APPENDIX 3

Coastal Hazard Assessment
(SMEC 2010)

Final Draft Report

Wyong Coastal Hazard Study

October 2010 3001053

AUSTRALIA | ASIA | MIDDLE EAST | AFRICA | PACIFIC

Project Name:	Wyong Coastal Hazard Study – Final Draft
Project Number:	3001053
Report for:	Umwelt Australia

PREPARATION, REVIEW AND AUTHORISATION

Revision #	Date	Prepared by	Reviewed by	Approved for Issue by
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3	1/10/10	M. Glatz & C. Adamantidis	C. Adamantidis and DECCW	C. Adamantidis

ISSUE REGISTER

Distribution List	Date Issued	Number of Copies
Umwelt Australia Pty Ltd:	1/10/10	1 (electronic)
SMEC staff:		
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SMEC Project File:	1/10/10	1

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Wyong Coastal Hazard Study
Main Report

For: Umwelt Australia

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GLOSSARY

Accretion	The accumulation of (beach) sediment, deposited by natural fluid flow processes.
ACES	A computer program, developed by the US Army Corps of Engineers, that is used to determine, among other things, levels of wave runup on natural beaches.
Aeolian	Adjective referring to wind-borne processes.
Astronomical tide	The tidal levels and character which would result from gravitational effects, e.g. of the Earth, Sun and Moon, without any atmospheric influences.
Backshore	(1) The upper part of the active beach above the normal reach of the tides (high water), but affected by large waves occurring during a high. (2) The accretion or erosion zone, located landward of ordinary high tide, which is normally wetted only by storm tides.
Bar	An offshore ridge or mound of sand, gravel, or other unconsolidated material which is submerged (at least at high tide), especially at the mouth of a river or estuary, or lying parallel to, and a short distance from, the beach.
Bathymetry	The measurement of depths of water in oceans, seas and lakes; also the information derived from such measurements.
Beach profile	A cross-section taken perpendicular to a given beach contour; the profile may include the face of a dune or sea wall, extend over the backshore, across the foreshore, and seaward underwater into the nearshore zone.
Berm	A nearly horizontal plateau on the beach face or backshore.
Breaker zone	The zone within which waves approaching the coastline commence breaking, typically in water depths of around 2 m to 3 m in fair weather and around 5 m to 10 m during storms
Breaking depth	The still-water depth at the point where the wave breaks.
Chart datum	The plane or level to which soundings, tidal levels or water depths are referenced, usually low water datum.
Coastal processes	Collective term covering the action of natural forces on the shoreline, and the nearshore seabed.
Datum	Any position or element in relation to which others are determined, as datum point, datum line, datum plane.
Deep water	In regard to waves, where depth is greater than one-half the wave length. Deep-water conditions are said to exist when the surf waves are not affected by conditions on the bottom, typically in water depths of around 60 m to 100 m.
Dunes	Accumulations of wind-blown sand on the backshore, usually in the form of small hills or ridges, stabilised by vegetation or control structures.
Dynamic equilibrium	Short term morphological changes that do not affect the morphology over a long period.
Ebb tide	A non-technical term used for falling tide or ebb current. The portion of the tidal cycle between high water and the following low water.
Elevation	The distance of a point above a specified surface of constant potential; the distance is measured along the direction of gravity between the point and the surface.
Erosion	On a beach, the carrying away of beach material by wave action, tidal currents or by deflation.
Flood tide	A non-technical term used for rising tide or flood current. In technical language, flood refers to current. The portion of the tidal cycle between low water and the following high water.
Geomorphology	That branch of physical geography that deals with the form of the Earth, the general configuration of its surface, the distribution of the land, water, etc.
High water (HW)	Maximum height reached by a rising tide. The height may be solely due to the periodic tidal forces or it may have superimposed upon it the effects of prevailing meteorological conditions. Nontechnically, also called the high tide.

Inshore	(1) The region where waves are transformed by interaction with the sea bed. (2) In beach terminology, the zone of variable width extending from the low water line through the breaker zone.
Inshore current	Any current inside the surf zone.
Inter-tidal	The zone between the high and low water marks.
Littoral	(1) Of, or pertaining to, a shore, especially a seashore. (2) Living on, or occurring on, the shore.
Littoral currents	A current running parallel to the beach, generally caused by waves striking the shore at an angle.
Littoral drift	The material moved parallel to the shoreline in the nearshore zone by waves and currents.
Littoral transport	The movement of littoral drift in the littoral zone by waves and currents. Includes movement both parallel (long shore drift) and perpendicular (cross-shore transport) to the shore.
Longshore	Parallel and close to the coastline.
Longshore drift	Movement of sediments approximately parallel to the coastline.
Low water (LW)	The minimum height reached by each falling tide. Non-technically, also called low tide.
Mean high water (MHW)	The average elevation of all high waters recorded at a particular point or station over a considerable period of time, usually 19 years. For shorter periods of observation, corrections are applied to eliminate known variations and reduce the result to the equivalent of a mean 19-year value. All high water heights are included in the average where the type of tide is either semidiurnal or mixed. Only the higher high water heights are included in the average where the type of tide is diurnal. So determined, mean high water in the latter case is the same as mean higher high water.
Mean high water springs (MHWS)	The average height of the high water occurring at the time of spring tides.
Mean low water (MLW)	The average height of the low waters over a 19-year period. For shorter periods of observation, corrections are applied to eliminate known variations and reduce the result to the equivalent of a mean 19-year value.
Mean low water springs (MLWS)	The average height of the low waters occurring at the time of the spring tides.
Mean sea level	The average height of the surface of the sea for all stages of the tide over a 19-year period, usually determined from hourly height readings.
Morphology	The form of a river/estuary/lake/seabed and its change with time.
Nearshore	In beach terminology, an indefinite zone extending seaward from the shoreline well beyond the breaker zone.
Nearshore circulation	The ocean circulation pattern composed of the nearshore currents and the coastal currents.
Nearshore current	The current system caused by wave action in and near the breaker zone, and which consists of four parts: the shoreward mass transport of water; longshore currents; rip currents; and the longshore movement of the expanding heads of rip currents.
Refraction	The process by which the direction of a wave moving in shallow water at an angle to the bottom contours is changed. The part of the wave moving shoreward in shallower water travels more slowly than that portion in deeper water, causing the wave to turn or bend to become parallel to the contours.
Rip current	A strong current flowing seaward from the shore. It is the return of water piled up against the shore as a result of incoming waves. A rip current consists of three parts: the feeder current flowing parallel to the shore inside the breakers; the neck, where the feeder currents converge and flow through the breakers in a narrow band or "rip"; and the head, where the current widens and slackens outside the breaker line.
Runup	The rush of water up a structure or beach on the breaking of a wave. The amount of run-up is the vertical height above still water level that the rush of water reaches. It includes wave setup.

SBEACH	A computer program, developed by the US Army Corps of Engineers, that is used to determine, among other things, wave transformation across the surf zone, beach and dune erosion and levels of wave runup on natural beaches.
Setup	Wave setup is the elevation of the nearshore still water level resulting from breaking waves and may be perceived as the conversion of the wave's kinetic energy to potential energy.
Shoal	(1) (noun) A detached area of any material except rock or coral. The depths over it are a danger to surface navigation. (2) (verb) To become shallow gradually.
Shore	That strip of ground bordering any body of water which is alternately exposed or covered by tides and/or waves. A shore of unconsolidated material is usually called a beach.
Shoreface	The narrow zone seaward from the low tide shoreline permanently covered by water, over which the beach sands and GRAVELS actively oscillate with changing wave conditions.
Shoreline	The intersection of a specified plane of water with the shore.
***Significant* wave**	A statistical term relating to the one-third highest waves of a given wave group and defined by the average of their heights and periods.
***Significant* wave height**	Average height of the highest one-third of the waves for a stated interval of time.
Spring tide	A tide that occurs at or near the time of new or full moon, and which rises highest and falls lowest from the mean sea level (MSL).
Storm surge	A rise or piling-up of water against shore, produced by strong winds blowing onshore. A storm surge is most severe when it occurs in conjunction with a high tide.
Sub-aerial beach	That part of the beach which is uncovered by water (e.g. at low tide sometimes referred to as drying beach).
Surf zone	The nearshore zone along which the waves become breakers as they approach the shore.
Swell	Waves that have traveled a long distance from their generating area and have been sorted out by travel into long waves of the same approximate period.
Tide	The periodic rising and falling of the water that results from gravitational attraction of the moon and sun acting upon the rotating earth. Although the accompanying horizontal movement of the water resulting from the same cause is also sometimes called the tide, it is preferable to designate the latter as tidal current, reserving the name tide for the vertical movement.

1 INTRODUCTION

Wyong Shire Council is preparing a Coastline Management Study and Plan in accordance with the coastline management system outlined in the framework of the State Government's Coastline Management Manual (1990) and the NSW Coastal Policy (1997).

A prerequisite for the establishment and implementation of a Coastline Management Study and Plan is undertaking a Coastline Process and Hazard Definition Study for the whole of the Wyong Shire coastline, specifically to identify and quantify hazards affecting the urban areas within the Shire. This report documents that study.

The Coastline Management Process is outlined by the NSW Coastline Management Manual (1990) and consists of a three stage process, overseen by a Coastal Management Committee consisting of community, agency and local government representatives.

The three stages in the process are:

- **Stage 1** - Carry out **Coastal Process/Hazard Definition Studies** for the coastline – which involves gaining a scientific understanding of the coastal processes and hazards that affect the coastline and specifically defining what areas are at risk from coastal hazards.
- **Stage 2** - Carry out a **Coastline Management Study** which includes setting up the project framework, defining and understanding coastal zone values, defining threats to these values and identifying management options.
- **Stage 3** – Develop a **CMP**, which is a description of how the coastline will be managed. The Plan is then reviewed by the public and Government. Plans must be approved by the Minister for Environment and Climate Change and must be gazetted by Council before being implemented.

This report covers the first stage of the process, preparation of a Coastal Process and Hazard Definition Study for the Wyong Shire coastline for the dune areas of the coastline. A separate report prepared by Shirley Consulting Engineers (SCE, 2010) provides analysis of coastline bluff recession mechanisms and geotechnical hazards for the Wyong Shire coastline.

The steps in the process are outlined in Figure 1.

For each location in the study area, the Study used photogrammetric data to determine storm bite. This information was then applied to LiDAR undertaken in 2007 to derive the position of the post-storm escarpment. The long-term beach recession at each beach was quantified by photogrammetric analysis and beach recession that would be caused by sea-level rise as a result of Climate Change was estimated using standard analytical procedures.

The Wyong Shire coastline consists of two long sections of sandy beach, Lakes Beach and Tuggerah Beach, as well as smaller beaches that are separated by rocky bluffs, specifically around Norah Head and south of The Entrance.

The study area for this project extends from Yumbool Point, Bateau Bay in the south, to Desoto Inlet, Catherine Hill Bay, in the north. However, the focus of this study is the urban areas of the Wyong coastline, including the coast around Noraville and Norah Head, The Entrance North and The Entrance, Blue Bay, Toowoon Bay, Shelly Beach and Bateau Bay in the south (Figure 2).

Further to the existing urban areas, Council has identified that additional coastal process/hazard definition is required for the following areas:

- between the northern end of Curtis Parade and the northern extent of the proposed Magenta Shores development (approximately 1.5 kilometres north of Curtis Parade) for future urban development;
- at surf club properties (including car parks) that do not have defined coastal hazards (ie. Shelly Beach, Toowoon Bay, The Entrance Beach, Soldiers Beach and Lakes Beach); and
- adjacent to the southern extent of development at Budgewoi to determine the potential for oceanic inundation of Budgewoi Road.

In areas where coastal hazards had been defined in previous studies, these have been reviewed and reassessed within this study, including Toowoon and Blue Bay, Blue Lagoon and Hargraves Beach. Bluff areas, including the areas around Bateau Bay, Norah Head, behind Toowoon and Blue Bay and between Karagi Point and Sea View Parade are addressed within the geotechnical assessment report undertaken as part of the Hazard Definition Study and have been assessed separately by Shirley Consulting Engineers Pty Ltd.

This report documents a detailed coastal hazard assessment of the beaches along Wyong Shire coastline, which has been undertaken using photogrammetric data analysis and analytical assessments. It describes the coastal processes affecting the beaches at Wyong Shire and the impact of these processes on the areas of the beach where property is at risk. The report quantifies the observed long-term beach changes at Wyong as well as estimating the beach recession that may be caused by sea level rise as a result of climate change. The risk to property is defined in terms of the present day risk, the 2050 planning period and the 2100 planning period.

2 COASTAL PROCESSES

2.1 Introduction

The beach is often perceived to be the sandy area between the waterline and the dunes. It includes the beach berm, where sand-binding grasses may exist, and any incipient foredune formations. Typically, however, on an open coast the overall beach system extends from some several kilometres offshore, in water depths of around twenty metres to the back beach dune or barrier region, which may extend up to several hundred metres inland (Figure 3). When examining the coastal processes of a beach system often it is necessary to consider this wider definition.

The principal hazards induced by the coastal processes that are relevant for a coastal hazard risk assessment of the beach along the Wyong Shire Council coastline include:

- short-term coastal erosion including that resulting from severe storms, the behaviour of estuary entrances and slope instability;
- long term coastline recession including that resulting from imbalances in the sediment budget, such as aeolian sand transport, climate change and beach rotation; and
- oceanic inundation of low lying areas.

The hydrodynamic forcing controlling the rate of these processes and hazards comprise the prevailing wave climate and water levels.

2.2 Short Term Coastal Erosion

2.2.1 Storm Cut

A beach typically comprises unconsolidated sands that can be mobilised under certain meteorological conditions. The dynamic nature of beaches is witnessed often during storms when waves remove the sand from the beach face and the beach berm and transport it, by a combination of longshore and rip currents, beyond the breaker zone where it is deposited in the deeper waters as sand bars (Figure 3). During severe storms, comprising long durations of severe wave conditions, the erosion continues into the frontal dune, which is attacked, and a steep erosion escarpment is formed. This erosion process usually takes place over several days to a few weeks. At Wyong, all the beaches are separated by rocky headlands, forming discrete beach compartments which are largely self-contained. However, the beaches are generally not overlying bedrock – except at Toowoon Bay. At South Entrance, there is a cliff behind the beach which limits the beach erosion.

The amount of sand eroded from the beach during a severe storm will depend on many factors including the state of the beach when the storm begins, the storm intensity (wave height, period and duration), direction of wave approach, the tide levels during the storm and the occurrence of rips. Storm cut is the volume of beach sand that can be eroded from the subaerial (visible) part of the beach and dunes during a *design* storm. Usually, it has been defined as the volume of eroded sand as measured above mean sea level (~ 0 m AHD datum). For a particular beach, the storm cut (or storm erosion demand) may be quantified empirically with data obtained from photogrammetric surveys, or it may be quantified analytically using a verified numerical model.

The history of severe storm erosion demand for the beach along Wyong Shire is detailed in Appendix B and the hazard risk assessment is in Appendix D.

2.2.2 Slope Instability

Slope instability refers to the instability of both sandy dune areas, and rocky bluffs and headlands.

Following storm cut the dune face dries out and may slump. This results from the dune sediments losing their apparent cohesive properties that come from the negative pore pressures induced by the water in the soil mass. This subsequent slumping of the dune face causes further dune recession.

Dune slumping is treated as a slope instability hazard and can be quantified with stability computations, which can serve as a guide to determining safe setback distances on frontal dunes that are prone to wave attack and slumping during storms.

Bluffs and headlands with varying slope angles and heights are common features along the shore. Potential slope instability in bluffs and headlands constitutes a foreshore hazard, also referred to as a slope instability hazard.

Slope instability of bluffs and headlands is a result of the continuing operation of physical processes as well as anthropogenic activities within a particular geological and geomorphological setting in the coastal landscape. The physical processes could include rainfall, climate, rock weathering and disintegration, surface and ground water movement, soil erosion, sea level fluctuation, wave impact and earthquakes. On the other hand, coastal urbanisation and land use, destruction of vegetation, either intentionally or otherwise (such as by bush fire or logging activities) may be regarded as anthropogenic factors. Slope failures in bluffs and headlands (both in rock and unconsolidated sediments) are one of several coastal hazards that threaten the coastal community and values. A condition of slope instability may create public safety hazards, threaten existing infrastructure and affect sustainable development and use of coastal areas.

2.3 Longer Term Beach Changes And Shoreline Recession

Following storms, ocean swell replaces the sand from the offshore bars onto the beach face where onshore winds move it back onto the frontal dune. This beach building phase, typically, may span many months to several years. Following the build-up of the beach berm and the incipient foredunes, and the re-growth of the sand trapping grasses, it can appear that the beach has fully recovered and beach erosion has been offset by beach building (Figure 4).

However, in some instances, not all of the sand removed from the berm and dunes is replaced during the beach building phase. Sand can be lost to sinks, resulting in longer term ongoing recession of the shoreline. Further, over decadal time scales, changes in wave climate can result in beach rotation. The signature of the medium-term oscillations in sub-aerial beach sand store caused by decadal variations in the SOI and the fluctuations resulting from minor storm events are apparent in the photogrammetric data for Wyong Shire. Long term recession at Wyong Shire beaches is not significant enough to erase the signature of the medium term changes.

2.3.1 Sediment Budget Deficit

Once the sand has been transported offshore into the surf zone, it may be moved alongshore under the action of the waves and currents and out of the beach compartment. Some of the sand that is transported directly offshore during storms may become trapped in offshore reefs, thereby preventing its return to the beach. Other direct losses of material from the beach may include the inland transport of sand under the action of onshore winds; this mechanism being called aeolian sand transport. Over the longer term, should the amount of sand taken out of the compartment by alongshore processes exceed that moved into the compartment from adjacent beaches or other sources, then there will be a direct and permanent loss of material from the beach and a deficit in the sediment budget for the beach (Figure 5). This will result in an increasing potential for dune erosion during storms and long term beach recession (Figure 6).

