and Hazard Components

Figure 4-7 provides a summary of the interpreted patterns of beach/dune volume change in representative compartments along the Kingscliff embayment, showing the likely trends and storm bite extent. The volume gain in zones 5-7 and the marked loss followed by gain in zones 8-10 are clearly evident. Zones 1-4 appear relatively stable, within a zone of fluctuation of about 130m^3/m. The other areas indicate a fluctuation of about 150-200m^3/m, consistent with the typically observed storm bite volume for NSW. A design storm bite volume of 200m^3/m relative to an accreted beach condition thus is adopted as reasonable.

However, it is evident that prolonged phases of either La Niña or El Niño conditions can affect the state of the beach on which the storm bite may occur during a major storm event. For example, a major storm that occurs over the ‘immediate’ planning period of the next few years or at 2050 and 2100 could follow adverse conditions of temporary recession associated with short to medium term variability. Furthermore, the conditions in 2050 and 2100 will be subject to the effects of sea level rise, other climate change factors and any geological time-scale trends of shoreline change. Those aspects are not readily defined and are unknown.

Accordingly, the strategy adopted for determining the erosion hazards is based on:

1 Establishing an ‘immediate’ erosion hazard line that incorporates.

    a. The storm bite component calculated on the basis of removal of 200m^3/m from above the erosion profile across the beach/dune above AHD for the most recent accreted situation, taken to be the 2007 condition, with the exception that the storm bite extent is at least as far landward as that measured to date.

    b. Variability and uncertainty related to short to medium term ENSO effects on wave conditions.

    c. Factors such as coastal works and structures such as training walls or seawalls which may be continuing to have effects and/or for which the option of future removal would be considered in the management study and plan.

2 Projecting the ‘immediate’ erosion extent, which contains the provisions above, to 2050 and 2100 by making provision for the expected shoreline recession caused by.

    a. Any underlying progressive trend of shoreline change.

    b. Sea level rise.

3 Providing for uncertainty and/or factors that are difficult to otherwise quantify in the future recession components by adopting ±20% upper and lower limits relative to the best estimate recession extents, thus establishing ‘minimum’ and ‘maximum’ hazard lines as the range within which the erosion hazard is considered most likely to occur, as mapped.

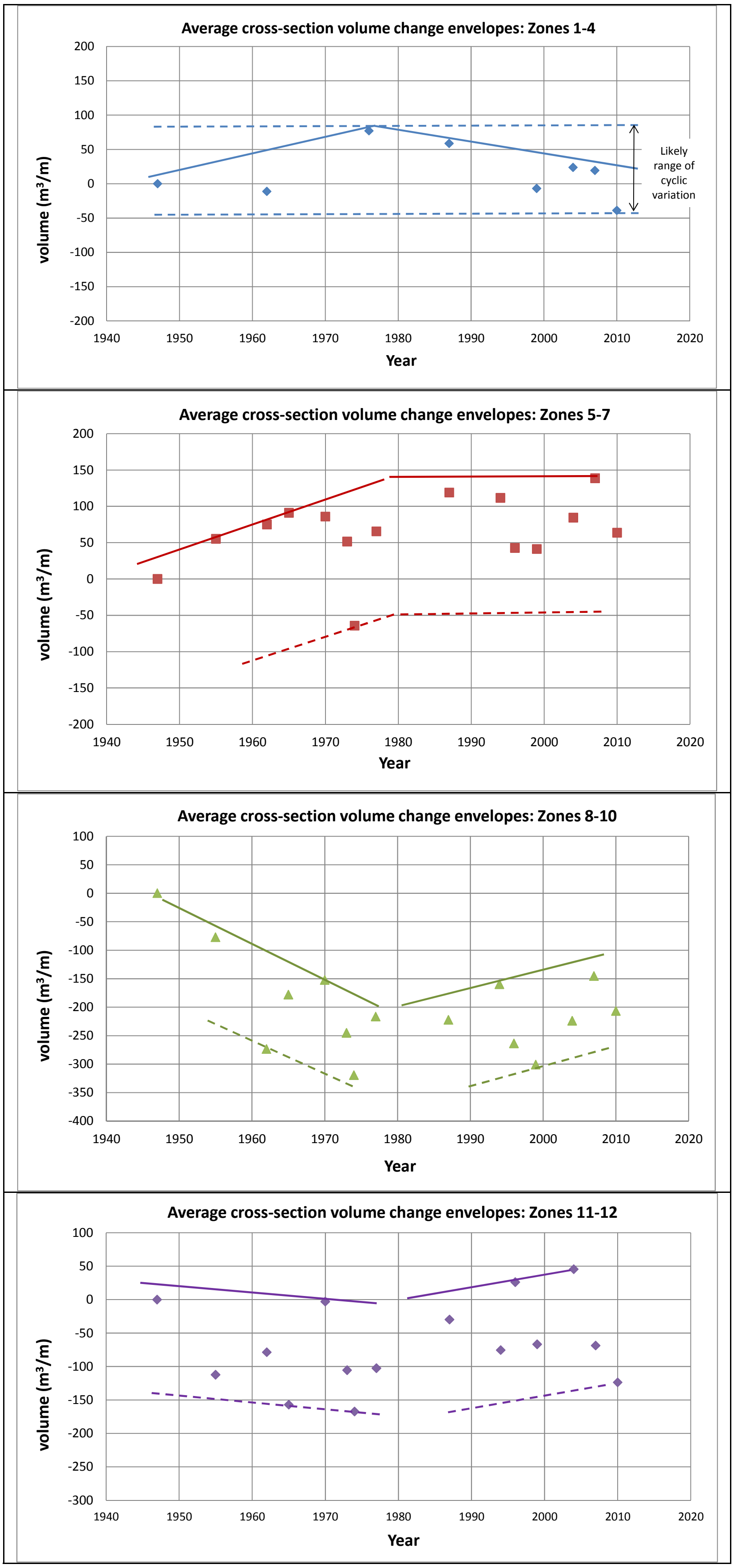


Figure 4-7 Beach/dune volume changes in Kingscliff embayment compartments Locations shown in Figure 4-6

That is, the erosion hazard extent (*H*) is determined in the form:

$H = (H1+H2+H3) + H4 + H5$ where

($H1+H2+H3$) is the immediate erosion extent comprising:

- The storm bite *H1* (based on 200m^3/m);
- Allowance for variability *H2* based on interpretation of the photogrammetry data and modelling, together with other available knowledge as appropriate, where short to medium term fluctuations have led to temporary shoreline or dune volume change relative to the prevailing mean trend condition; and
- Allowance *H3* for other factors such as effects of anthropogenic works that may alter the beach/dune condition relative to the prevailing mean trend condition, determined from photogrammetry data and modelling, together with other available knowledge as appropriate.

H4 is the shoreline recession assessed from the photogrammetry data and associated considerations to occur in the absence of sea level rise effects.

H5 is the shoreline recession assessed from the EVO model and/or conventional Bruun Rule factors to occur due to sea level rise effects.

Provisions incorporated in the Kingscliff erosion hazard extents have thus been analysed and quantified on the basis of the photogrammetry data, the EVO modelling and other available knowledge as appropriate. The primary emphasis is on the measured data. Modelling has been used primarily to determine the recession impacts of sea level rise, in conjunction with consideration of the Bruun Rule method. It has also provided insights into both the variability related to ENSO conditions and the likely shoreline shape in the case where no seawalls exist along the shoreline.

Because of the variability affecting the available data, the adopted rates of underlying shoreline recession are based on consideration of:

- The regional pattern of shoreline changes as measured in previous photogrammetry analyses (WBM Oceanics Australia 2000; 2001);
- The assessed likely long term sediment budget related to the gradient in longshore transport and shoreward sand supply;
- Allowance for location along the embayment, being greater at the southern end and less than average at the northern end; and
- Provision for sensitivity to uncertainty by factoring the best estimate rates up and down for the ‘maximum’ and ‘minimum’ rates respectively.

The EVO model yields a varying extent of recession along the embayment due to sea level rise, being generally about 40m for 0.84m rise from 2010 to 2100, but larger at 75m at the southern end and less at 20m near Fingal Head. The Bruun Rule would yield a recession of about 35-50m for the nearshore slopes in the northern NSW-SE Queensland region. This is reasonably consistent with the model result. Sensitivity to the uncertainty in the provision to be made is provided for by factoring the model result up and down ±20% for the ‘maximum’ and ‘minimum’ cases respectively.

The adopted hazard components are summarised in Table 4-1 and Table 4-2.

Table 4-1 Adopted long term recession trends

Location	Minimum (m/yr)	Best estimate (m/yr)	Maximum (m/yr)
Cudgen Ck to Bowls Club	0.12	0.15	0.2
Kingscliff North (zones 7-8)	0.10	0.12	0.14
Dreamtime Beach (zones 5-6)	0.08	0.10	0.12
Dreamtime Beach (zones 1-2)	0.04	0.05	0.06

Table 4-2 Adopted recession due to sea level rise to 2100

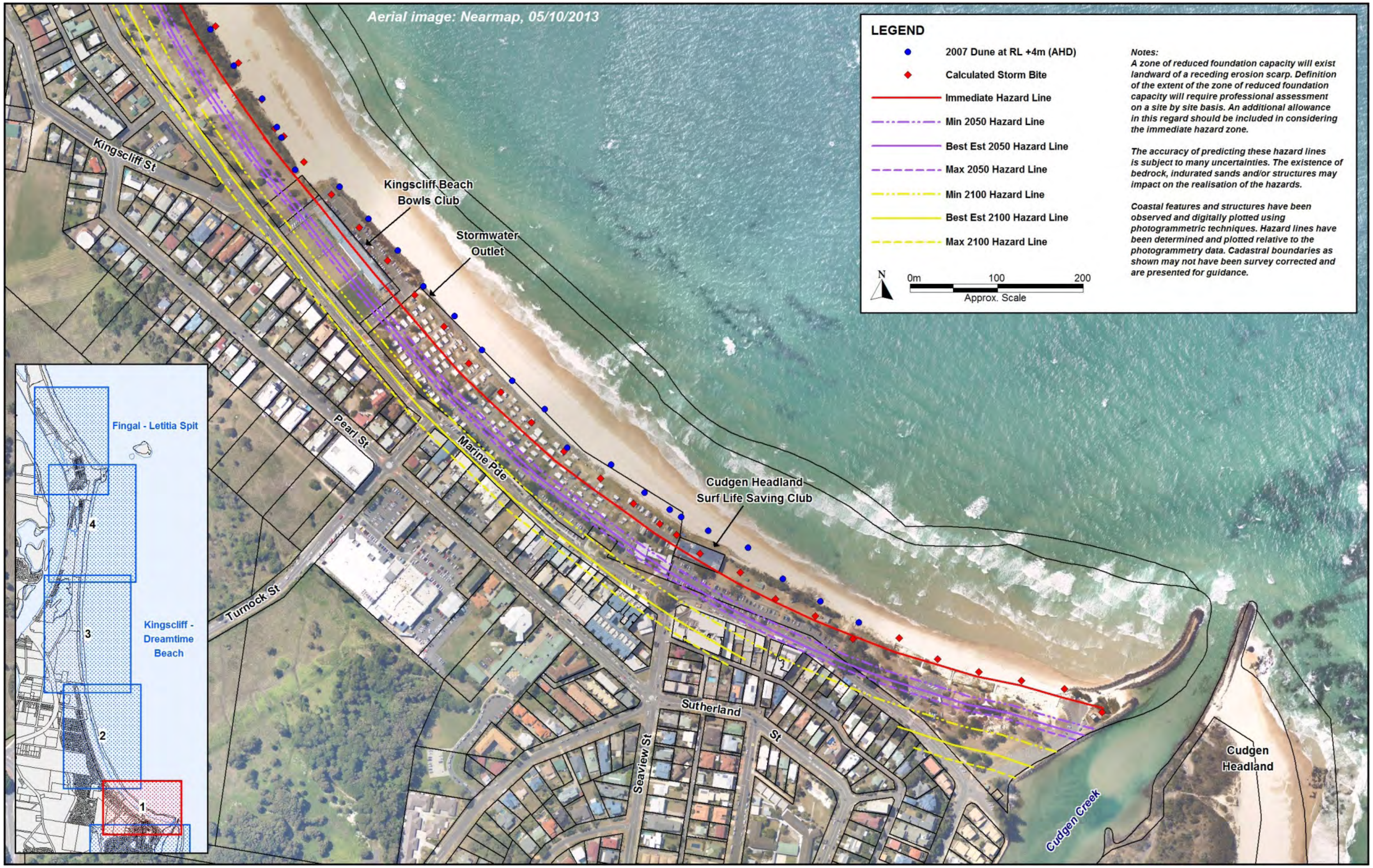
Location	Minimum (m)	Best estimate (m)	Maximum (m)
Kingscliff south (zone 12)	60	75	90
Caravan Park	40	50	60
Bowls Club	36	45	54
Dreamtime Beach (central)	32	40	48
Dreamtime Beach (north)	16	20	24

4.4.3 Erosion Hazard Zones

The erosion hazards have been mapped in GIS to show their positions relative to road and property cadastral boundaries. They are shown in Figure 4-8 to Figure 4-11 for the entire Kingscliff embayment.

The 2050 and 2100 erosion hazard extents incorporate the immediate erosion hazard and represent its projected extent following shoreline recession over those respective time-frames. It should be noted that there is a zone of reduced foundation capacity that extends landward of these erosion hazard lines, as discussed in Section 3.8.

It should be noted that the erosion hazards are based on the Kingscliff seawalls not being in place. This does not presume that they would be removed but rather is intended to provide Tweed Council with advice on where the erosion could extend should they be removed, depending on consideration in subsequent management planning. They incorporate sensitivity provisions for the identified variability in how the beach system behaves, particularly in response to ENSO variations in wave conditions, and uncertainties in determination of recession associated with sea level rise, underlying long term trends of change and other factors (refer Section 3.5 and Section 4.4.1).

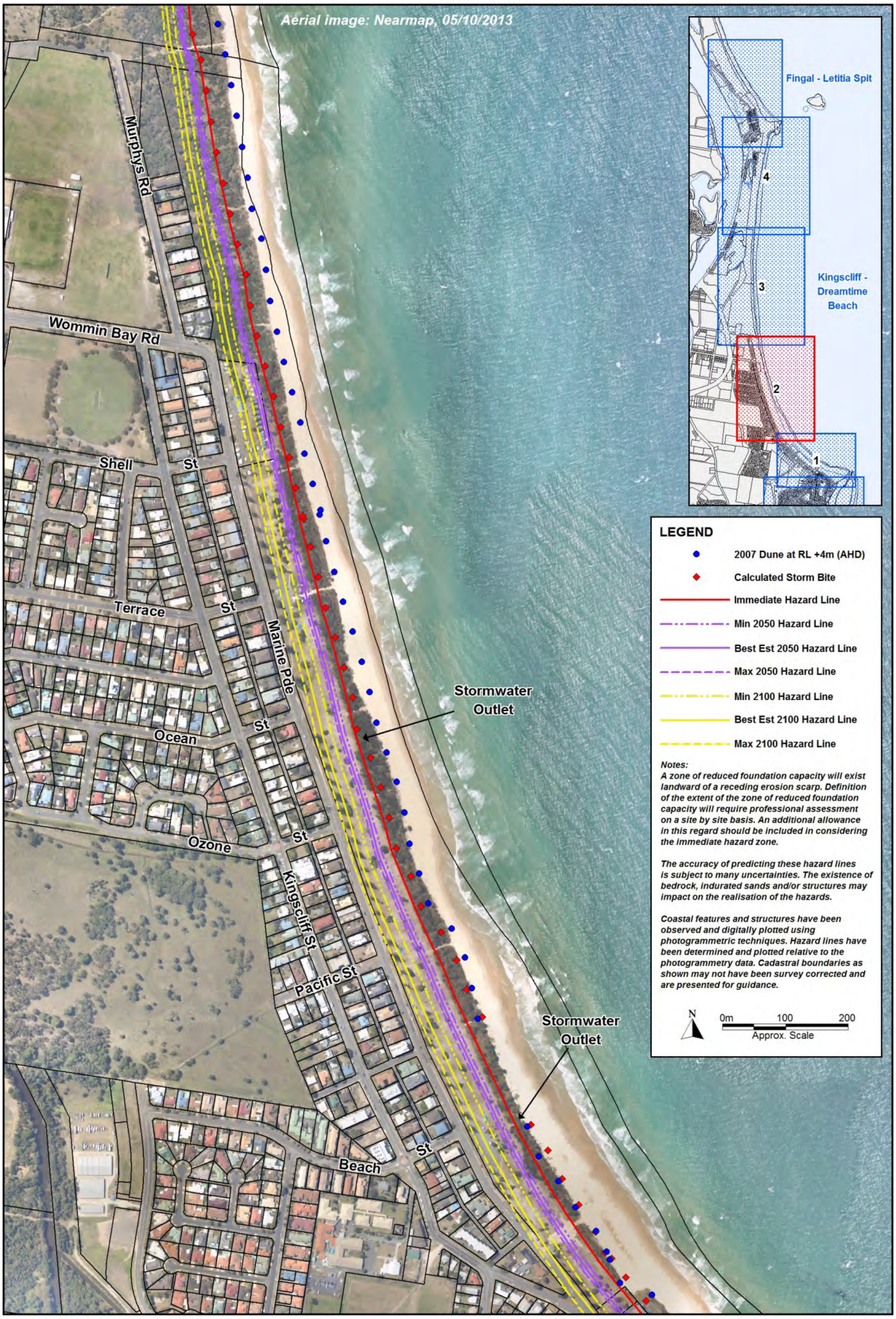


Notes:
A zone of reduced foundation capacity will exist landward of a receding erosion scarp. Definition of the extent of the zone of reduced foundation capacity will require professional assessment on a site by site basis. An additional allowance in this regard should be included in considering the immediate hazard zone.

The accuracy of predicting these hazard lines is subject to many uncertainties. The existence of bedrock, indurated sands and/or structures may impact on the realisation of the hazards.

Coastal features and structures have been observed and digitally plotted using photogrammetric techniques. Hazard lines have been determined and plotted relative to the photogrammetry data. Cadastral boundaries as shown may not have been survey corrected and are presented for guidance.

Figure 4-8 Erosion hazard zones: Kingscliff



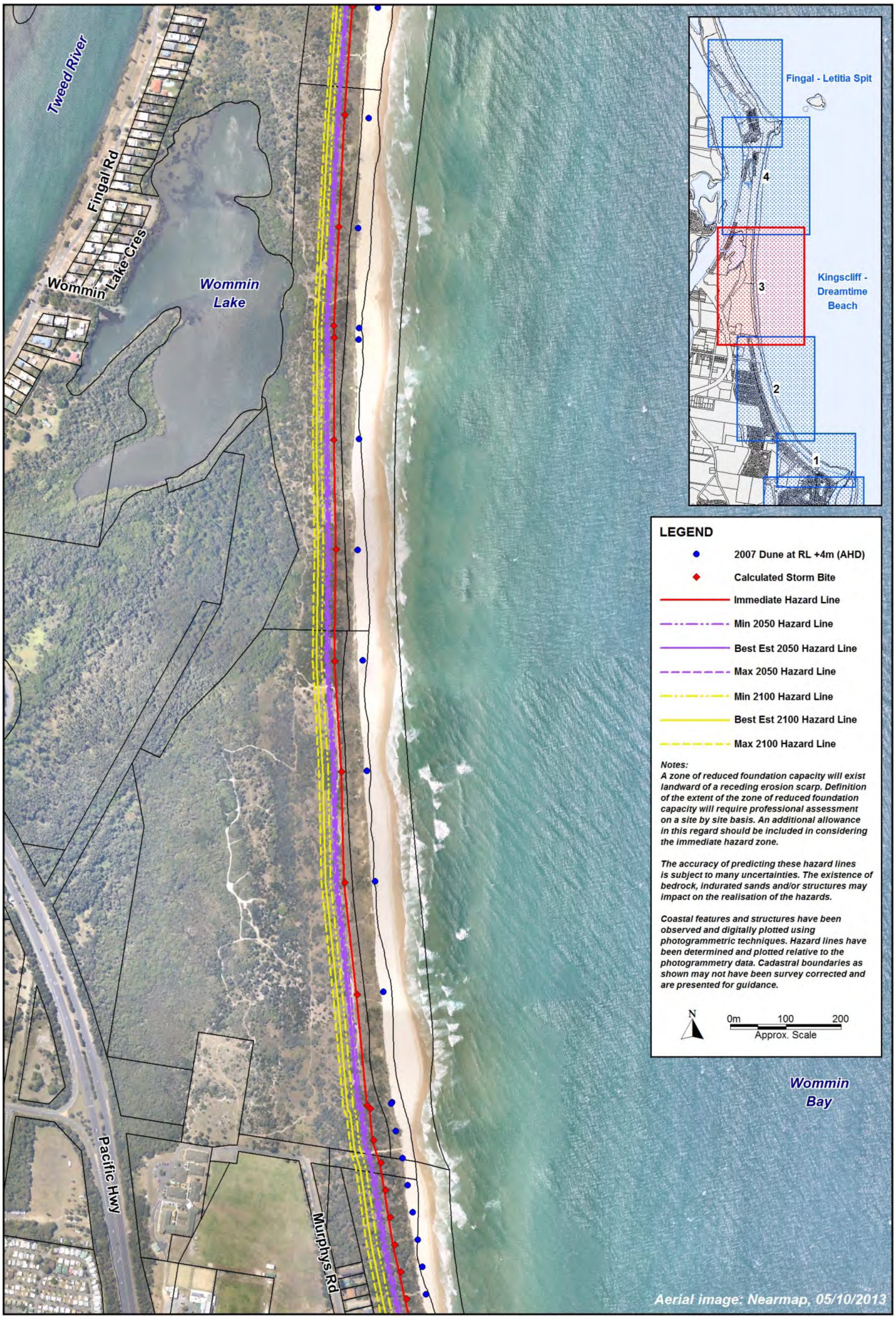
Notes:

A zone of reduced foundation capacity will exist landward of a receding erosion scarp. Definition of the extent of the zone of reduced foundation capacity will require professional assessment on a site by site basis. An additional allowance in this regard should be included in considering the immediate hazard zone.

The accuracy of predicting these hazard lines is subject to many uncertainties. The existence of bedrock, indurated sands and/or structures may impact on the realisation of the hazards.

Coastal features and structures have been observed and digitally plotted using photogrammetric techniques. Hazard lines have been determined and plotted relative to the photogrammetry data. Cadastral boundaries as shown may not have been survey corrected and are presented for guidance.

Figure 4-9 Erosion hazard zones: Kingscliff North



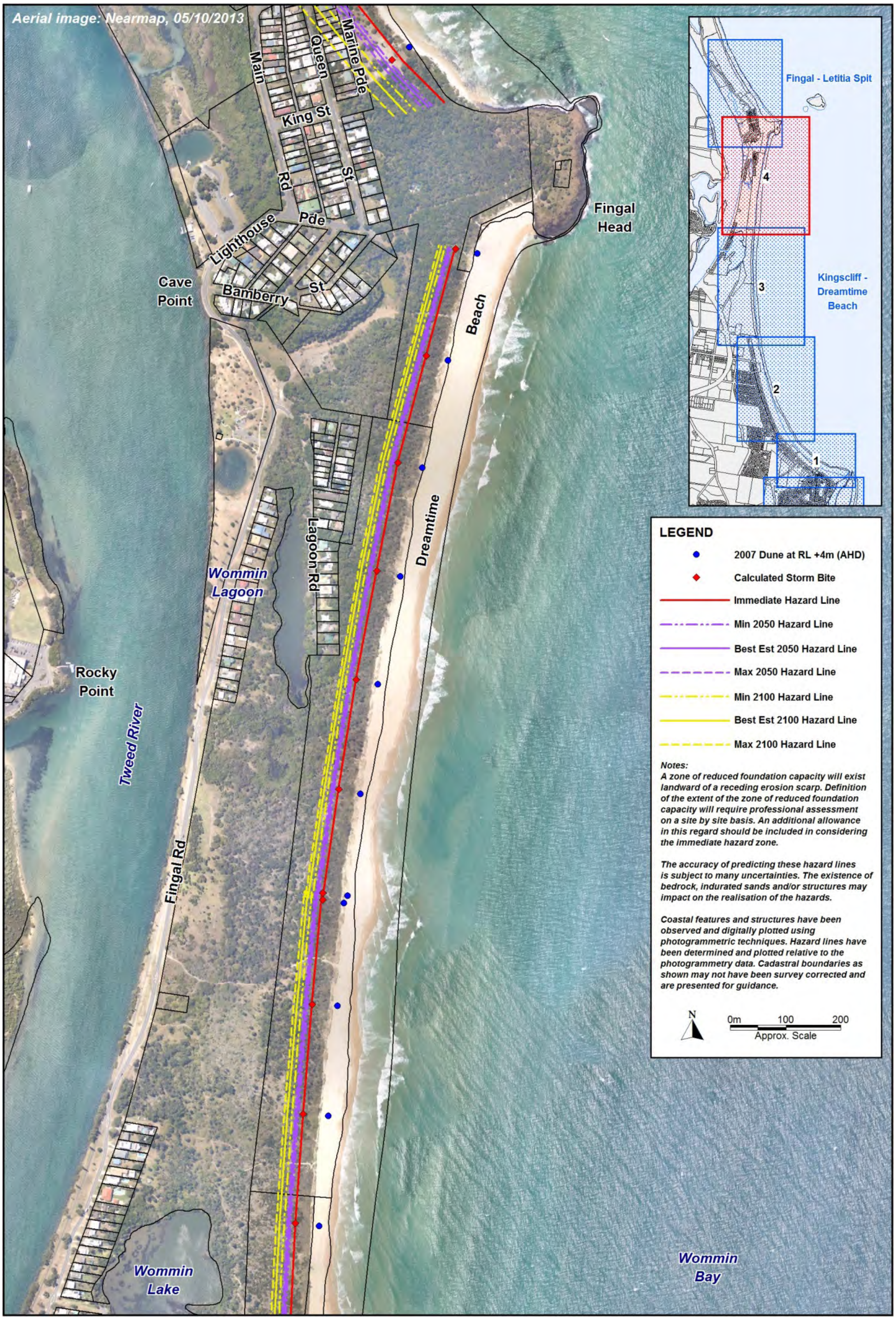
Notes:

A zone of reduced foundation capacity will exist landward of a receding erosion scarp. Definition of the extent of the zone of reduced foundation capacity will require professional assessment on a site by site basis. An additional allowance in this regard should be included in considering the immediate hazard zone.

The accuracy of predicting these hazard lines is subject to many uncertainties. The existence of bedrock, indurated sands and/or structures may impact on the realisation of the hazards.

Coastal features and structures have been observed and digitally plotted using photogrammetric techniques. Hazard lines have been determined and plotted relative to the photogrammetry data. Cadastral boundaries as shown may not have been survey corrected and are presented for guidance.

Figure 4-10 Erosion hazard zones: Murphys Road to Wommin Lake



Notes:
A zone of reduced foundation capacity will exist landward of a receding erosion scarp. Definition of the extent of the zone of reduced foundation capacity will require professional assessment on a site by site basis. An additional allowance in this regard should be included in considering the immediate hazard zone.

The accuracy of predicting these hazard lines is subject to many uncertainties. The existence of bedrock, indurated sands and/or structures may impact on the realisation of the hazards.

Coastal features and structures have been observed and digitally plotted using photogrammetric techniques. Hazard lines have been determined and plotted relative to the photogrammetry data. Cadastral boundaries as shown may not have been survey corrected and are presented for guidance.

Figure 4-11 Erosion hazard zones: Dreamtime Beach

4.5 Coastal Inundation Hazard

4.5.1 Wave Run-up and Overtopping

The Kingscliff embayment is subject to varying incident wave conditions along its length due to the variation in its orientation the nature of wave propagation from deep water and location relative to Sutherland Point. SWAN wave modelling has been undertaken in this study for input to the EVO-MOD model and to determine nearshore conditions for wave run-up determination.

Based on the wave and water level information presented in Chapter 2 and Section 3.6, it is adopted that the design conditions for assessment of wave run-up and overtopping potential are as follows:

100 year ARI significant wave height: 7.5m

100 year ARI storm tide level: 1.44m AHD

Wave refraction coefficients for various locations along the Kingscliff embayment relative to deep water are shown in Figure 4-22.

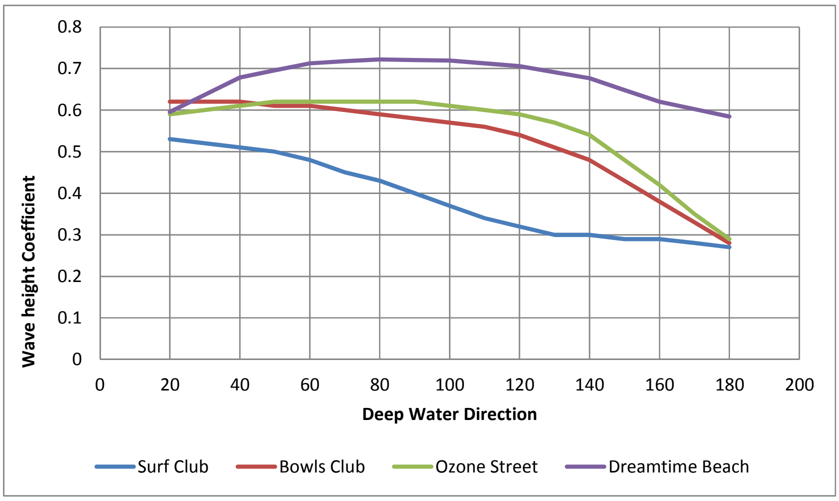


Figure 4-12 Wave height coefficients at Kingscliff embayment relative to deep water heights

Peak wave conditions from major storm events will come from directions south from about 70-80 degrees. Only minor wave incidence occurs from north to northeast directions (Figure 2-10). Based on the coefficients in Figure 4-12, the design maximum nearshore wave heights are calculated as listed in Table 4-3. Using the method of Nielsen and Hanslow (1991) for run-up (including wave setup), with an adopted wave period of 12 seconds, design run-up levels relative to existing sea level for the different parts of the embayment are calculated as listed in Table 4-3.

Table 4-3 Calculated wave run-up levels: existing sea level

Location	Storm tide level (m AHD)	Wave height Hs (m)	Run-up component (m)	Run-up level on storm tide (m)
Surf Club	1.44	3.38	2.65	4.09
Bowls Club	1.44	4.5	3.06	4.50
Ozone Street	1.44	4.65	3.11	4.55
Dreamtime Beach	1.44	5.4	3.35	4.79

These run-up levels have been correlated with the existing dune heights along the embayment, based on the photogrammetry and recent Lidar topography data. This indicates:

- No potential for overtopping north of the Bowls Club where dune heights are in excess of 6m (AHD);
- The dune crest levels along the Kingscliff caravan park are typically at 4.0-4.5m (AHD) and are approximately at the design run-up limit, with some minor overtopping feasible in the lower parts;
- Generally sufficient dune heights along the Surf Club area to prevent overtopping; and
- A clear potential for overtopping adjacent to Faulks Park (zone 12) where dune levels are generally at RL 3.5m (AHD).