Obvious processes that may lead to a deficit in the sediment budget of a beach include wind blown sand off the beach (aeolian sand transport causing transgressive dune migration), mining the beach for heavy minerals and beach sand extraction operations. Other processes, which are not so obvious because they occur underwater, include the deposition of littoral drift into estuaries and the transport of quantities of littoral drift alongshore and out of a beach compartment, which may be larger than any inputs.

The quantification of sediment budgets for coastal compartments is exceedingly difficult. The usual practice is to identify the processes and to quantify the resulting beach recession using photogrammetric techniques. Long term rates of shoreline recession have been quantified for the different beaches along the Wyong Shire coastline using photogrammetric techniques (Appendix B).

2.3.2 Enhanced *Greenhouse* Effect

Another factor that may affect the long-term trends on beaches is a rise in sea level resulting from the *Greenhouse Effect*. A rising sea level may result in beach recession on a natural beach and an increased potential for dune erosion on a developed beach where the dune line may be being held against erosion by a seawall.

In the longer term, there may be global changes resulting from a postulated warming of the earth due to the accumulation in the atmosphere of certain gases, in particular carbon dioxide, resulting from the burning of fossil fuels (the *Greenhouse Effect*). The current consensus of scientific opinion is that such changes could result in global warming of 1.5° to 4.5°C over the next 100 years. Such a warming could lead to a number of changes in climate, weather and sea levels. These, in turn, could cause significant changes to coastal alignments and erosion.

Global warming may produce also a worldwide sea level rise caused by the thermal expansion of the ocean waters and the melting of some ice caps. According to the Intergovernmental Panel on Climate Change (IPCC, 2007), the upper range estimate for sea level rise for the 21st century is 0.59 m (Figure 7). This is made up of various components, including thermal expansion of the oceans (the largest component), melting of the Greenland and Antarctic ice sheets and melting of land-based glaciers. There is emerging evidence in the current measurements and observations, suggesting the IPCC's 2007 report may have underestimated the future rate of sea level rise.

The NSW Government through the NSW Sea Level Rise Policy Statement have set the NSW Sea Level Rise Planning benchmark at the upper bound levels of a 0.40 m increase above 1990 levels by 2050 and 0.90 m by 2100. The rationale behind the NSW Government's adoption of the respective planning benchmark allowances for SLR are detailed in the DECCW publication "Derivation of the NSW Government's sea level rise planning benchmarks – Technical Note (DECCW, 2009a). The benchmarks are based on the sea level rise developed by Australian and international experts and include globally averaged sea level rise, accelerated ice melt, and regional sea level rise variations. Appendix C documents the full range of sea level rise estimates adopted for the hazard assessment.

There are no predictions for any increase in winter storm wind speeds and, hence, wave heights for this part of the NSW coast as a result of climate change (Figure 8). Foreshore recession resulting from a *Greenhouse*-induced sea level rise has been assessed using the *Bruun Rule* (Appendix C).

2.4 Coastal Inundation

An increase in water level at the shoreline results from the breaking action of waves causing what is termed wave setup and wave run-up. Wave setup may be perceived as the conversion of part of the wave's kinetic energy into potential energy. The amount of wave setup will depend on many factors including, among other things, the type, size and periods of the waves, the nearshore bathymetry and the slope of the beach and foreshore. Typically, wave setup on an open-coast beach during severe storms can be around 1 m to 2 m.

The energy of a wave is dissipated finally as the water runs up the beach or shoreline. Wave run-up is the vertical distance the wave will reach above the level of the tide and storm surge and can be several metres. Wave run-up at any particular site is very much a function of the wave height and period, the foreshore profile and slope, surface roughness and other shoreline features on which the breaking waves impinge.

Should dune levels be low or the foreshore not protected by dunes, flooding and damage to structures can result from the coincidence of elevated ocean water levels and wave run-up.

An assessment of coastal inundation due to wave run-up for Wyong Shire has been carried out in Appendix D.

2.5 Hydrodynamic Forcing

2.5.1 Introduction

Critical to a coastline hazard risk assessment is the definition and quantification of waves and water levels that shape the beaches.

2.5.2 Wave Climate And Storms

The central coast of NSW experiences a high wave energy. The offshore swell wave climate (wave height, period and direction occurrences) has been recorded by the NSW Government Manly Hydraulics Laboratory with Waverider buoys located offshore from Sydney for many years. The Waverider buoy located at Sydney has measured wave direction also since 1992.

Summary wave statistics have been published in Lord and Kulmar (2000). The wave data show that the predominant swell wave direction is south-southeast (SSE) with over 70% of swell wave occurrences directed from the SSE quadrant. The average deep water *significant* wave height, as measured at Sydney, is around 1.5 m (Figure 9) and the average wave period is around 9 seconds. Analysis of storms recorded at Sydney has provided wave height/duration data for various annual recurrence intervals, which are presented in Figure 10.

For the storm erosion hazard risk analysis, a 1% storm event was adopted, having a maximum wave height duration of 12 hours, ensuring coincidence with a high tide, with a *significant* wave height of 6.8 m.

Figure 11 documents the extreme storm events that occurred between 1941 and 2008, with the estimated *significant* wave heights for these events. It plots also the dates for which beach photogrammetry was available for analysis.

2.5.3 Extreme Water Levels

During storms, the ocean water level and that at the shoreline is elevated above the normal tide level. While these higher levels are infrequent and last only for short periods, they may exacerbate any storm damage on the foreshore. Elevated water levels allow larger waves to cross the offshore sand bars and reefs and break at higher levels on the beach. Further, they may cause flooding of low lying areas and increase tail water control levels for river flood discharges.

The components of these elevated water levels comprise the astronomical tide, barometric water level setup, wind setup, wave setup and runup (Figure 12). All of the components do not act or occur necessarily independently of each other but their coincidence and degree of inter-dependence, generally, is not well understood.

The tides of the NSW coast are semidiurnal with a diurnal inequality. This means that there are two high tides and two low tides each day and there is a once-daily inequality in the tidal range. The mean tidal range is around one metre and the tidal period is around 12.5 hours. Tides vary according to the phases of the moon. The higher spring tides occur near and around the time of new or full moon and rise highest and fall lowest from the mean sea level. The average spring tidal range is 1.3 metres and the maximum range reaches two metres. Neap tides occur near the time of the first and third quarters of the moon and have an average range of around 0.8 metres.

Storm surge is the increase in water level above that of the normal tide that results from the low barometric pressures, which are associated with severe storms and cause sea level to rise, and strong onshore winds that pile water up against the coast. Storm surge due to these factors is a contributing factor to measured tidal anomalies (or variations from predicted astronomical tide levels). Measured values of tidal anomalies at Sydney include 0.59 m for the extreme storm event of 25 – 26 May 1974 and 0.54 m for the extreme storm event of 31 May – 2 June 1978, which were computed to have recurrence intervals of 77 and 39 years respectively (Haradasa *et al.*, 1991). Both of these extreme events were coincident with spring high tides with the water level in the 1974 event reaching the maximum recorded at Fort Denison of 1.48 m AHD.

Return periods for ocean water levels comprising tidal stage and tidal anomalies for Sydney, which are representative of the study region, are presented in Figure 13.

3 COASTAL HAZARD ASSESSMENT

3.1 Introduction

The coastal hazard assessment for Wyong Shire comprised quantifying the three principal hazards, namely:

- short-term storm beach fluctuations;
- long term beach recession; and
- oceanic inundation.

For the beaches of Wyong Shire coastline, the storm cut (or storm erosion demand) has been quantified empirically with data obtained photogrammetrically. An *equivalent* storm erosion volume has been derived empirically based on the schema presented in Nielsen *et al.* (1992) and storm erosion volumes derived from photogrammetry data between 1973 and 1974 on the one hand and between 2006 and 2008 on the other. These two timeframes were selected for analysis because they represented closely spaced data sets before and after well documented storm events on the NSW central coast (May-June 1974 and June 2007). These storm events are the largest storms on the historical record, and their impacts on the Wyong coastline are well documented.

A detailed description of the storm erosion protocol and the derivation of the results are provided in Appendix D.

3.2 Short Term Beach Fluctuations

3.2.1 Design Storm Erosion

Design storm erosion volumes for Wyong Shire beaches are calculated in Appendix D. An analysis of equivalent storm erosion volumes resulting from the 1974 storms followed the schema of Nielsen *et al.* 1992 (see Figure 14). The values were derived at the local maxima of the landward movement of the RL 4m contour for the different beaches, as measured between the 1973 and 1974 or 2006 and 2008 photogrammetric data and applied to the whole beach, to take account of the formation of rip-heads and to arrive at a conservative estimate of storm erosion demand for the beach. These contours have been chosen as they best represent the dune face movement.

The design storm erosion demand has been based empirically on the measured erosion caused by the 1974 storms. The storms of May-June 1974 caused widespread damage to coastal structures and beaches along the central coast of New South Wales (Foster *et al.*, 1975). These storms were associated with an intense low pressure cell adjacent to the coast south of Sydney. A waverider buoy in deep water offshore of Port Kembla recorded a wave height history for the event, which lasted between 25 May and mid June 1974. Over this time, the maximum *significant* offshore wave height reached a peak of 6.4 m 24 hours into the storm, with a second peak of Hs = 6.8 m reached 60 hours into the storm. As these storms occurred within a short timeframe of each other, they have been combined and considered as a single storm event.

Because nearshore waves causing dune erosion are depth-limited, wave duration of moderate wave heights becomes a more important factor for dune erosion than peak offshore wave heights of short duration. It was the long duration of moderately high waves combined with extreme water levels that made this particular 1974 storm so destructive.

The 1974 storm event was coincident with maximum spring tides, with a maximum tidal anomaly measured at Fort Denison of 0.59 m and a maximum ocean water level of 1.48 m on AHD (Kulmar and Nalty, 1997). The individual measurable attributes of the storm include wave height, duration, wind speed and water level. The combined exceedance probability of all these parameters makes it difficult to ascribe an Annual Exceedance Probability (AEP) to the storm event, though recent extreme value analysis of the Fort Denison record (Watson and Lord, 2008) indicates that the water level reached on 25 May 1974 had an ARI in the order of 300 years.

At other locations in NSW, a relationship between beach erosion and whether an adjacent estuary entrance is open or closed has been found – such a relationship was found at Shoalhaven Heads on the NSW south coast (SMEC Australia, 2007). It was found that more beach erosion occurred when a coastal storm event coincides with an open entrance.

From this analysis, an envelope of values for the loss of sand volume was calculated for each of the different beaches along the Wyong Shire coastline and the result is shown in Table 1.

Table 1 – Selected storm bites for the different beaches along Wyong Shire coastline

Location	Adopted Storm bite (m^3/m)
Shelly Beach (Block 1)	200
Shelly Beach (Block 2-3)	250
Toowoon Bay (Block P-Q-R)	70
Toowoon Bay (Block S)	50
Blue Bay (Block T)	140
Blue Bay (Block U)	110
Blue Bay (Block V)	100
South Entrance Beach	N/A
North Entrance Beach (Block A-F)	250
North Entrance Beach (Block G-H)	150
Soldiers Beach (Block 1)	100
Soldiers Beach (Block 2)	130
Soldiers Beach (Block 3)	160
Soldiers Beach (Block 4-5)	200
Lakes Beach	250
Hargraves Beach (Block I)	180
Hargraves Beach (Block J)	190

The exceedance probability of the measured storms at Wyong Shire is not known, but as they are the largest storms to have occurred over the period of the photogrammetric record, they were adopted for analysis along the Wyong Shire shoreline. The maximum measured erosion between 1973 and 1974 for the different beaches, which encompasses these large storm events, were adopted as the design storm erosion. It is considered that a storm that would lead to the design storm erosion demand would have a very low risk of being exceeded over the next 50 years. The estimated storm erosion demand from the 1974 and 2007 storms for the various locations along the Wyong Shire coastline are plotted in Figures 15 to 22.

3.2.2 Estuary Entrance Instability

Short term beach fluctuations can be enhanced at natural estuary entrances, such as at Tuggerah Lake entrance. Estuary entrance instability has been examined in Appendix B, and it was found that this hazard is currently restricted to the zone along the beach berm at the entrance at the southern end of North Entrance Beach.

3.3 Long Term Recession

3.3.1 Introduction

Processes such as sea level rise, aeolian processes and the littoral drift of sediment are natural loss components of the sediment budget of a beach. Similarly, biogenic production of sand from the shells of benthic fauna, and sediment transported into the littoral zone from nearby estuaries are natural sources of sediment for a beach. If, in the long term, the losses of sediment from a beach are greater than the gains, then a gradual beach recession will result.

Detailed measurements of the sediment budget for the beach at Wyong Shire were beyond the scope of this study. However, an assessment of the long term beach recession rate has been made empirically using photogrammetric data, and this is described in Appendix B.

3.3.2 Measured Long Term Beach Recession

Table 2 illustrates the beach recession rates measured for the various beaches in the study area.

Generally, it was found that most of the beaches in the study area are not undergoing significant long term beach recession. Between the storms of May 1974 and those of June 2007, several beaches had been recovering in sand volume as a result of a lack of storm activity. However, a major storm in June 2007 led to erosion of the beaches within the study area. Accordingly, the photogrammetric analysis used to calculate long term recessionary trends includes data from 2008 (so the impact of the June 2007 storms are included).

The detailed analysis for each beach in the study area is described below.

Table 2 – Measured Long-term Beach Erosion Rates at various beaches in the Wyong Shire

Beach	Adopted long term recession rate (m/yr)
Shelly Beach	Nil
Toowoon Bay (Block P-Q-R-S)	0.1
Blue Bay (Block T-U-V)	0.1
South Entrance	Nil
North Entrance (Block A)	Nil
North Entrance (Block B)	0.1
North Entrance (Block C)	0.5
North Entrance (Block D)	0.2
North Entrance (Block E-F-G)	Nil
North Entrance (Block H)	0.1
Soldiers Beach (Block 1-2)	Nil
Soldiers Beach (Block 3-4-5)	0.2
Hargraves Beach (Block I)	Nil
Hargraves Beach (Block J)	0.05
Lakes Beach	0.5

3.3.3 Future Beach Recession – Sea Level Rise

Sea level rise may lead to a shoreline response of coastal recession. The most widely accepted method of estimating shoreline response to sea level rise is the Bruun Rule (Appendix C). Measurements of sea level rise show that there is considerable variation in the data. These variations are due to processes acting at inter-decadal scales, such as the El Niño Southern Oscillation (ENSO) phenomenon. Figure 23 illustrates the concept of beach recession as a result of sea level rise.

The possibility of increased storm wave heights has been investigated as part of this study. Hennessy *et al.* (2004) do not predict any increase in winter storm wind speeds for the NSW coast. The background to this is provided in Appendix C.

Foreshore recession resulting from a *Greenhouse*-induced sea level rise has been assessed using the *Bruun Rule* (Appendix C). The results are shown in Table 3.

Table 3 – Predicted beach erosion due to sea level rise

Beach	Block	Total Predicted Sea Level Rise (m)		Equilibrium Nearshore Slope (1:X)	Total Beach Recession (m)		Total Beach Erosion (m3/m)	
		2050	2100		2050	2100	2050	2100
Shelly Beach	1	0.40	0.90	35	15.2	34.2	72.9	164.0
	2			42	17.4	39.2	189.8	426.9
	3			37	14.8	33.3	128.8	289.7
Toowoon Bay	Whole Bay	0.40	0.90	13	5.2	11.7	52.0	116.9
Blue Bay	Whole Bay	0.40	0.90	11	4.4	9.8	39.5	88.8
South Entrance	Whole Beach	0.40	0.90	N/A*	N/A*	N/A*	N/A*	N/A*
North Entrance	A	0.4	0.9	30	11.8	26.6	73.3	164.9
	B			29	11.6	26.1	104.4	234.9
	C			45	18.0	40.4	152.7	343.7
	D			31	12.6	28.3	104.8	236.0
	E			35	14.1	31.5	105.8	237.9
	F			39	15.4	34.5	92.0	207.0
	G			37	14.6	33.0	102.5	230.7
	H			45	14.8	33.3	128.5	283.1
Soldiers Beach	1	0.4	0.9	29	11.6	26.1	143.7	323.4
	2			32	12.9	29.0	149.4	336.1
	3			44	17.4	39.2	123.8	278.6
	4-5			39	15.4	34.7	155.7	350.3
Lakes Beach	Whole Beach	0.40	0.90	72	28.9	65.0	190.8	429.2
Budgewoi Lake	Dune Arm	0.40	0.90	29	11.5	25.9	81.7	183.8
Hargraves Beach	I	0.4	0.9	25	10.2	22.9	58.7	132.1
	J			16	6.7	15.0	45.9	103.3

*South Entrance Beach is underlain by rock all along its length.

It should be noted that these recession rates assume that the dune is composed of erodible material and that the nearshore beach profile is in equilibrium with the wave climate. Where a superficial layer of sandy beach overlies bedrock or if there is presence of bedrocks seaward of the beach, erosion would be limited (i.e. Toowoon Bay, Blue Bay and Blue Lagoon).

The active profile slope for each beach in Table 3 was determined with reference to the bathymetric data as well as known locations of nearshore reefs and rock platforms which are not part of the equilibrium beach profile. Several schemas exist, based on analytical and laboratory studies, to determine closure depth and length of the active zone, including those of Swart (1974) and Hallermeier (1981, 1983).

Hallermeier (1981, 1983) defines a simple zonation of an onshore-offshore beach profile consisting of a *littoral* zone, *shoal* zone or buffer zone, and offshore zone where surface wave effects on the bed are negligible. Based on an analytical approach, supported by laboratory data and some field data, Hallermeier defines two water depths bounding the shoal zone, defined by d_s and d_o.

Use of the Hallermeier (1981, 1983) formulation for estimating the closure depth gives an inner limit for the depth of closure of around 16.50 m and an outer limit of around 40 m. The closure depths and the equilibrium profile lengths have been assessed from the beach profile graph, as well as the results of the Hallermeier calculations, which are detailed in Appendix C.

3.4 Inundation

An increase in water level at the shoreline results from the breaking action of waves causing what is termed wave setup and wave runup. Wave setup may be perceived as the conversion of part of the wave's kinetic energy into potential energy. The amount of wave setup will depend on many factors including, among other things, the type, size and periods of the waves, the nearshore bathymetry and the slope of the beach and foreshore. Typically, wave setup on an open-coast beach during severe storms can be around 1 m to 2 m.

Coastal inundation would occur if the frontal dune is low enough to allow overtopping during a major storm.

The hazard of coastal inundation was assessed in the areas considered most at risk, namely Hargraves Beach, Lakes Beach north of the surf club, North Entrance Beach at Curtis Parade, and Blue Bay. Wave runup levels were estimated using a combination of numerical models, as detailed in Appendix D.

Significant runup levels were assessed at the various locations in the study area (the level along the beach at which the average of the highest 33% of waves would reach during a large storm, expressed in m AHD). The storm event used in the calculations assumed a 1-in-100-year (1% AEP) significant wave height combined with a 1-in-100-year (1% AEP) water level which is a conservative assumption, as it is unlikely that a 1% AEP wave height would occur concurrently with a 1% AEP water level. During a large storm, however, wave runup can reach a level higher than the *significant* wave runup, and the highest waves could reach levels up to 1 m higher than the *significant* wave runup. Furthermore, the wave runup levels were assessed based on an *average* profile condition at each location – if the beach is in an eroded state, wave runup may have a greater impact than if the beach is in a relatively accreted state.

Table 4 details the runup levels assessed for each relevant location in the study area.

Table 4 – Wave Runup levels for Wyong Shire, 1% AEP water level combined with 1% AEP wave height

Beach	Profile Location (Block-Profile)	Water Level	Maximum Wave RunUp Level from ACES	2% Wave RunUp Level from ACES	Significant Wave RunUp Level from ACES	Maximal Offshore Water Level	Maximal Run Up
		m	m	m	m	m AHD	m AHD
Shelly Beach	1-3	1.207	4.62	4.18	3.17	1.48	7.307
	1-8	0.99	4.35	3.96	3.00	1.48	6.820
	2-2	1.005	4.44	3.96	3.00	1.48	6.925
	2-19	1.051	4.27	3.89	2.95	1.48	6.801
	3-5	1.05	4.19	3.82	2.90	1.48	6.720
Toowoon and Blue Bays	Q-8	1.111	2.96	2.77	2.11	1.48	5.551
	R-12	1.202	2.92	2.74	2.09	1.48	5.602
	S-15	1.184	3.03	2.84	2.16	1.48	5.694
	T-7	1.144	3.07	2.87	2.18	1.48	5.694
	U-7	1.192	3.84	3.53	2.68	1.48	6.512
	V-9	1.18	3.91	3.58	2.72	1.48	6.570
South Entrance	SLSC	1.315	3.56	3.29	2.50	1.48	6.355
	Boatshed	1.172	3.78	3.48	2.64	1.48	6.432
North Entrance	A-32	1.17	3.78	3.48	2.64	1.48	6.430
	B-13	0.958	3.72	3.43	2.60	1.48	6.158
	C-18	1.272	3.97	3.64	2.76	1.48	6.722
	C-37	1.11	4.62	4.18	3.17	1.48	7.210
	D-15	1.164	4.93	4.44	3.36	1.48	7.574
	D-40	1.186	5.43	4.86	3.67	1.48	8.096
	D-56	1.187	5.43	4.86	3.67	1.48	8.097
	E-14	1.153	5.17	4.64	3.51	1.48	7.803
	E-34	1.234	5.43	4.86	3.67	1.48	8.144
	F-11	1.212	5.17	4.64	3.51	1.48	7.862
	F-28	1.153	5.17	4.64	3.51	1.48	7.803
	G-12	1.069	4.19	3.82	2.90	1.48	6.739
	H-2	1.058	1.69	1.45	1.09	4.48	7.228
Soldiers Beach	1-2	1.058	4.19	3.82	2.90	1.48	6.728
	2-4	1.153	4.12	3.76	2.85	1.48	6.753
	3-5	1.168	4.27	3.89	2.95	1.48	6.918
	SLSC	1.224	4.44	4.03	3.05	1.48	7.144
Lakes Beach	SLSC	0.95	2.77	2.61	1.99	1.48	5.200
Budgewoi Lake	Dune Arm	0.925	3.45	3.2	2.43	1.48	5.855
Hargraves Beach	I-1	1.043	3.5	3.24	2.46	1.48	6.023
	I-5	1.042	3.14	2.93	2.23	1.48	5.662
	I-10	1.298	3.07	2.87	2.18	1.48	5.848
	I-15	1.399	3.23	3	2.28	1.48	6.109
	I-20	1.208	3.84	3.53	2.68	1.48	6.528
	I-25	1.091	4.12	3.76	2.85	1.48	6.691
	J-1	1.033	4.55	3.7	2.76	1.48	7.063
	J-6	0.954	4.39	3.58	2.66	1.48	6.824
	J-12	1.092	4.35	3.96	3.00	1.48	6.922
	J-17	1.171	4.44	4.03	3.05	1.48	7.091
	J-22	1.157	4.19	3.82	2.90	1.48	6.827

4 HAZARD MAPPING AND RISK ASSESSMENT

4.1 Hazard Mapping

The derivation of the dune erosion hazard for the present day, 2050 and 2100 planning periods is presented in detail in Appendix D. For each planning period, the erosion hazard has been defined as:

- a line delineating the limit of wave impact and dune slumping (*Zone of Wave Impact and Slope Adjustment*); and
- a line delineating the limit of the area behind the dune face where the capacity of the sand to support building foundations is reduced because of the sloping dune escarpment (*Zone of Reduced Foundation Capacity*).

In addition, the sensitivity of the hazard lines to the upper-range sea level rise scenarios for 2050 and 2100 was examined – the locations of the 2050 and 2100 hazard lines assuming an upper range sea level rise scenario were overlayed on the hazard maps for comparison purposes. The mapping has been based on analysis of the photogrammetric data and aerial laser scan data of the coastline from 2007 (with the beaches in a relatively accreted state prior to the June 2007 storms) providing accurate positioning of the hazard lines.

4.2 Risk Assessment

A risk assessment for the present day, 2050 planning period and 2100 planning period has been carried out for the urban area of Wyong Shire. This risk assessment was carried out with reference to the hazard mapping done for each of the three planning periods. The results of this risk assessment are summarised below. The maximum run-up maps are given in D.3 to D.10 of the Appendix D and the hazard maps are given D.19 to D.43 in Appendix D for the immediate, 2050 and 2100 planning periods along the Wyong Shire coastline. Qualitative dune hazard analysis has been carried out at Bateau Bay, Pebbly Beach and the southern end of Cabbage Tree Harbour and these have been mapped in Figures D.44 to D.48.

We have assumed that the sandy portions of the beaches are erodible, although some specific areas are protected by seawalls and revetments. The effectiveness of these structures in a large storm is not known, and some may not be designed to acceptable coastal engineering standards. The coastal hazard assessment may therefore be conservative in those areas where coastal revetments are in place.

4.2.1 Wave Runup

Most of the caravan park south of Shelly Beach would be impacted by wave run-up as well as a section of the caravan park located along Toowoon Bay. Some low-lying houses along the southern half of Blue Bay could also be affected by wave run-up. South Entrance surf club, boatshed and swimming pool would also be impacted. Several dwelling along Curtis Parade at North Entrance as well as most houses located along Hargraves Beach could be affected by wave run-up.

4.2.2 Present Day

The assessment of coastal hazards has concluded that no private dwellings are at immediate risk of storm damage at Shelly Beach. A small section of the caravan park located at the southern end of Shelly Beach will be impacted. A narrow section of the caravan park north of Shelly Beach lies within the *Zone of Reduced Foundation Capacity*.

Around five dwellings are at immediate risk at Blue Bay as well as around 25 lots. Additional 19 dwellings and two lots lie within the *Zone of Reduced Foundation Capacity*. Some houses along the coast may potentially be at geotechnical risk.

At South Entrance, the entire sandy portion of the beach is under threat from erosion in a large storm event.

Some 18 dwellings and 28 lots lie within the *Zone of Slope Adjustment* and some additional 17 dwellings, the surf club and one lot will be subject to reduced foundation capacity along North Entrance Beach.

Soldiers Beach SLSC lies within the *Zone of Reduced Foundation* Capacity.

Along Hargraves Beach, some 30 dwellings and nine lots are at immediate risk and an additional four lots and five dwellings lie within the *Zone of Reduced Foundation Capacity*.

Lakes Beach Surf Club partially lies within the *Zone of Slope Adjustment*.

At the southern end of Cabbage Tree Harbour, a qualitative assessment assuming a storm erosion demand of 50 m^3/m and assuming sandy underlying strata showed that four buildings lie partially seaward of the *Zone of Slope Adjustment*.

4.2.3 2050 Planning Period

For the 2050 planning period, a larger section of the caravan park south of Shelly Beach lies within the *Zone of Slope Adjustment* and the SLSC will suffer from *Reduced Foundation Capacity*.

Along Toowoon and Blue Bays, some 27 dwellings and three lots will be at immediate risk and an additional dwelling and five lots will lie within the *Zone of Reduced Foundation Capacity*.

Some 38 dwellings and 25 lots will be at immediate risk at North Entrance and additional 21 dwellings and 6 lots will lie within the *Zone of Reduced Foundation Capacity*.

Soldiers Beach and Lakes Beach SLSCs will completely lie within the *Zone of Slope Adjustment*.

At Hargraves Beach, some 36 dwellings and 8 lots will be at immediate risk and three additional dwellings will lie within the *Zone of Reduced Foundation Capacity*.

4.2.4 2100 Planning Period

For the 2100 planning period, a larger section of the caravan park south of Shelly Beach lies within the *Zone of Slope Adjustment* and the SLSC will be at immediate risk.

At Toowoon and Blue Bays 27 dwellings and six lots will be at immediate risk. However, this risk depends on the foundation of the houses. Some of the dwellings located along Toowoon Bay which are based on rock may not be affected as illustrated on the maps.

At North Entrance, most dwellings and lots along Curtis Parade as well as most of the building seaward of Hutton Road south of the SLSC will be at immediate risk. Some additional 30 dwellings and six lots would be at immediate risk and 20 buildings and three lots will lie within the *Zone of Reduced Foundation Capacity*.

At Hargraves Beach, some 40 dwellings and seven lots will be at immediate risk and some additional six dwellings and four lots will lie within the *Zone of Reduced Foundation Capacity*.

4.2.5 Opening Of Budgewoi Lake Towards The Ocean

The study of the sand arm separating Budgewoi Lake from the ocean shows that some overtopping may occur in the future due to the generally low height at this location. Most of the sand arm has a height ranging from 3 to 4m with an 8-metre high dune on the ocean side. In a storm, this high dune will either be eroded or translated landward.

For the 2050 planning period, Central Coast Highway might be at risk due to the sea level rise induced landward recession of the dune which could reach the road.

For the 2100 planning period, Central Coast Highway will lie within the *Zone of Reduced Foundation Capacity.*

To prevent the road from being affected by erosion and wave impact, future sand nourishment along the sand arm would be advised, with minimum dune crest levels maintained above the maximum wave runup level.

There may be a risk of a new entrance into Budgewoi Lake being created as a result of long term dune recession and overtopping in this vicinity by 2100 and this would have far reaching ecological and hazard repercussions within the lake. Tidal range would significantly increase, salinity regime would change and many additional dwellings along the Lake would become subject to inundation as a result.

4.2.6 Assessment of additional locations

Assessment of additional locations using available data was undertaken at Bateau Bay, Pebbly Beach and the southern end of Cabbage Tree Harbour. Insufficient data was available to determine definitive dune erosion hazards at these locations. However, it was considered that by 2100, dune erosion at Bateau Bay could occur over the entire sandy portion of the beach.

At Pebbly Beach, it was considered unlikely that any infrastructure would come under threat from dune erosion prior to 2100.

At the southern end of Cabbage Tree Harbour, insufficient data was available to undertake a coastal hazard analysis, but a sensitivity analysis using storm erosion demand values of 50 m^3/m and 100 m^3/m was undertaken assuming that the underlying strata consisted of sand. This sensitivity analysis showed that four buildings may lie partially within the present day *Zone of Slope Adjustment*.

5 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary And Conclusions

Detailed technical studies using an updated empirical database have allowed for the quantification of the coastal hazards along the Wyong Shire coastline. The assessment has been made on the basis of detailed photogrammetric survey data.

AS4997-2005 "*Guidelines for the design of maritime structures*" (AS, 2005) recommends that a storm event having a 5% probability of being exceeded over a 50 year period be adopted for risk analyses. Several large storm events occurred over the period of the photogrammetric data record, including a major storm in May-June 1974. The exceedance probability of these storms at Wyong Shire is not known, but as they are the largest storms to have occurred over the period of the photogrammetric record, they were adopted for analysis along the Wyong Shire shoreline. The maximum measured erosion between 1973 and 1974 for the different beaches, which encompasses these large storm events, were adopted as the design storm erosion.

The available photogrammetric data has indicated that several beaches were accreting, some other were only slightly eroding – i.e. less than 0.2m/yr – and only Lakes Beach and the northern half of North Entrance Beach were eroding at a higher pace – i.e 0.5m/yr.

The prognosis for a future sea level rise, as a result of global warming, could increase the rate of long term recession. High estimate sea level rise scenarios in line with the NSW Sea Level Rise Policy Statement, indicated a sea level rise from the 1990 sea level of 0.40 m by 2050, and 0.90 m by 2100. This led to an "upper range" assessment of beach recession of up to 29.6 m by 2050 and 66.4 m by 2100 in the most vulnerable locations. It is possible that these estimates are conservative, as the Bruun analysis does not take the presence of underlying bedrock into account – especially at Toowoon Bay.

The number of dwellings and lots at immediate risk or suffering from reduced foundation capacity were estimated for each location.

Future changes to the coastal dynamics along Budgewoi Lake are also possible, leading to an increased potential for breakthrough of the Lake through the sand arm north of Lakes Beach.

Wave runup analysis for the design storm has indicated that wave runup level along Wyong Shire coastline is generally around 6 to 7m AHD with higher values for North Entrance where the runup level can reach up to around 8.1m AHD. This indicates that some overtopping may occur at Shelly Beach caravan park, at the southern end of Blue Bay, at South Entrance swimming pool, along Curtis Parade at North Entrance and along Hargraves Beach. However, the impact would be limited due to absorption of the wave run-up along the dune and if the houses and roads are affected, the impact would not be significant as the energy would be reduced.

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FIGURES

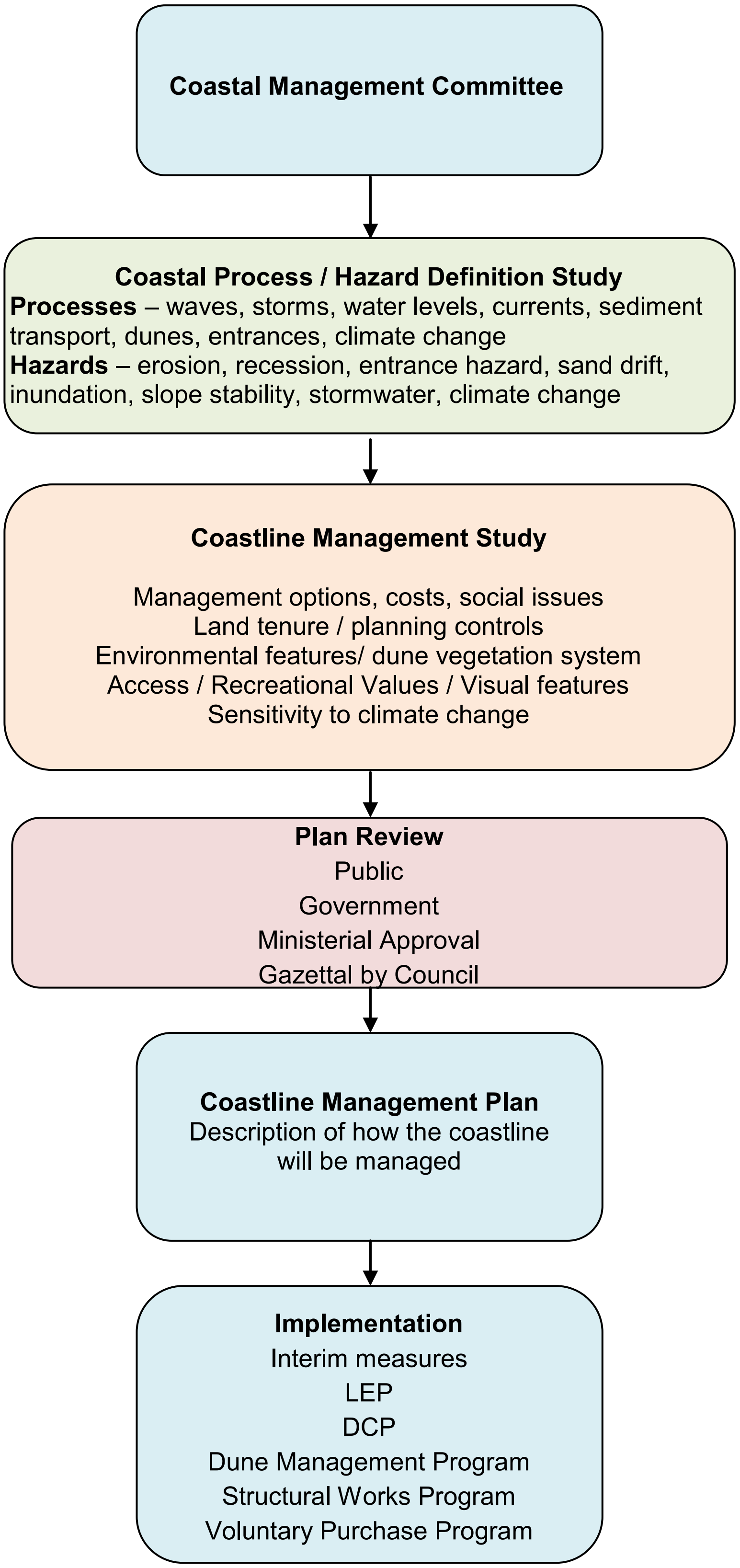


Figure 1 – The NSW Coastline Management process (NSW Government, 1990)