The immediate design levels are adopted to include a sea level rise of 0.06m since 1990. With future sea level rise, the potential for overtopping will increase further. Table 4-4 lists the potential run-up levels for the ‘immediate’, 2050 and 2100 scenarios, based on linear addition to existing levels of the Tweed Shire Council adopted projected sea level rise components of 0.4m and 0.9m respectively from 1990.

Table 4-4 Calculated wave run-up levels: with sea level rise

Location	Immediate (mAHD)	2050 (mAHD)	2100 (mAHD)
Surf Club	4.09	4.43	4.93
Bowls Club	4.50	4.84	5.34
Ozone Street	4.55	4.89	5.39
Dreamtime Beach	4.79	5.13	5.63

This places other parts of Kingscliff south from the Bowls Club at significant risk of wave overtopping and inundation across the hind-dune area. The extents of the inundation hazard for each planning timeframe are illustrated in Figure 4-13. The overtopping potential is substantially affected by the presence or otherwise of seawalls, with potentially higher runup but less shoreward momentum. Management options involving seawalls may require review of these inundation extents.

4.5.2 Cudgen Creek Estuary Inundation

Design 100 year ARI inundation levels within the lower estuary of Cudgen Creek downstream of the road bridge are determined on the basis of the factors outlined in Section 3.6.1.4 to include:

- The present design storm tide level of +1.44m (AHD), including the 0.06m rise in sea level since 1990;
- A flood flow gradient provision of 0.4m;
- A wave setup component of 0.6m, based on 10% of the local design wave height at the creek mouth of approximately 6m; and
- Future climate change induced sea level rise.

The local design wave height of 6m is derived on the basis of model propagation of the adopted 100 year ARI design deep water height of 7.5m (refer Section 2.2.3) to the Cudgen Creek mouth area at Sutherland Point.

Figure 4-13 Kingscliff wave inundation hazard zones

These levels are consistent with the findings outlined in BMTWBM (2010) in which:

- Review of various independent studies (Lawson & Treloar 1994; WBM 2000; CSIRO 2000; Cardno 2004; SMEC 2007) yielded 100 year ARI design ocean levels for flood investigations in the range 1.9m to 2.17m (AHD). The mean value of those levels is 2.04m (AHD); and
- Recorded water level data for the flood event of 2005 (refer Figure 5-8 of that report) indicates a flood flow gradient of about 0.4m between Kingscliff recorder located on the training walls and the ocean.

The adopted 100 year ARI design inundation levels for the immediate, 2050 and 2100 time-frames are thus as listed in Table 4-5.

Table 4-5 Cudgen Creek lower estuary design water levels: with sea level rise

Immediate (mAHD)	2050 (mAHD)	2100 (mAHD)
2.44	2.78	3.28

The extents of the inundation hazard for each planning timeframe are illustrated in Figure 4-14.

Aerial image: Nearmap, 05/10/2013

Figure 4-14 Cudgen Creek lower estuary inundation hazard zones

5 TWEED SHIRE COASTLINE HAZARDS ASSESSMENT

5.1 General Considerations

Additional to the detailed assessment for the Kingscliff study area as described in Chapter 4, coastal hazards have been re-assessed also at each of the other developed area beach units in Tweed Shire in terms of the potential erosion hazard components. This has involved consideration of all of the available data and information relevant to each beach, particularly the updated photogrammetric analyses and revised sea level rise impact assessments undertaken for this study, following the methodology outlined in Chapter 3.

Broadly, the key erosion components relate to the immediate storm bite and the progressive longer term shoreline retreat associated with longshore transport differentials and sea level rise. In conjunction with the actual erosion, consideration needs to be given to a zone of reduced foundation capacity which exists landward of the resultant erosion scarp. Hazards relating to local influences associated with the potential for oceanic inundation and entrance instability have also been updated where applicable.

The various hazard components are discussed below for each beach unit within the study area from south to north.

5.2 Pottsville

5.2.1 Coastal Erosion Processes

The coastline at Pottsville is shown in Figure 5-1. This area forms part of the northern extension of the embayed unit extending from Cape Byron to Hastings Point, with intermediate shoreline controls at Brunswick Heads and Black Rocks. It thus lies within the regional coastal system described in Chapter 2, with northward net longshore sand transport of about 450,000-500,000m^3/yr. There is a positive northward gradient in the net longshore transport rate, offset either fully or partially by a shoreward supply from the shore-face.

The principle mechanisms for coastal erosion there are:

- Short term storm bite erosion;
- Underlying long term shoreline recession due to any differential between the longshore transport gradient and shoreward sand supply; and
- Shoreline recession due to sea level rise.

The coastal system at Pottsville has been subject to significant disturbance in the past. Sand mining activities during the 1960s led to re-shaping of the dune topography, typically with sand relocated from the former high main dune to other areas (Figure 5-1). Interference with the dune system has ceased and dune management practices are in place to ensure minimal losses of sand by wind drift.

The entrance to Mooball Creek was stabilised with training walls in 1966-67. The creek mouth is no longer subject to significant migration and impact on the adjacent foreshore. Nevertheless, the shoreline and dune system to its immediate north has been affected by those works and has evolved to a new dynamic equilibrium shape, with some progradation of the foredune in front of the high main dune (Figure 5-1).

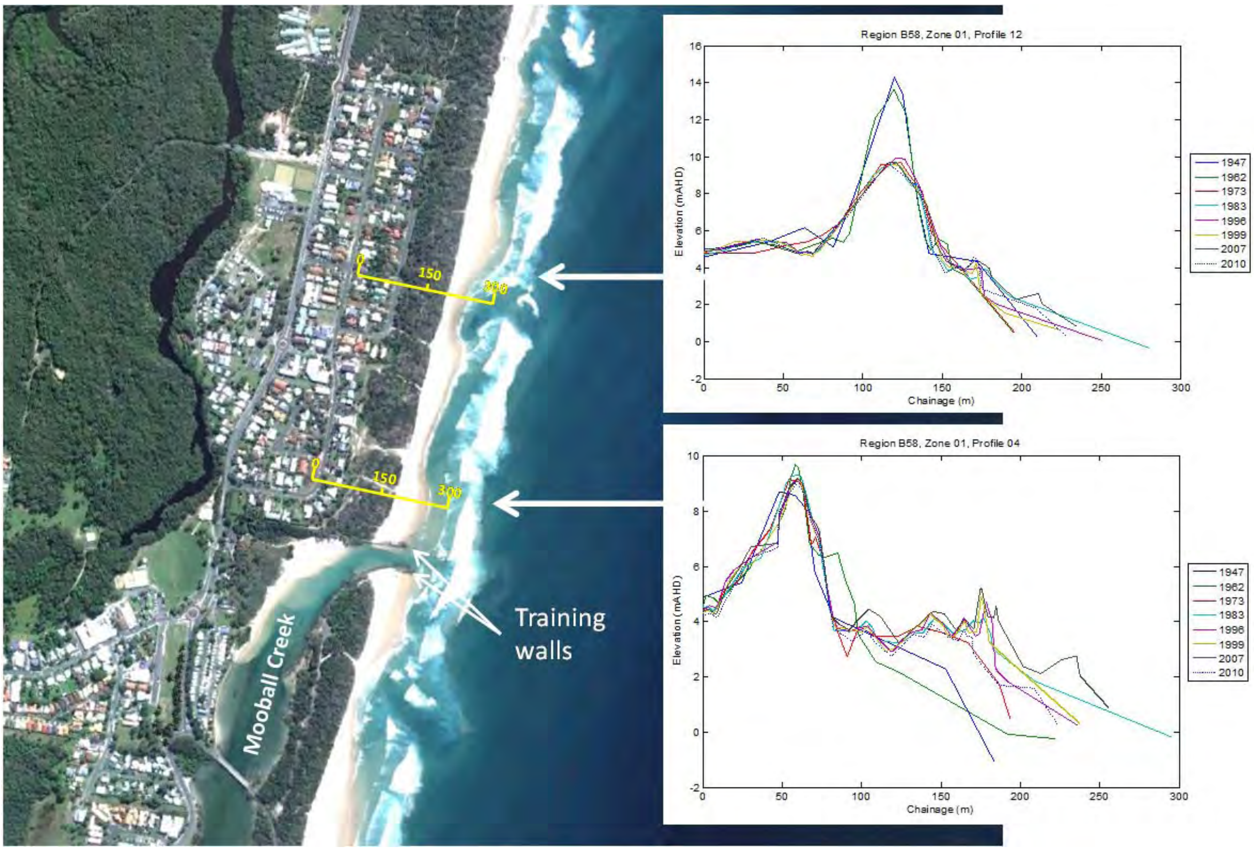


Figure 5-1 Pottsville coastal form and dune topography

5.2.2 Previous Coastal Hazard Assessments

This section of coast was the northern extremity of the Byron Bay – Hastings Point Erosion Study (PWD 1978), which indicated significant erosion over the period 1947 – 1977. The subsequent detailed assessment by WBM Oceanics Australia (2001) utilised photogrammetry analysis covering 1947 to 1999 from available aerial photography and showed that:

- Realignment of the shoreline in response to the training wall construction with updrift accretion and downdrift erosion was rapid initially and had slowed to a point where the coastline had effectively realigned to a new dynamic equilibrium.
- The prevailing shoreline retreat due to longshore sand transport differentials was assessed as:
  - A best estimate of the regional rate at 0.1m/yr from the southern Shire boundary up to Pottsville (south) with upper and lower limits of 0.2 and 0.075m/yr respectively; reducing to; and
  - A best estimate of 0.05m/yr immediately south of Hastings Point with upper and lower limits of 0.1 and 0.04m/yr respectively.

The previously assessed erosion hazard also made provision for:

- A storm bite component equivalent to sand removal from the foredune of 200 m^3/m above AHD for an accreted beach condition, reduced to 160m^3/m relative to the eroded condition in 1999; and

- A recession component of up to 25m for 0.5m of sea level rise, representing a Bruun Rule factor of 50:1.

5.2.3 Re-assessed Short Term Storm Bite

Consistent with previously determined information, this re-assessment has adopted a general regional storm bite component equivalent to sand removal from the foredune of 200m^3/m above AHD, relative to a typical non-eroded beach state. Taking into consideration the recent beach changes identified in the photogrammetry, showing accretion in 2007 and some erosion in 2010, the design storm bite of 200m^3/m has been applied relative to the 2007 condition. Because there is no evidence of significant beach/dune volume variability associated with varying ENSO conditions, the storm bite thus determined represents the immediate hazard zone.

This line is typically 40 to 50m landward from the 2007 frontal dune edge, greater distances corresponding to areas where the dunes are lower. There is no development within the immediate hazard zone at Pottsville.

5.2.4 Re-assessment of Long Term Shoreline Movement

5.2.4.1 Updated Photogrammetric Analysis

The Pottsville section of coast has been analysed in three sections related to the photogrammetry data, as listed in Table 5-1, corresponding to locations shown in Figure 5-2.

Table 5-1 Photogrammetry data description: Pottsville

Block	Location	Length	No of profiles	Comments
B58-1	Pottsville	1,000m	20	Substantial development and/or mining disturbance to main dune to 1962, with apparent sand removal. Effects of creek training in 1967 evident.
B58-2	Pottsville (north)	1,200m	6	Substantial mining disturbance to main dune and sand removal to 1962.
B58-3	Hastings Pt (south)	1,000m	5	Substantial mining disturbance to main dune and sand removal to 1962.

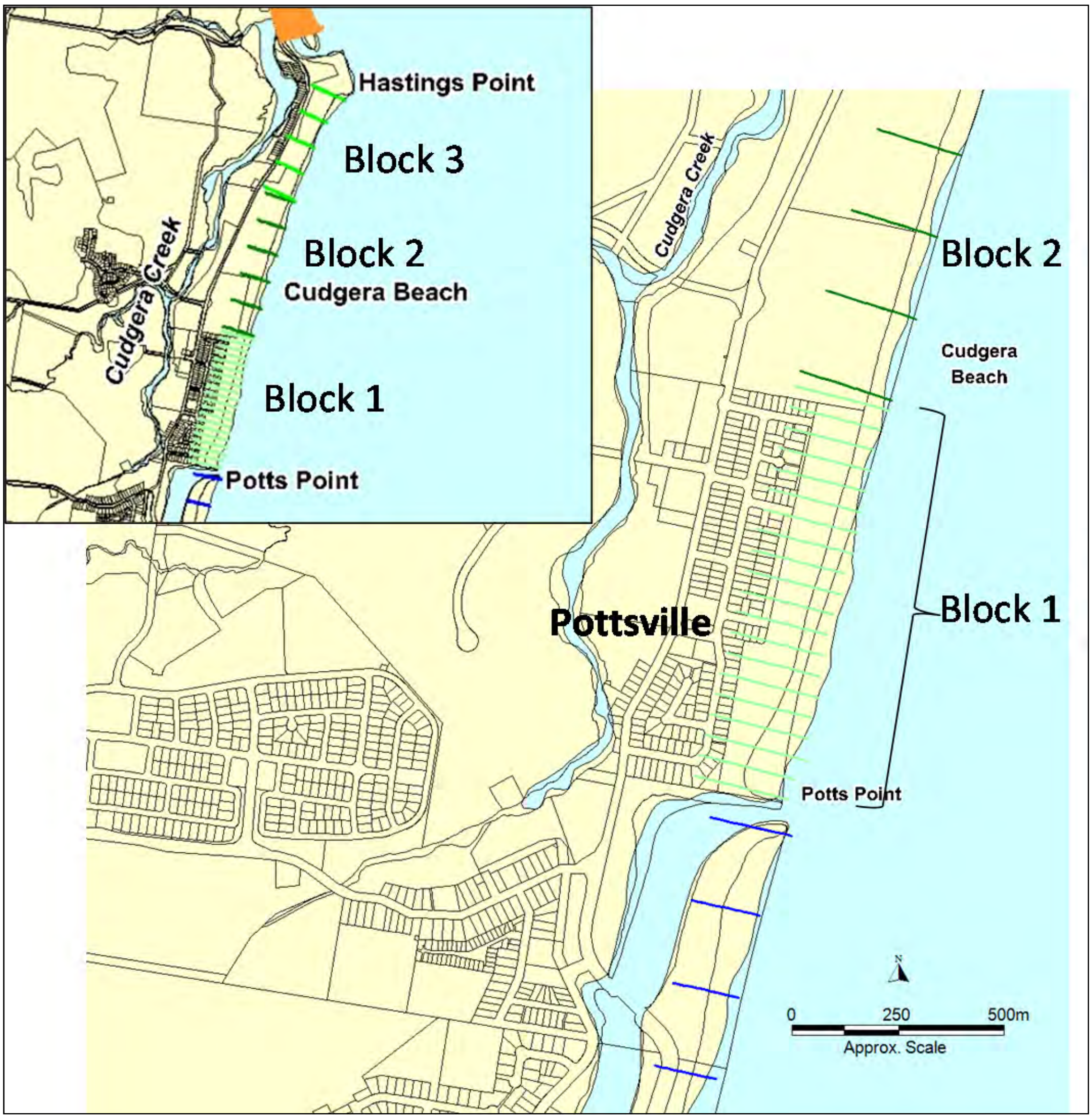


Figure 5-2 Location of photogrammetry lines: Pottsville to Hastings Point

Because of the substantial interference with the dunes here, analysis of scarp movements as an indicator of prevailing longer term trends is not feasible for this section of coast. Volumetric analysis has been undertaken, as summarised in Figure 5-3. The analyses have taken account of sand removal unrelated to the coastal processes, in which case a landward limit cut-off has been applied.

Interpretation of this data depends largely on how much reliability can be placed on the oldest (1947) date of photography and the effects of sand mining and road construction on artificial sand relocation/removal in the hind-dune area. The 1947 photography is potentially inaccurate due to its high level, thick dune vegetation cover and flare over bare sand beach areas making the land surface difficult to define. As such, it is considered that the 1947 and 1962 (mining) data are likely to be less reliable in consideration of the long term trend of coastal change in the area.

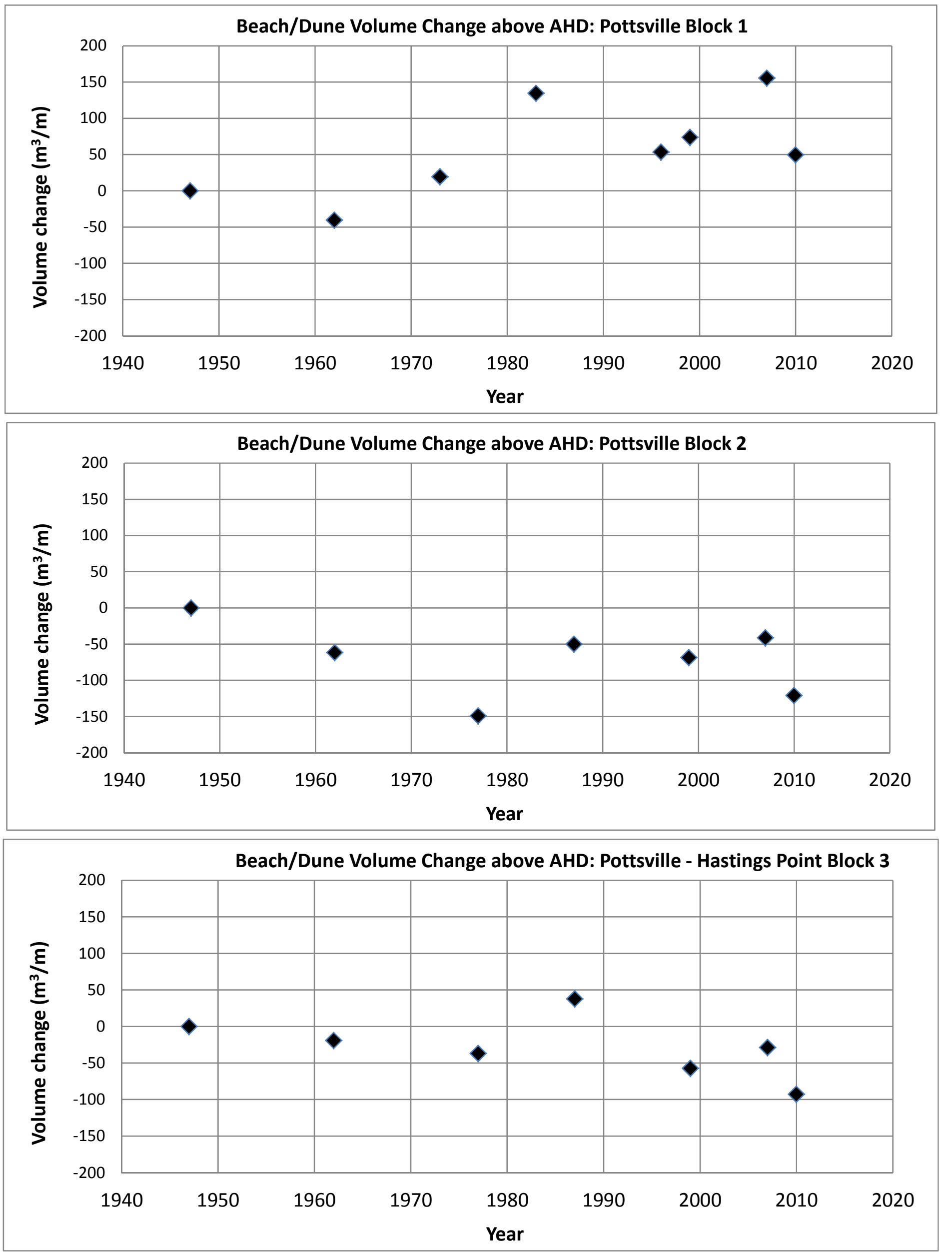


Figure 5-3 Volumetric Analysis - Section B58; Pottsville to Hastings Point

Immediately north of the Mooball Creek mouth (Block 1), there is clear evidence of a net accretion of the foreshore following the creek training. This will have prevented the meandering pattern of the creek there and led to progressive dune strengthening. Further north (Block 2), there is evidence of sand loss over the period 1947 to 1977, probably related to storm erosion and the downdrift erosion from the training walls, but reasonable stability since then. The beach/dune immediately south of Hastings Point (Block 3) shows a slight sand loss since 1990. The prior stability is expected due to its proximity to the controlling headland. The reduction in volume after 1990 relative to the longer term trend is minor and the 2010 condition, common to other locations in the region, is almost certainly associated with storm erosion during 2009.

As such, the assessed underlying shoreline recession rate in this section of coast is consistent with the regional trend, partially stabilised by its proximity to Hastings Point. While the data suggests reasonable stability, the adopted best estimate recession rate is 0.05m/year to cater for uncertainties and limitations in the data and the indications from other information including the modelling undertaken that there is some long term recession occurring due to the alongshore sand transport gradient. Upper and lower limits on this recession rate are adopted as 0.1m/year and 0.02m/year respectively.

5.2.4.2 Sea Level Rise Recession

The Bruun Rule approach would yield recession provisions in the range 14-20m by 2050 and 34-50m by 2100, as listed in Table 3-1. However, the regional model takes account of the alongshore sand transport processes that the Bruun Rule does not and yields somewhat less recession updrift (south) of Hastings Point and the training walls at Pottsville than the Bruun Rule. The modelling of sea level rise recession for the Pottsville area indicates:

- 15m recession by 2050; and
- 26m recession by 2100.

This is at the lower end of the range for the Bruun Rule at 2050 and significantly less at 2100. In recognition of the uncertainties involved in the modelling and the objective of precautionary conservatism, the adopted recession distances at Pottsville provide for -20% and +30% variation relative to best estimate values. The best estimates have been adopted to be the average of the modelled recession distance and Bruun Rule best estimate. As such, the sea level rise components to the erosion hazard at Pottsville are adopted as shown in Table 5-2.

Table 5-2 Adopted recession due to sea level rise to 2100

	2050	2100
Minimum	12m	26m
Best Estimate	15m	32m
Maximum	20m	42m

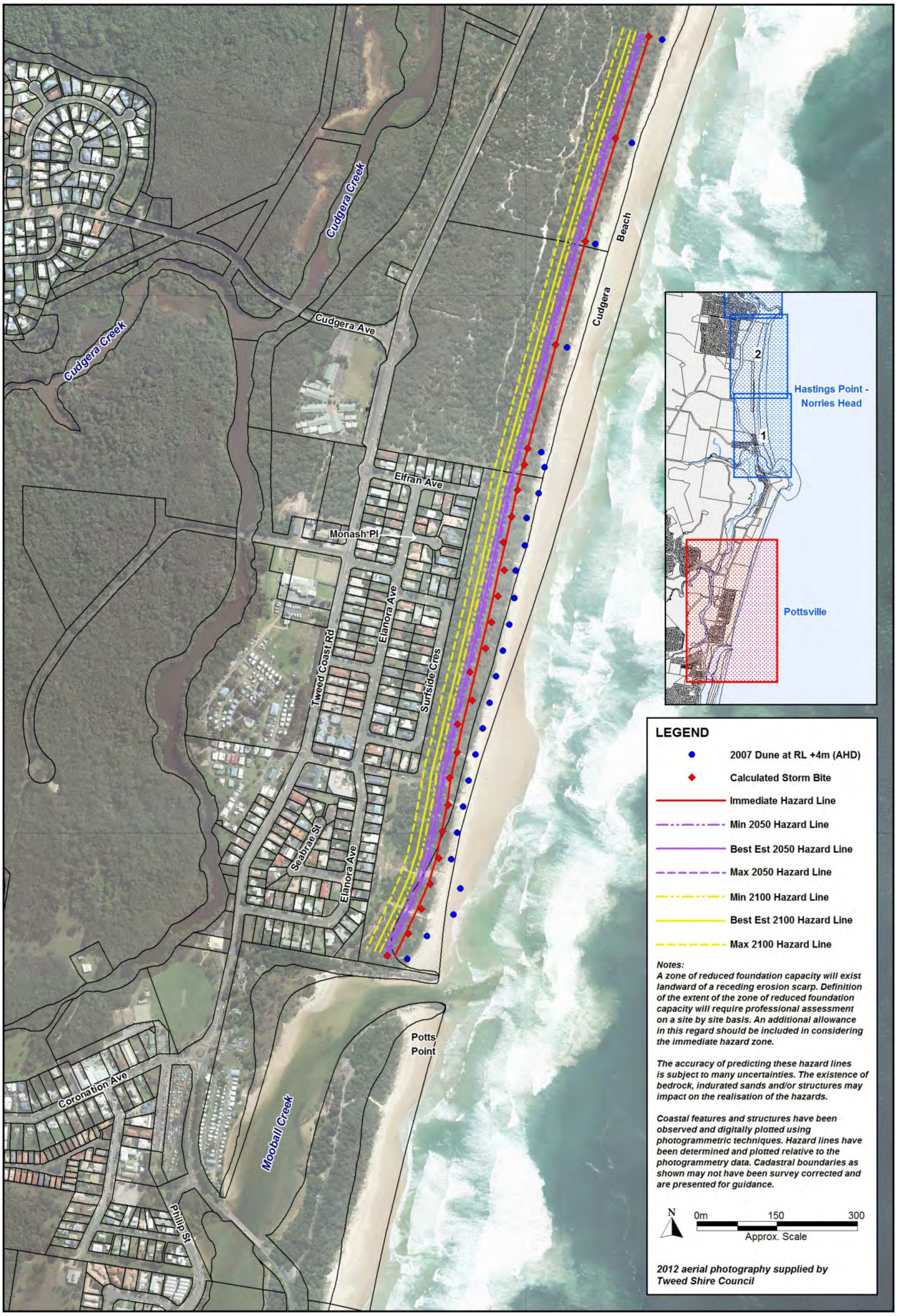
5.2.5 Erosion Hazard Assessment

The erosion hazard extents have been derived on the basis of:

- The immediate erosion hazard likely to occur due to a severe storm event or a closely spaced series of large storm events, or due to persistent erosion occurring over the next few years; and
- Longer term erosion hazards determined by adding to the immediate hazard line the additional recession associated with the underlying recession trends and the assessed sea level rise components over the planning periods to 2050 and 2100.

These erosion hazard extents are illustrated in Figure 5-4. The developed areas of Pottsville are landward of the projected 2050 and 2100 year hazard zones.

Thus the 2050 and 2100 erosion hazard extents incorporate the immediate erosion hazard and represent its projected extent following shoreline recession over those respective time-frames. It should be noted that there is a zone of reduced foundation capacity that extends landward of these erosion hazard lines, as discussed in Section 3.8.



Notes:
A zone of reduced foundation capacity will exist landward of a receding erosion scarp. Definition of the extent of the zone of reduced foundation capacity will require professional assessment on a site by site basis. An additional allowance in this regard should be included in considering the immediate hazard zone.

The accuracy of predicting these hazard lines is subject to many uncertainties. The existence of bedrock, indurated sands and/or structures may impact on the realisation of the hazards.

Coastal features and structures have been observed and digitally plotted using photogrammetric techniques. Hazard lines have been determined and plotted relative to the photogrammetry data. Cadastral boundaries as shown may not have been survey corrected and are presented for guidance.

2012 aerial photography supplied by Tweed Shire Council

Figure 5-4 Erosion hazard extents: Pottsville

5.2.6 Coastal Entrance Instability

The Mooball Creek mouth is trained and provides stability against any significant effects of migration of the creek on adjacent beaches. There may be some short term exchanges of beach sand with deposits in the lower estuary. However these are small in the context of the movements of sand in the beach system.

5.2.7 Coastal Inundation Hazard

Storm tides together with wave setup and run-up will affect the beach/dune system in this area. Storm tide and wave statistics relevant to the area are presented in Chapter 2. Wave propagation modelling provides an estimate of the nearshore design storm conditions, allowing for refraction and attenuation due to bed friction across the continental shelf, as follows:

- Significant wave height (*Hs*): 6.75m
- Wave period (*Tp*): approx. 12s

The $R_{2\%}$ run-up associated with these waves on the natural beach/dune profiles along this beach unit is calculated to be 3.76m above the still water level. With provision for the design 100 year storm tide level of 1.44m, this corresponds to design run-up levels for the immediate, 2050 and 2100 year planning periods as follows:

	Run-up level (m AHD)
Immediate	5.20
2050	5.54
2100	6.04

The dune system is generally sufficiently high to accommodate this impact without direct inundation of developed areas from the sea. While there may be some overwash within the frontal dune area, it will not extend to or overtop the main dune, which has crest levels typically in the range 8-10m (AHD). Accordingly, no development is currently at risk from the assessed coastal inundation hazard. Should the height of the frontal dune be diminished due to coastal recession in the future, the inundation risk may increase.

5.2.8 Mooball Creek Estuary Inundation

Design inundation levels within the lower estuary of Mooball Creek downstream of the road bridge are determined on the basis of the factors outlined in Section 3.6.1.4 to include:

- The present design storm tide level of +1.44m (AHD), including the 0.06m rise in sea level since 1990,
- A flood flow gradient provision of 0.4m,
- A wave setup component of 0.68m, based on 10% of the local design wave height at the creek mouth of approximately 6.75m; and
- Future sea level rise components of 0.4m and 0.9m since 1990 to 2050 and 2100 respectively.

The design inundation levels are thus as listed in Table 5-3.

Table 5-3 Mooball Creek lower estuary water levels: with sea level rise

Immediate (mAHD)	2050 (mAHD)	2100 (mAHD)
2.52	2.86	3.36

The extents of the inundation hazard for each planning timeframe are illustrated in Figure 5-5.