Figure 2 – Wyong Shire Coastline Study Area

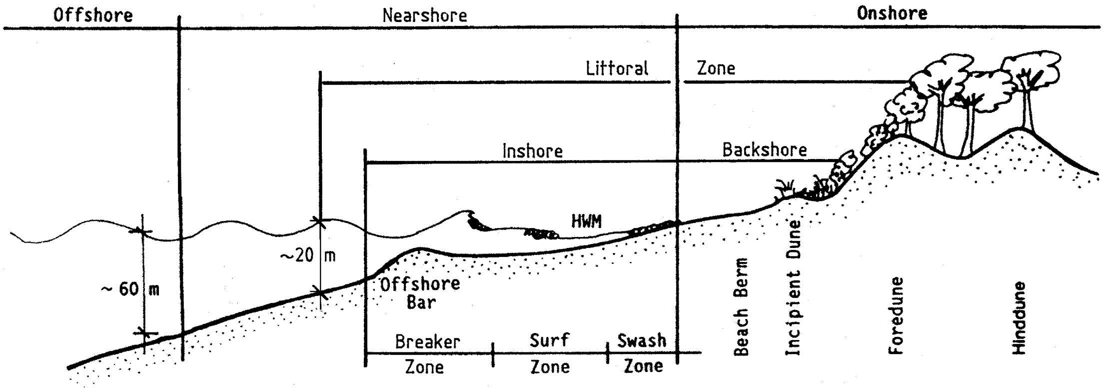


Figure 3 – Beach definition sketch (open coast beaches) – NSW Government (1990)

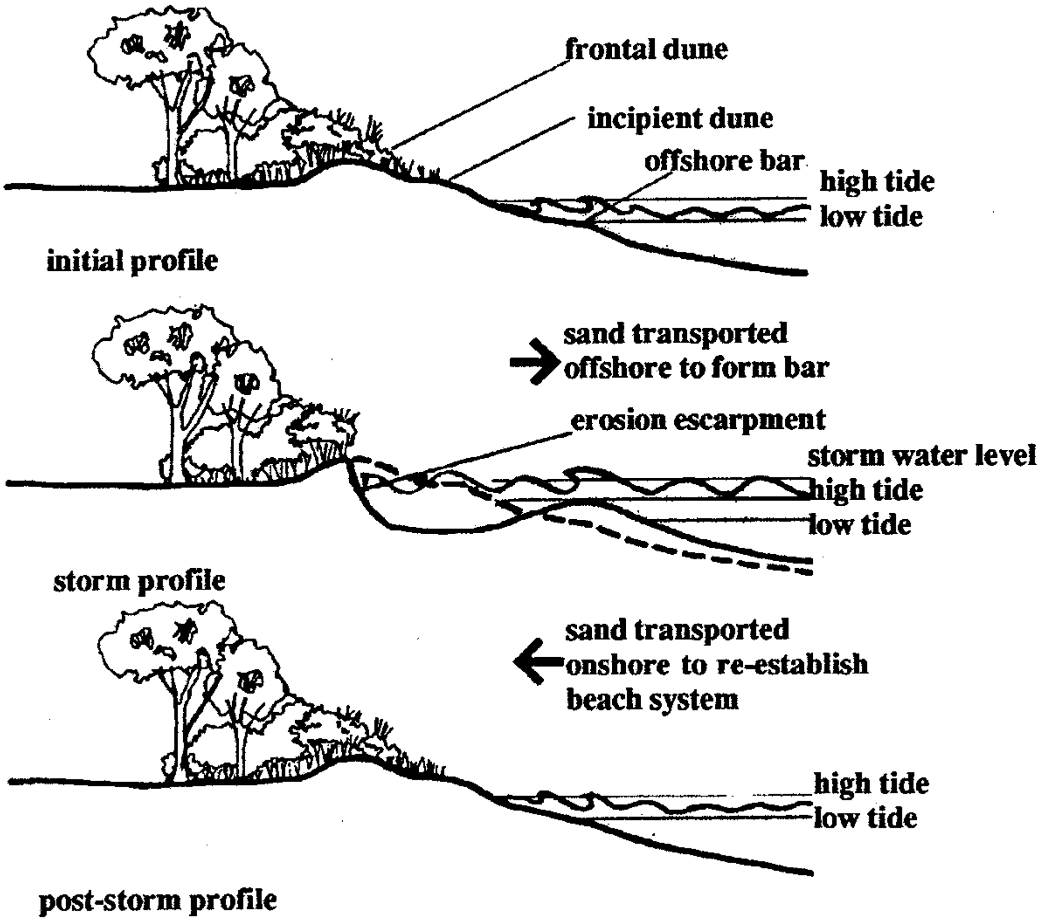


Figure 4 – Beach storm erosion/accretion cycle (NSW Government, 1990)

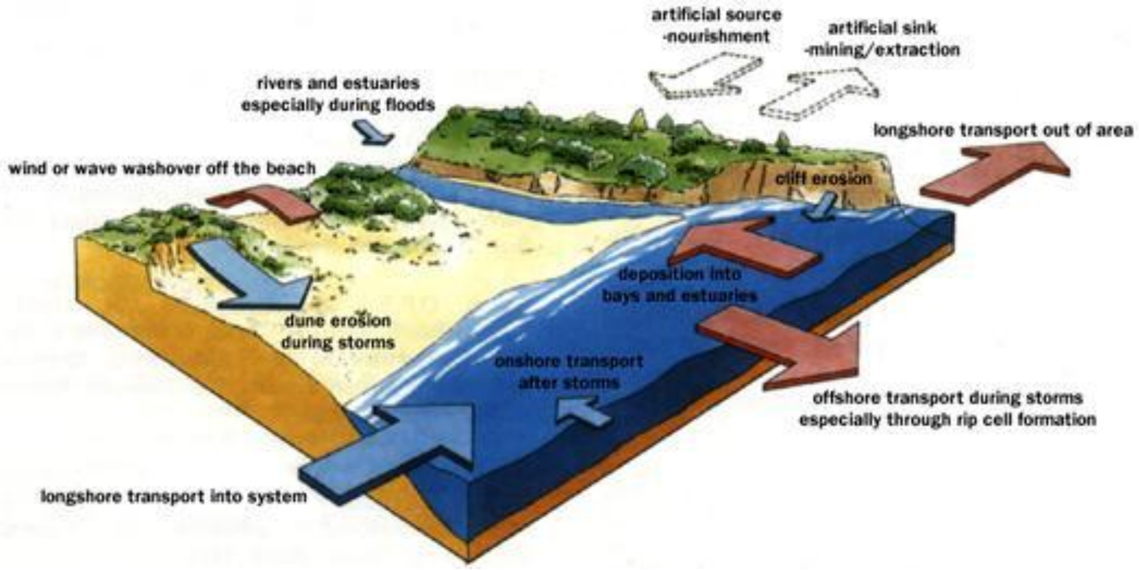


Figure 5 – Sediment budget schema (NSW Government, 1990)

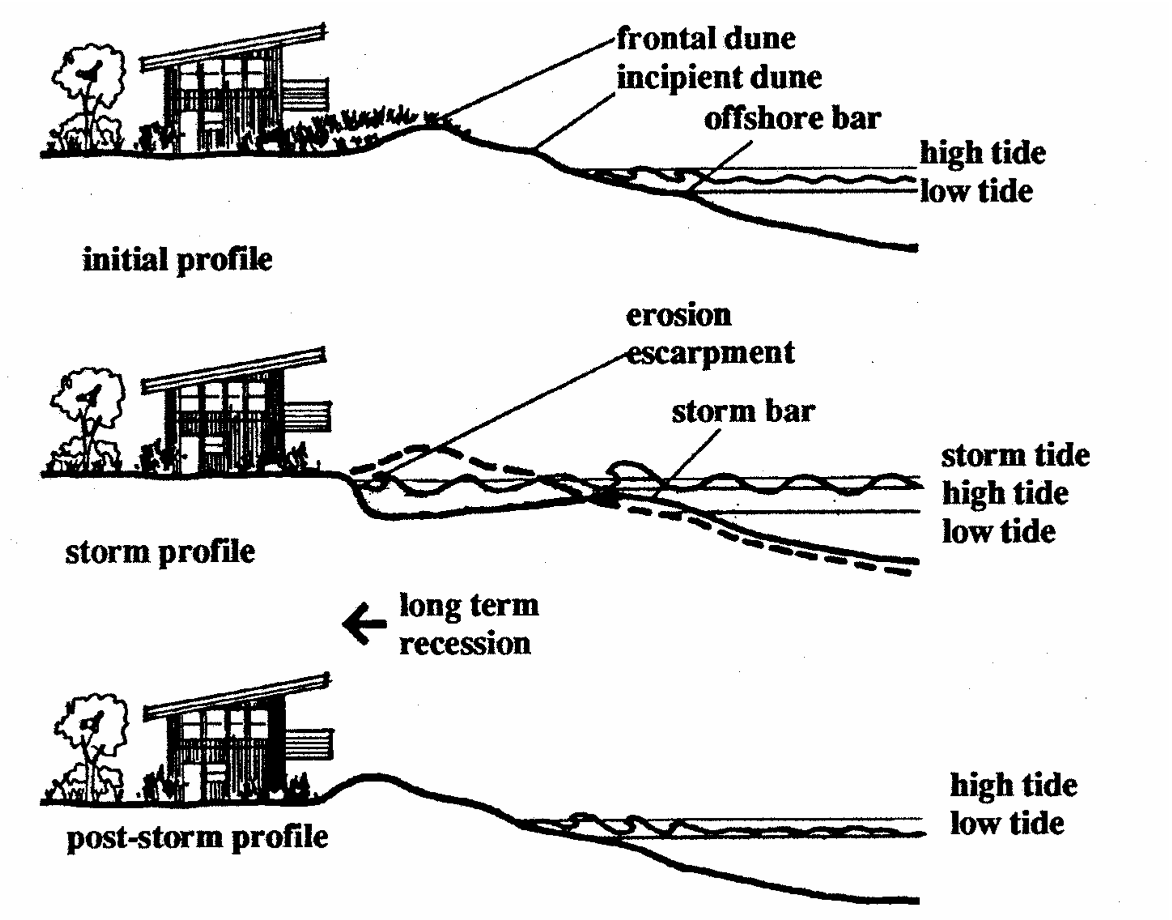
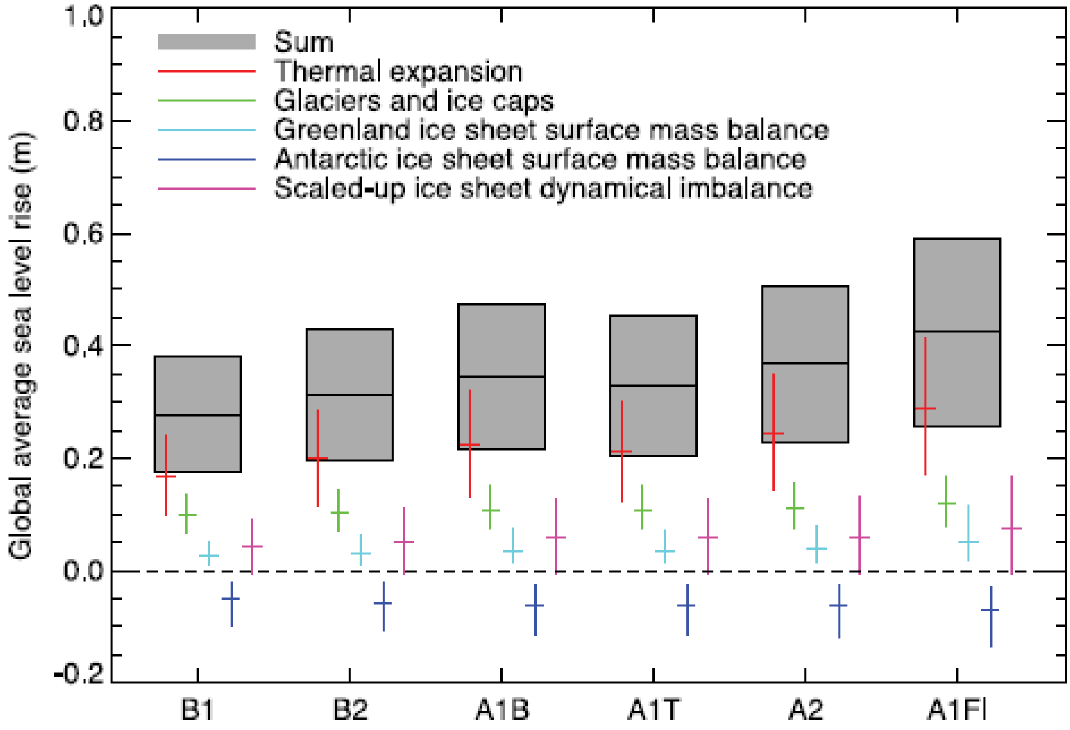


Figure 6 – Long term erosion schema (NSW Government, 1990)



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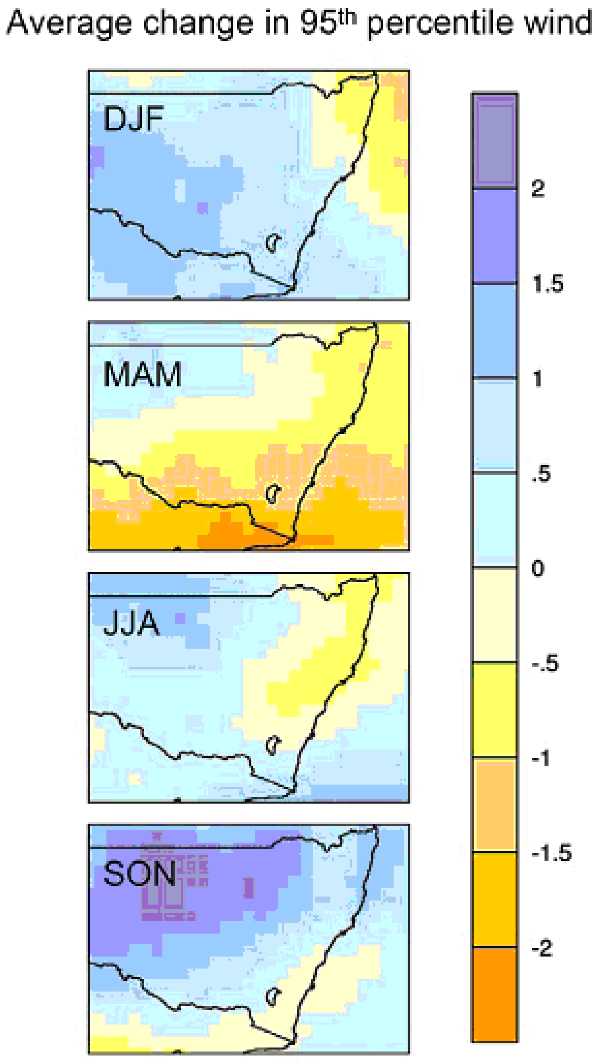
Average change in 95th percentile winds

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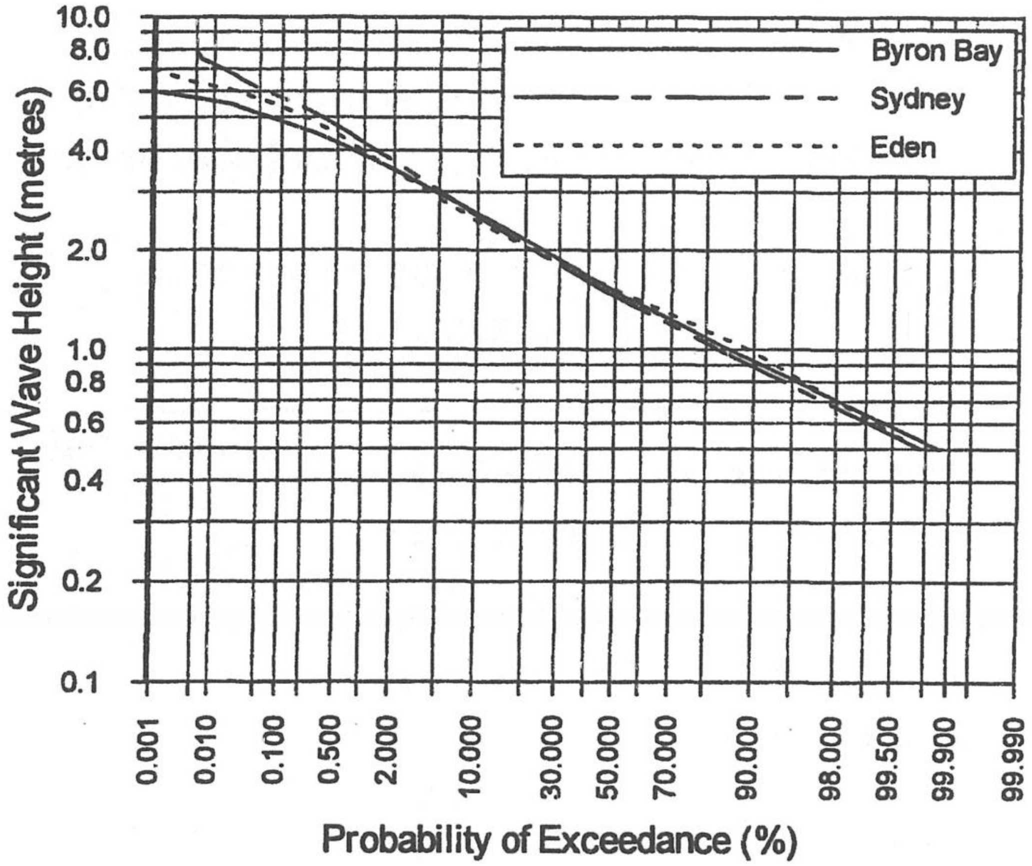