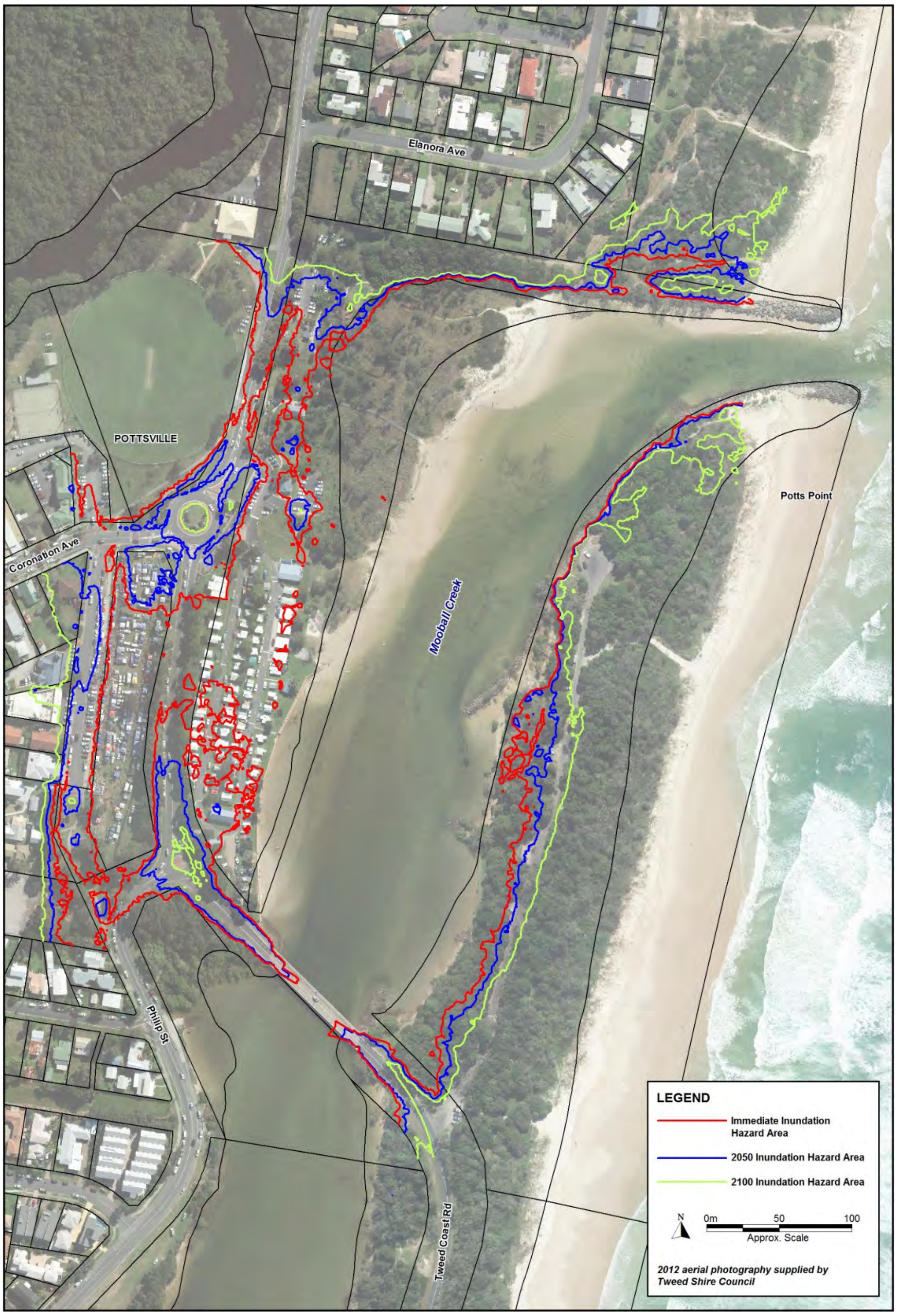


Figure 5-5 Mooball Creek lower estuary inundation hazard zones

5.3 Hastings Point to Norries Head

5.3.1 Coastal Erosion Processes

The coastline at Hastings Point is shown in Figure 5-6. This area is a relatively short embayed unit extending between Hastings Point and Norries Head and is expected to be relatively stable due to the controlling effects of those headlands. It thus lies within the regional coastal system described in Chapter 2, with northward net longshore sand transport of about 450,000-500,000m^3/yr. There is a positive northward gradient in the net longshore transport rate, offset either fully or partially by a shoreward supply from the shore-face.

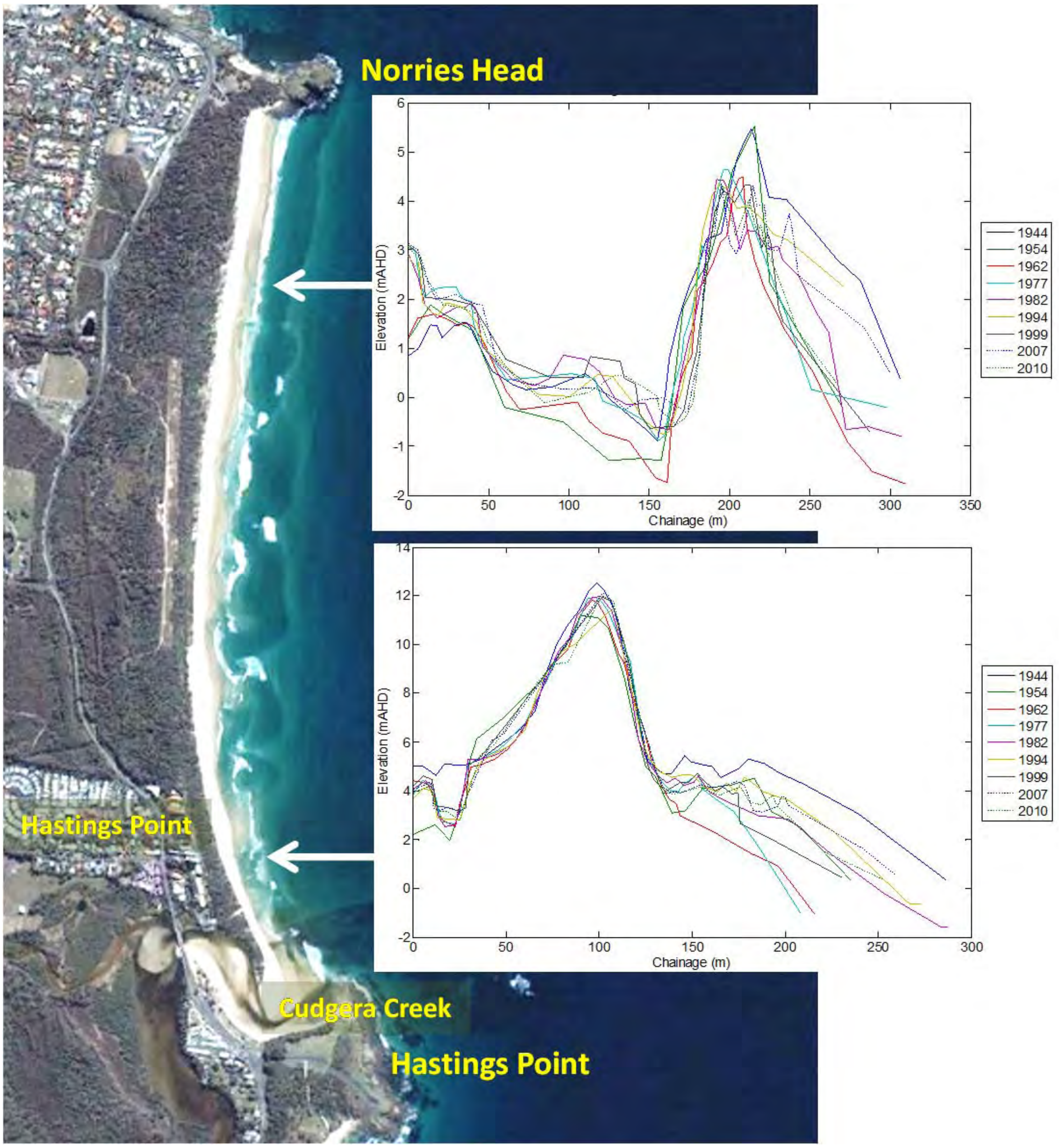


Figure 5-6 Hastings Point coastal form and dune topography

The principle mechanisms for coastal erosion there are:

- Short term storm bite erosion;

- Underlying long term shoreline recession due to any differential between the longshore transport gradient and shoreward sand supply; and
- Shoreline recession due to sea level rise.

The coastal system at Hastings Point has been subject to significant disturbance in the past. Sand mining activities led to re-shaping of the dune topography, typically with sand relocated from the former high main dune to other areas. Interference with the dune system has ceased and dune management practices are in place to ensure no losses of sand by wind drift.

Migration of the entrance channel to Cudgera Creek, together with breakthrough and/or overtopping of the northern spit shoreline of the creek during flood events may enhance erosion at the southern end of the beach.

5.3.2 Previous Coastal Hazard Studies

No detailed coastal process studies of this section of coast have been undertaken to date. The previous erosion hazard assessment undertaken for this beach (WBM Oceanics Australia 2001) determined prevailing shoreline recession due to longshore sand transport differentials to be:

- A best estimate of the regional rate at 0.1m/yr for the southern end of the beach at Hastings Point with upper and lower limits of 0.2 and 0.075m/yr respectively; reducing to; and
- A best estimate of 0.05m/yr immediately south of Norries Head with upper and lower limits of 0.1 and 0.04m/yr respectively.

The previously assessed erosion hazard also made provision for:

- A storm bite component equivalent to sand removal from the foredune of 200 m^3/m above AHD for an accreted beach condition, reduced to 160m^3/m relative to the eroded condition in 1999; and
- A recession component of up to 25m for 0.5m of sea level rise, representing a Bruun Rule factor of 50:1.

The entire spit area at the mouth of Cudgera Creek was assessed to be vulnerable to erosion , breakthrough and/or overtopping.

5.3.3 Re-assessed Short Term Storm Bite

Consistent with previously determined information, this re-assessment has adopted a general regional storm bite component equivalent to sand removal from the foredune of 200m^3/m above AHD, relative to a typical non-eroded beach state. Taking into consideration the recent beach changes identified in the photogrammetry, showing accretion in 2007 and some erosion in 2010, the design storm bite of 200m^3/m has been applied relative to the 2007 condition. Because there is no evidence of significant beach/dune volume variability associated with varying ENSO conditions, the storm bite thus determined represents the immediate hazard zone.

This line is typically 40 to 50m landward from the 2007 berm location and 20-30m landward of the 2010 dune erosion scarp, the greater distances corresponding to areas where the dunes are lower. There is no development within the immediate hazard zone at Hastings Point.

As in the previous hazard assessment, the whole of the small spit at the mouth of Cudgera Creek is prone to erosion and a zone of increased erosion hazard exists associated with migration and/or overtopping or breakthrough of the entrance channel, as discussed in Section 5.3.7 below.

5.3.4 Long Term Shoreline Movement

5.3.4.1 Updated Photogrammetric Analysis

The section of coast from Hastings Point to Norries Head has been analysed in three sections as listed in Table 5-4, with locations shown in Figure 5-7.

Table 5-4 Photogrammetry data description: Hastings Point to Norries Head

Block	Location	Length	No of profiles	Comments
A76-P	Hastings Point	720m	36	Minor interference to hind-dune area.
A76-1	Hastings Point to Norries Head	800m	4	Significant interference and sand removal in the hind-dune area.
A76-2	Hastings Point to Norries Head	1,400m	7	Significant interference and sand removal in the hind-dune area.

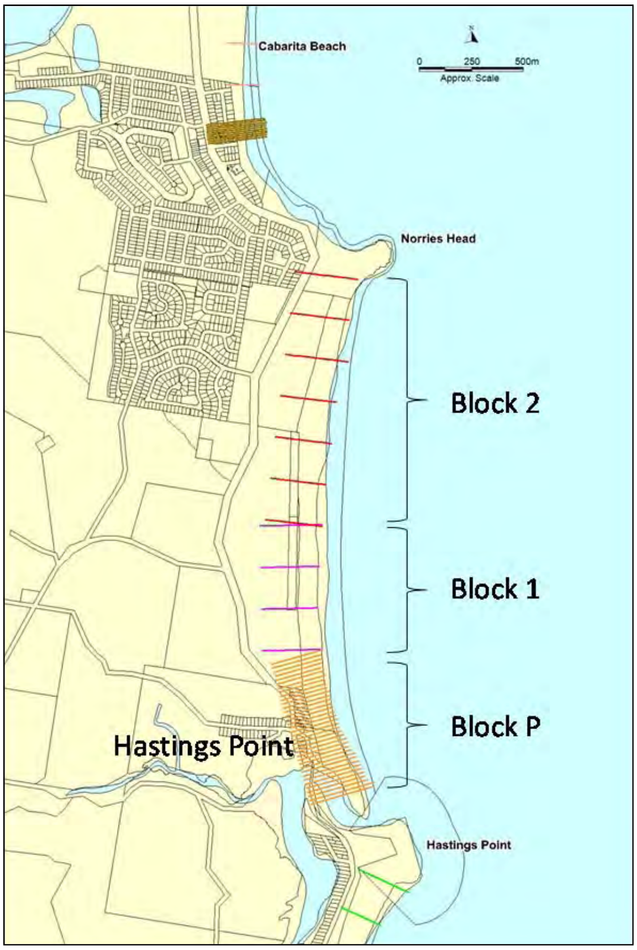


Figure 5-7 Location of photogrammetry lines at Hastings Point to Norries Head

Because of the substantial interference with the dunes here, analysis of scarp movements as an indicator of prevailing longer term trends is not feasible for this section of coast. It is evident that there has been net sand removal unrelated to coastal processes in the hind-dune area at some locations. As such, volumetric assessment has been adopted (Figure 5–8), with a landward limit cut-off applied in the analysis. As well, Blocks 1 & 2 have limited data and show similar trends, and thus are assessed together as one combined data set.

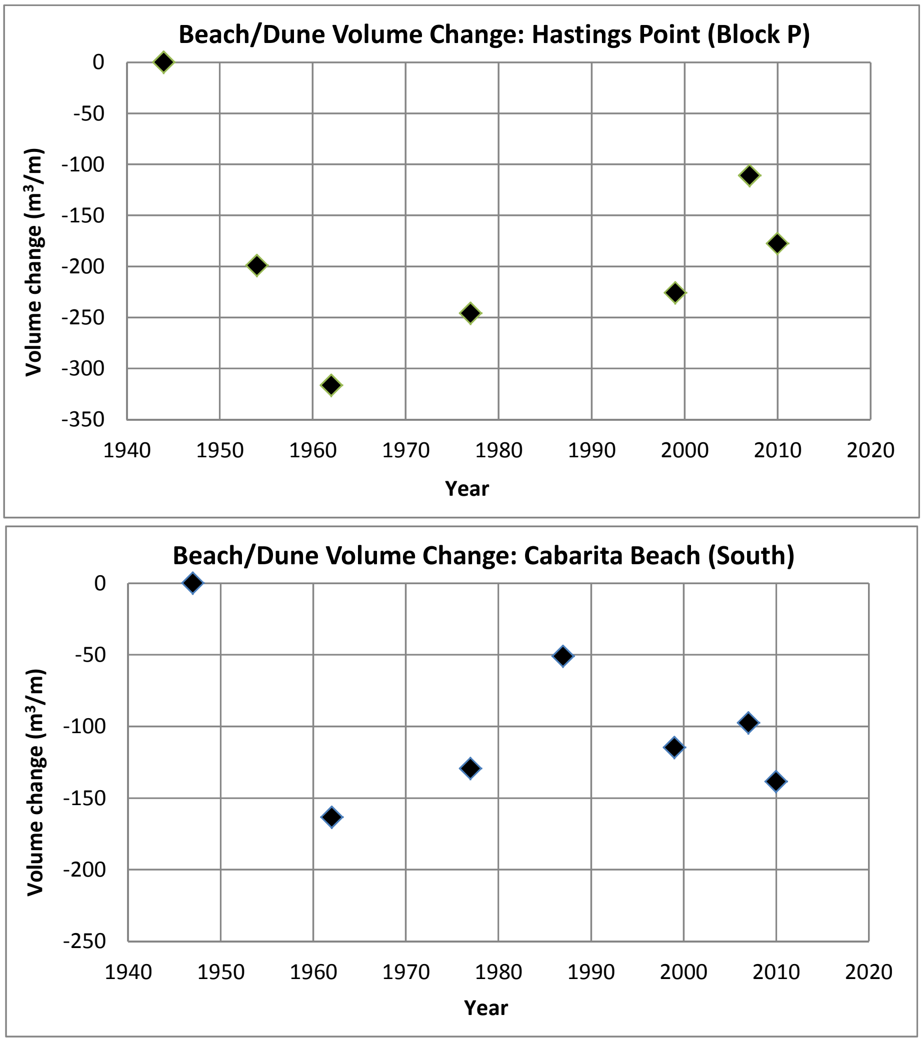


Figure 5–8 Volumetric Analysis - Section A76; Hastings Point to Norries Head

It can be seen from these data that this section of coast shows substantial reduction in volume from 1947 to 1955-1962. The significance of that loss depends on the reliability of the 1944 data, which remains uncertain, and the extent to which the loss is associated with major storm events and/or interference with the dunes during sand mining. The assessed trend for Hastings Point (Block P) is relative stability or net gain of sand since that time (1962). The pattern for the area immediately south of Norries Head (Blocks 1&2) is of stability or possible slight accretion over time since 1962. This apparent stability or only slight retreat since 1944/47 is the result of the relatively short length of this section of beach between the controlling headlands.

A tendency for some accretion south of Norries Head is feasible given the extensive dune stabilisation works carried out there, stabilising the connection across to the mainland and leading to a change in the balance of sand movement past Norries Head. This would have led to development of the foredune to the immediate south, representing a 'one-off' adjustment after which natural prevailing patterns of long term change, consistent with the regional sand budget, would re-establish.

However, it would be expected that the shoreline at Hastings Point would be experiencing recession over the long term, associated with the assessed longshore sand transport gradient, despite that being partially offset by some shoreward sand supply. That the data does not identify any clear recession pattern is most probably due to variability associated with other factors that exceeds and masks the underlying trend.

5.3.4.2 Adopted Recession Trend Rates

The photogrammetric analysis undertaken for this study does not identify a clear shoreline recession trend rate. Nevertheless, the regional context processes as discussed in Chapter 2 suggests that a minor recession would most probably prevail over the longer term. Accordingly, it is considered appropriate to adopt a most probable best estimate recession rate of 0.075m/yr for the southern section of the beach unit at Hastings Point reducing to 0.02m/yr just south of Norries Head. This is somewhat greater than that predicted in the modelling of Patterson (2013), which suggests a rate less than 0.05m/year at Hastings Point.

As such, the assessed underlying shoreline recession rate in this section of coast is consistent with the regional trend, partially stabilised by its proximity to the controlling headlands. While the data suggests reasonable stability, the recommended recession rates for Hastings Point are thus:

- Best estimate: 0.075m/year;
- Lower limit: 0.05m/year; and
- Upper limit: 0.12m/year.

5.3.4.3 Sea Level Rise Recession

The Bruun Rule approach to estimating recession due to sea level rise would yield distances in the range 12-20m by 2050 and 30-50m by 2100, as listed in Table 3-1, with allowance for the uncertainty involved in both the extent of sea level rise and the Bruun Rule factor used by applying -20% and +30% variation to the best estimate factor of 45:1. Additionally, the regional model has been used to simulate the sea level rise provision taking account of the alongshore sand transport processes that the Bruun Rule does not include. These processes tend to reduce the recession extent updrift (south) of headlands and exacerbate it immediately downdrift.

The modelling of sea level rise recession for Hastings Point as shown in Figure 3-4 indicates:

- 18m recession by 2050; and
- 34m recession by 2100.

This is reasonably consistent with the range indicated by the Bruun Rule, although at the lower end of the range at 2100, the reason being the stability provided by its proximity to Norries Head as a control point. However, it is immediately downdrift of Hastings Point where recession may be exacerbated relative to the open coast average. It is reasonably consistent with the recession predicted in the independent modelling undertaken by Patterson (2013). In recognition of the uncertainties involved in the modelling and the objective of precautionary conservatism, the adopted recession values are those given by the Bruun Rule, as shown in Table 5-5. However, where the recession would extend into dunes of height significantly greater than 5m, the recession distances are reduced in proportion to the total active height from the dune crest to the depth of closure.

Table 5-5 Bruun Rule shoreline recession provisions at Hastings Point

	2050	2100
Minimum	12m	30m
Best Estimate	15m	38m
Maximum	20m	50m

5.3.5 Erosion Hazard Assessment

The erosion hazard extents have been derived on the basis of:

- The immediate erosion hazard likely to occur due to a severe storm event or a closely spaced series of large storm events, or due to persistent erosion occurring over the next few years; and
- Longer term erosion hazards determined by adding to the immediate hazard line the additional recession associated with the underlying recession trends and the assessed sea level rise components over the planning periods to 2050 and 2100.

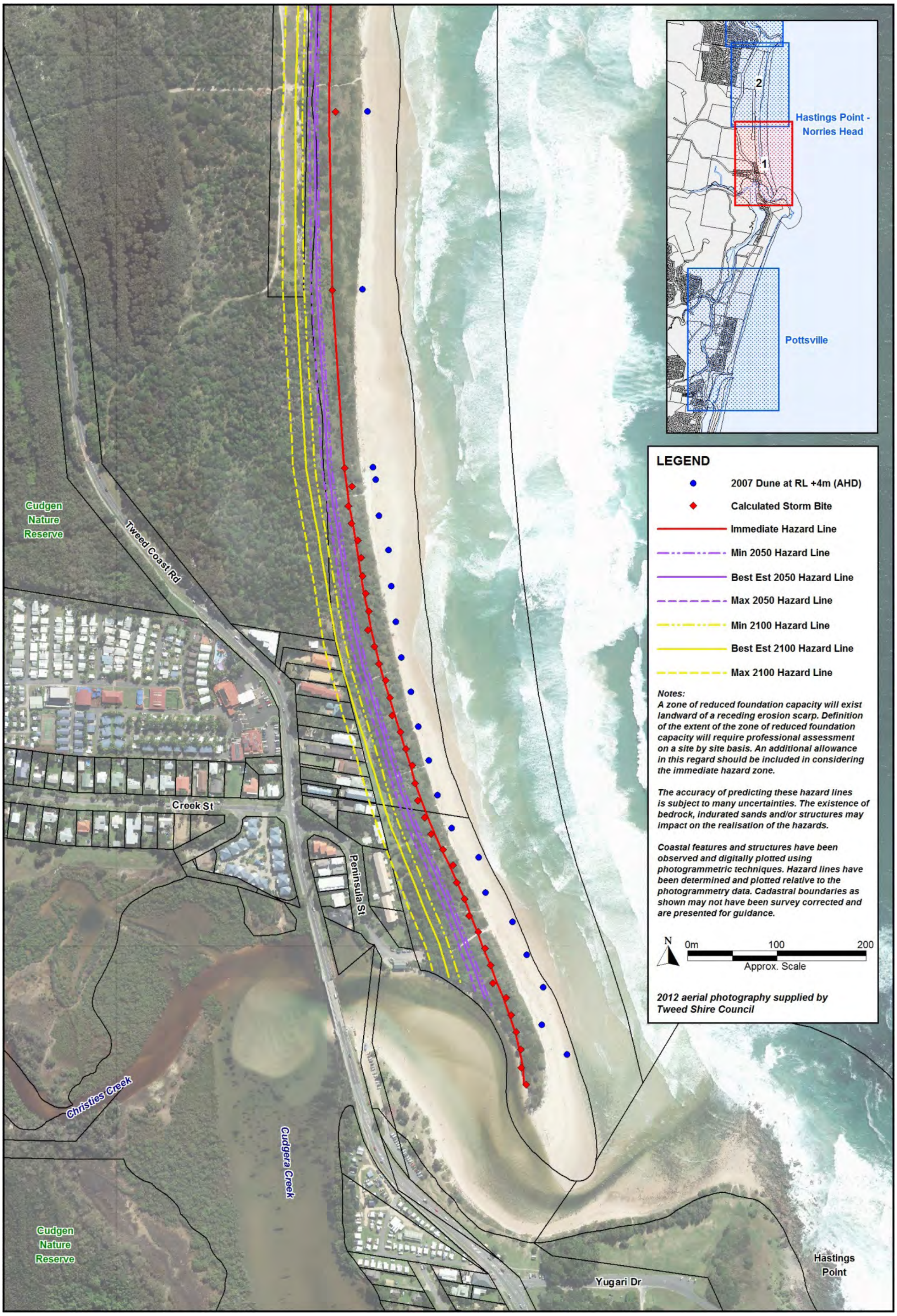
Thus, the 2050 and 2100 erosion hazard extents incorporate the immediate erosion hazard and represent its projected extent following shoreline recession over those respective time-frames. It should be noted that there is a zone of reduced foundation capacity that extends landward of these erosion hazard lines, as discussed in Section 3.8.

The erosion hazard extents are illustrated in Figure 5-9 and Figure 5-10. The developed areas of Hastings Point are unlikely to be affected by the erosion hazard to 2100, however there is a possibility indicated by the ‘maximum’ 2100 hazard line that erosion may extend into the northern properties due to the effects of sea level rise by that time

5.3.6 Coastal Entrance Instability

While the Cudgera Creek mouth is not trained, natural rock outcrops provide stability against any significant effects of migration of the creek to the south. The channel can, and has migrated along the beach to the north creating an increased erosion hazard zone in the immediate vicinity of the entrance. There may be some short term exchanges of beach sand with deposits in the lower estuary, however these are small in the context of the movements of sand in the beach system.

However, the spit extending in front of the creek (Figure 5-11) has relatively low dune crest levels (3.5-4m AHD) and is vulnerable to overtopping and potential breakthrough during major storm events. This entire spit area is considered to be within the erosion hazard both in the immediate near term and with future sea level rise.



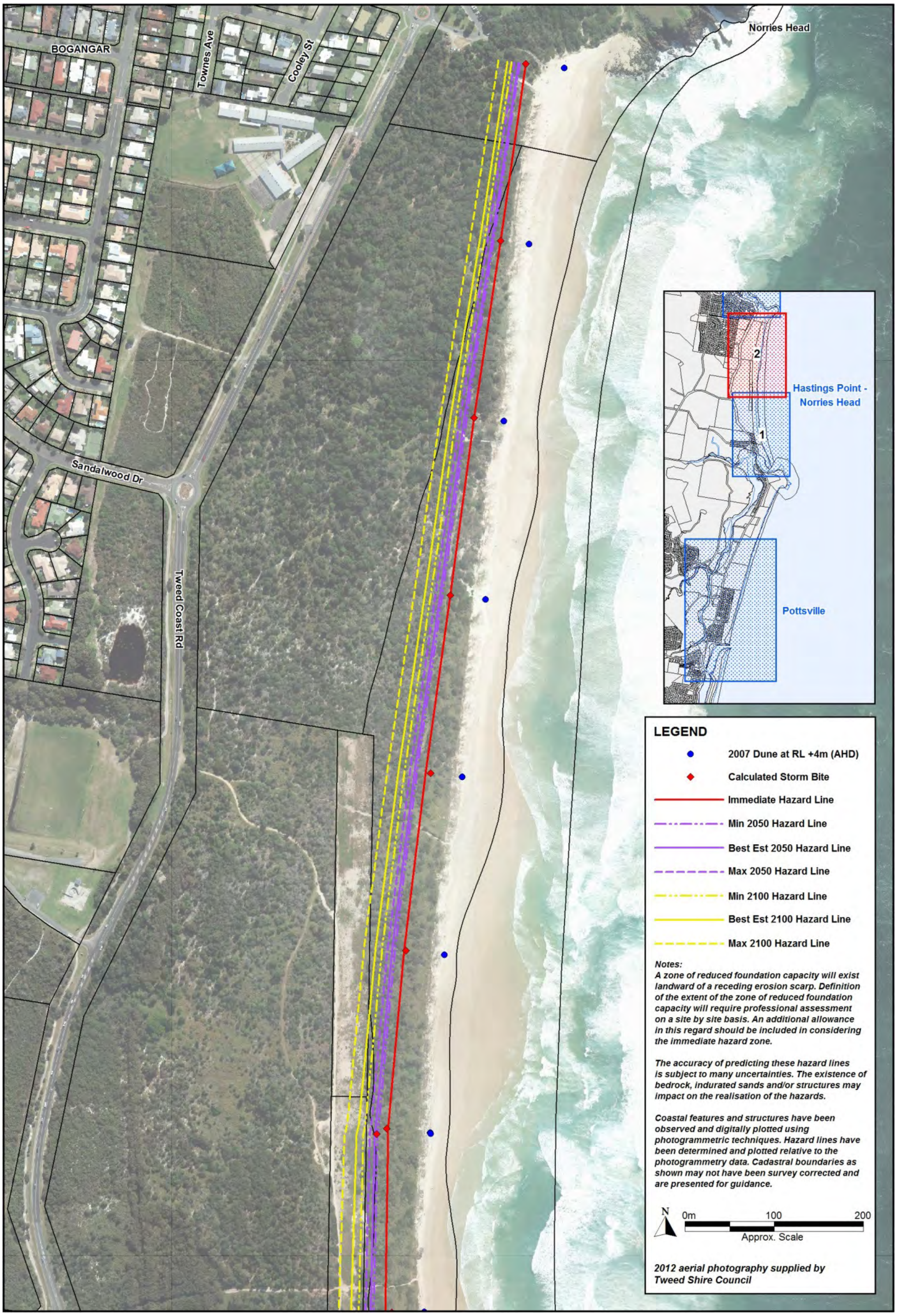
Notes:
A zone of reduced foundation capacity will exist landward of a receding erosion scarp. Definition of the extent of the zone of reduced foundation capacity will require professional assessment on a site by site basis. An additional allowance in this regard should be included in considering the immediate hazard zone.

The accuracy of predicting these hazard lines is subject to many uncertainties. The existence of bedrock, indurated sands and/or structures may impact on the realisation of the hazards.

Coastal features and structures have been observed and digitally plotted using photogrammetric techniques. Hazard lines have been determined and plotted relative to the photogrammetry data. Cadastral boundaries as shown may not have been survey corrected and are presented for guidance.

2012 aerial photography supplied by Tweed Shire Council

Figure 5-9 Erosion hazard extents: Hastings Point



Notes:
A zone of reduced foundation capacity will exist landward of a receding erosion scarp. Definition of the extent of the zone of reduced foundation capacity will require professional assessment on a site by site basis. An additional allowance in this regard should be included in considering the immediate hazard zone.

The accuracy of predicting these hazard lines is subject to many uncertainties. The existence of bedrock, indurated sands and/or structures may impact on the realisation of the hazards.

Coastal features and structures have been observed and digitally plotted using photogrammetric techniques. Hazard lines have been determined and plotted relative to the photogrammetry data. Cadastral boundaries as shown may not have been survey corrected and are presented for guidance.

2012 aerial photography supplied by Tweed Shire Council

Figure 5-10 Erosion hazard extents: Pottsville to Norries Head (Cabarita South)

Figure 5-11 Zone of wave overwash and coastal entrance instability – Cudgera Creek

5.3.7 Coastal Inundation Hazard

Storm tides together with wave setup and run-up will affect the beach/dune system in this area. Storm tide and wave statistics relevant to the area are presented in Chapter 2. Wave propagation modelling provides an estimate of the nearshore design storm conditions, allowing for refraction and attenuation due to bed friction across the continental shelf, as follows:

- Significant wave height (*Hs*): 6.75m
- Wave period (*Tp*): approx. 12s

The $R_{2\%}$ run-up associated with these waves on the natural beach/dune profiles along this beach unit is calculated to be 3.76m above the still water level. With provision for the design 100 year storm tide level of 1.44m, this corresponds to design run-up levels for the immediate, 2050 and 2100 year planning periods as follows:

	Run-up level (m AHD)
Immediate	5.20
2050	5.54
2100	6.04

North of Cudgera Creek, the dune system is generally sufficiently high to accommodate this impact without direct inundation of developed areas from the sea. While there may be some overwash within the frontal dune area, it will not extend to or overtop the main dune, which has crest levels typically in the range 6-10m (AHD). Accordingly, no development is currently at risk from the assessed coastal inundation hazard. Should the height of the frontal dune be diminished due to coastal recession in the future, the inundation risk may increase.

However, the dune formed on the spit extending in front of the creek (Figure 5-11) has generally lower crest levels, at about 3.5-4m at the southern end. Those dunes are vulnerable to wave overtopping and overwash that could extend about 10-20m landward of the erosion extent, with potential breakthrough during major storm events both in the immediate near term and with increased likelihood in the future due to shoreline recession and sea level rise.

5.3.8 Cudgera Creek Estuary Inundation

Design inundation levels within the lower estuary of Cudgera Creek downstream of the road bridge are determined on the basis of the factors outlined in Section 3.6.1.4 to include:

- The present design storm tide level of +1.44m (AHD), including the 0.06m rise in sea level since 1990;
- A flood flow gradient provision of 0.4m;
- A wave setup component of 0.68m, based on 10% of the local design wave height at the creek mouth of approximately 6.75m; and
- Future sea level rise.

The design inundation levels are thus as listed in Table 5-6.

Table 5-6 Cudgera Creek lower estuary water levels: with sea level rise

Immediate (mAHD)	2050 (mAHD)	2100 (mAHD)
2.52	2.86	3.36

The extents of the inundation hazard for each planning timeframe are illustrated in Figure 5-12.

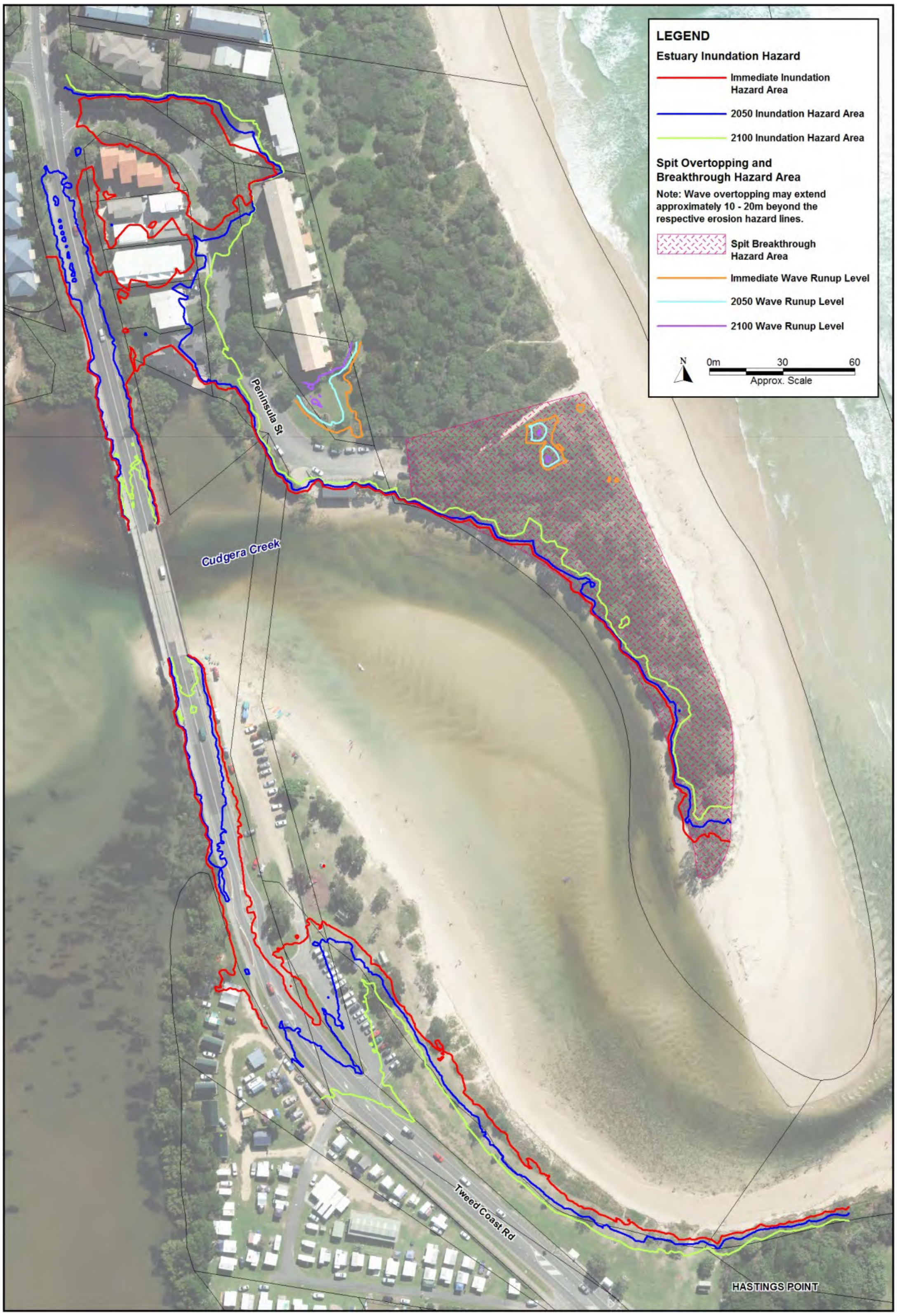


Figure 5-12 Cudgera Creek lower estuary inundation hazard zones

5.4 Norries Head to Sutherland Point

5.4.1 Coastal Erosion Processes

The coastal unit between Norries Head and Sutherland Point (Figure 5-13 and Figure 5-14) is a relatively longer embayed unit within the regional coastal system described in Chapter 2, with northward net longshore sand transport of about 500,000m^3/yr. There is a positive northward gradient in the net longshore transport rate, offset either fully or partially by a shoreward supply from the shore-face.

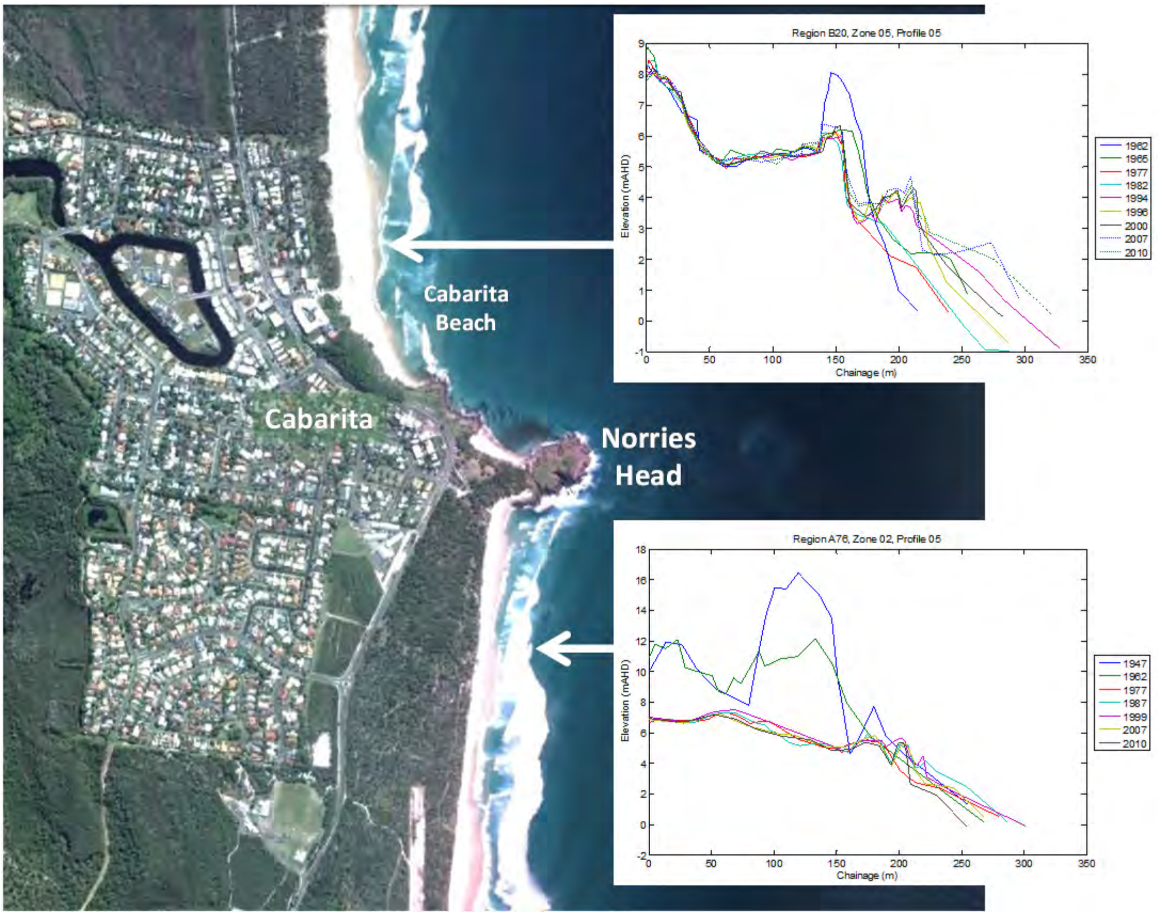


Figure 5-13 Cabarita Beach coastal form and dune topography

The dune system of Bogangar Beach has been extensively mined for heavy minerals. Mining took place mainly during the 1950s, 60s and 70s, involving removal of the heavy mineral content (some 1-2%) of the sand volume and re-contouring the dunes. Only the dunes within the area of Bogangar (Cabarita Beach) Township were not mined. The sand mining operations are of significance in assessment of historical coastline movements in that the dune re-contouring prevents direct comparison of beach/dune profiles at particular locations within the mined area when determining overall distance and volume changes.

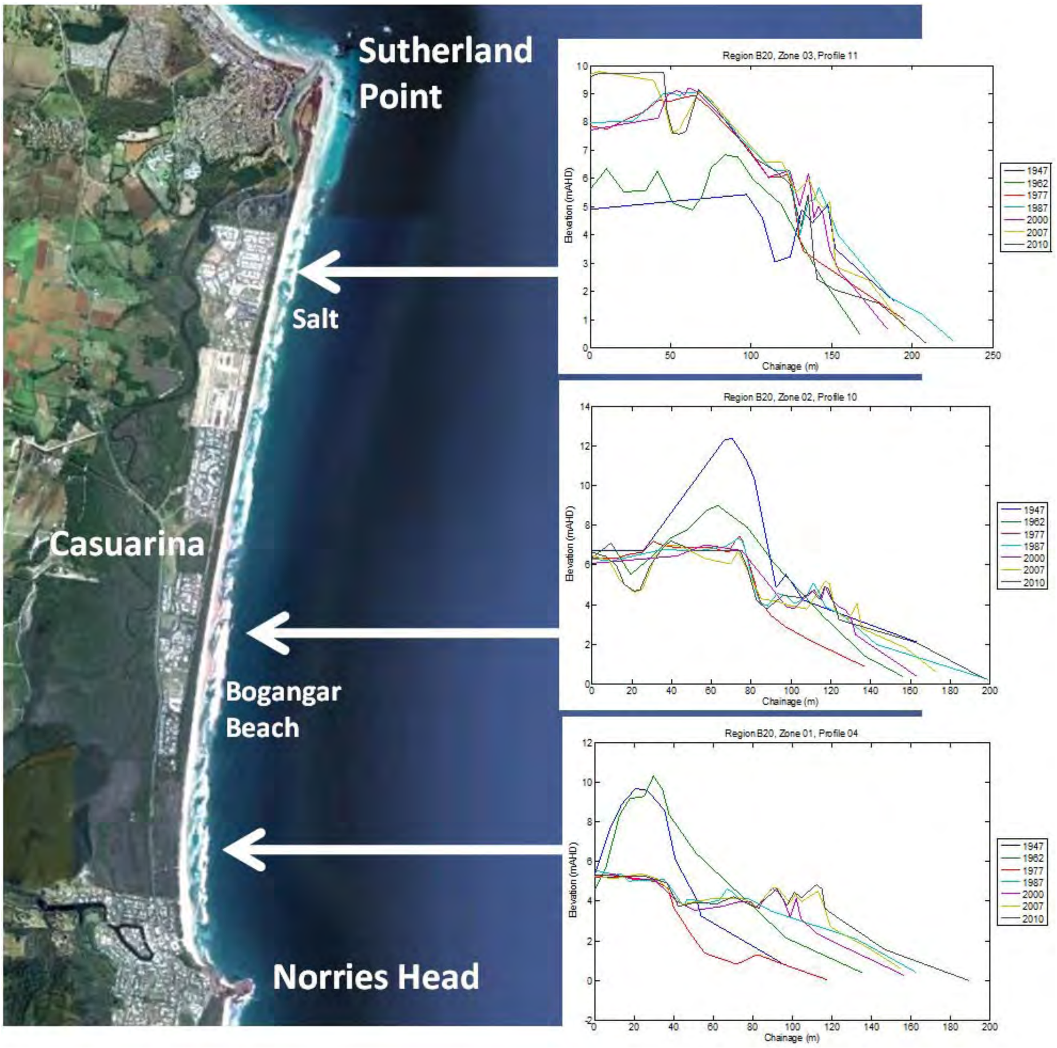


Figure 5-14 Norries Head to Sutherland Point coastal form and dune topography

The real extent of the re-contouring carried out, and any net gain or loss of sand within the active foredune areas is not presently known. The height of the natural Holocene dune system at Bogangar (up to 10-15 metres) is indicative of a period of extensive sand drift at an earlier time in its evolution. Extensive parts have subsequently been re-shaped and developed to establish the township communities of Casuarina and Salt.

An alongshore gradient in the rates of longshore transport of sand has been proposed as a possible cause of progressive long term erosion of Bogangar Beach. As well, past sea level rise would have contributed to some recession there. As such, the principle mechanisms for future coastal erosion along the Cabarita Beach/Bogangar/ Casuarina Beach area are:

- Short term storm bite erosion;
- Underlying long term shoreline recession due to any differential between the longshore transport gradient and shoreward sand supply; and
- Shoreline recession due to sea level rise.

5.4.2 Previous Coastal Hazard Studies

There have been a number of previous coastal hazard studies undertaken for this section of coastline, including PWD (1979b), PWD (1982), PWD (1983), Winders Barlow & Morrison (1988) and WBM Oceanics Australia (2001). These have all indicated shoreline recession at rates reducing northward from a maximum at Cabarita Beach to a minimum near Sutherland Point.

PWD (1982) determined a longshore transport differential of 110,000m^3/year for the 8 kilometre length of Bogangar Beach by interpolation of the rates derived for other locations in the region. They thus derived an average recession rate of about 0.8m/year for the beach unit. Additionally, they determined the linear movements of the “erosion scarp” along the 400 metre stretch of beach fronting Cabarita Beach township from aerial photography for the dates 1962, 1971, 1975 and 1976, yielding average recession rates of 1.0-1.9m/year.

The WBM (1988) analysis based on photogrammetry to that time indicated rates of shoreline retreat at Cabarita Beach township in the range 0.26-0.38m/year. The more northern profiles were considered to give a more reliable indication of sustained recession and showed indicative rates in the range 0.12-0.29m/year over the period 1944 to 1984. It was suggested at that time that a retreat rate at Cabarita Beach township of around 0.10-0.30m/year was appropriate for planning purposes.

The previous erosion hazard assessment study (WBM Oceanics Australia 2001) determined an alongshore transport gradient as little as 10,000-15,000m^3/year, about 10% of that suggested by PWD (1982). It adopted an average recession of about 0.1m/year for this part of the coast, based on the photogrammetry to that date and consideration of the regional processes.

Utilising more recent ground survey, the WBM 2000a report indicated that there had been no further retreat of the main dune erosion scarp since 1974. The surveys showed the present foredune condition was such that a major storm occurring then was unlikely to erode beyond the older scarp. At that time it was suggested that an appropriate retreat rate at Cabarita Beach township for planning purposes could be around 0.10-0.30m/yr. This has been further reviewed with updated data to 2010 in the present study.

5.4.3 Short Term Storm Bite

Consistent with previously determined information, a general regional design volume of 200m^3/m above mean sea level is generally recommended for open coast beaches. This is consistent also with experience at southeast Queensland beaches. For a typical foredune height of about 4-5m, this corresponds to a recession of the foredune dune of about 40-50m.

Analysis of the photogrammetry data in the present study indicates that 2007 represents a relatively accreted condition. The erosion in 2010 had variable effects along this coastal unit. In the south at Cabarita Beach, the beach and dune is somewhat more accreted in 2010 than in 2000 and 2007 and substantially more accreted than in 1977 (Figure 5-15). Towards the northern end, the 2010 erosion extended approximately as far landward as it had previously in 1999/2000, but still not to the 1977 scarp (Figure 5-16).

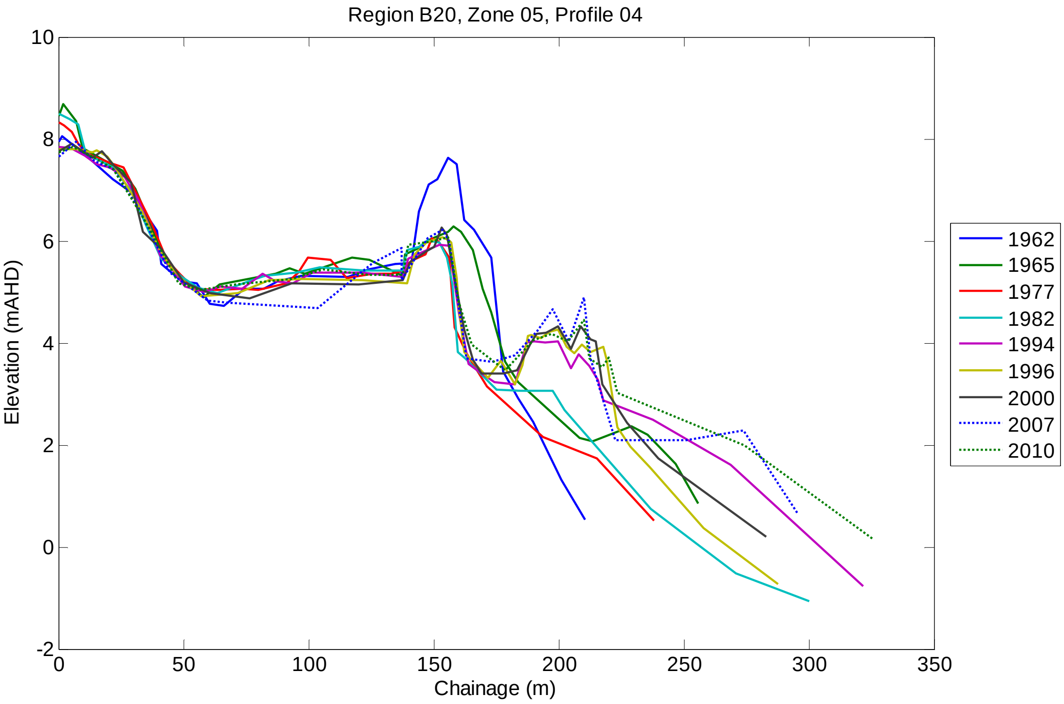


Figure 5-15 Cabarita Beach profiles showing the most accreted beach condition in 2010

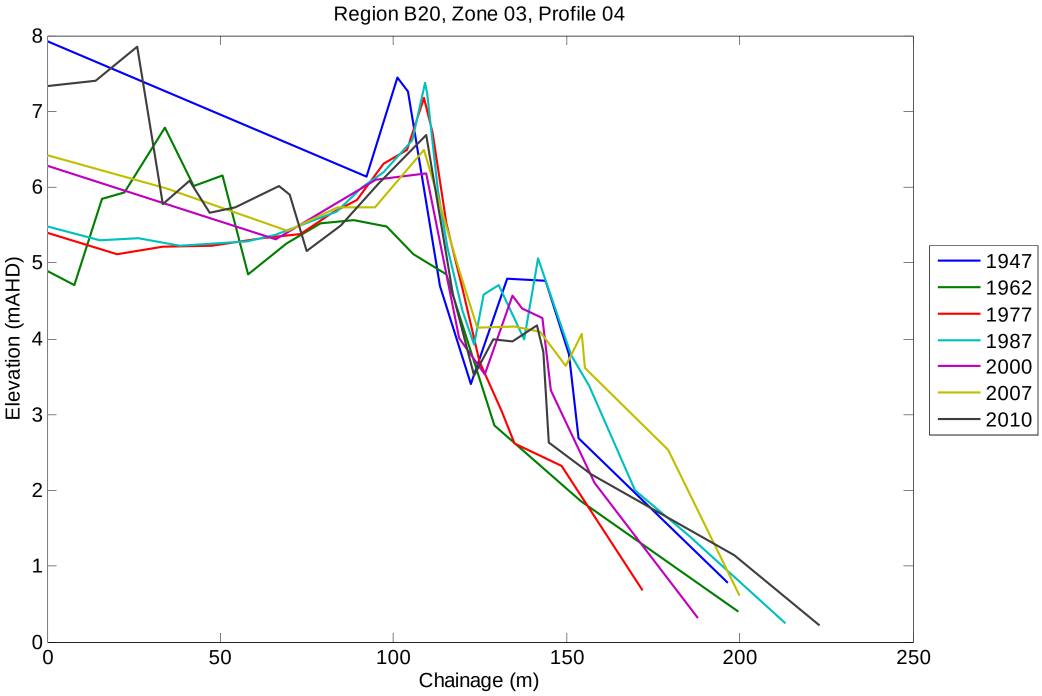


Figure 5-16 Profiles at Casuarina showing foredune erosion in 2010 2007

The storm bite has been calculated on the basis of erosion of 200m^3/m above AHD relative to the 2007 condition. Generally, this yields an erosion distance approximately back to the older historical 1977 scarp. Only at Cabarita Beach is the storm bite extent seaward of the 1977 scarp. The reason for this is unclear, however it is most likely that the earlier storm responses were affected by headland effects associated with strengthening of the dune connection between the mainland and Norries Head around that time. This would have caused a temporary phase of downdrift recession at

Cabarita Beach until the northward alongshore sand transport supply around the headland was fully restored. Thus, it is not considered appropriate to assume that the 1977 scarp represents a benchmark for storm bite extent at Cabarita Beach.

5.4.4 Long Term Shoreline Movement

5.4.4.1 Updated Photogrammetric Analysis

This section of coast includes Cabarita Beach at the southern end (Blocks Q & 1) and Casuarina Beach along the central area (Blocks 2 & 3). It has thus been analysed in four sections as follows (see Figure 5-17 for locality):

Block	Location	Length	No of profiles	Comments
B20-Q	Cabarita Beach	500m	10	Minor interference to hind-dune area associated with township development.
B20-1	Cabarita Beach (North)	1,200m	6	Significant interference and sand redistribution in the hind-dune area.
B20-2	Casuarina Beach	3,600m	18	Significant interference and sand redistribution in the hind-dune area.
B20-3	Casuarina Beach (north)	4,000m	20	Significant interference and sand redistribution in the hind-dune area.

Analysis of scarp movement as an indicator of long term trends is not feasible in this section. Volumetric analysis has been undertaken, as summarised in Figure 5–18. With the exception of Block Q (Cabarita Beach), the 1947 and 1962 (pre-mining) data must be regarded with some caution along the Casuarina Beach area because of the gross changes to the dunes which have occurred there.

It can be seen from these data that Cabarita Beach shows a substantial continuing trend of accretion over time. This is related primarily to expansive growth of the foredune which now extends some 50 metres seaward of the older 1977 dune scarp, formed in 1967/74. This accretion trend has been sustained over the past 30 years, including periods of both El Niño and La Niña conditions. While it may in part represent recovery from major storm-related sand losses during the mid 20th century, it appears also to signify permanent shoreline recovery from the effects of changes at Norries Head. In that regard, the beach/dune immediately south of Norries Head was substantially stabilised and its connection to the mainland made permanent. This may have had a short term negative impact (higher recession rates) at Cabarita Beach during the 1960s and 1970s which has now been overcome with restoration of the normal sand flow past Norries Head, manifesting as apparent long term gain over the period of photogrammetry. That accretion trend would not be sustained into the longer term future and would be expected to give way to resumption of the natural underlying recession trend.

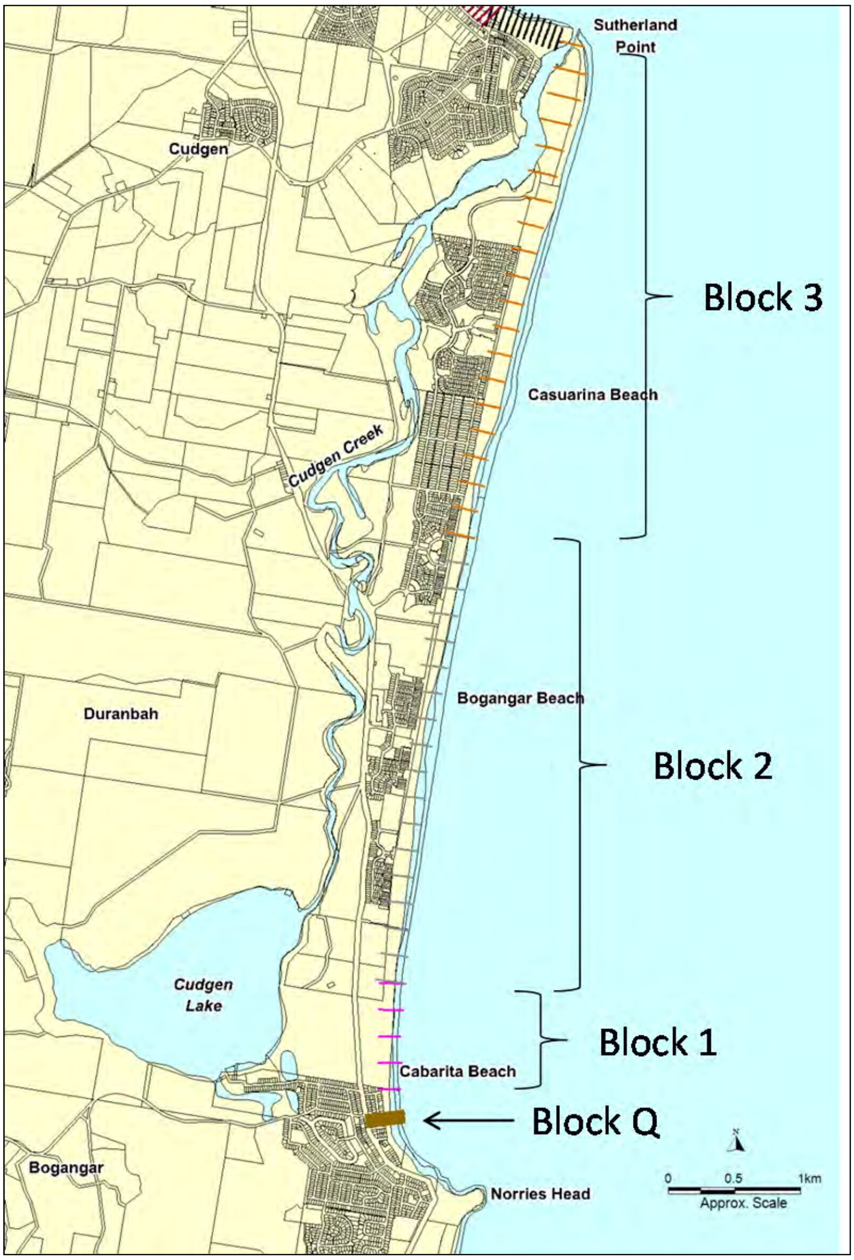


Figure 5-17 Location of photogrammetry profiles – Norries Head to Sutherland Point

As such, a future long term trend of slight retreat of this section of coast is likely, probably somewhat higher than the regional average rate due to its location at the southern end of the coastal embayment, but lower than those which have been observed over shorter time frames in the past. The average recession rate further north along the embayment is expected to be similar to the regional average.

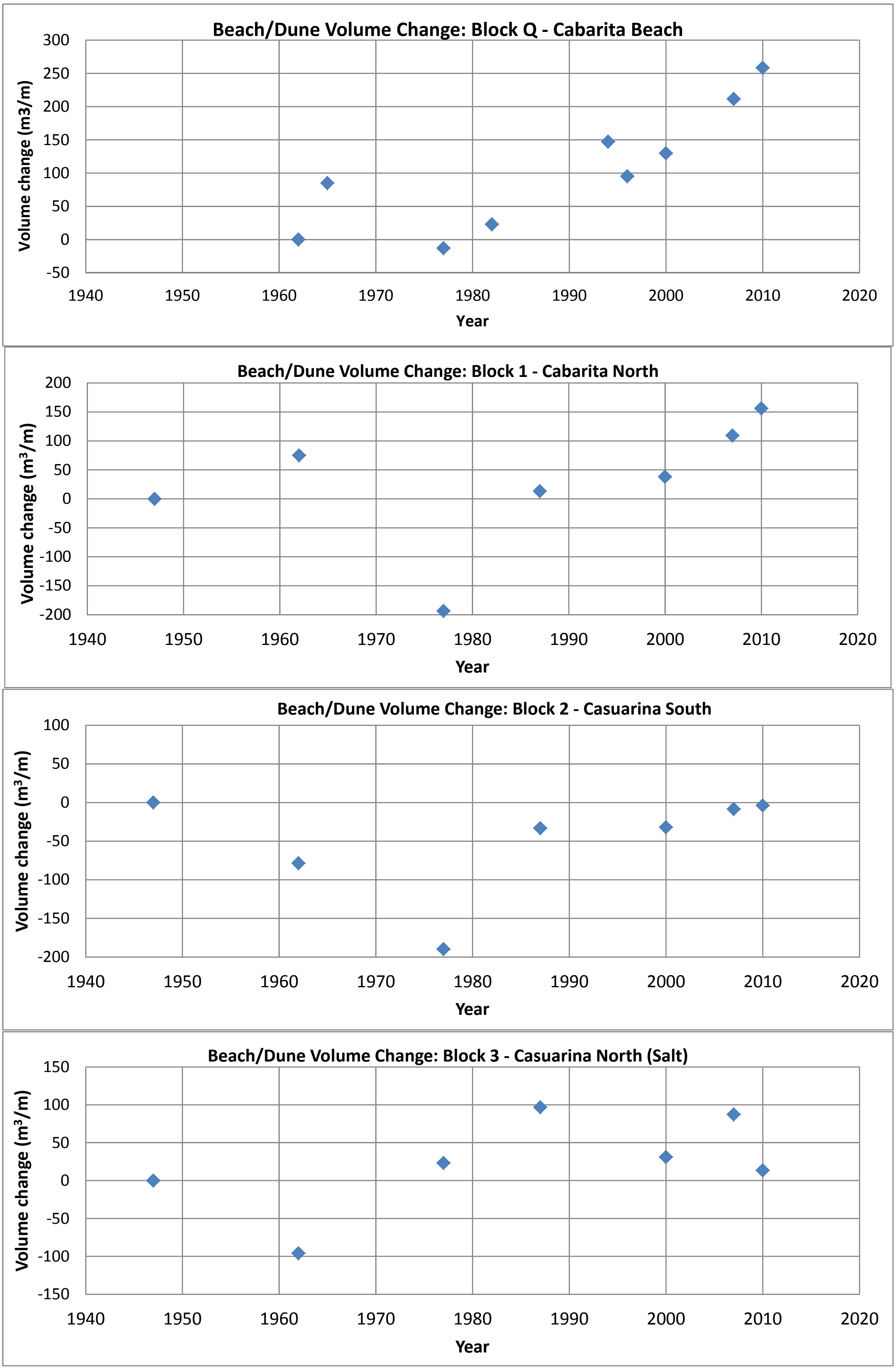


Figure 5–18 Volumetric Analysis - Norries Head to Sutherland Point

However, analysis of any recession trend from the data for the beach section north of Cabarita, Beach including Casuarina Beach is not conclusive, particularly since parts of the pre-mining data are not directly compatible with the more recent data due to apparent substantial relocation of dune sand and changes to profiles by the mining activities. A longer term pattern of stability or slight volumetric accretion is indicated by the available data.