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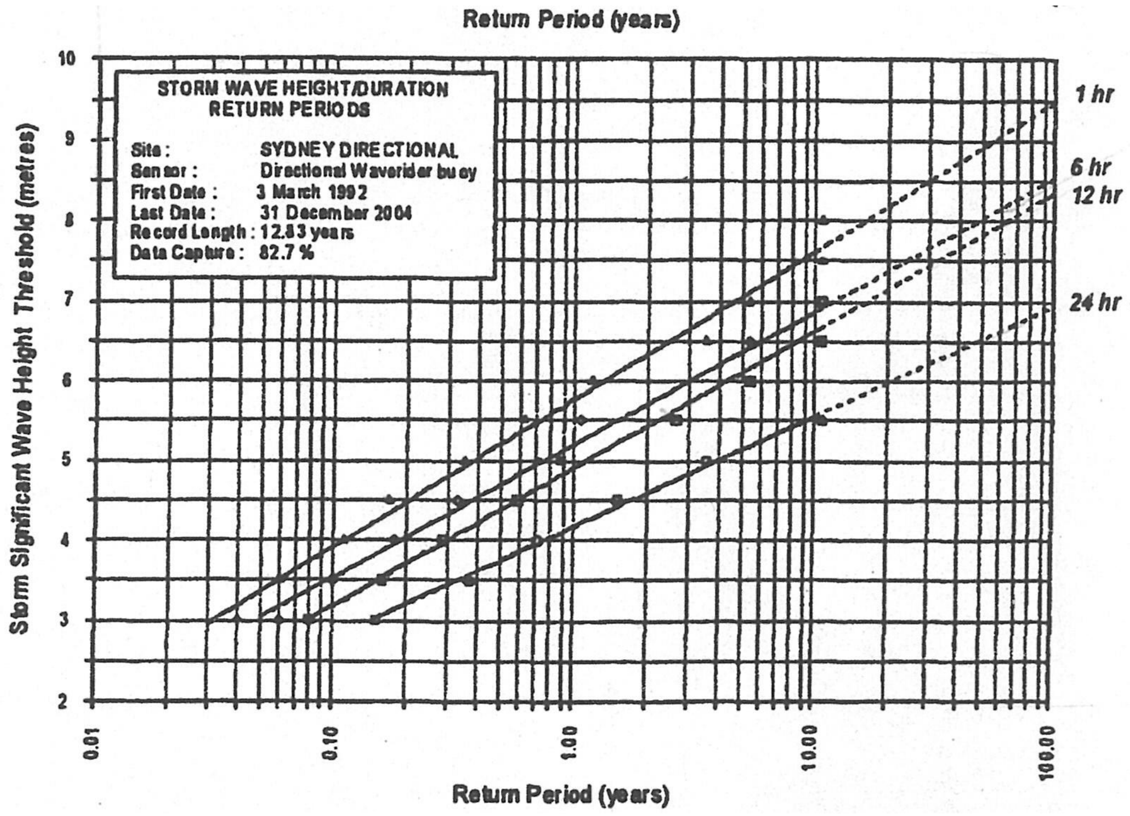

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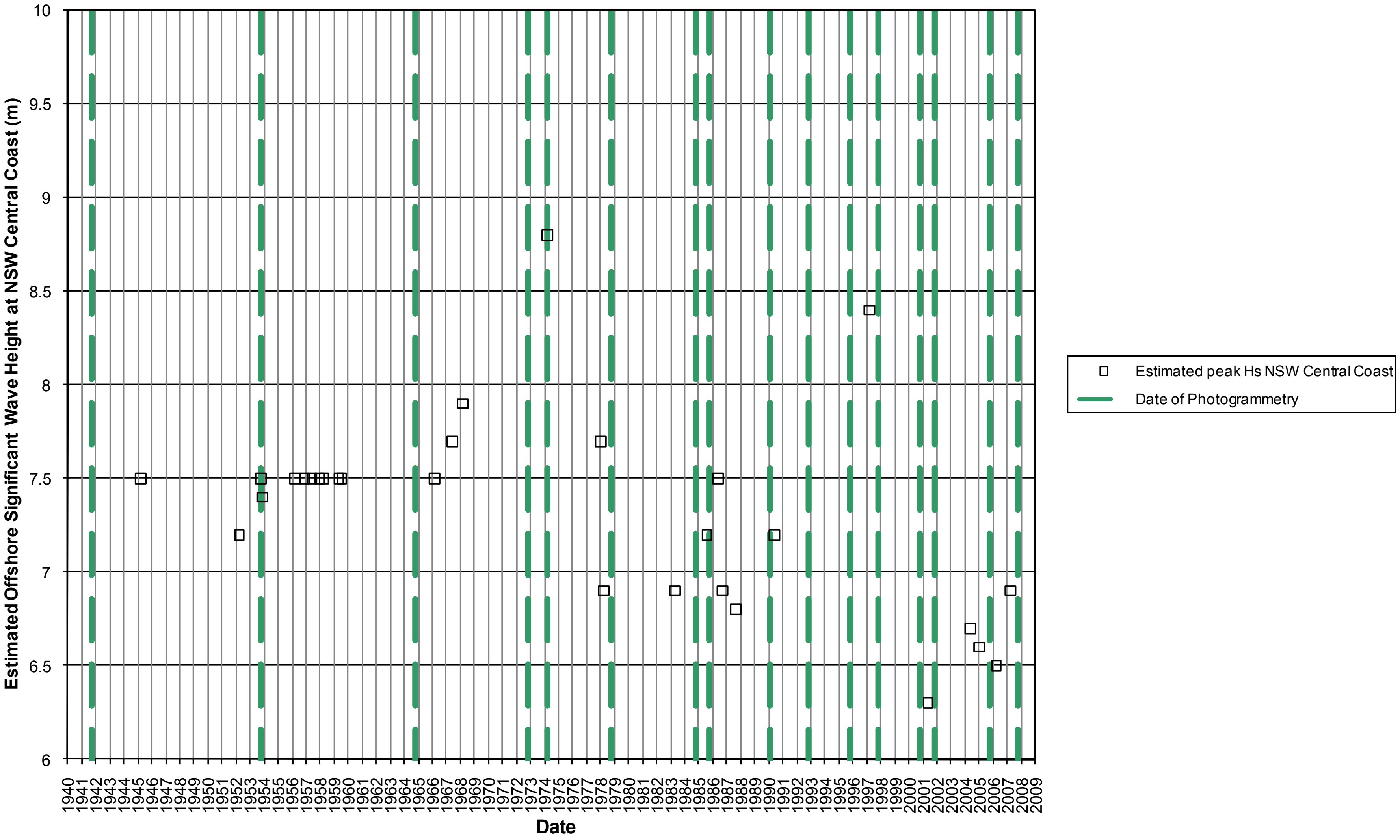
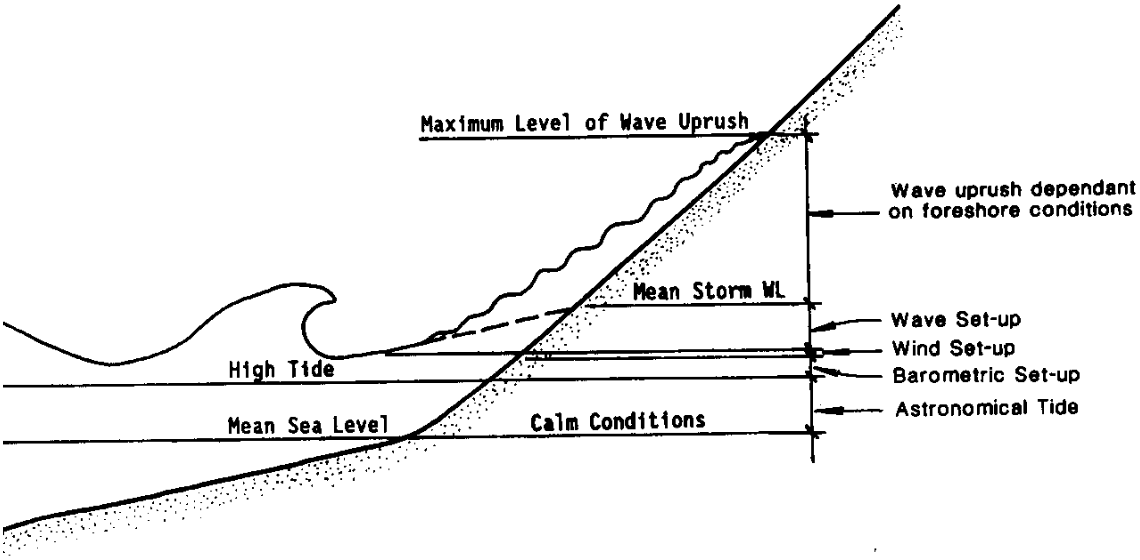


Figure 11 – Extreme Storm events vs. Photogrammetry Dates



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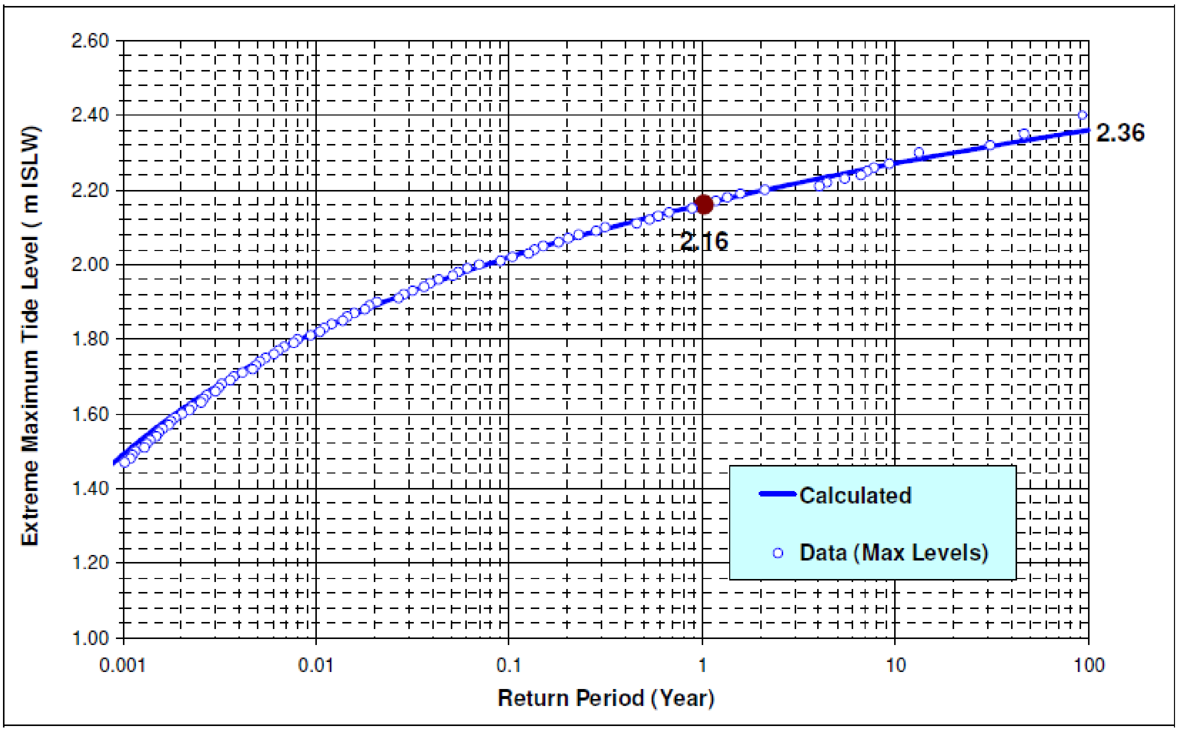

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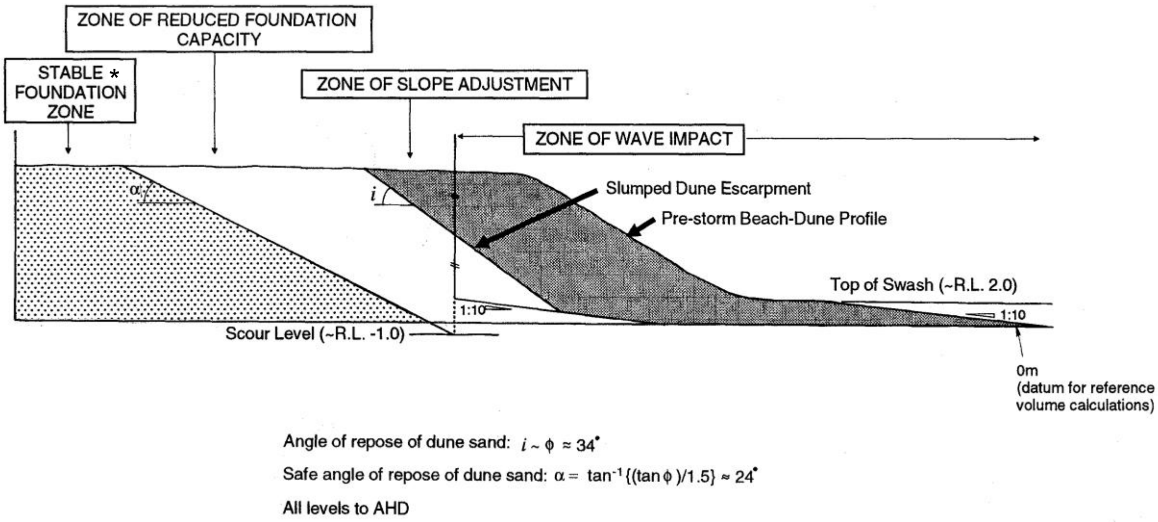


Figure 14 – Dune stability schema (after Nielsen et al., 1992)

**Note – The term "Stable Foundation Zone" refers to a Dune Stable Foundation Zone which does not take into account any land stability, or other geotechnical hazards that may exist in the same area. The identified geotechnical hazards are described in a separate report by SCE (2010).*

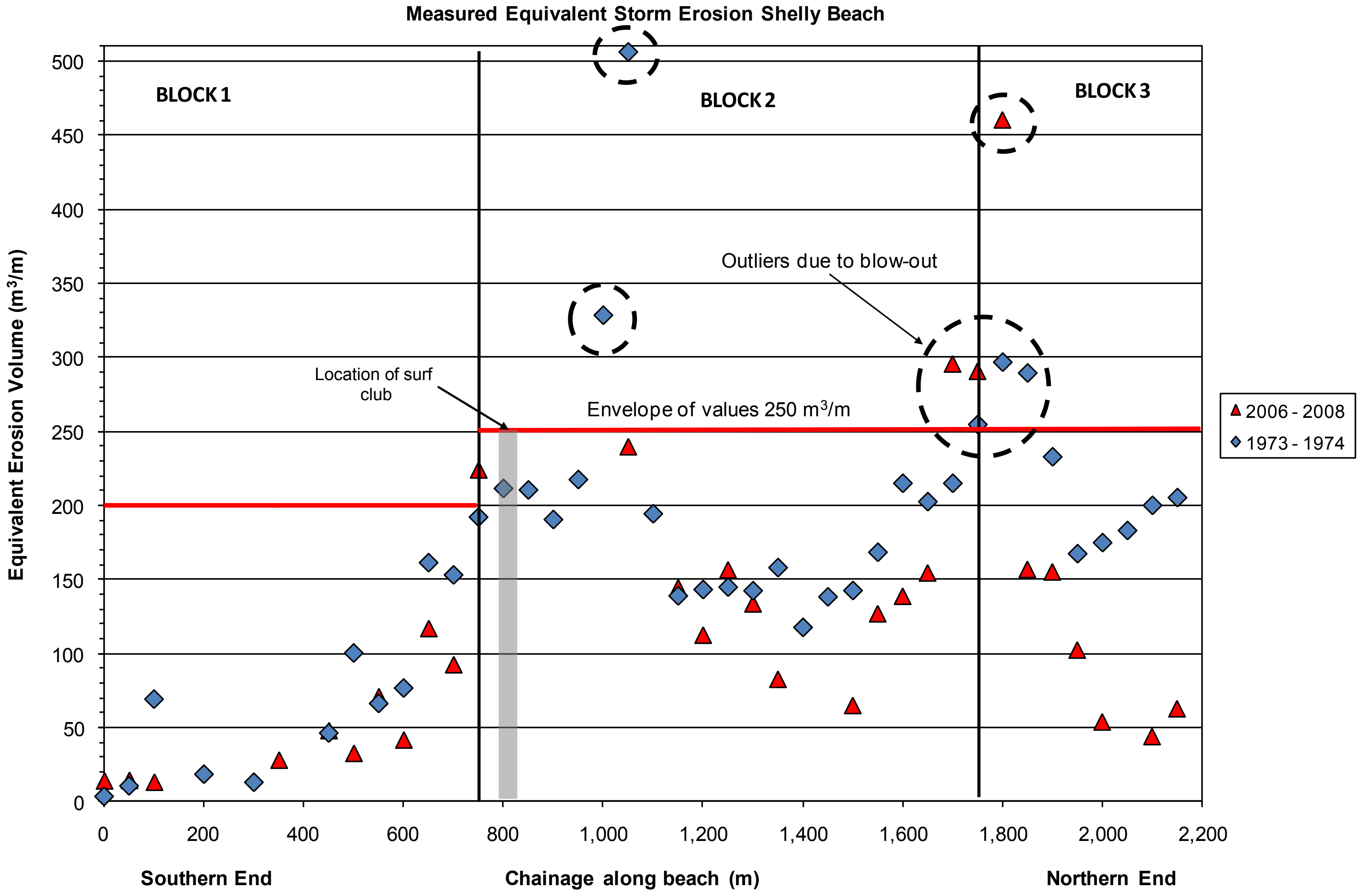
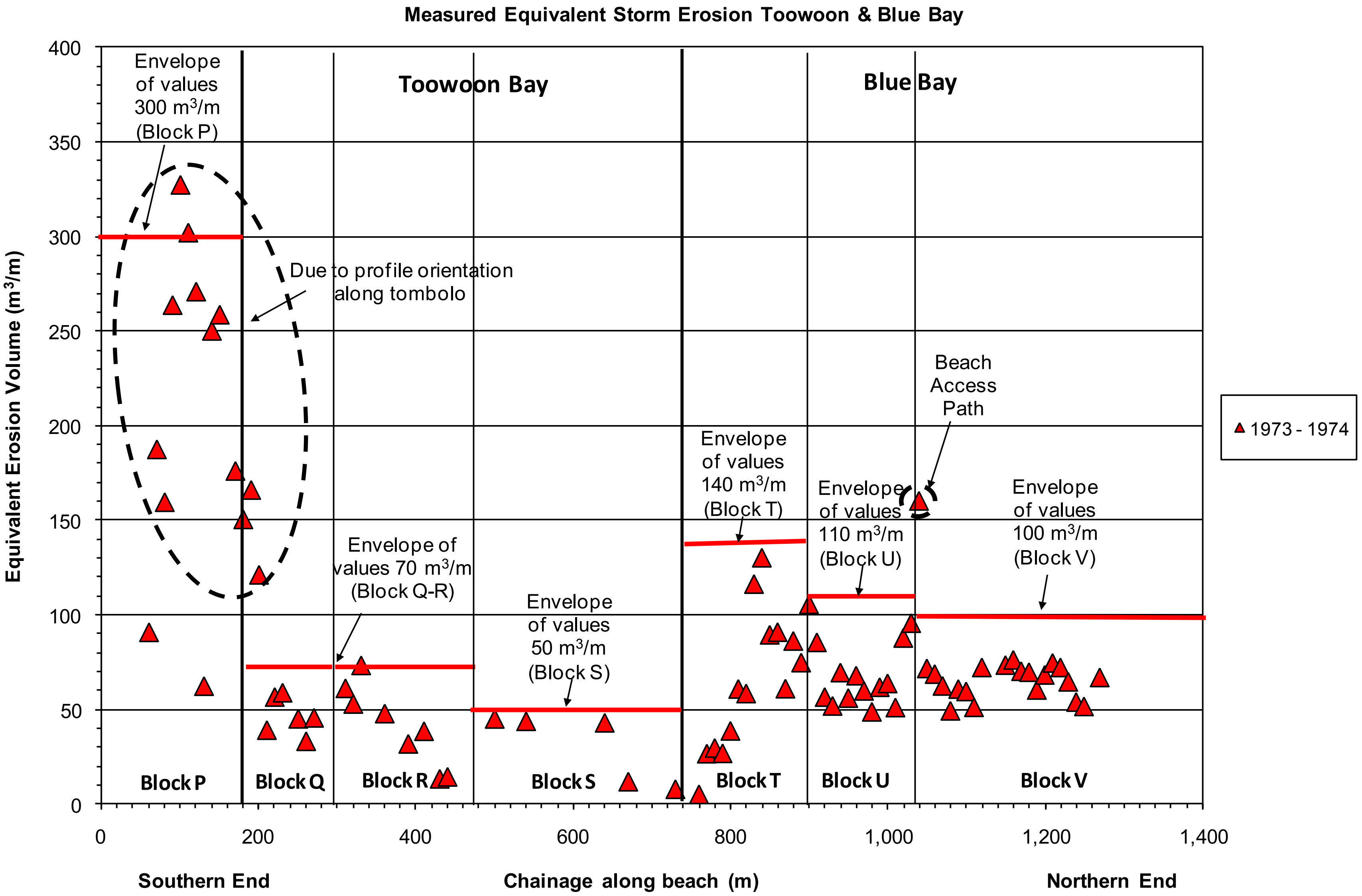