5.4.4.2 Adopted Recession Trend Rates

Relative stability of this section of coast is indicated by the updated photogrammetry. Based on other information from the regional context, a future long term trend of slight recession, at the regional average rate of about 0.1m/year, is recommended.

This may be higher towards the southern end of the embayment at Cabarita Beach township due to its location at the southern end of the coastal embayment and a rate of 0.15m/year has been adopted there as a best estimate, although the available photogrammetry shows a slight trend of overall accretion for the period covered by the data. To cater for natural variability and uncertainty, upper and lower retreat rates of 0.25 m/yr and 0.1 m/yr are recommended for Cabarita Beach, based on possibility of ENSO-related effects there. While higher rates of recession have been observed in the past over shorter time frames, it is considered that these would not be sustainable over longer planning periods.

The beach section at the northern end of the embayment is expected to be experiencing long term recession at or lower than the regional average. This is consistent with the previous hazard assessment and the recommended recession rates there are 0.1m/yr for the central area, reducing to 0.05m/yr just south of Sutherland Point. A band of uncertainty is again recommended for inclusion in defining the hazard zones.

Thus the recommended underlying recession rates for this section of coastline are as follows, providing for progressive variation along the beach:

Cabarita Beach

- Best estimate: 0.15m/year
- Minimum: 0.1m/year
- Maximum: 0.25m/year

Casuarina South (Bogangar)

- Best estimate: 0.125m/year
- Minimum: 0.075m/year
- Maximum: 0.175m/year

Casuarina North (Salt)

- Best estimate: 0.1m/year
- Minimum: 0.05m/year
- Maximum: 0.15m/year

5.4.4.3 Sea Level Rise Recession

The Bruun Rule approach would yield recession provisions in the range 12-20m by 2050 and 30-50m by 2100, as listed in Table 3-1. The regional model takes account of the alongshore sand transport processes that the Bruun Rule does not include and tends to reduce the recession updrift (south) of Sutherland Point and exacerbate it immediately downdrift (north) of Norries Head due to the effects of the headland controls. The modelling of sea level rise recession for this section of coastline indicates reducing extents from south to north, as listed in Table 5-7. These are consistent with the distances indicated by the Bruun Rule in the central part of the beach unit but greater at the southern end and less further north.

Table 5-7 Modelled recession due to sea level rise: Norries Head to Sutherland point

	2050	2100
Cabarita Beach	30m	70m
Casuarina South (Bogangar Beach)	24m	50m
Casuarina North (Salt)	22m	32m

In recognition of the objective of precautionary conservatism, the larger modelled recession values are adopted as the best estimate at the southern end of the beach unit (Cabarita Beach / Bogangar), with variation to provide for uncertainty of -20% and +30% there. At north Casuarina (Salt), the Bruun Rule distances are adopted as the best estimate, with the same proportional provision for uncertainty.

The sea level rise components to the erosion hazard thus adopted along this section of coastline are shown in Table 5-8 to Table 5-10.

Table 5-8 Adopted recession due to sea level rise to 2100: Cabarita Beach

	2050	2100
Minimum	24m	56m
Best Estimate	30m	70m
Maximum	40m	90m

Table 5-9 Adopted recession due to sea level rise to 2100: Casuarina (Bogangar)

	2050	2100
Minimum	19m	40m
Best Estimate	24m	50m
Maximum	31m	65m

Table 5-10 Adopted recession due to sea level rise to 2100: Casuarina North (Salt)

	2050	2100
Minimum	12m	30m
Best Estimate	15m	38m
Maximum	20m	50m

Where the recession would extend into dunes that are significantly higher than 5m, the recession distances are factored down in proportion to the active profile height from the dune crest to the depth of closure.

5.4.5 Erosion Hazard Assessment

The erosion hazard extents have been derived by applying the adopted underlying recession trend rates together with the assessed sea level rise effects to the immediate hazard extents as described above. Thus, the 2050 and 2100 erosion hazard extents incorporate the immediate erosion hazard and represent its projected extent following shoreline recession over those respective time-frames. These are shown for planning periods to 2050 and 2100 in Figure 5–19 to Figure 5–22. It should be noted that there is a zone of reduces foundation capacity that extends landward of these erosion hazard lines, as discussed in Section 3.8.

The maximum 2050 year hazard line just reaches the seaward property boundary in central Cabarita Beach while the best estimate and maximum limits extend into the properties to varying extents at 2100. All existing structures are landward of the best estimate 2050 year line except for the surf pavilion building. The projected 2100 year hazard zone extends substantially into the seaward properties at Cabarita Beach and to varying extents for the properties to the north.

Further to the north along Bogangar - Casuarina, the 2050 year hazard zone does not extend into the seaward properties. The best estimate 2100 hazard extent is close to the seaward property boundaries, though generally slightly to the seaward side except adjacent to the southern end of Lorne Street where it encroaches into the properties. The maximum likely 2100 extent encroaches into the seaward parts of the properties along most of the developed length.

5.4.6 Coastal Inundation Hazard

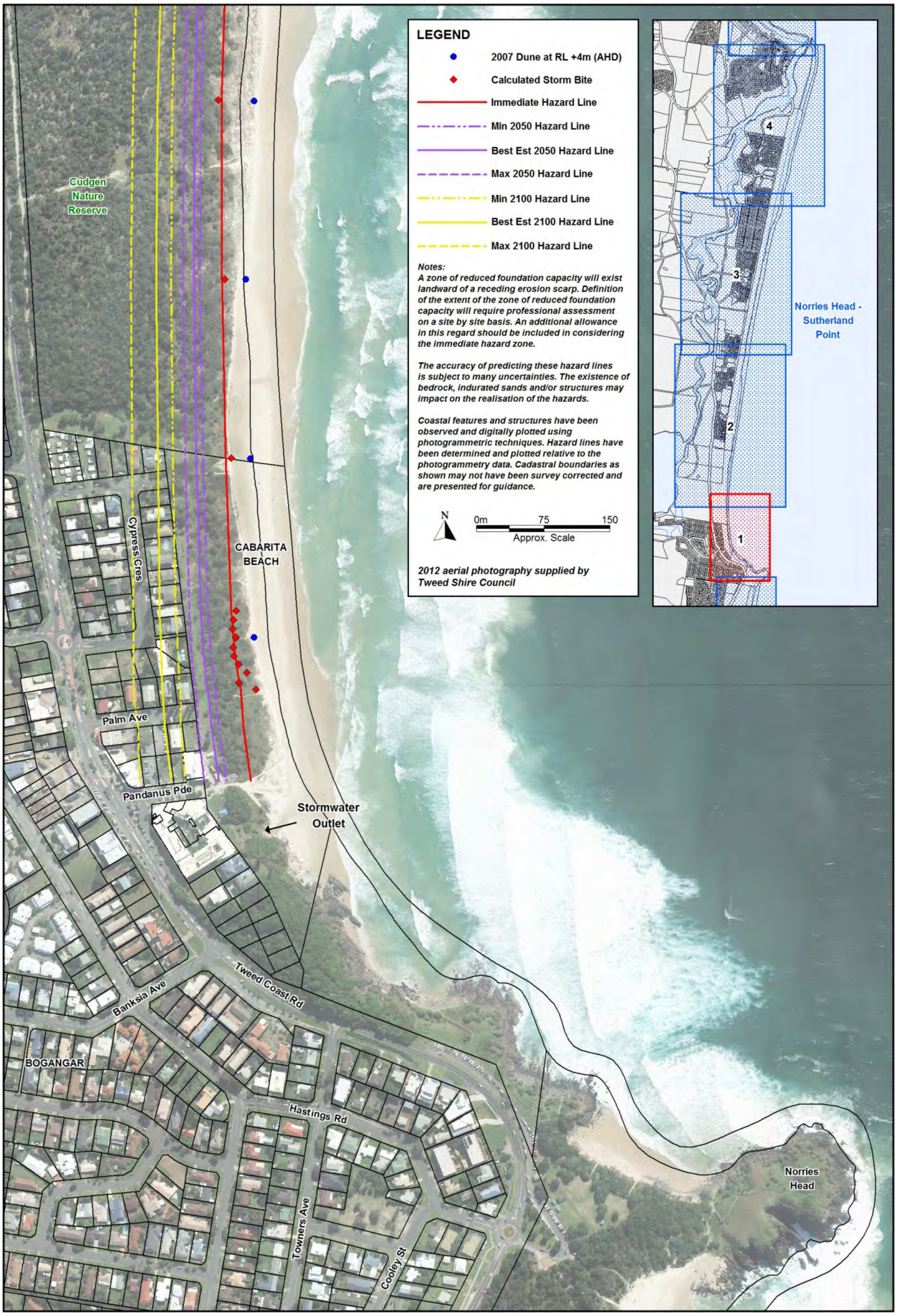
Storm tides together with wave setup and run-up will affect the beach/dune system in this area. Storm tide and wave statistics relevant to the area are presented in Chapter 2. Wave propagation modelling provides an estimate of the nearshore design storm conditions, allowing for refraction and attenuation due to bed friction across the continental shelf, as follows:

- Significant wave height (*Hs*): 6.75m
- Wave period (*Tp*): approx. 12s

The design $R_{2\%}$ run-up associated with these waves on the natural beach/dune profiles along this beach unit is calculated to be 3.76m above the design 100 year storm tide level of 1.44m, corresponding to design run-up levels for the immediate, 2050 and 2100 year planning periods as follows:

	Run-up level (m AHD)
Immediate	5.20
2050	5.54
2100	6.04

The dune system is generally sufficiently high to accommodate this impact without direct inundation of developed areas from the sea. Accordingly, no development is currently at risk from the assessed coastal inundation hazard. However, with sea level rise or should the height of the frontal dune be diminished due to coastal recession in the future, the inundation risk may increase. There is an area at the southern end of Bogangar Beach (Figure 5–23) where the dune crest levels are lower, at about 5.0-5.5m AHD. Under extreme conditions with future sea level rise, it is possible that some oceanic wave overwash may occur there. However, it is probable that the natural processes of dune building will allow the crest levels to grow as sea levels rise, reducing that risk.



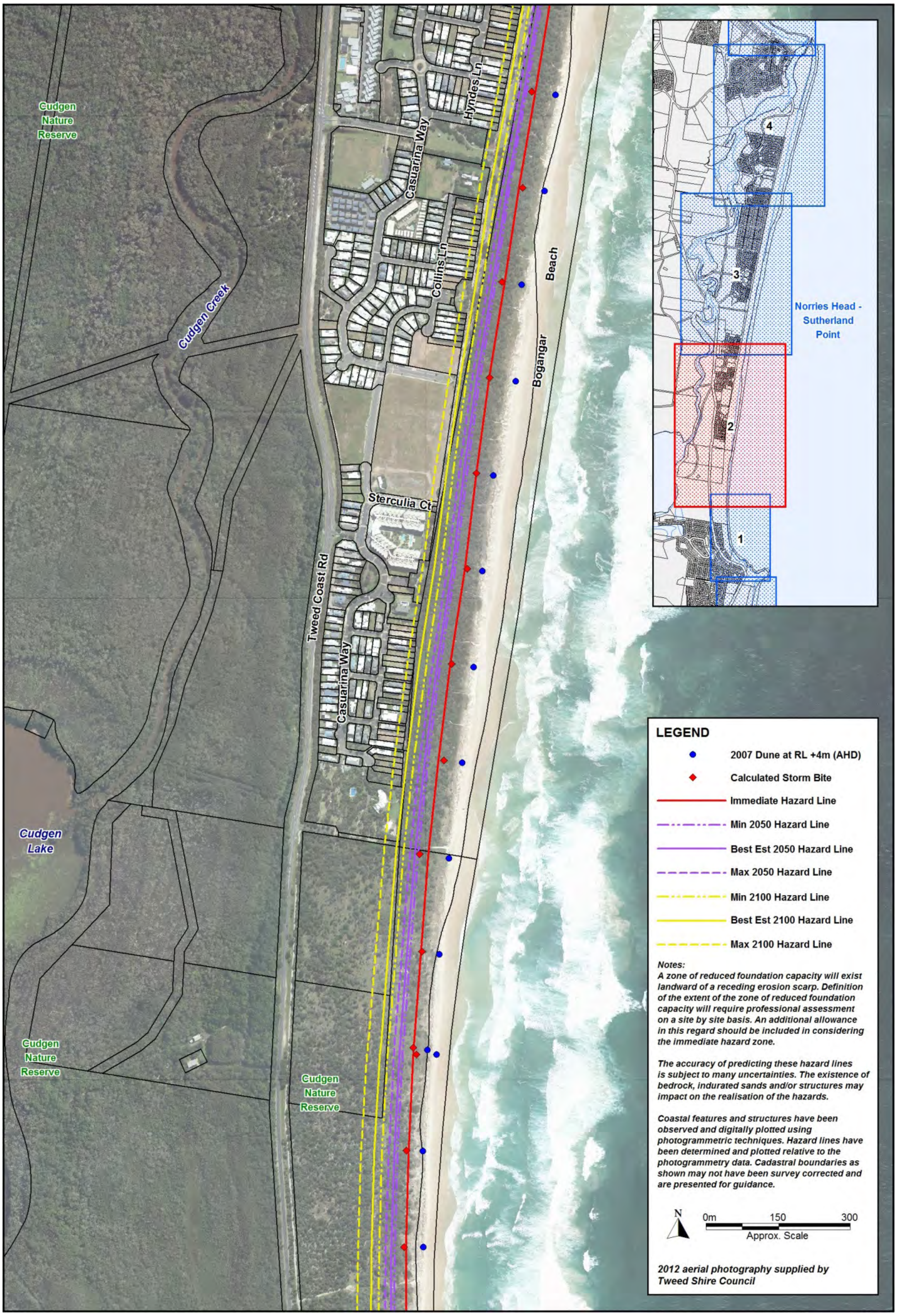
Notes:
A zone of reduced foundation capacity will exist landward of a receding erosion scarp. Definition of the extent of the zone of reduced foundation capacity will require professional assessment on a site by site basis. An additional allowance in this regard should be included in considering the immediate hazard zone.

The accuracy of predicting these hazard lines is subject to many uncertainties. The existence of bedrock, indurated sands and/or structures may impact on the realisation of the hazards.

Coastal features and structures have been observed and digitally plotted using photogrammetric techniques. Hazard lines have been determined and plotted relative to the photogrammetry data. Cadastral boundaries as shown may not have been survey corrected and are presented for guidance.

2012 aerial photography supplied by Tweed Shire Council

Figure 5–19 Erosion hazard extents for Cabarita Beach



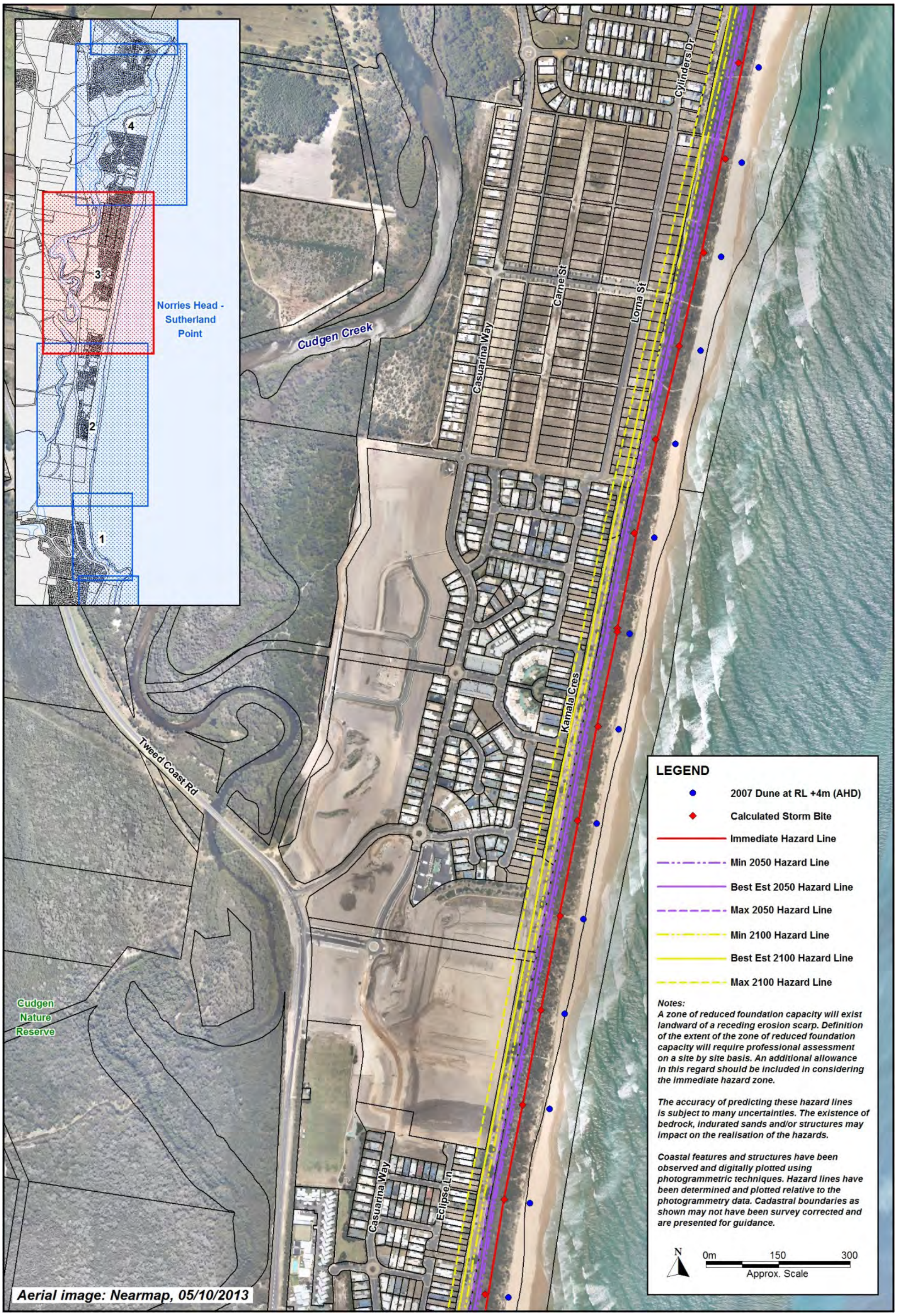
Notes:
A zone of reduced foundation capacity will exist landward of a receding erosion scarp. Definition of the extent of the zone of reduced foundation capacity will require professional assessment on a site by site basis. An additional allowance in this regard should be included in considering the immediate hazard zone.

The accuracy of predicting these hazard lines is subject to many uncertainties. The existence of bedrock, indurated sands and/or structures may impact on the realisation of the hazards.

Coastal features and structures have been observed and digitally plotted using photogrammetric techniques. Hazard lines have been determined and plotted relative to the photogrammetry data. Cadastral boundaries as shown may not have been survey corrected and are presented for guidance.

2012 aerial photography supplied by Tweed Shire Council

Figure 5–20 Erosion hazard extents for Casuarina South (Bogangar)



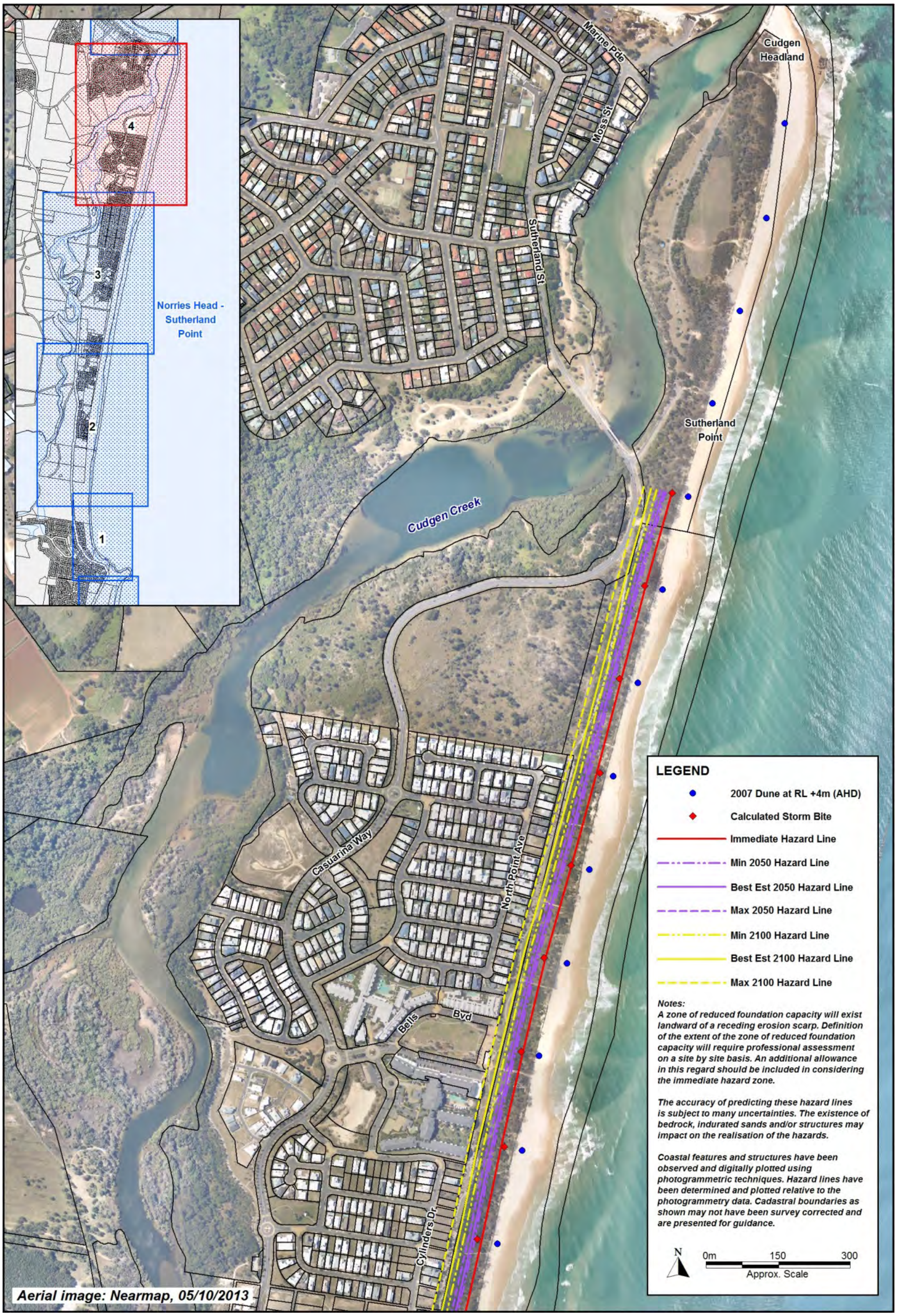
Notes:

A zone of reduced foundation capacity will exist landward of a receding erosion scarp. Definition of the extent of the zone of reduced foundation capacity will require professional assessment on a site by site basis. An additional allowance in this regard should be included in considering the immediate hazard zone.

The accuracy of predicting these hazard lines is subject to many uncertainties. The existence of bedrock, indurated sands and/or structures may impact on the realisation of the hazards.

Coastal features and structures have been observed and digitally plotted using photogrammetric techniques. Hazard lines have been determined and plotted relative to the photogrammetry data. Cadastral boundaries as shown may not have been survey corrected and are presented for guidance.

Figure 5–21 Erosion hazard extents for Casuarina (Central)



Notes:

A zone of reduced foundation capacity will exist landward of a receding erosion scarp. Definition of the extent of the zone of reduced foundation capacity will require professional assessment on a site by site basis. An additional allowance in this regard should be included in considering the immediate hazard zone.

The accuracy of predicting these hazard lines is subject to many uncertainties. The existence of bedrock, indurated sands and/or structures may impact on the realisation of the hazards.

Coastal features and structures have been observed and digitally plotted using photogrammetric techniques. Hazard lines have been determined and plotted relative to the photogrammetry data. Cadastral boundaries as shown may not have been survey corrected and are presented for guidance.

Aerial image: Nearmap, 05/10/2013

Figure 5–22 Erosion hazard extents for Casuarina North (Salt)

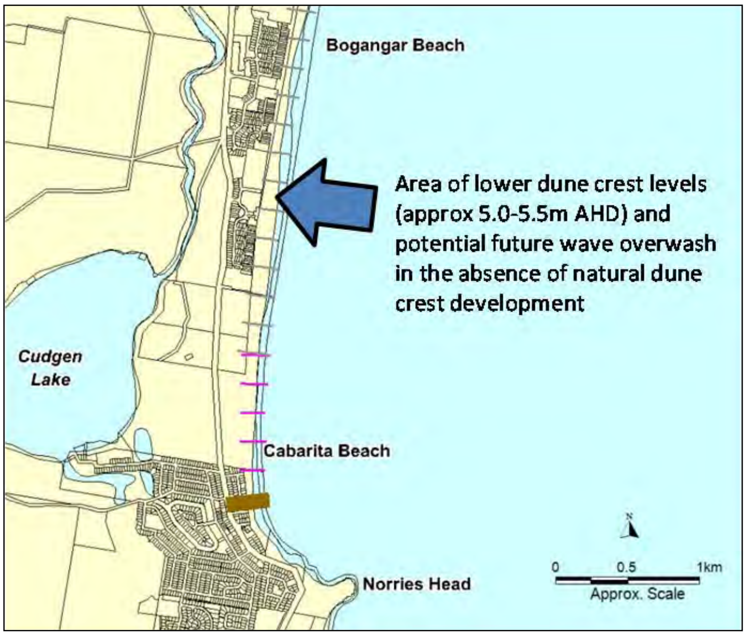


Figure 5–23 Zone of lower dune crest levels and potential future wave overwash

5.5 Fingal Head / Letitia Spit

5.5.1 Coastal Erosion Processes

The Letitia Spit coastal unit between Fingal Head and Point Danger (Figure 5-24) is an embayed unit within the regional coastal system described in Chapter 2, with northward net longshore sand transport of about 550,000m^3/yr. It is located in the lee and immediately north of Cook Island which intercepts and modifies the propagation of prevailing waves to the shoreline.

The Tweed River entrance training walls at the northern end of the Spit have had a significant impact on the adjacent shoreline since they were extended in 1962. Substantial accretion occurred along Letitia Spit, together with growth of the sub-tidal delta at the entrance. Although the accretion reduced with distance south of the entrance, the evidence showed that it extended as far as Fingal Head.

A sand bypassing system was installed at the river entrance and commenced operation in 2001. The operational strategy of the bypassing led to significant changes to the shoreline of Letitia Spit (BMT WBM 2010). Future shoreline behaviour along Letitia Spit will continue to be dependent on the bypassing strategies pursued.

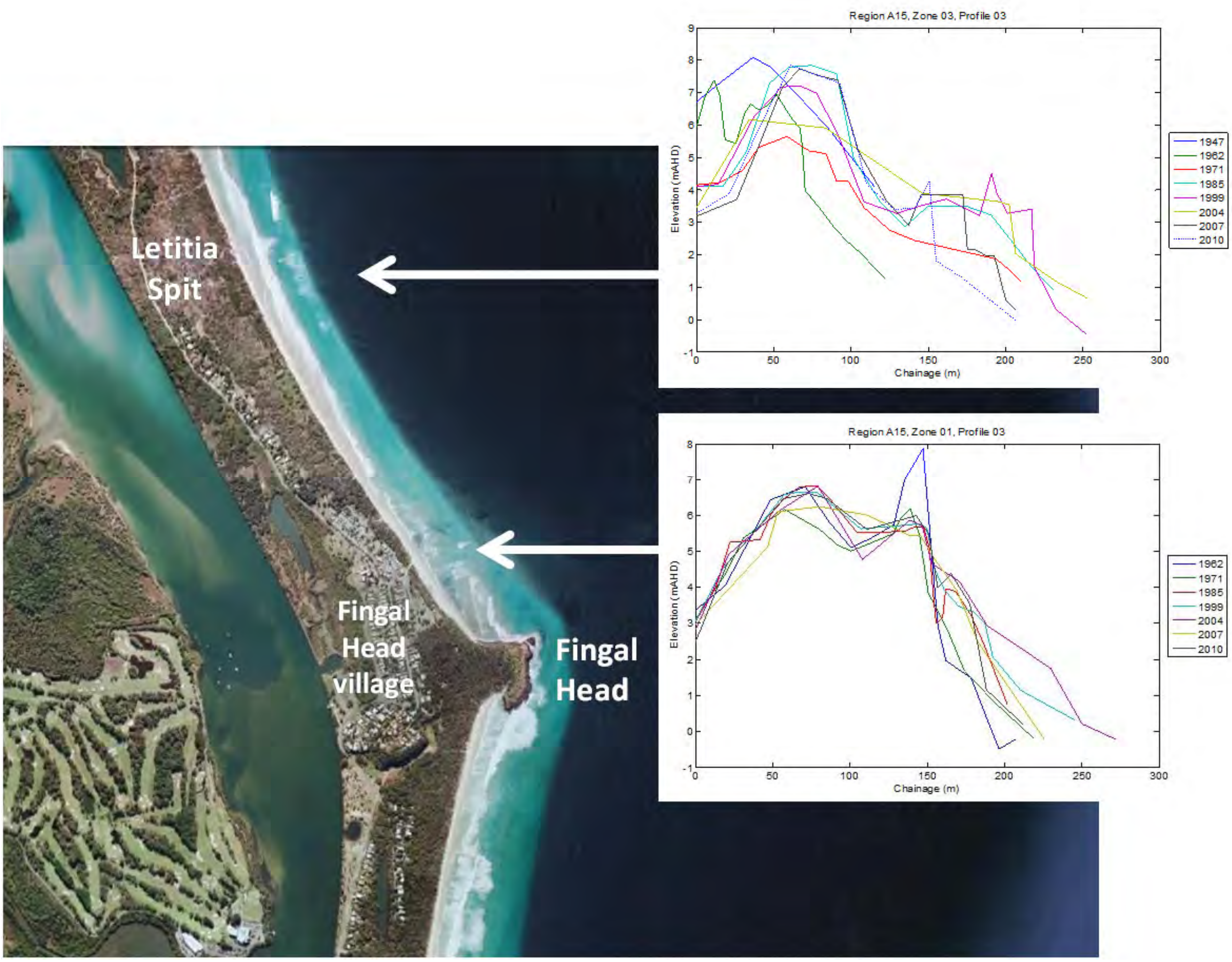


Figure 5-24 Fingal Head / Letitia Spit coastal form and dune topography

5.5.2 Previous Coastal Processes and Hazard Studies

In addition to the geomorphological processes described elsewhere herein, there have been various studies of the behaviour of Letitia Spit, predominately to assess the longshore sand transport and impacts on the beach system of constructing the Tweed River entrance training walls and operating the Tweed River Entrance Sand Bypassing (TRESB) system (Delft Hydraulics Laboratory 1970; Macdonald and Patterson 1984; Roelvink & Murray 1993; Hyder *et al* 1997; Patterson 1999; BMT WBM 2011; Patterson *et al* 2011).

The previous erosion hazard study (WBM Oceanics Australia 2001) noted that:

- The growth of the beach system in response to the training wall construction had essentially ceased, with only slight ongoing accretion;
- Accretion is apparent as far south as Fingal Head; and
- It is feasible that any longer term influence of regional shoreline recession may once again begin to manifest, particularly at the southern end (Fingal Head).

A most probable recession rate of 0.05m/year was adopted for Fingal Head, reducing further north. However, the potential for initial retreat of Letitia Spit would depend on the bypassing strategies adopted.

5.5.3 Short Term Storm Bite

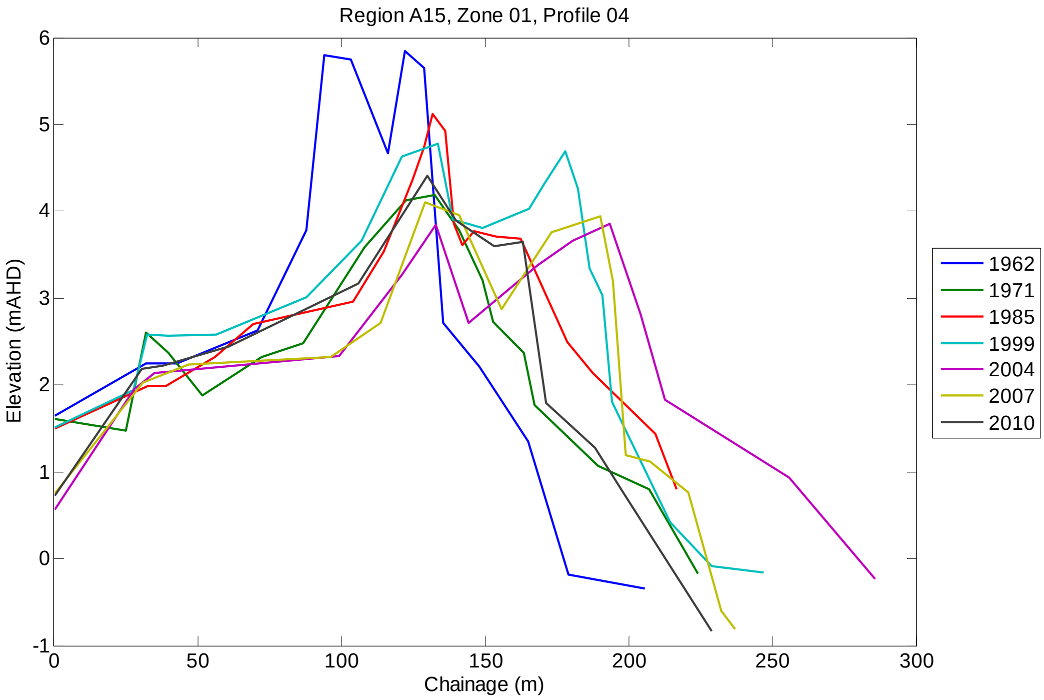
Consistent with previously determined information, a storm bite component equivalent to sand removal from the foredune of 200 m^3/m is adopted. The 2007 beach/dune condition has been used as the basis of the storm bite distance calculation. This is more conservative than that adopted for the previous hazard assessment because some shoreline recession occurred over the period 1999 to 2007 as a result of the bypassing operations. It is known (BMT WBM 2010) that higher than average rates of bypassing were undertaken over the first 5 years. This shows in the photogrammetry data as a period of shoreline retreat and volume loss compared with the situation in 1999 (Figure 5-25). The rates have more recently reduced to sustainable levels, consistent with the sand supply, and a trend of stabilisation or recovery of the beach is anticipated in the immediate near future.

5.5.3.1 Updated Photogrammetric Analysis

This section of coast includes the village of Fingal Head at the southern end (Block 1) and Letitia Spit along the central and northern area (Blocks 2 to 5) to the Tweed River. The behaviour of northern part of Letitia Spit is substantially affected by the sand bypassing activities. This re-assessment covers only the southern area of Blocks 1 to 3, as illustrated in Figure 5–26 as follows:

Block	Location	Length	No of profiles	Comments
A15-1	Fingal Head	800m	4	Some interference due to development.
A15-2	Letitia Spit (South)	600m	3	Significant interference and sand redistribution in the hind-dune area.
A15-3	Letitia Spit	600m	3	Significant interference and sand redistribution in the hind-dune area.

Volumetric analysis has been carried out as the most suitable indicator of shoreline change, consistent with the other beach areas in this study. The results are summarised in Figure 5–27, showing the progressive growth of the beach/dune system since 1962.



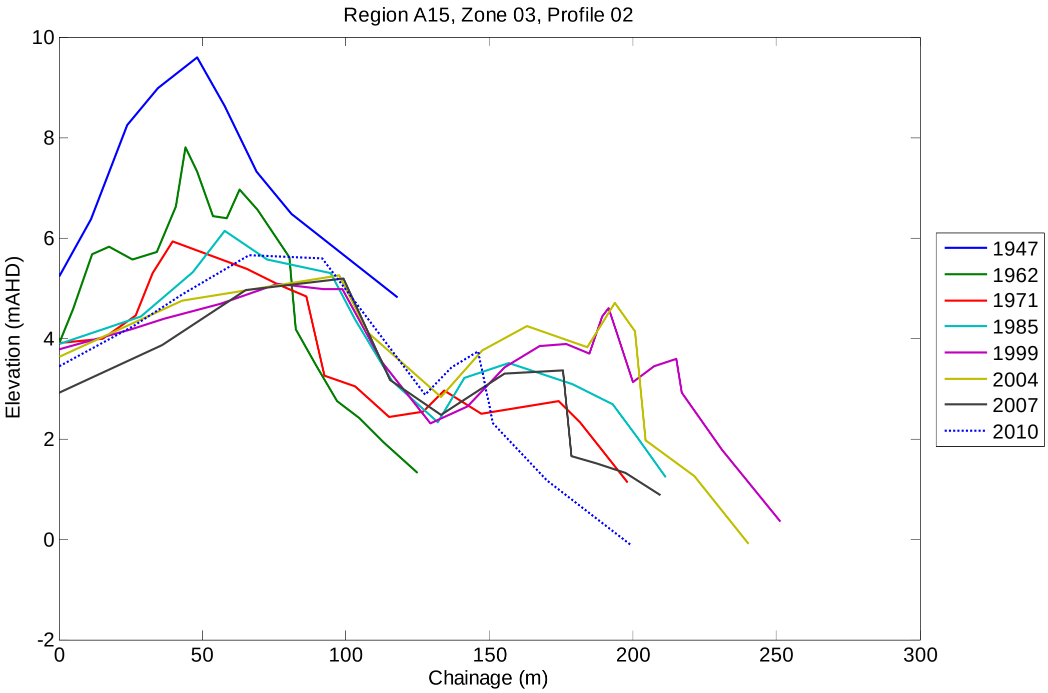


Figure 5-25 Typical profiles at southern Letitia Spit showing relative erosion in 2007

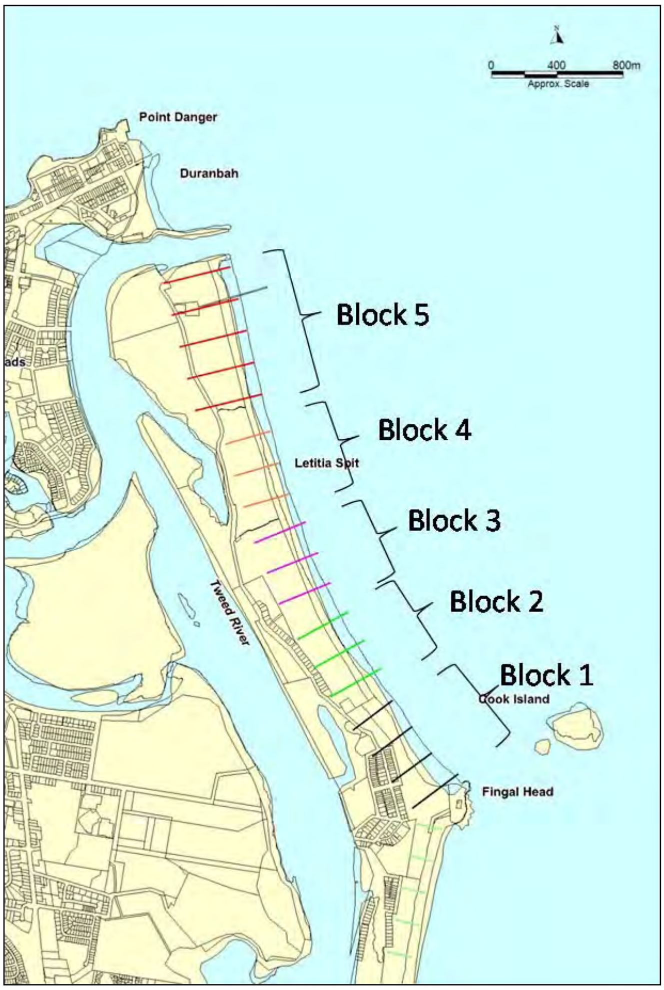


Figure 5–26 Location of photogrammetry profiles – Fingal head/Letitia Spit

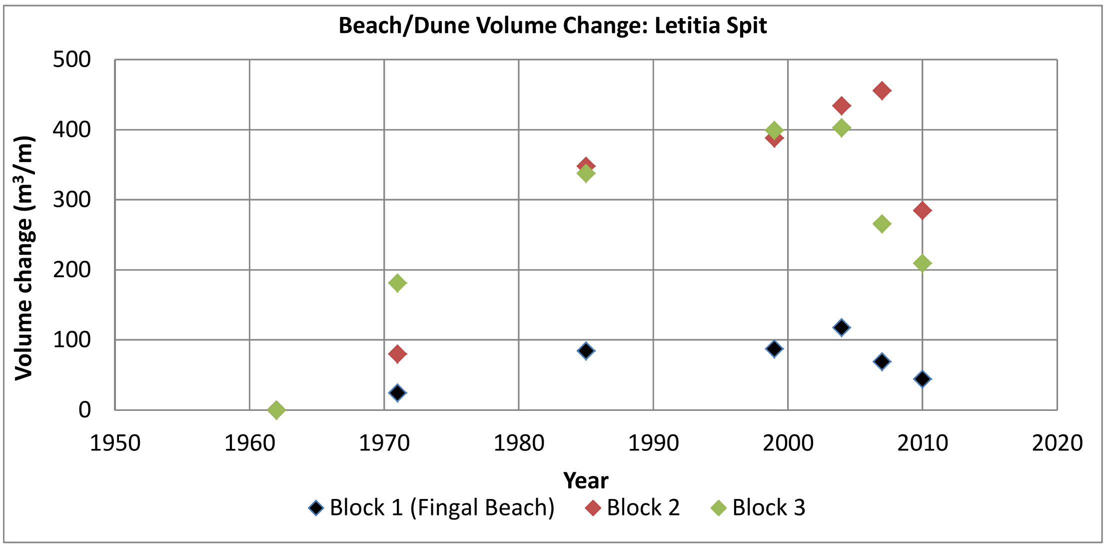


Figure 5–27 Volumetric Analysis – Fingal Head/Letitia Spit

Of particular note from these data with respect to future behaviour of the coastal system in this area are the following:

- The volumetric growth of the system in response to the training wall construction reversed around 2005 as a result of the sand bypassing operations, with reduction in volume through to 2010;

- Net volume gains relative to the condition in 1970 remain evident at each of the locations as far south as Fingal Head (Block 1);
- It is feasible that the trend of volume reduction is temporary and the shoreline will stabilise with reduction in the sand bypassing rates; and
- Any longer term influence of regional shoreline retreat may once again begin to manifest in the future, particularly at the southern end (Fingal Head).

Thus, while no trend of future shoreline retreat can be derived from the data, it is adopted as appropriate to apply the regional erosion rate of 0.1m/year at Fingal Head, reducing to 0.05m/year at the central Letitia Spit area, for long term planning purposes. This will be dependent on the sand bypassing strategies adopted at the Tweed River entrance.

5.5.3.2 Adopted Recession Trend Rates

It is evident from the updated photogrammetry that the growth of the system in response to the training wall construction has ceased in response to the sand bypassing operations at the Tweed River. It is feasible that any longer term influence of regional shoreline retreat may once again begin to manifest in the near future. This would likely be experienced initially at the southern end (Fingal Head). However, this will be dependent on the sand bypassing strategies adopted.

For the purposes of this assessment, a most probable best estimate recession rate of 0.1m/year is recommended for the southern end at Fingal Head reducing to zero at the Tweed River entrance. With provision for the uncertainties, the recommended underlying recession rates for planning purposes are:

Fingal Head

- Best estimate: 0.10m/year
- Minimum: 0.05m/year
- Maximum: 0.15m/year

Central Letitia Spit (Block 3)

- Best estimate: 0.05m/year
- Minimum: 0.02m/year
- Maximum: 0.10m/year

5.5.3.3 Sea Level Rise Recession

The Bruun Rule approach to estimating recession due to sea level rise would yield distances in the range 12-20m by 2050 and 30-50m by 2100, as listed in Table 3-1, with allowance for the uncertainty involved in both the extent of sea level rise and the Bruun Rule factor used by applying -20% and +30% variation to the best estimate factor of 45:1. Additionally, the regional model has been used to simulate the sea level rise provision taking account of the alongshore sand transport processes that the Bruun Rule does not include. These processes tend to reduce the recession extent updrift (south) of headlands and exacerbate it immediately downdrift. The modelling of sea level rise recession at Fingal Head/Letitia Spit as shown in Figure 3-4 indicates:

Fingal Head

- 22m recession by 2050
- 60m recession by 2100

Central Letitia (Block 3)

- 15m recession by 2050
- 35m recession by 2100

These model results are reasonably consistent with the upper limit of the Bruun Rule distances, although somewhat higher at both 2050 and 2100 due to its location downdrift of Fingal Head as a control point. In recognition of the uncertainties involved in the modelling and the objective of precautionary conservatism, the adopted best estimate recession values are those given by the model, with uncertainty provisions of -20% and +30% applied to them, as shown in Table 5-11 and Table 5-12. Where the recession would extend into dunes of height significantly greater than 5m, the recession distances are reduced in proportion to the total active height from the dune crest to the depth of closure.

Table 5-11 Adopted recession due to sea level rise to 2100: Fingal Head

	2050	2100
Minimum	18m	48m
Best Estimate	22m	60m
Maximum	29m	78m

Table 5-12 Adopted recession due to sea level rise to 2100: Central Letitia Spit

	2050	2100
Minimum	12m	28m
Best Estimate	15m	35m
Maximum	20m	45m

5.5.4 Erosion Hazard Assessment

The erosion hazard extents have been derived on the basis of:

- The immediate erosion hazard likely to occur due to a severe storm event or a closely spaced series of large storm events, or due to persistent erosion occurring over the next few years; and
- Longer term erosion hazards determined by adding to the immediate hazard line the additional recession associated with the underlying recession trends and the assessed sea level rise components over the planning periods to 2050 and 2100.

Thus, the 2050 and 2100 erosion hazard extents incorporate the immediate erosion hazard and represent its projected extent following shoreline recession over those respective time-frames. It should be noted that there is a zone of reduced foundation capacity that extends landward of these erosion hazard lines, as discussed in Section 3.8.

These erosion hazard extents are illustrated in Figure 5-28. Most of the developed area at Fingal Head is landward of the projected best estimate 2050 year hazard zone. The maximum likely 2050 hazard encroaches into the north-eastern parts of three allotments at the northern end of Marine

Parade, affecting also the Fingal Rovers Surf Club and Fingal Head Holiday Park. The 2100 best estimate erosion hazard encroaches into eight residential allotments there and extends through the Surf Club and substantial parts of the Holiday Park.

These hazard extents are highly dependent on the sea level rise component of recession, being assessed to be significantly greater here than that for the regional average because of its location immediately north of Fingal Head. There is considerable uncertainty about the projected amount of recession. Furthermore, the underlying recession trend depends on the operational strategies of the Tweed River entrance sand bypassing. Close monitoring of the future shoreline changes is important and strongly recommended for this location to provide continuing updated data for further erosion hazard assessments.

5.6 Coastal Inundation Hazard

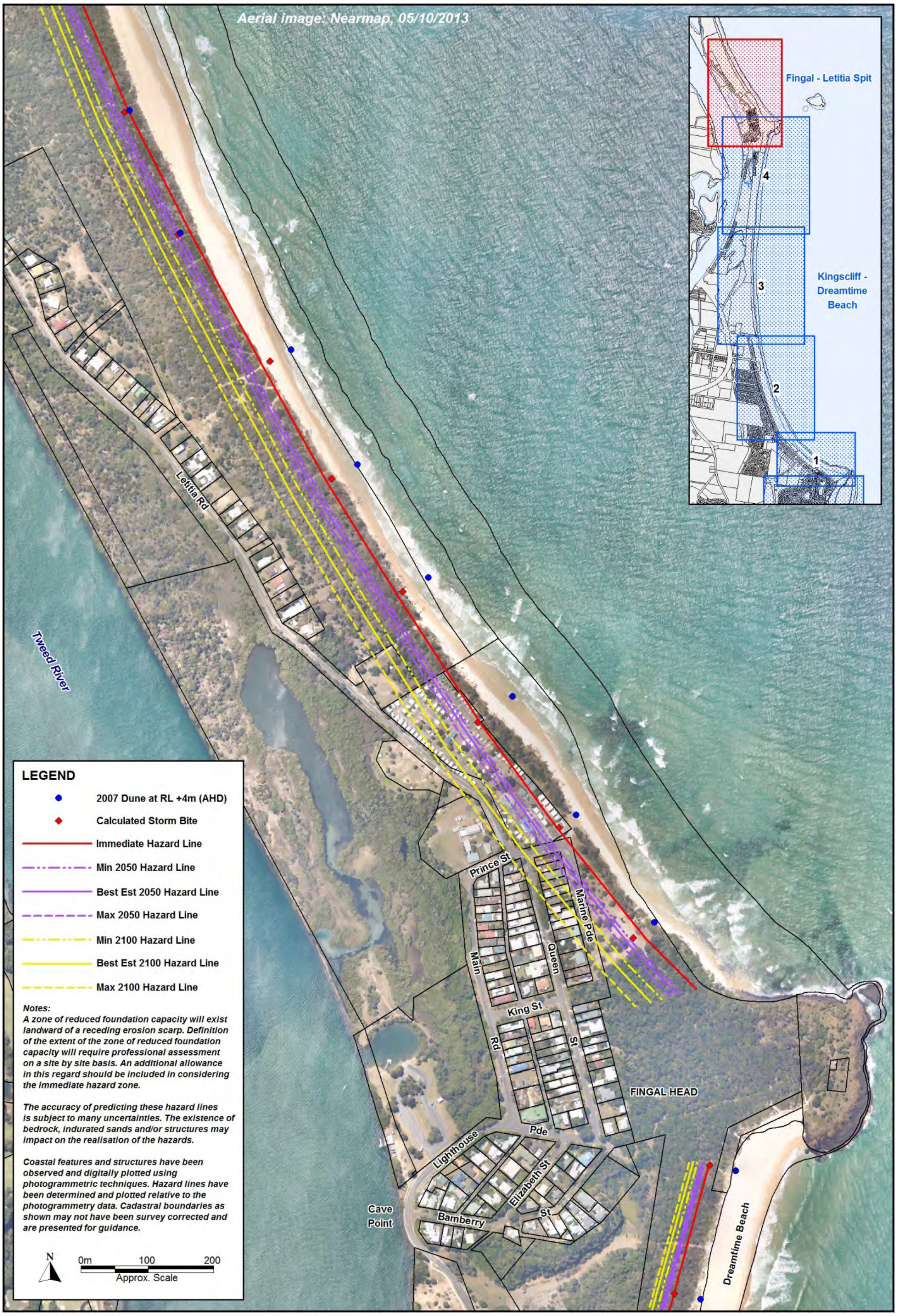
Storm tides together with wave setup and run-up will affect the beach/dune system in this area. Storm tide and wave statistics relevant to the area are presented in Chapter 2. Wave propagation modelling provides an estimate of the nearshore design storm conditions, allowing for refraction and attenuation due to bed friction across the continental shelf. The prevailing waves are generally significantly lower in height in the area at Fingal Head more sheltered from the predominant southeast waves than further north along Letitia Spit. The potential run-up levels vary accordingly. The design condition thus relates to deep water waves from east-northeast. Nearshore wave heights for storm events with wave period of 12 seconds have been determined from SWAN analysis as follows:

- Fingal Head: 5.78m
- Letitia Spit (central): 5.93m

The $R_{2\%}$ run-up levels associated with these waves on the natural beach/dune profiles along this beach unit are calculated to be 3.47 and 3.52m above the still water level at Fingal Head and central Letitia Spit respectively. With provision for the design 100 year storm tide level of 1.44m, this corresponds to design run-up levels for the immediate, 2050 and 2100 year planning periods as follows:

	Fingal Head run-up level (m AHD)	Letitia run-up level (m AHD)
Immediate	4.91	4.96
2050	5.25	5.30
2100	5.75	5.80

The dune system is generally sufficiently high to accommodate this impact without direct inundation of developed areas from the sea. As such, there is no development at risk from the inundation hazard. However, there is one area just north of Fingal Head where the design storm bite erosion would effectively remove the whole frontal dune exposing lower hind dune areas to inundation (Figure 5-29). Longer term recession in these areas would be expected to mirror the natural processes with frontal dune building limiting the inundation potential.



Notes:

A zone of reduced foundation capacity will exist landward of a receding erosion scarp. Definition of the extent of the zone of reduced foundation capacity will require professional assessment on a site by site basis. An additional allowance in this regard should be included in considering the immediate hazard zone.

The accuracy of predicting these hazard lines is subject to many uncertainties. The existence of bedrock, indurated sands and/or structures may impact on the realisation of the hazards.

Coastal features and structures have been observed and digitally plotted using photogrammetric techniques. Hazard lines have been determined and plotted relative to the photogrammetry data. Cadastral boundaries as shown may not have been survey corrected and are presented for guidance.

Figure 5-28 Erosion hazard extents: Fingal Head – Letitia Spit

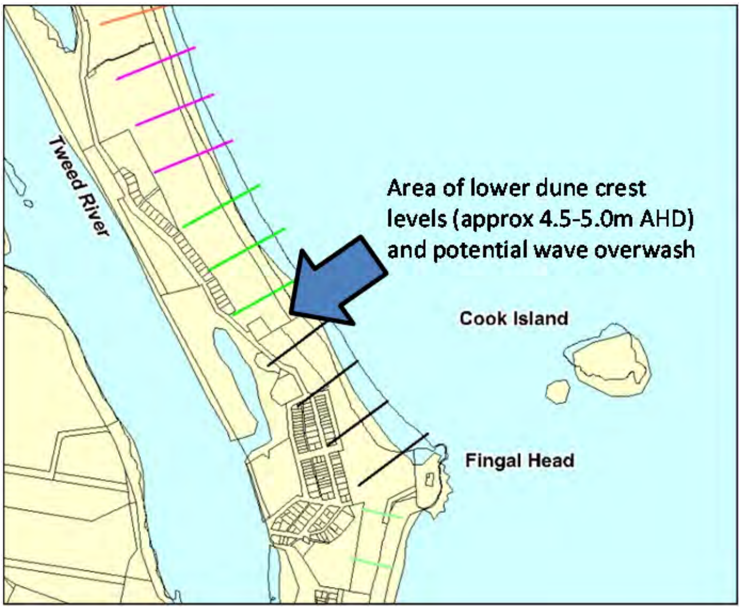


Figure 5-29 Zone of limited potential wave overwash – Letitia Spit

6 GLOSSARY OF TERMS

Accreted Profile	The profile (cross-section) of a sandy beach that develops in the "calm" periods between major storm events. During such periods, swell waves move sediment from the offshore bar beach onto the beach to rebuild the beach berm.
Barometric Setup	The increase in mean sea level caused by a drop in barometric pressure.
Bathymetry	The measurement of depths of water, also information derived from such measurements.
Beach Berm	That area of shoreline lying between the swash zone and the dune system.
Beach Erosion	The offshore movement of sand from the sub-aerial beach during storms.
Beach Nourishment	The supply of sediment by mechanical means to supplement sand on an existing beach or to build up an eroded beach.
Blowout	The removal of sand from a dune by wind drift after protective dune vegetation has been lost. Unless repaired promptly, the area of blowout will increase in size and could lead to the development of a migrating sand dune and its associated problems.
Breaking Waves	As waves increase in height through the shoaling process, the crest of the wave tends to speed up relative to the rest of the wave. Waves break when the speed of the crest exceeds the speed of advance of wave as a whole. Waves can break in three modes: spilling, surging and plunging.
Breakwater	Structure protecting a shoreline, harbour, anchorage or basin from ocean waves.
Buffer Zone	An appropriately managed and unalienated zone of unconsolidated land between beach and development, within which coastline fluctuations and hazards can be accommodated in order to minimise damage to the development.
Coastal Structures	Those structures on the coastline designed to protect and rebuild the coastline and/or enhance coastal amenity and use.
Coastline Hazards	Detrimental impacts of coastal processes on the use, capability and amenity of the coastline. The Coastline Management Manual identifies seven coastline hazards: • Beach erosion • Shoreline recession • Entrance Instability • Sand drift • Coastal inundation • Slope and cliff instability • Stormwater erosion
Damage Potential	The susceptibility of coastline development to damage by coastline hazards.
Diffraction	The "spreading" of waves into the less of obstacles such as breakwaters by the transfer of wave energy along wave crests. Diffracted waves are lower in height than the incident waves.

Dune Field	The system of incipient dunes, foredunes and hind dunes that is formed on sandy beaches to the rear of the beach berm.
Dune Maintenance	The management technique by which dunes, dune vegetation and dune protective structures are kept in good “working order”; activities may include weed/pest/fire control, replanting, fertilising, repair of fences and accessways, and publicity.
Dune Management	The general term describing all activities associated with the restoration and/or maintenance of the role and values of beach dune systems; dune management activities and techniques include planning, dune reconstruction, revegetation, dune protection, dune maintenance, and community involvement.
Dune Protection	The management technique by which the dune system is protected from damage by recreational and development activities; dune protection activities generally include the use of fences, accessways and signposts to restrict and control access to dune systems.
Dynamic Equilibrium	The average condition about which the beach position and/or nearshore profile shape varies in the short term in response to varying wave and water level conditions and which remains essentially constant or only slowly changing over the longer term.
Dynamic Stability	The condition in which there is a non-changing long term average beach position despite short term variability in response to varying wave and water level conditions.
Flood Tide	The inflow of coastal waters into bays and estuaries caused by the rising tide.
Foredune	The larger and more mature dune lying between the incipient dune and hinddune area. Foredune vegetation is characterised by grasses and shrubs. Foredunes provide an essential reserve of sand to meet erosion demand during storm conditions. During storm events, the foredune can be eroded back to produce a pronounced dune scarp.
Greenhouse Effect	A term used to describe the likely global warming predicted to accompany the increasing levels of carbon dioxide and other “greenhouse” gases in the atmosphere.
Groynes	Low walls build perpendicular to a shoreline to trap longshore sediment. Typically, sediment buildup on the updrift side of a groyne is offset by erosion on the downdrift site.
Groyne Field	A system of regularly spaced groynes along a section of shoreline.
Hinddunes	Sand dunes located to the rear of the Foredune. Characterised by mature vegetation including trees and shrubs.
Incipient Dune	The most seaward and immature dune of the dune system. Vegetation characterised by grasses. On an accreting coastline, the incipient dune will develop into a Foredune.
Littoral Zone	Area of the coastline in which sediment movement by wave, current and wind action is prevalent. The littoral zone extends from the onshore dune system to the seaward limit of the offshore zone and possibly beyond.
Longshore Currents	Currents flowing parallel to the shore within the inshore and nearshore zones. Longshore currents are typically caused by waves approaching the beach at an angle. The “feeder” currents to rip cells are another example of longshore currents.