Figure 15 – Upper envelope for storm bite, Shelly Beach



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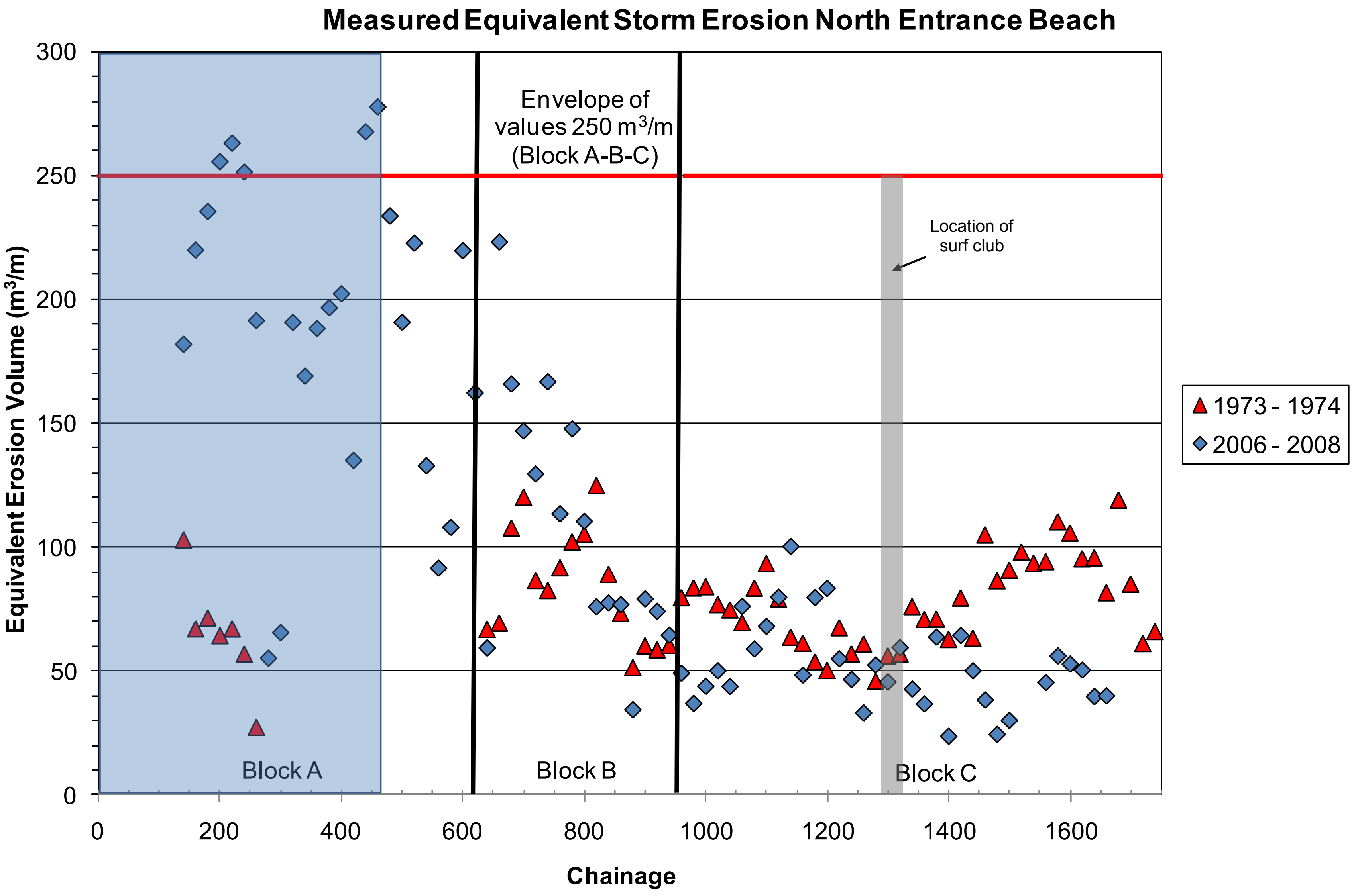

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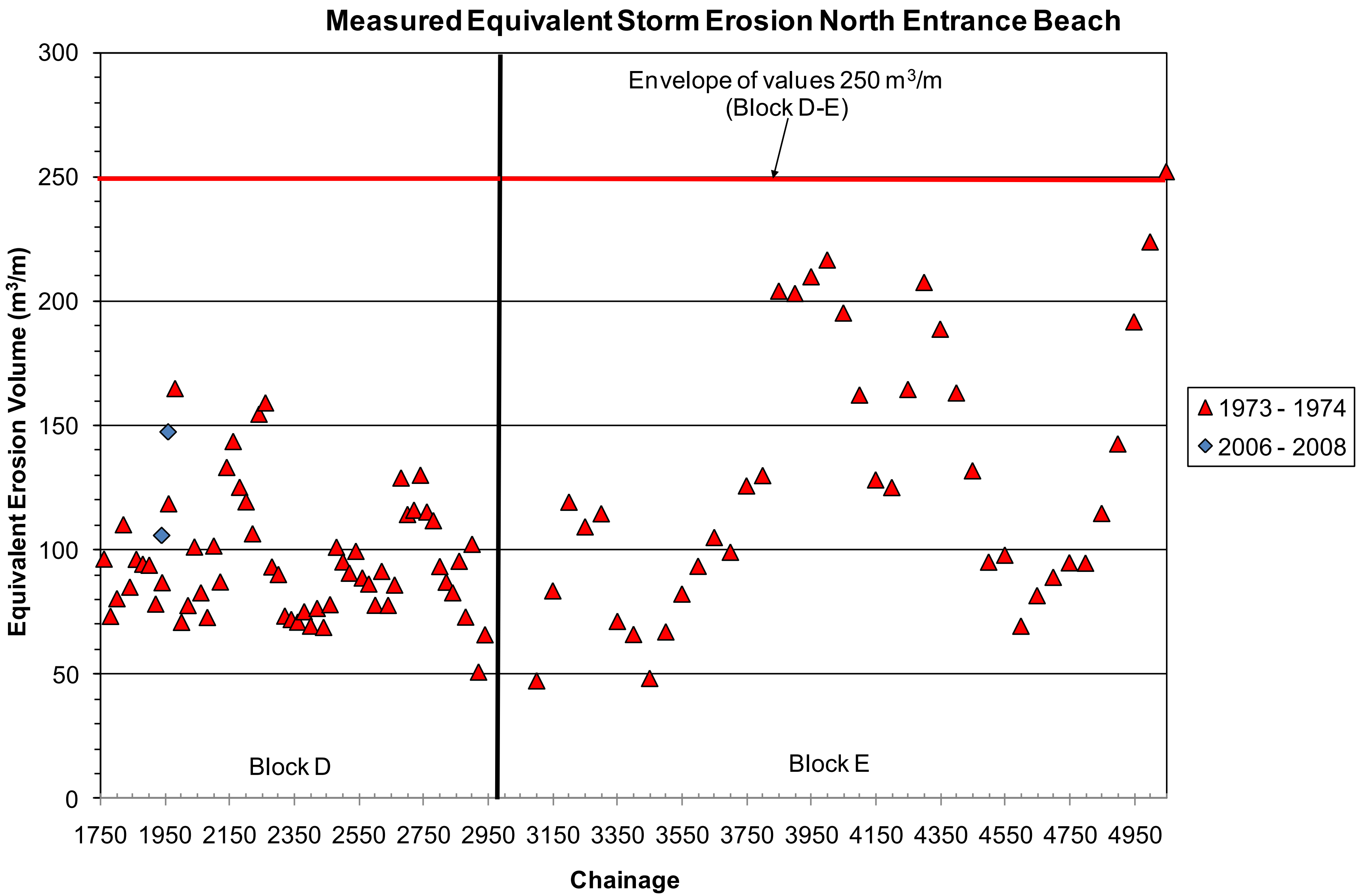


Figure 18 – Upper envelope for storm bite, North Entrance (Block D-E)

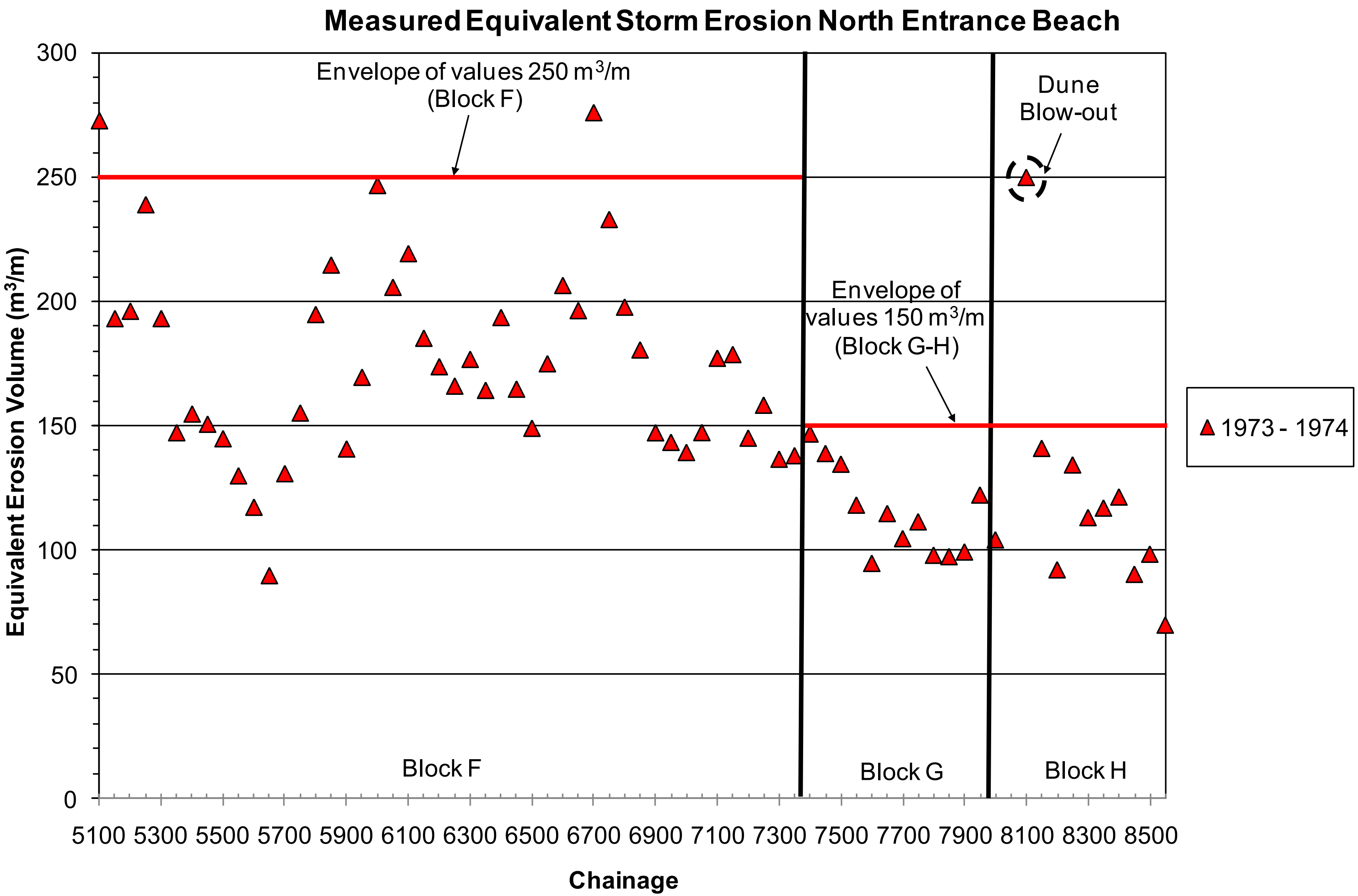


Figure 19 – Upper envelope for storm bite, North Entrance (Block F-H)

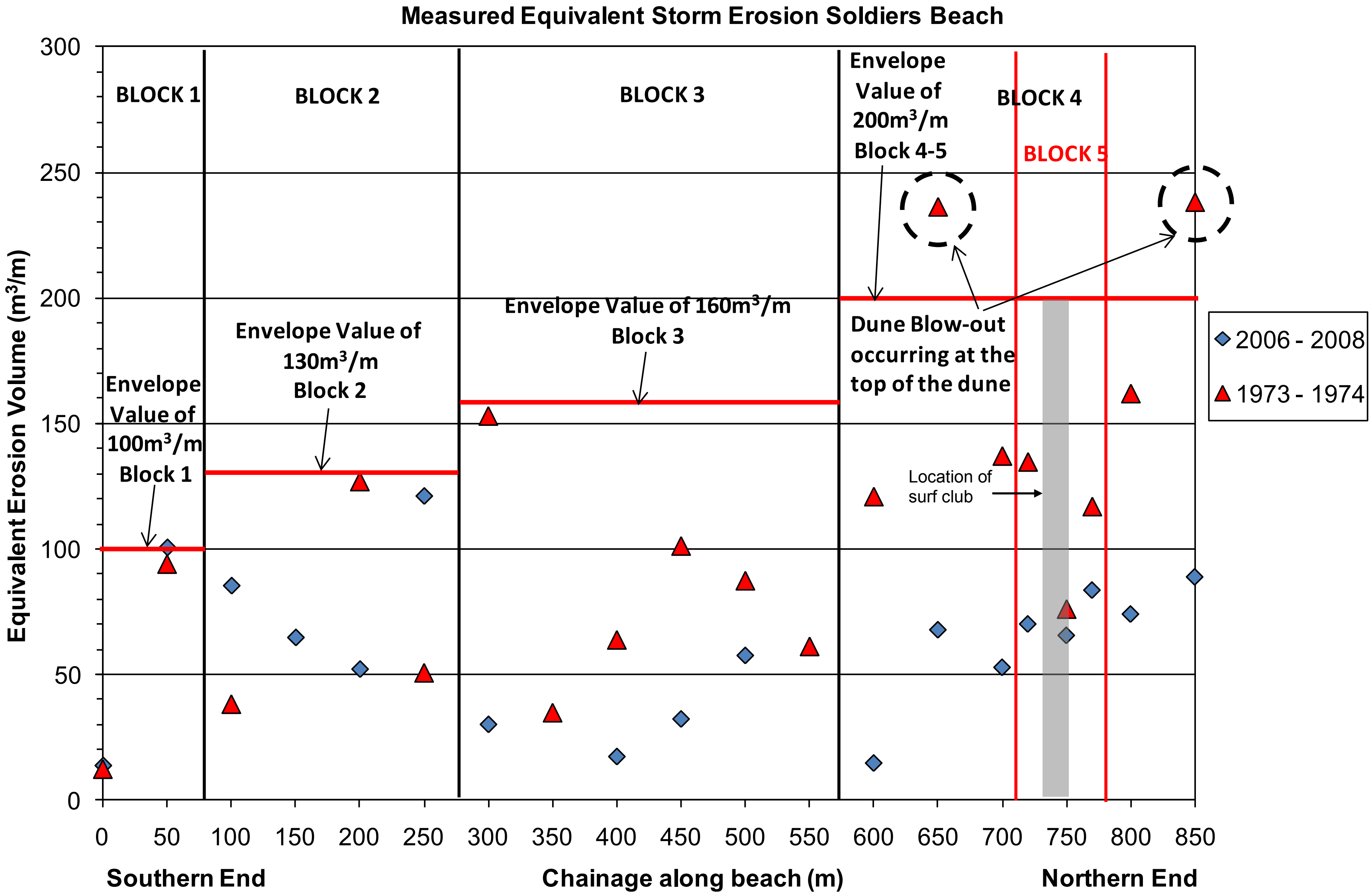


Figure 20 – Upper envelope for storm bite, Soldiers Beach

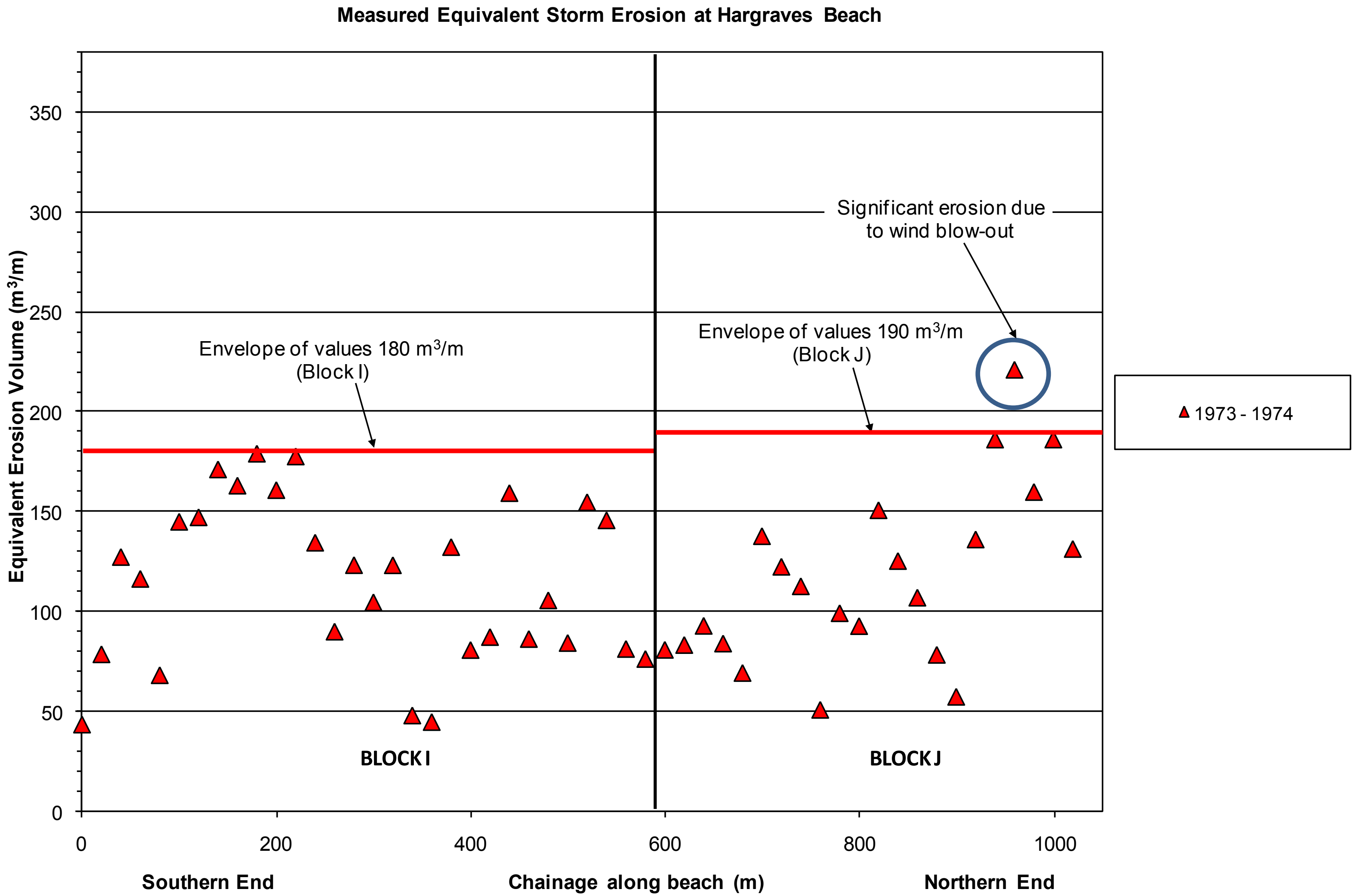


Figure 21 – Upper envelope for storm bite, Hargraves Beach

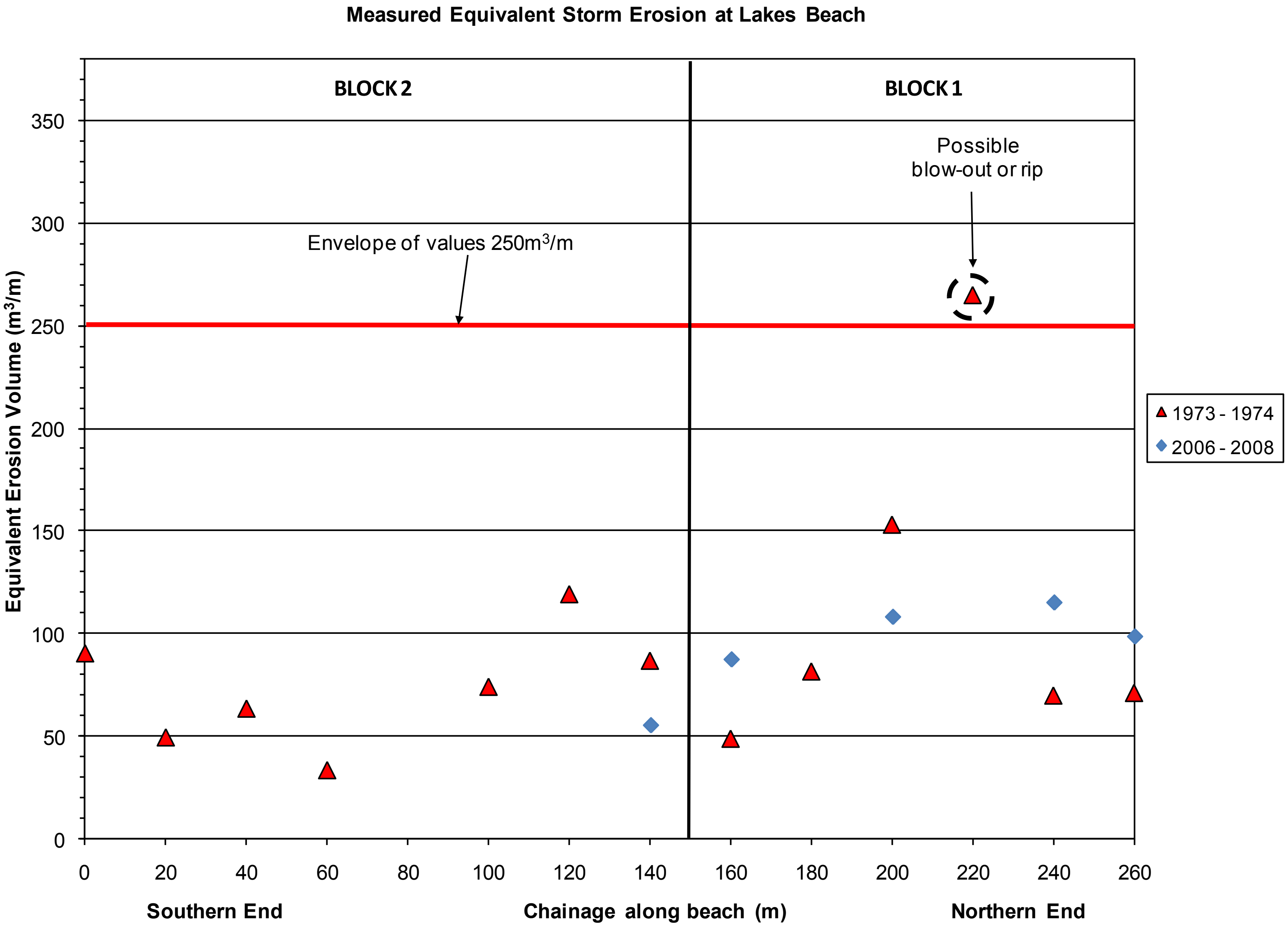
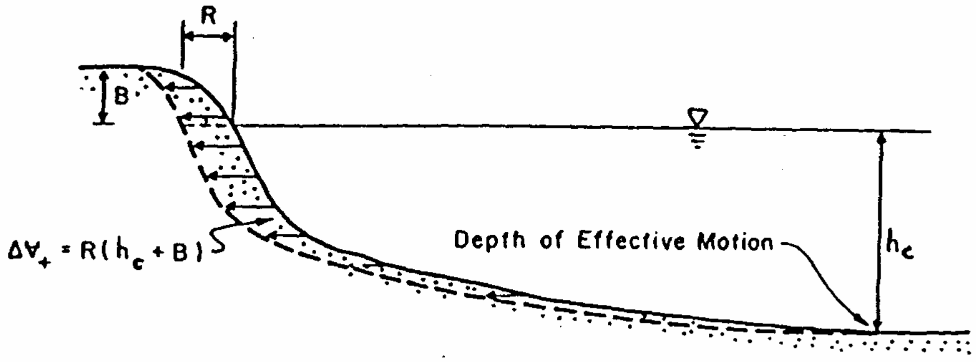
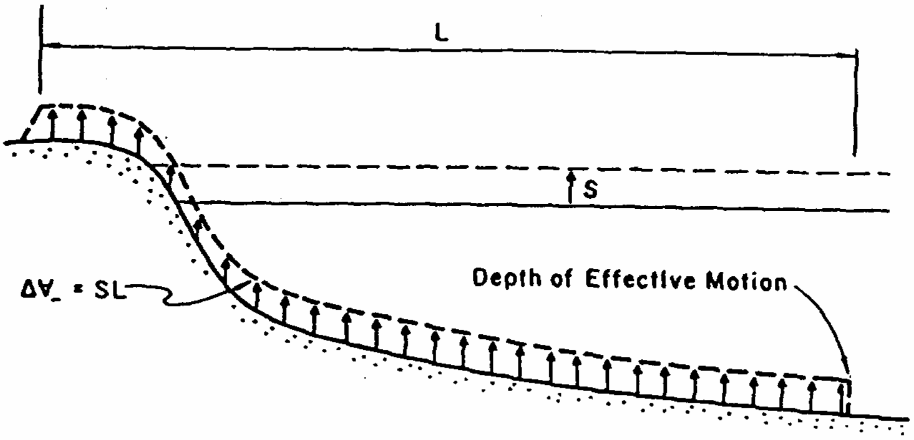


Figure 22 – Upper envelope for storm bite, Lakes Beach



(a) Volume of Sand "Generated" by Horizontal Retreat, R, of Equilibrium Profile Over Vertical Distance (h_c + B)



(b) Volume of Sand Required to Maintain An Equilibrium Profile of Active Width, L, Due to a Rise, S, in Mean Water Level.

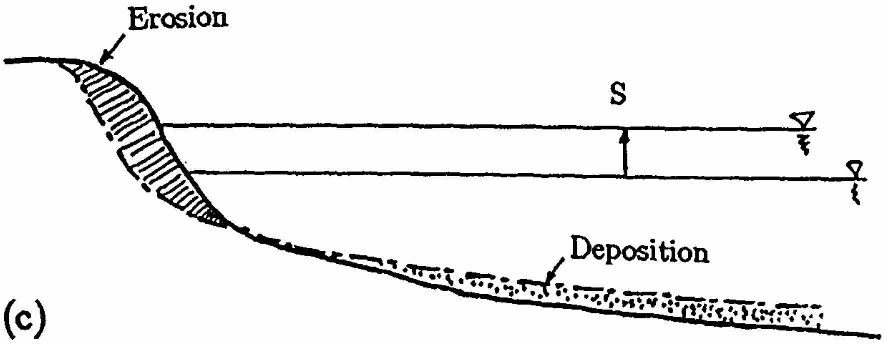


Figure 23 – Concept of shoreline recession due to sea level rise

Project Name:	Wyong Coastal Hazard Study – Final Draft
Project Number:	3001053
Report for:	Umwelt Australia

PREPARATION, REVIEW AND AUTHORISATION

Revision #	Date	Prepared by	Reviewed by	Approved for Issue by
1	26/02/10	M. Glatz	C. Adamantidis	C. Adamantidis
2	28/05/10	C. Adamantidis and M. Glatz	C. Adamantidis	C. Adamantidis
3	1/10/10	C. Adamantidis and M. Glatz	C. Adamantidis	C. Adamantidis

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Appendix A

Storm Information

For: Umwelt Australia

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1 INTRODUCTION

Coastal processes along the Wyong Shire coastline are impacted greatly by intense tropical and non-tropical storms which occur along the NSW coastline at irregular intervals. These storms are responsible for episodic events of sand transport and erosion which are evident when examining data such as photogrammetry in detail.

It is important to document the history of storms along the Wyong Shire coastline in order to ascertain whether the observed beach changes can be related to the specific occurrence of these storms. The ultimate goal is to delineate which observed changes are caused by episodic events such as large coastal storms and which changes have underlying causes which are due to long-term cycles, natural fluctuations or are caused by anthropogenic influences.

The drop in atmospheric pressure and the winds and waves which often accompany large coastal storms can cause the ocean to rise above its normal level and if this occurs concurrently with high astronomical tides, flooding of low-lying coastal land and beach erosion can result (Blain Bremner & Williams, 1985).

2 STORM CATEGORIES

Storms which affect the NSW coast can fall under one of several categories – namely:

- Tropical Cyclones
- Easterly Trough Lows
- Inland Trough Lows
- Continental Lows
- Secondary Lows; and
- Anticyclonic Intensifications.

The more severe storms affecting the coast between Jervis Bay and Sugarloaf Point (north of Port Stephens) are often the result of secondary developments of large depressions in the southern Tasman Sea, or coastal intensifications of inland lows which have moved east and crossed the coast. (Blain Bremner & Williams, 1985).

Blain Bremner and Williams (1985) documented all storms along the NSW coast between 1880 and 1980, with estimates of *significant* wave height made by examining synoptic charts from these dates, as well as historical shipping and press reports. Storms were assigned a severity rating based on a gradation of the *significant* wave heights. The storms were compartmentalised in terms of their severity and their location along the coast, whether they affected the far north coast, mid north coast, central coast or south coast. The beaches of Wyong Shire are considered to be affected by storms impacting on the central coast sector of NSW.

The categories of storms are illustrated in Table A.1.

Table A.1 – Classification of Storms by Intensity (Blain Bremner and Williams, 1985)

Category	Significant Wave Height (m)	Severity
X	> 6.0 m	Extreme
A	5.0 m – 6.0 m	Severe
B	3.5 m – 5.0 m	Moderate
C	2.5 m – 3.5 m	Low

Further work was carried out by Lawson and Treloar (1986) expanding on the work of Blain Bremner and Williams to identify storms occurring between 1980 and 1985, using a combination of synoptic charts and waverider buoy data.

Category X storms since 1985 were identified by examining Sydney Waverider buoy records from Public Works Department annual wave climate summaries from 1992 – 1995, and Public Works Department reports on NSW coastal storms for 1997. Estimated wave height data, covering the period between 1937 and 2008 for extreme Category X storms (*significant* wave heights greater than 6.0m) is presented in Table A.2. This enabled Category X storms to be identified for the period of the photogrammetry (from 1941 – 2008). It should be noted that exact wave heights were not available for many storms prior to 1966.

Category A, B and C storms (*i.e. significant* offshore wave heights less than 6.0m) were not included in the analysis.

Figure A.1 documents the extreme storm events and estimated *significant* wave heights for these events, and also plots the dates for which beach photogrammetry was available for analysis.

Table A.2 – Extreme Storm Events (Hs) at Wyong Shire, 1937 – 1998

Date	Estimated H_s
21/06/1937	8
11/06/1945	>6
14/06/1952	7.2
03/01/1954	>6
20/02/1954	7.4
09/06/1956	>6
20/02/1957	>6
23/08/1957	>6
10/03/1958	>6
30/06/1958	>6
20/07/1959	>6
04/10/1959	>6
20/05/1966	>6
05/09/1967	7.7

Date	Estimated H_s
14/05/1968	7.9
25/05/1974	8.8
19/03/1978	7.7
31/05/1978	6.9
09/07/1983	6.9
25/10/1985	7.2
06/08/1986	7.5
20/11/1986	6.9
11/11/1987	6.8
03/08/1990	7.2
10/05/1997	8.2
27/07/2001	6.3
19/07/2004	6.7
23/03/2005	6.6
03/06/2006	6.5
08/06/2007	6.9

From Table A.2 and Figure A.1, it can be seen that the extreme storm event of 25–26 May 1974 had the highest estimated *significant* wave height of 8.8 m. This storm also coincided with spring high tides, and included a tidal anomaly at Sydney of 0.59 m. The storm caused widespread damage along the NSW coast and was considered to be the worst storm to have occurred since records began.

Appendix B describes the impact of the May 1974 storm as evidenced by the photogrammetric data.

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Blain Bremner & Williams Pty Ltd (1985), “Elevated Ocean Levels – Storms affecting NSW Coast 1880 – 1980”, Blain Bremner & Williams Report No. 85041, NSW Public Works Department, Coastal Branch.

Bureau of Meteorology, Significant Weather - May 1997, http://www.bom.gov.au/inside/services_policy/public/sigwxsum/sigw0597.shtml

Department of Commerce Manly Hydraulics Laboratory (2008), Crowdy Head Waverider Storm History data 1985 – 2007, owned by Department of Environment and Climate Change.

Lawson and Treloar Pty Ltd (1986), “Elevated Ocean Levels – Storms affecting NSW Coast 1980 – 1985”, NSW Public Works Department, Coastal Branch Report No. 86026.

NSW Government (1990), “Coastline Management Manual”, September 1990.