Mass Transport	The net shorewards current associated with the movement of waves through the nearshore and inshore zones. Sediment transport from the offshore bar by this current is responsible for the rebuilding of storm eroded beaches during inter-storm periods.
Nearshore Zone	Coastal waters between the offshore bar and the 60m depth contour. Swell waves in the nearshore zone are unbroken, but their behaviour is influenced by the presence of the seabed. (This definition is adopted for simplicity in the Coastline Management Manual and is based on wave motion considerations rather than sedimentology).
Offshore Bar	Also known as a longshore bar. Submerged sandbar formed offshore by the processes of beach erosion and accretion. Typically, swell waves break on the offshore bar.
Offshore Zone	Coastal waters to the seaward of the nearshore zone. Swell waves in the offshore zone are unbroken and their behaviour is not influenced by the presence of the seabed. (See note to “Nearshore Zone”).
Onshore/Offshore Transport	The process whereby sediment is moved onshore and offshore by wave, current and wind action.
Pocket Beaches	Small beach systems typically bounded by rocky headlands. Because of the presence of the headlands and the small size of these beaches, longshore currents are relatively insignificant in the overall sediment budget.
Reflected Wave	That part of an incident wave that is returned seaward when a wave impinges on a steep beach, barrier, or other reflecting surface.
Refraction	The tendency of wave crests to become parallel to bottom contours as waves move into shallower waters. This effect is caused by the shoaling processes which slows down waves in shallower waters.
Revetment	(Refer to Seawall)
Rip Currents	Concentrated currents flowing back to sea perpendicular to the shoreline. Rip currents are caused by wave action piling up water on the beach. Feeder currents running parallel to the shore (longshore currents) deliver water to the rip current.
Sand Bypassing	A procedure whereby sand deposited on the updrift side of a training wall or similar structure is mechanically delivered to the downdrift side. This facilitates the natural longshore movement of the sediment.
Sand Drift	The movement of sand by wind. In the context of coastlines, “sand drift” is generally used to describe sand movement resulting from natural or man-induced degradation of dune vegetation, resulting in either nuisance or major drift. Sand drift damage buildings, roads, railways and adjoining natural features such as littoral rainforest or wetlands; sand drift can be a major coastline hazard.
Sand Drift Control	The repair and maintenance of sand dunes to minimise sand drift. The protection and fostering of dune vegetation is an important element of such programs.

Sand Dunes	Mounds or hills of sand lying to landward of the beach berm. Sand dunes are usually classified as an incipient dune, a foredune or hinddunes. During storm conditions, incipient and foredunes may be severely eroded by waves. During the intervals between storms, dunes are rebuild by wave and wind effects. Dune vegetation is essential to prevent sand drift and associated problems.
Scarp	Also known as the Dune Scarp and Backbeach Erosion Escarpment. The landward limit of erosion in the dune system caused by storm waves. At the end of a storm the scarp may be nearly vertical; as it dries out, the scarp slumps to a typical slope of 1V:1.5H.
Seawalls	Walls build parallel to the shoreline to limit shoreline recession.
Sea Waves	Waves in coastal waters resulting from the interaction of different wave trains and locally generated wind waves. Typically, sea waves are of short wavelength and of disordered appearance.
Sediment Budget	An accounting of the rate of sediment supply from all sources (credits) and the rate of sediment loss to all sinks (debits) from an area of coastline to obtain the net sediment supply.
Sediment Sink	A mode of sediment loss from the coastline, including longshore transport out of area, dredging, deposition in estuaries, windblown sand, etc.
Sediment Source	A mode of sediment supply to the coastline, including longshore transport into the area, beach nourishment, fluvial sediments from rivers, etc.
Semi-Diurnal Tides	Tides with a period, or time interval between two successive high or low waters, of about 12.5 hours. Tides along the New South Wales coast are semi-diurnal.
Shoaling	The influence of the seabed on wave behaviour. Such effects only become significant in water depths of 60m or less. Manifested as a reduction in wave speed, a shortening in wave length and an increase in wave height.
Shoreline Recession	A net long term landward movement of the shoreline caused by a net loss in the sediment budget.
Shadow Area	Areas behind breakwaters and headlands in the less of incident waves. Waves move into shadow areas by the process of diffraction.
Significant Wave Height	The average height of the highest one third of waves recorded in a given monitoring period. Also referred to as $H_{1/3}$ or H_S.
Slope Readjustment	The slumping of a backbeach erosion escarpment from its near vertical post-storm profile to a slope of about 1V:3H.
Storm Profile	The profile (cross-section) of a sandy beach that develops in response to storm wave attack. Considerable volumes of sediment from the beach berm, the incipient dune and the Foredune can be eroded and deposited offshore. The landward limit of the storm profile is typically defined by a backbeach erosion escarpment (dune scarp).
Storm Surge	The increase in coastal water level caused by the effects of storms. Storm surge consists of two components: the increase in water level caused by the reduction in barometric pressure (barometric setup) and the increase in water level caused by the action of wind blowing over the sea surface (wind setup).

Storm Bar	An offshore bar formed by sediments eroded from the beach during storm conditions.
Surf Zone	Coastal waters between the breaker zone and the swash zone characterised by broken swell waves moving shorewards in the form of bores.
Swash Zone	That area of the shoreline characterised by wave uprush and retreat.
Swell Waves	Wind waves remote from the area of generation (fetch) having a uniform and orderly appearance characterised by regularly spaced wave crests.
Swept Prism	The active area of the coastal system in which sediment may be mobilised by the forces of wind and wave action. On a sandy beach, it extends into the dune system and offshore to the limit of the nearshore zone.
Tidal Prism	The volume of water stored in an estuary or tidal lake between the high and low tide levels; the volume of water that moves into and out of the estuary over a tidal cycle.
Tides	The regular rise and fall of sea level in response to the gravitational attraction of the sun, moon and planets. Tides along the New South Wales coastline are semi-diurnal in nature, ie. they have a period of about 12.5 hours.
Training Walls	Walls constructed at the entrances of estuaries and rivers to improve navigability.
Vegetation Degradation	The process by which coastal vegetation is “degraded” or damaged; this reduces the effectiveness of vegetation in protecting coastal landforms and increases the potential for erosion of underlying soil materials by wind (resulting in sand drift), water or waves.
Wave Height	The vertical distance between a wave trough and a wave crest.
Wave Hindcasting	The estimation of wave climate from meteorological data (barometric pressure, wind) as opposed to wave measurement.
Wave Length	The distance between consecutive wave crests or wave troughs.
Wave Period	The time taken for consecutive wave crests or wave troughs to pass a given point.
Wave Rider Buoy	A floating device used to measure water level variation caused by waves. It is approximately 0.9m in diameter and is moored to the sea floor.
Wave runup	The vertical distance above mean water level reached by the uprush of water from waves across a beach or up a structure.
Wave Setup	The increase in water level within the surf zone above mean still water level caused by the breaking action of waves.
Wave Train	A series of waves originating fro the same fetch with more or less the same wave characteristics.
Wind Setup	The increase in mean sea level caused by the “piling up” of water on the coastline by the wind.
Wind Waves	The waves initially formed by the action of wind blowing over the sea surface. Wind waves are characterised by a range of heights, periods and wavelengths. As they leave the area of generation (fetch), wind waves develop a more ordered and uniform appearance and are referred to as swell or swell waves.

Windborne Sediment Transport	Sand transport by the wind. Sand can be moved by the processes of suspension (fine grains incorporated in the atmosphere), saltation (medium grains "hopping" along the surface) and traction (large grains rolled along the surface).

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APPENDIX A: KINGSCLIFF EMBAYMENT PHOTOGRAMMETRY DATA

Figure A- 1 Locations of photogrammetry analysis zones

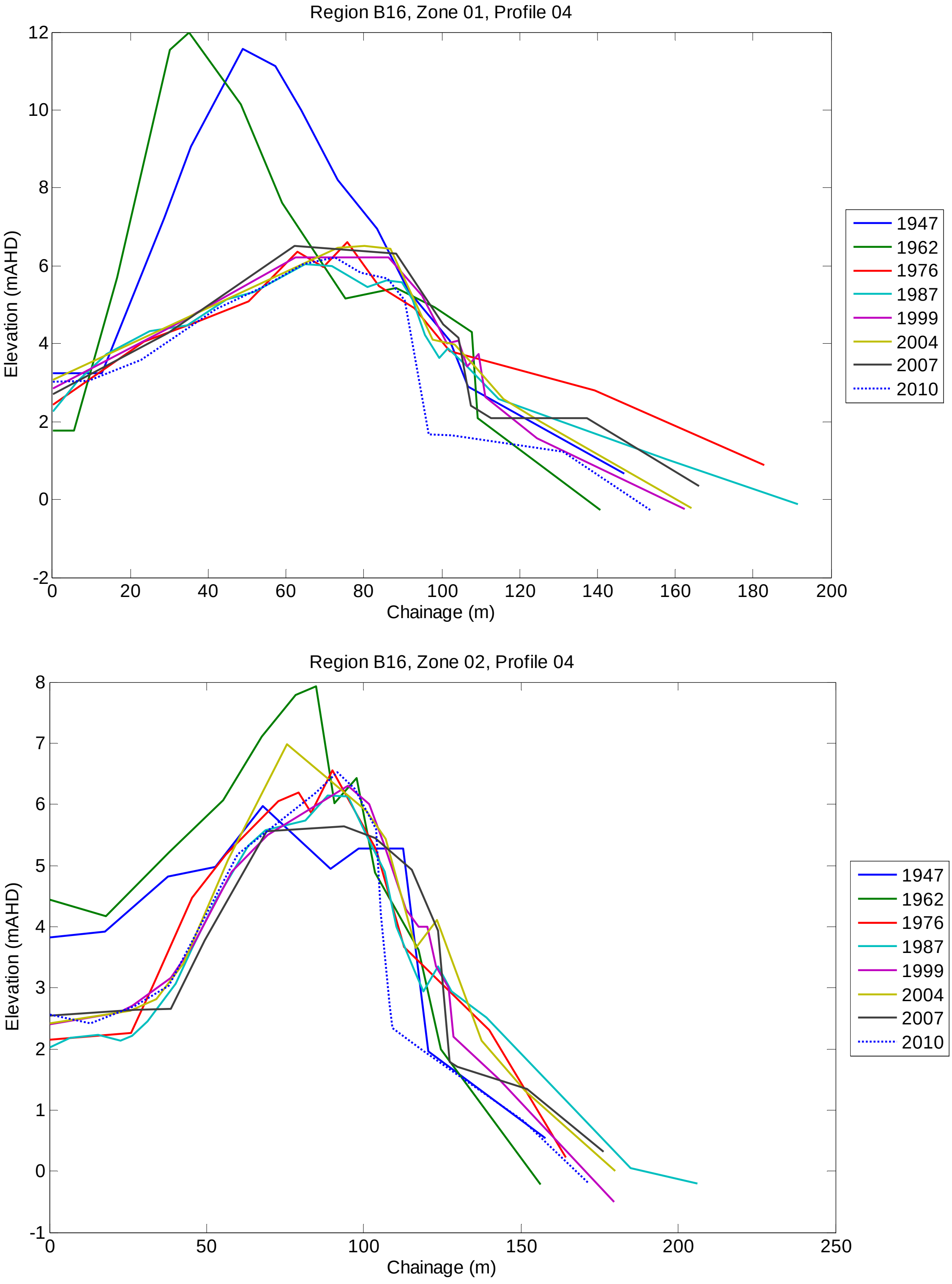
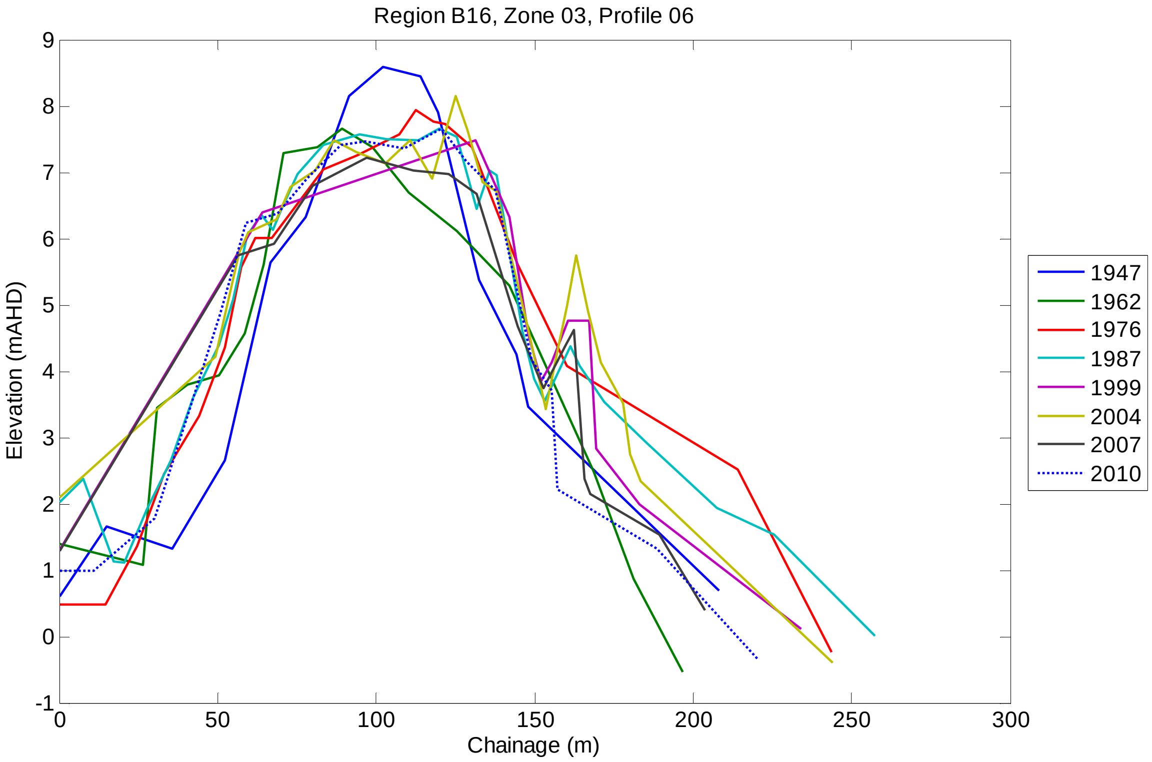


Figure A- 2 Photogrammetry profiles: Zone 01 (top) & Zone 02 (bottom)

Locations shown in Figure 4-6



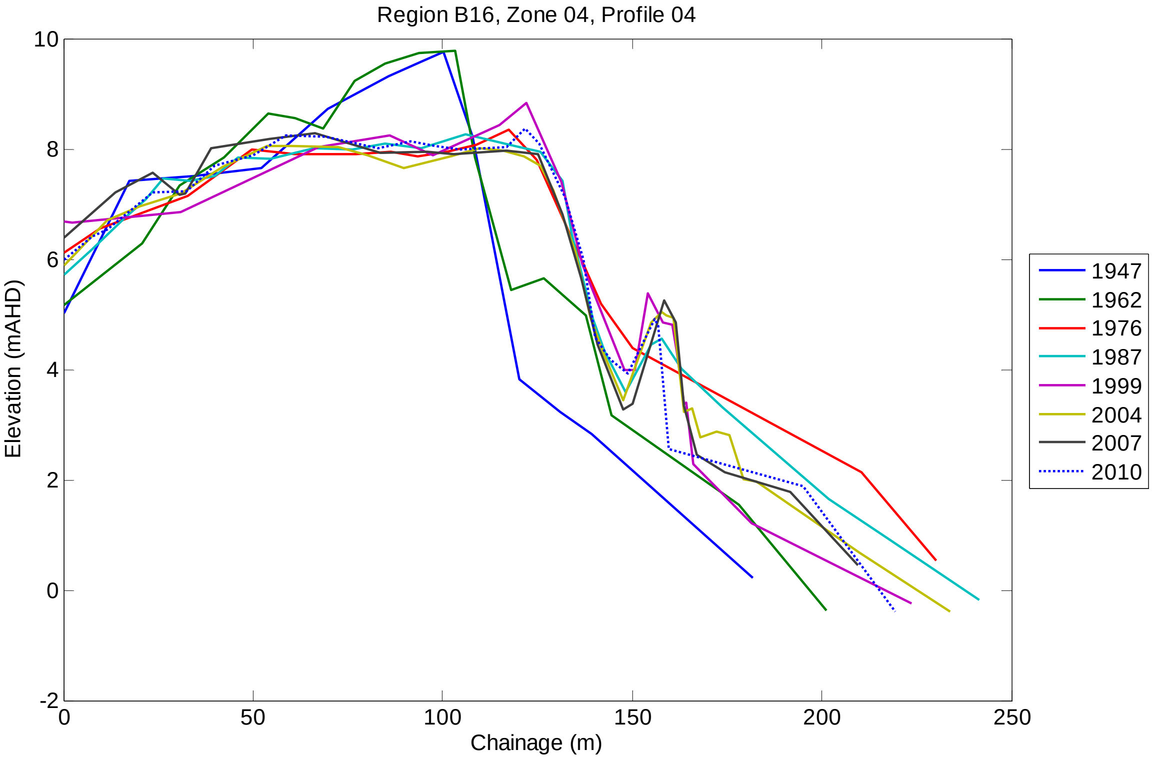
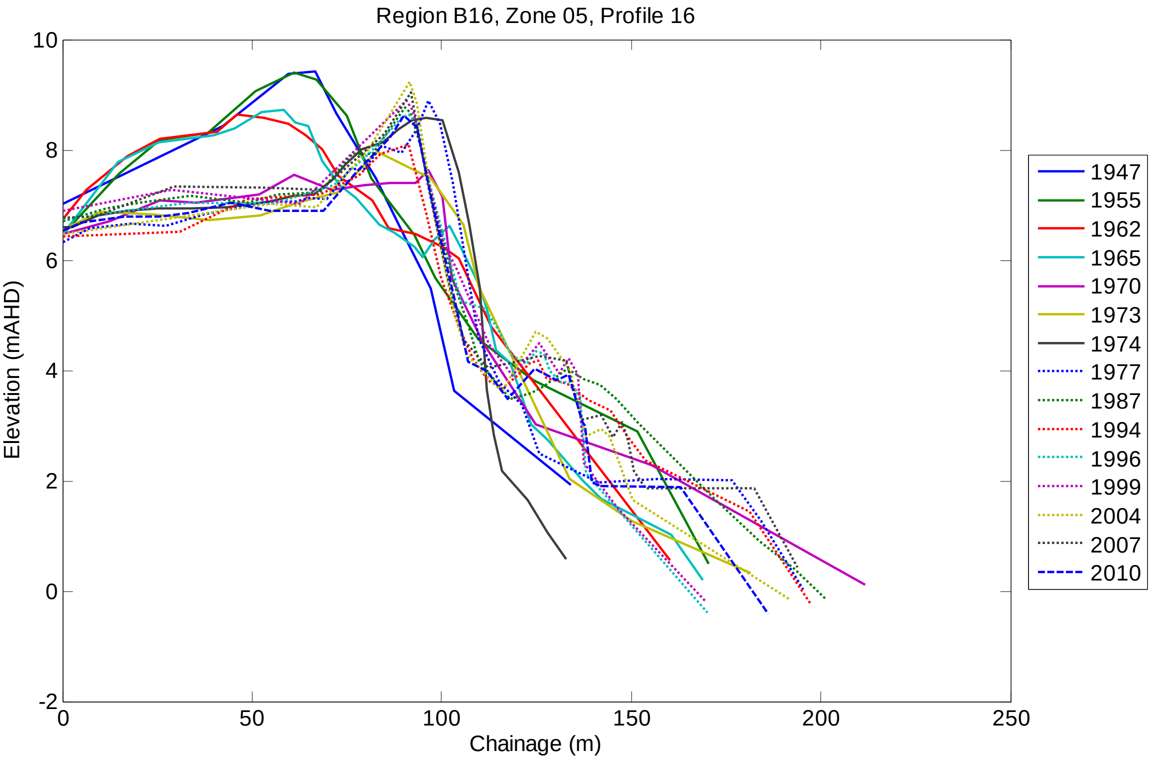


Figure A- 3 Photogrammetry profiles: Zone 03 (top) & Zone 04 (bottom)

Locations shown in Figure 4-6



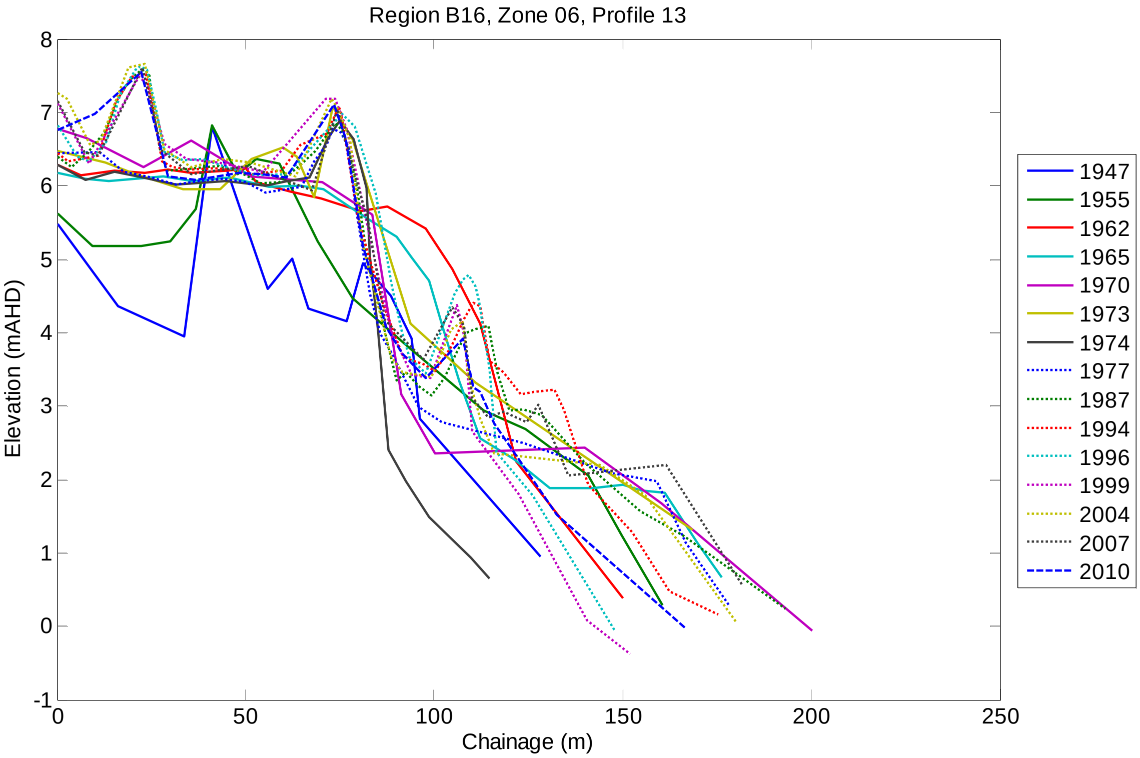
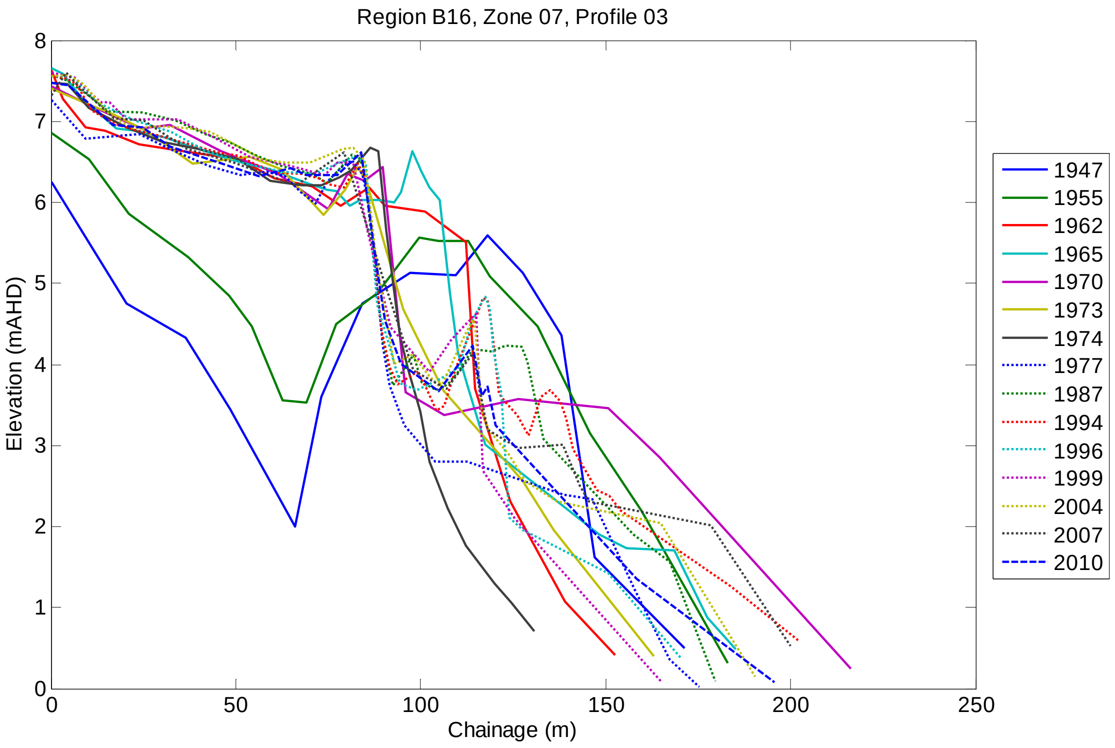


Figure A- 4 Photogrammetry profiles: Zone 5 (top) & Zone 06 (bottom)

Locations shown in Figure 4-6



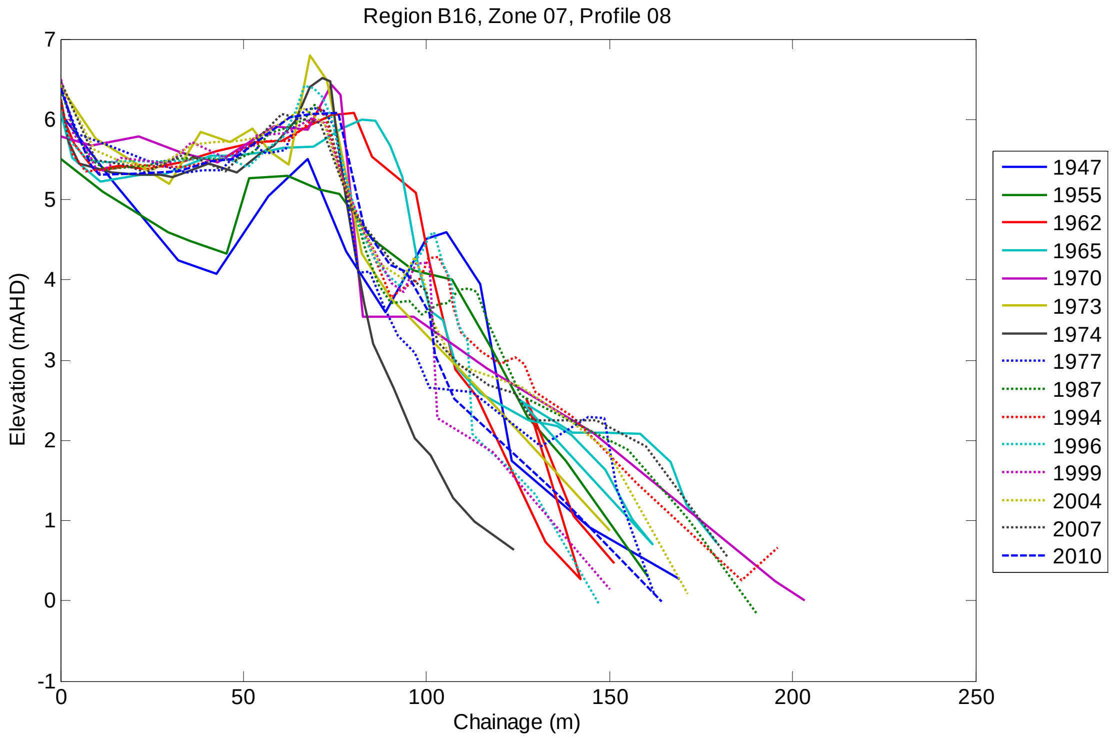


Figure A- 5 Kingscliff Embayment Photogrammetry Profiles: Zone 7

Locations shown in Figure 4-6

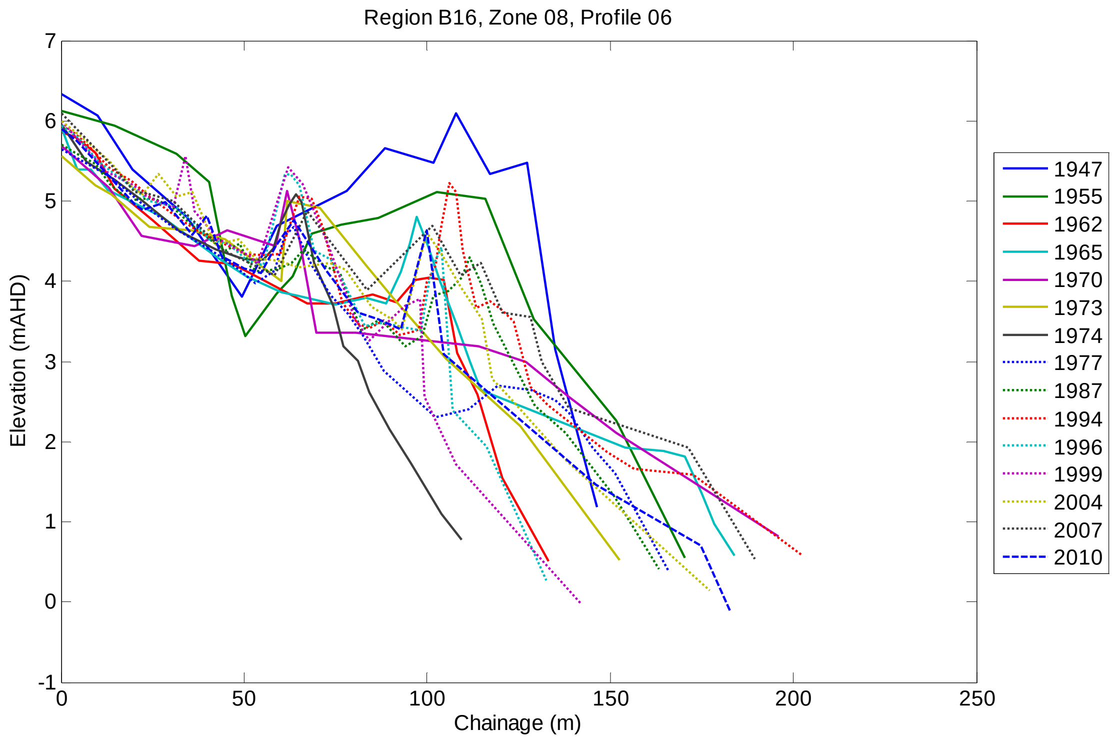


Figure A- 6 Kingscliff Embayment Photogrammetry Profiles: Zone 8

Locations shown in Figure 4-6

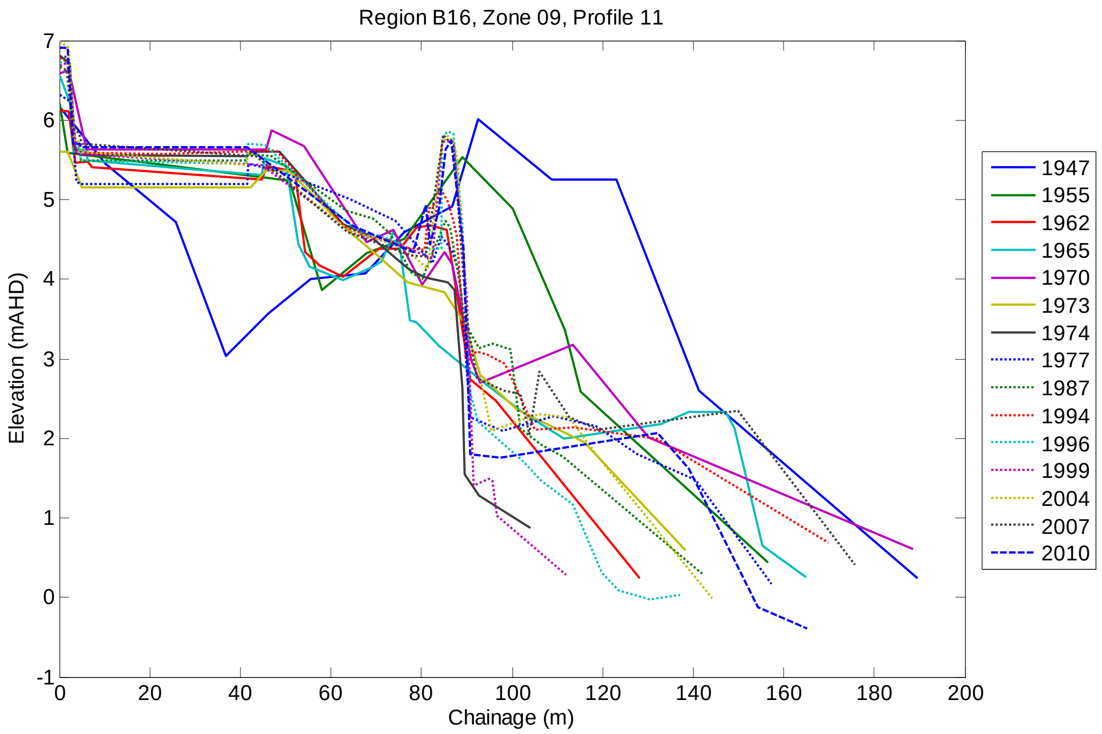
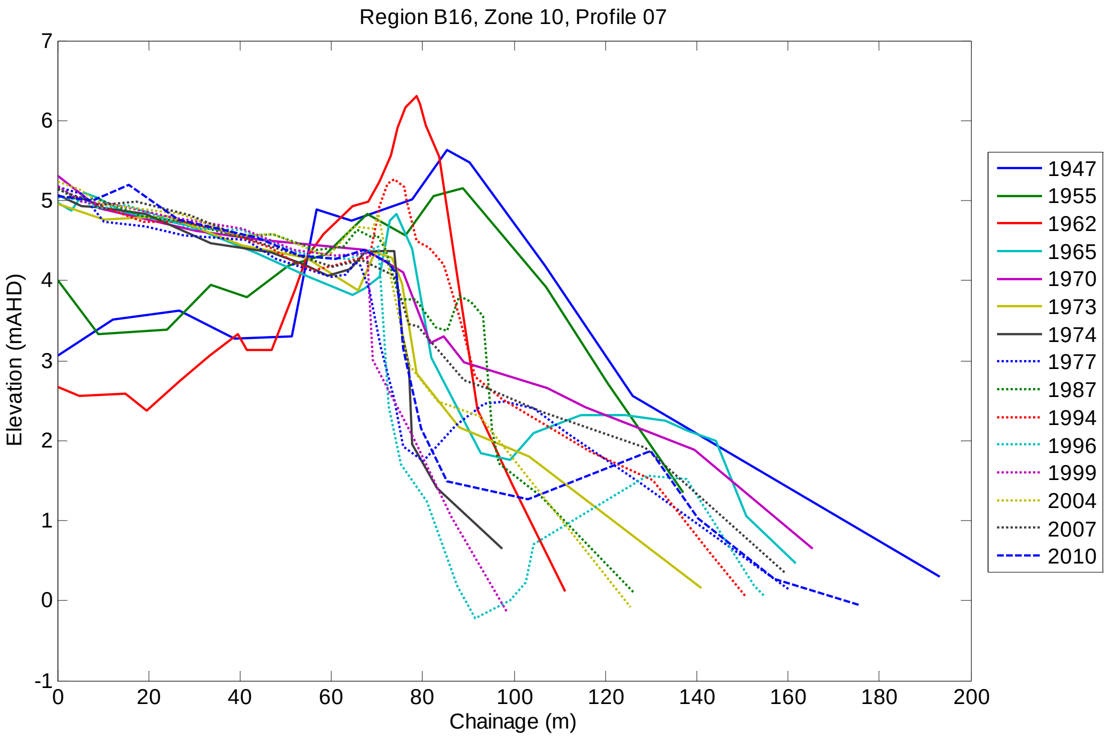


Figure A- 7 Kingscliff Photogrammetry Profiles: Zone 9 (Bowls Club)

Locations shown in Figure 4-6



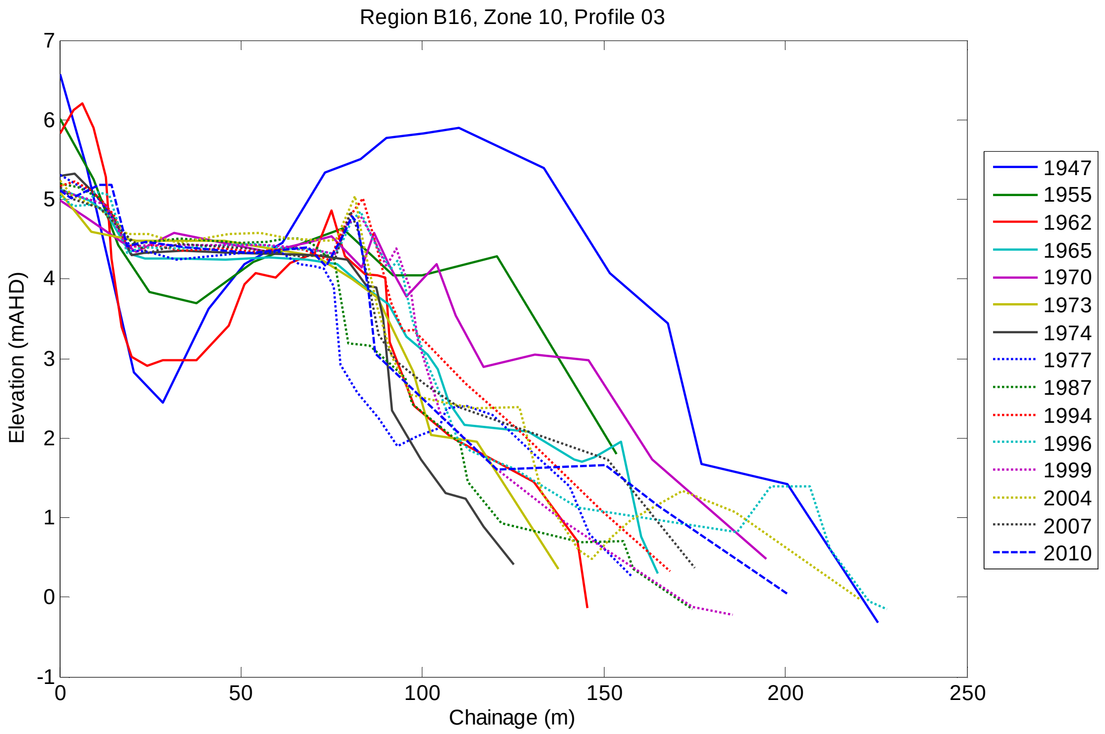
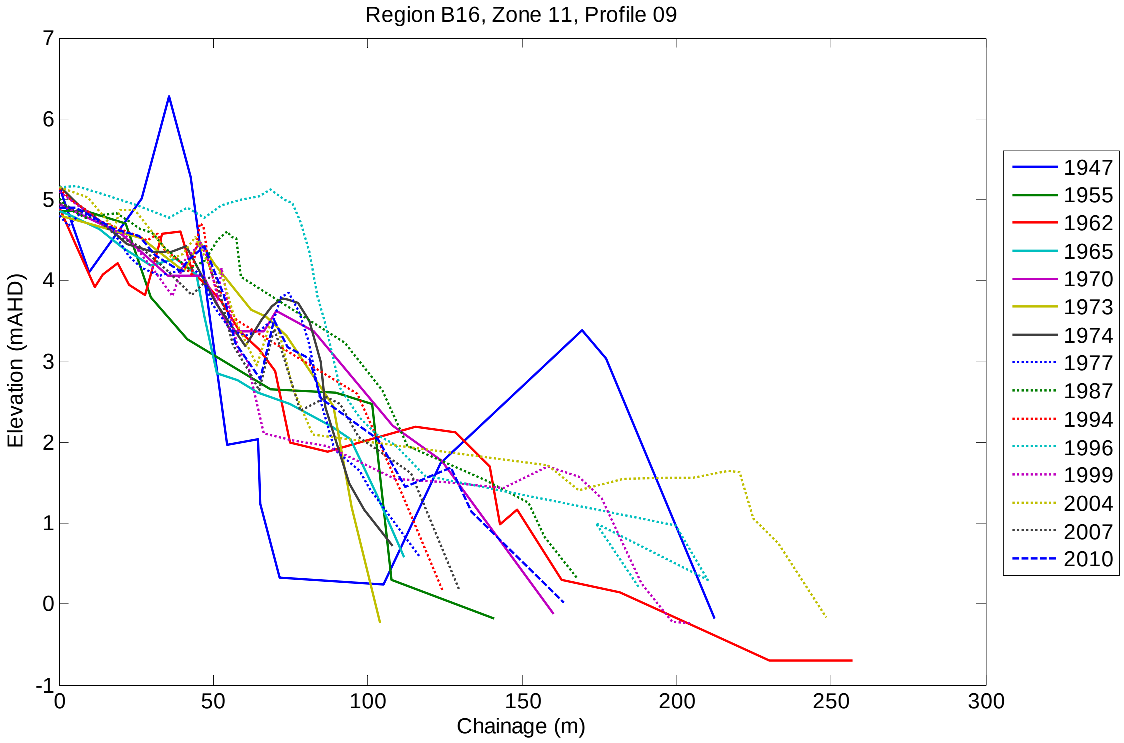


Figure A- 8 Kingscliff Photogrammetry Profiles: Zone 10 (Caravan Park)

Locations shown in Figure 4-6



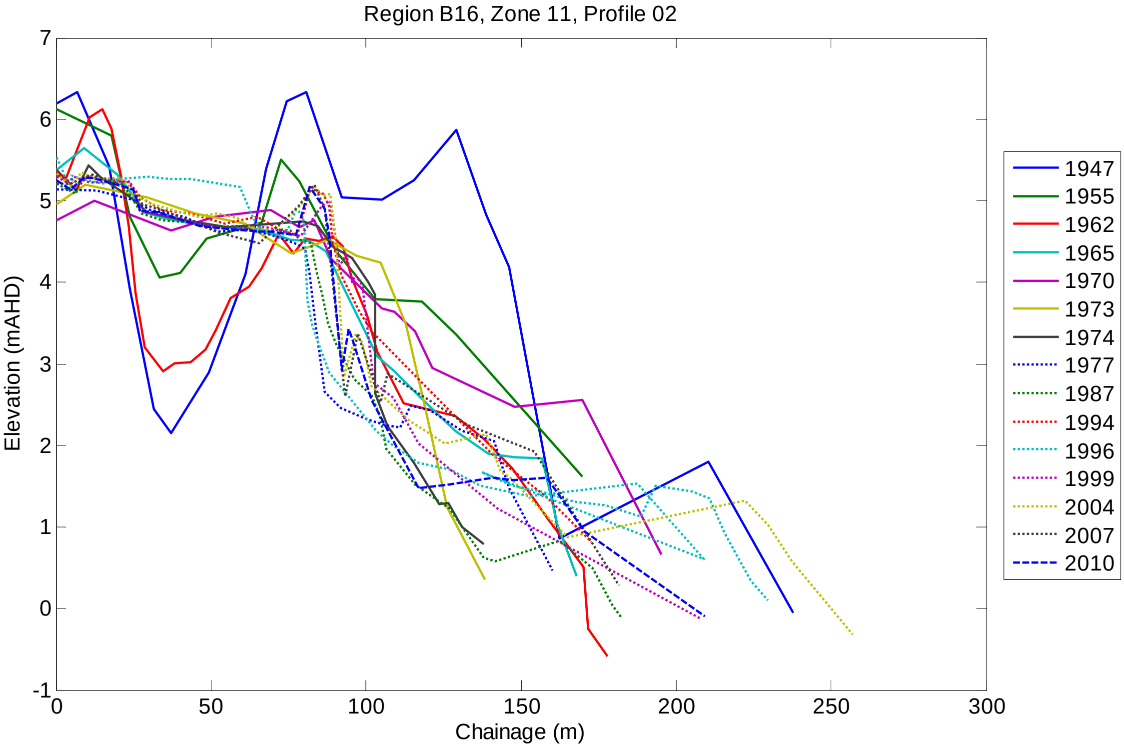
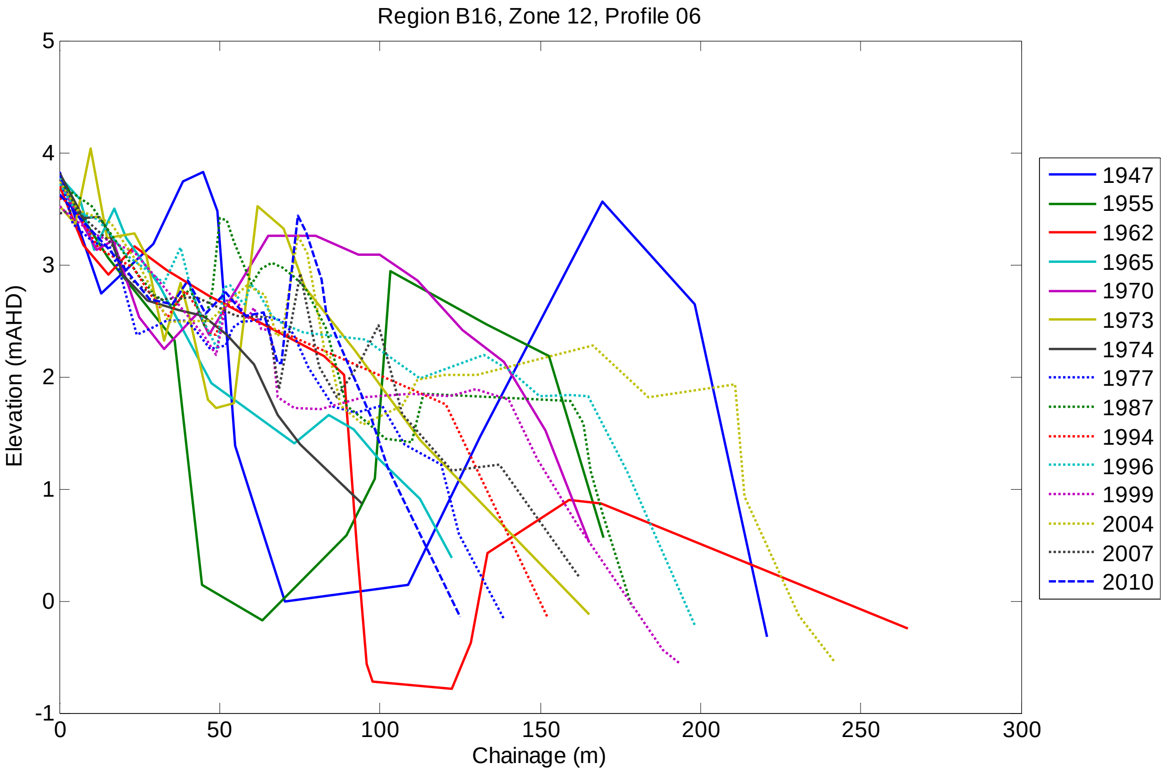


Figure A- 9 Kingscliff Photogrammetry Profiles: Zone 11 (Surf Club)

Locations shown in Figure 4-6



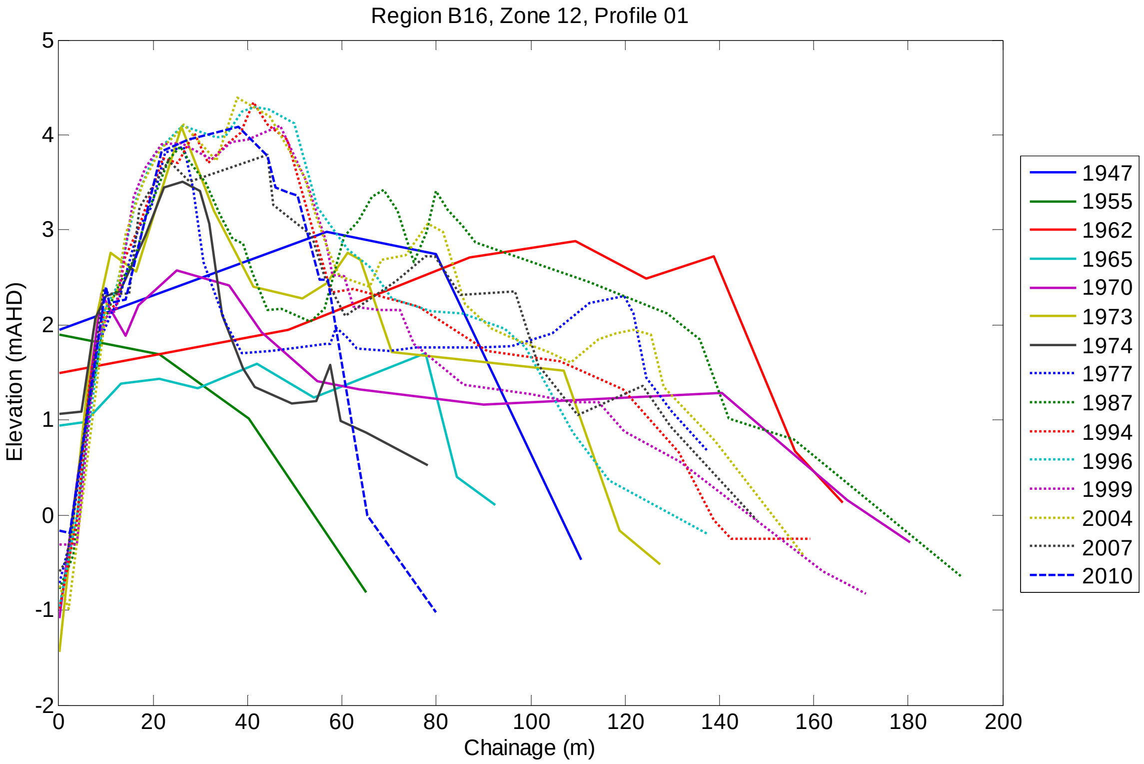


Figure A- 10 Kingscliff Photogrammetry Profiles: Zone 12

Locations shown in Figure 4-6

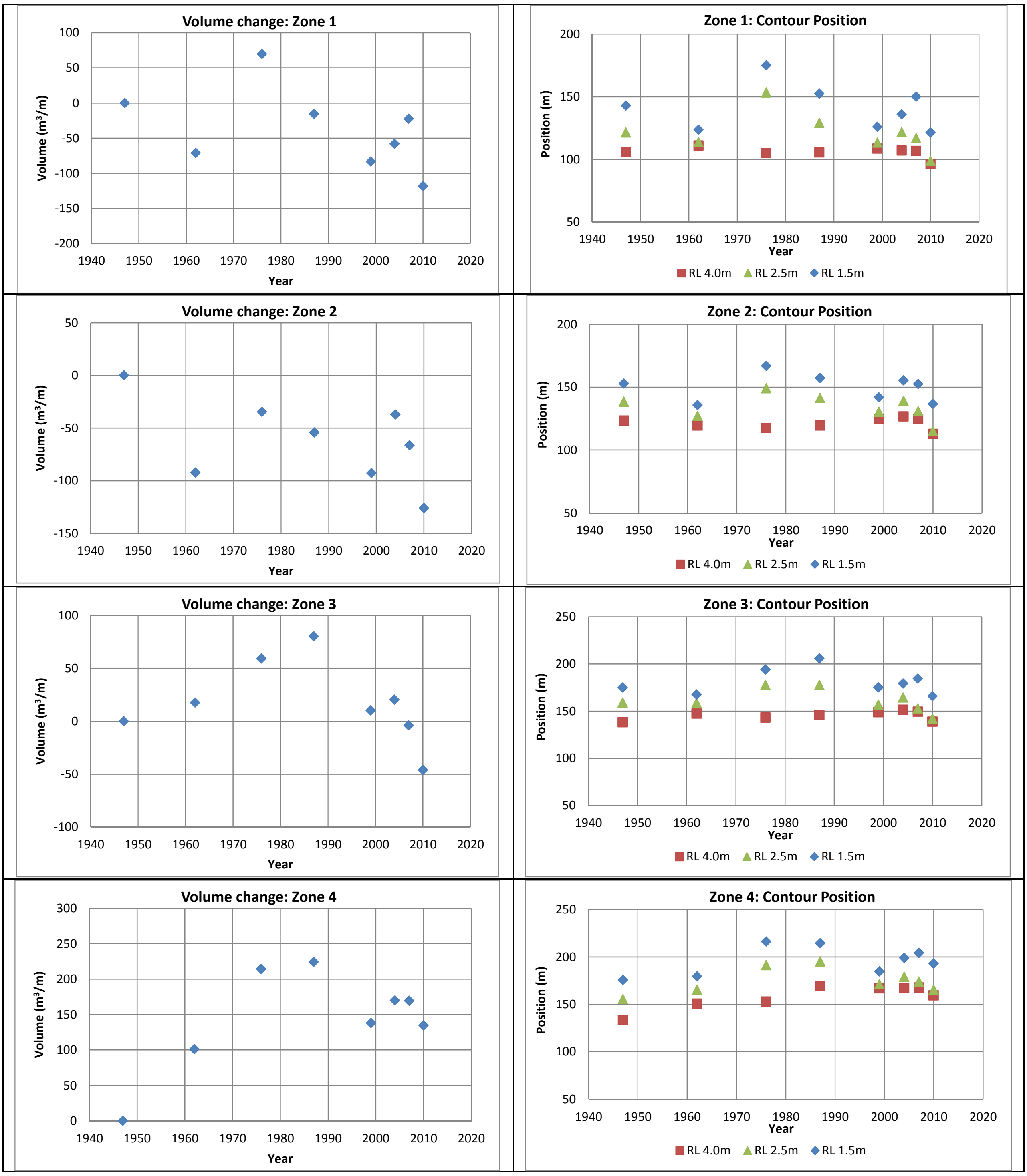


Figure A- 11 Beach/dune volumes and distances: Kingscliff Zones 1 to 4

Locations shown in Figure 4-6

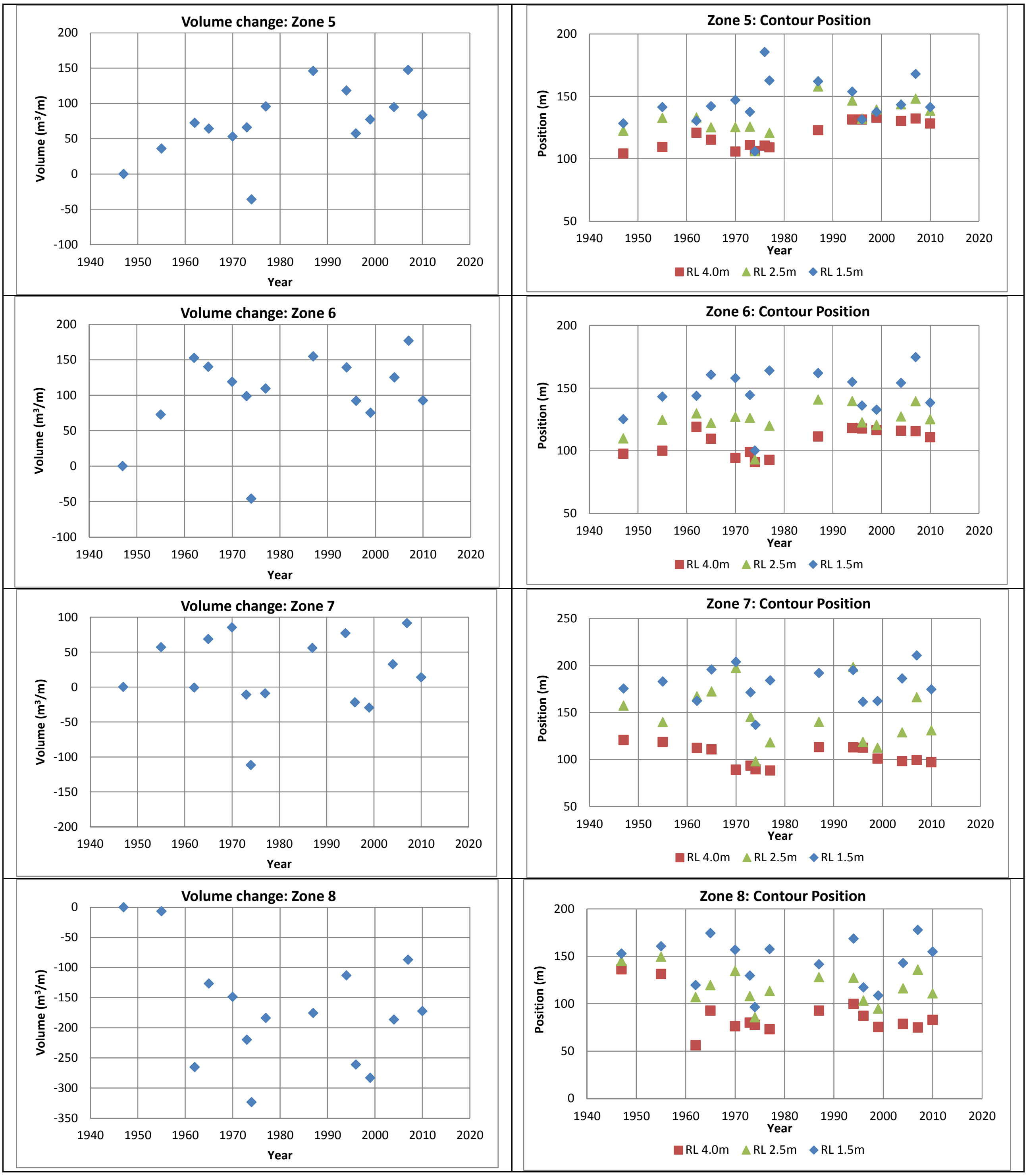


Figure A- 12 Beach/dune volumes and distances: Kingscliff Zones 5 to 8

Locations shown in Figure 4-6

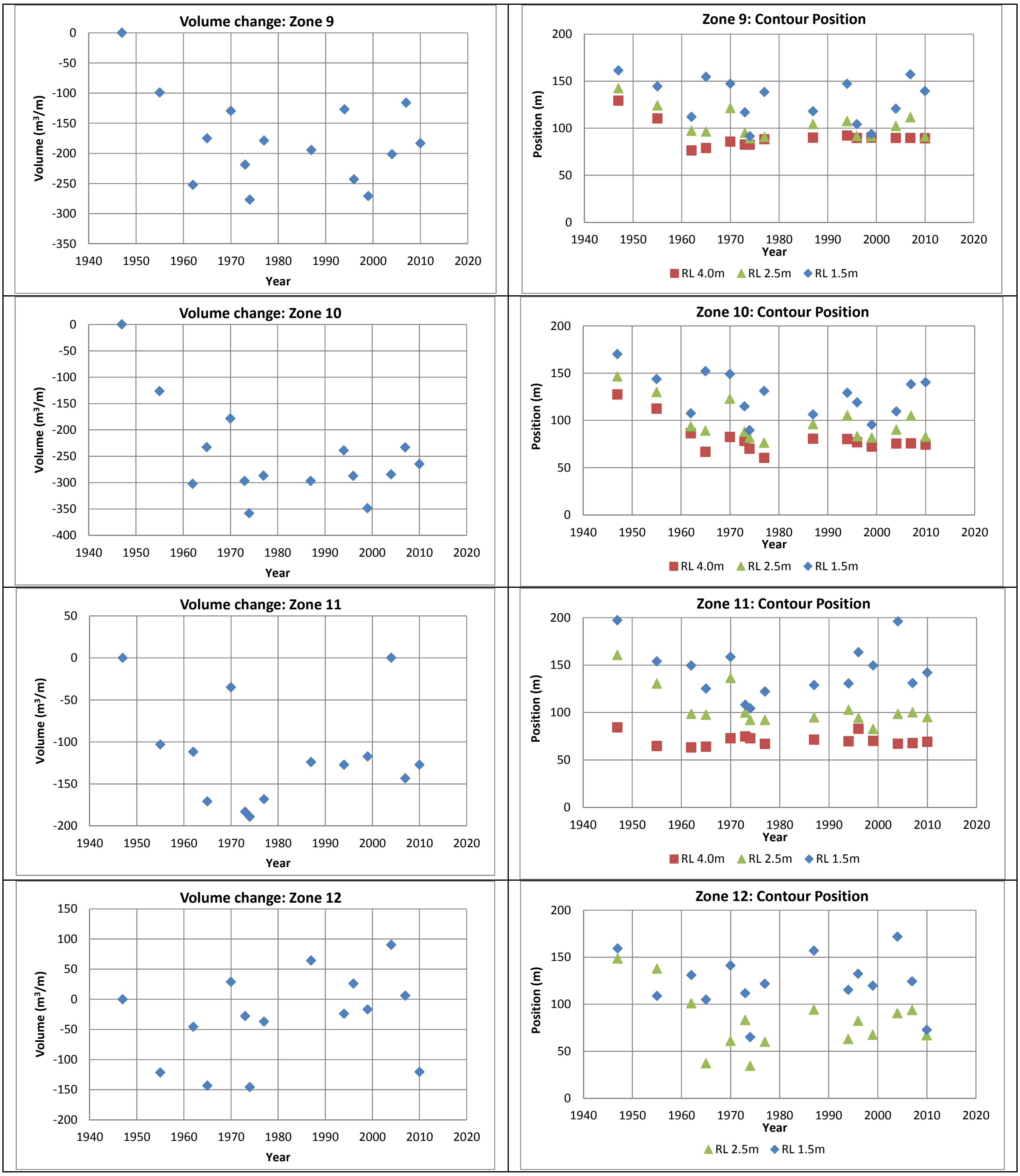


Figure A- 13 Beach/dune volumes and distances: Kingscliff Zones 9 to 12

Locations shown in Figure 4-6

APPENDIX B: TWEED SHIRE COASTAL HAZARD MAPS

Refer separate A3 Appendix B hazard mapping atlas

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