FIGURES

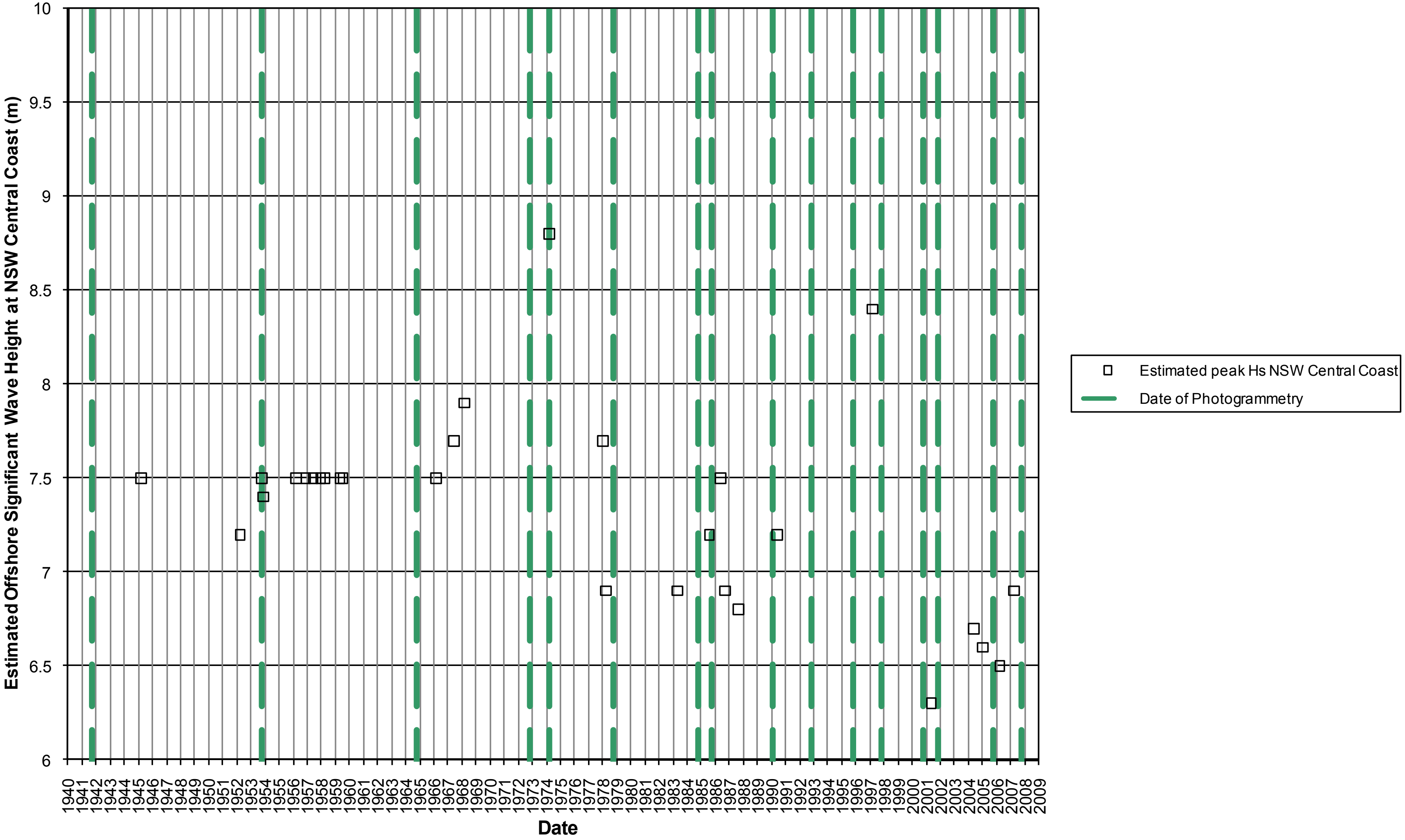

Figure A.1 – Extreme Storm events vs. Photogrammetry Dates

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PREPARATION, REVIEW AND AUTHORISATION

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Appendix B

Photogrammetric Analysis

For: Umwelt Australia

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1 INTRODUCTION

Photogrammetry is a technique for mapping ground terrain from vertical aerial photography. It allows the surface elevation of the *subaerial* beach (the portion of the beach above the water line) to be measured along transect lines on the beach. The technique has been used for many years to produce topographic maps and is a useful tool for analysing changes to subaerial beach profiles over time, particularly as historical aerial photography often spans many decades. The technique cannot be used, however, to analyse changes to the beach profile below the water line and is thus limited to analysing only part of the total littoral system.

Photogrammetric surveys along the lengths of the various beaches in the Wyong Shire were undertaken by the Department of Infrastructure, Planning and Natural Resources (DIPNR) using various aerial photographs dating from 1941 - 2002. The beaches for which relevant photogrammetric survey data were obtained for this Study include:

- Blue Lagoon;
- Shelly Beach;
- Toowoon Bay;
- Blue Bay;
- The Entrance North / Tuggerah Beach;
- Soldiers Beach;
- Hargraves Beach; and
- Lakes Beach.

This Appendix describes the photogrammetric data for each beach, as well as documenting the techniques used to quantify subaerial beach changes using the digital data files.

Figure B.1 illustrates the dates of photogrammetry analysed along with the occurrence of major storm events offshore of the Wyong Shire coast.

1.1 Blue Lagoon And Shelly Beach

Photogrammetry for Blue Lagoon and Shelly Beach were obtained for the following years of aerial photography:

- 1941
- 1954
- 1973
- 1974
- 1985
- 1990
- 2001
- 2006
- 2008

For the photogrammetric surveys, Shelly Beach was divided into three blocks, delineating the beach from south to north. Figure B.2 illustrates the block divisions along the beach. The southernmost section of the beach, which covers the area fronting the Blue Lagoon

Caravan Park, is within the Block 1 division, with the area fronting the Surf Club within the Block 2 division. Digital files containing the geographic locations and elevations of transects in each of these blocks for each year of photogrammetry have been obtained and analysed for this study.

Figure B.3 is a typical view of the beach state at Block 1, at the Blue Lagoon Caravan Park, looking south. An extensive rock platform can be seen offshore at approximately mid tide level. Figure B.4 shows a view of the beach state looking northwards over Block 2, towards the Surf Club area. Structures of interest in this area are the surf club building, car park, watchtower and toilet block.

1.2 Toowoon Bay And Blue Bay

Photogrammetry for Toowoon Bay and Blue Bay were obtained for the following years of aerial photography:

- 1941
- 1973
- 1974
- 1990
- 1993
- 1996
- 1998
- 2001
- 2006
- 2008

For the photogrammetric surveys, Toowoon Bay and Blue Bay were divided into seven blocks, delineating the beaches from south to north. Figure B.5 illustrates the block divisions along Toowoon Bay and Blue Bay. The southernmost block, Block P, covers the area south of the tombolo and the area fronting the Surf Club site. Block R covers the area fronting the Kim's Beach Hideaway property. Blocks T, U and V cover Blue Bay, including the Werrina Parade area. Digital files containing the geographic locations and elevations of transects in each of these blocks for each year of photogrammetry have been obtained and analysed for this study.

Figure B.6 is a typical view of the beach state at Block P, looking over the surf club site (where construction was taking place at the time of the photograph, September 2004). The extent of rocky reef offshore can be clearly seen in the photograph. Figure B.7 is a view looking south along Block R, with the Kim's Beach Hideaway cabins on the right of the photograph. The dune crest in front of the cabins is at approximately 5.0m AHD. Figure B.8 shows a view of urban development at Toowoon Bay at Block S. Note that much of this development is built upon a steep, rocky bluff area.

Figure B.9 is a view of Blue Bay at Block T. Note the existence of rocky reef offshore and the lack of natural dune fronting the urban development. Figure B.10 is a view of Blue Bay looking northward. It can be seen that the houses are fronted by a steep escarpment and that fill, including rocks, has been placed randomly along the escarpment to protect some of the properties from erosion.

1.3 The Entrance North

Photogrammetry for North Entrance Beach was obtained for the following years of aerial photography:

- 1941
- 1954
- 1973
- 1974
- 1979
- 1986
- 1993
- 2001
- 2006
- 2008

For the photogrammetric surveys, North Entrance Beach was divided into eight blocks, delineating the beach from south to north. Figure B.11 illustrates the block divisions along the southern part of the beach, and Figure B.12 illustrates the block divisions along the northern part of the beach. Block A covers the sand spit at the entrance to Tuggerah Lake; Block B covers the area of development near Hutton Road; Block C covers the stretch of beach surrounding the surf club; Block D covers the area where urban development has occurred, north of the surf club (including the Curtis Parade area); and Block E covers the area of the future Magenta Shores development. Blocks F, G and H cover the stretch of beach to the north, which does not have urban development but which was subject to sand mining in the 1960's and 1970's. Digital files containing the geographic locations and elevations of transects in each of these blocks for each year of photogrammetry have been obtained and blocks A to E have been analysed for this study.

Figure B.13 is a view looking south along Tuggerah Beach, at Block B, where urban development is in close proximity to the beach. Figure B.14 is a view of the surf club, looking south. There is considerable dune width in front of the surf club at the time of the photograph (September 2004). Figure B.15 is a view looking northward along Tuggerah Beach from the surf club at Block C. It can be seen that beach nourishment was being undertaken at the time of the photograph, with sand being moved northward along the beach from the Tuggerah Lake entrance. The entire length of beach can be seen in this photograph, and the expansive dune fields at the northern end of the beach are evident. Figure B.16 is a view of the urban development at Curtis Parade, Block D. The proximity of the urban development to the active beach zone and the lack of a vegetated dune fronting the properties are of interest to this Study.

1.4 Soldiers Beach

Photogrammetry for Soldiers Beach Surf Club was obtained for the following years of aerial photography:

- 1941
- 1965
- 1973
- 1974
- 1986

- 1993
- 1996
- 2001
- 2006
- 2008

For the photogrammetric surveys, Soldiers Beach was divided into five blocks, delineating the beach from south to north. Figure B.17 illustrates the block divisions along the beach. The area fronting the Surf Club is within the Block 4 and 5 divisions. Digital files containing the geographic locations and elevations of transects in each of these blocks for each year of photogrammetry have been obtained and the profiles in Block 4 and 5 have been analysed for this study.

Figure B.18 is a typical view of Soldiers Beach looking south towards the Surf Club area.

1.5 Hargraves Beach

Photogrammetry for Hargraves Beach was obtained for the following years of aerial photography:

- 1954
- 1965
- 1973
- 1974
- 1979
- 1986
- 1993
- 1996
- 2001
- 2006
- 2008

For the photogrammetric surveys, Hargraves Beach was divided into two blocks, delineating the beach from south to north. Figure B.19 illustrates the block divisions along the beach. The beach is fronted by urban development along most of its length. Digital files containing the geographic locations and elevations of transects in each of these blocks for each year of photogrammetry have been obtained and analysed for this study.

Figure B.20 is a typical view of the beach looking south at Block I, and Figure B.21 shows a view of the beach looking northwards over Block J. At the time these photographs were taken (September 2004), an incipient dune had formed along the beach in front of the urban development.

1.6 Lakes Beach

Photogrammetry for Lakes Beach was obtained for the following years of aerial photography:

- 1965

- 1973
- 1974
- 1985
- 1993
- 2001
- 2006
- 2008

For the photogrammetric surveys, the area fronting Lakes Beach Surf Club was described by six profiles within a single block. Figure B.22 illustrates the block divisions along the beach. Digital files containing the geographic locations and elevations of each of these transects for each year of photogrammetry have been obtained and analysed for this study.

Figure B.23 is a typical view of the beach at Lakes Beach Surf Club, looking south.

2 SHORT TERM FLUCTUATIONS

2.1 Storm Erosion

The amount of sand eroded from the beach during a severe storm will depend on many factors including the state of the beach when the storm begins, the storm intensity (wave height, period and duration), direction of wave approach, the tide levels during the storm and the occurrence of rips. Storm cut is the volume of beach sand that can be eroded from the subaerial (visible) part of the beach and dunes during a *design* storm. Usually, it has been defined as the volume of eroded sand as measured above mean sea level (~ 0 m AHD datum). For a particular beach, the storm cut (or storm erosion demand) may be quantified empirically with data obtained from photogrammetric surveys, or it may be quantified analytically using a verified numerical model.

For Wyong Shire coastline, details of the empirical analysis are given below.

2.2 Quantifying Storm Erosion Demand From Historical Storms

Photogrammetric data were available for 1973 and 1974 for the different beaches along Wyong Shire Council coastline, which allows a good estimation of the storm bite of the May-June 1974 storm events. Photogrammetric data were also available for 2006 and 2008, which allows the storm bite resulting from the June 2007 storm to be determined.

For empirical measurement of short-term dune recession, it was found that the most appropriate photogrammetric profiles to compare were the 1973 and 1974 photogrammetric profiles and the 2006 and 2008 profiles. An *equivalent* storm erosion has been estimated empirically for the different beaches using these data and by applying the protocol described in Nielsen *et al.* (1992). This protocol is outlined below.

2.3 Storm Erosion / Dune Stability Schema

A generalised dune stability schema relating to storm erosion is presented schematically in Figure B.24. The following four stability zones (*Zone of Wave Impact*, *Zone of Slope Adjustment*, *Zone of Reduced Foundation Capacity* and *Dune Stable Foundation Zone*) have been delineated as follows (after Nielsen *et al*., 1992):

- The *Zone of Wave Impact* delineates an area where any structure or its foundations would suffer wave attack during a severe storm. It is that part of the beach that is seaward of the dune erosion escarpment.
- A *Zone of Slope Adjustment* was delineated to encompass that portion of the seaward face of the dune that would slump to the natural angle of repose of the dune sand following removal by wave erosion of the *Design Storm Erosion Demand*. That presents the steepest stable dune profile under the conditions specified.
- A *Zone of Reduced Foundation Capacity* for building foundations was delineated to take account of the reduced bearing capacity of the sand adjacent to the dune erosion escarpment. It was considered that structural loads should be transmitted only to soil foundations outside the zone within which the *Factor of Safety* was less than 1.5 during extreme scour conditions at the face of the dune. This allows for the design assumption that the soil may develop its full bearing capacity.
- The *Dune Stable Foundation Zone* is that portion of the dune that is unaffected by the wave erosion processes and within which no special foundation requirements need to be made. This zone does not take into account any land stability or other geotechnical hazards that may exist in the same area. The identified geotechnical hazards are described in a separate report by SCE (2010).

To determine the impact of storm erosion on a homogeneous sand dune, the *design storm erosion demand* is subtracted from the available sand storage on the beach. The slumped storm erosion profile is idealised as comprising a steep dune escarpment at a slope (i) equal to the natural angle of repose of dune sand (φ) to the top of the swash zone at low tide, taken to be RL 2 m (approximately on AHD), then a steep nearshore beach face of slope 1:10 down to RL 0 m (AHD – the datum for the reference volume calculations; see Figure B.25). A flatter slope (α) extending landward from the limit of beach scour and incorporating a Factor of Safety of 1.5 ($\tan\alpha = \tan\varphi/1.5$) defines the limit of the *Zone of Reduced Foundation Capacity* beyond which surface footings can be used safely.

For the assessment of slope stability of eroded dunes, a value of 35° has been adopted for the angle of internal friction for dune sands. While the schema of Nielsen *et al.* (1992) recommends a value of 34°, advice from Andrew Shirley (pers. comm. 2010) is that the friction angle of dune sand is typically about 32°, with more angular beach sand in the wave impact zone having a friction angle of about 33°. For a 5 m high dune, the sensitivity of the friction angle used in the calculations would lead to a difference of less than 1 metre in the spatial location of the *Zone of Slope Adjustment*.

2.4 Estimation Of Storm Erosion Volumes

The impact of two major storms, the May 1974 storm and the June 2007 storm, was able to be assessed using the photogrammetric data. For this Study, photogrammetry data were available immediately following the May 1974 storm, and also a relatively short time before the storm (1973). Likewise, photogrammetric data were available a relatively short time before and after the June 2007 storm. This enabled the impact of the storms on the dune escarpments of the beaches to be assessed.

The impact of the 1974 and 2007 storms was assessed for every beach, with site specific conditions being taken into account when considering the impact along different sections of each beach. The assessment of the storm bite was undertaken using two different methods:

- Dune face movement assessment: this method consists of observing the movement of a characteristic level of the dune (e.g. RL4m) landward or seaward over time;
- Volume change assessment: this method consists of observing the volume changes over time and calculating the beach recession or accretion using the calculated volume change rate over the height of the dune.

In addition, it was found that the vertical accuracy of the photogrammetry was important in assessing the impact of the storms, especially for relatively protected beaches such as Toowoon Bay and Blue Bay where the impact of the storm is less severe than for an open coast beach such as Shelly Beach or North Entrance.

Upon examination of the 1973 and 1974 profiles, errors were apparent in the datum of these profiles at some of the beaches examined. The correction of these errors, as well as a description of the impact of the 1974 storm for each beach in the Study Area as gleaned from the photogrammetric data, is given below.

2.4.1 Photogrammetry Error Correction

Significant errors in the data that relate to the setup of the stereo models were found, which would have resulted in significant errors in the hazard definition if not discovered and amended. It was found that some of the stereo models were set up such that the datum of the levels is in error. Significant datum errors for the 1974 data as well as for the

1973 data in were uncovered in Toowoon Bay (Figures B.26 and B.27). This resulted in a variable relative error between the 1973 and 1974 photography, which is shown in Figure B.28. Similar errors were uncovered for the photogrammetry of some of the other beaches in the Study Area, including Soldiers Beach, North Entrance Beach and Shelly Beach. Amendment of each profile data set was carried out, to ensure that the measured erosion for the 1974 storms was reasonable and suitable for use in the analysis.

Previous assessments (Public Works, Coasts and Rivers Branch, 1990) did not identify these errors and reported an accretion of Toowoon Bay following the 1974 storm. The apparent accretion was solely an artefact of the incorrect data, which had not been checked adequately. Subsequent re-analysis of the photogrammetry undertaken by DECC&W confirmed the errors in these data.

As the datum errors were not consistent, amendment of each profile data set to ensure that the measured erosion for the 1974 storms was reasonable and suitable for use in the analysis was required.

2.4.2 Storm Erosion at Blue Lagoon and Shelly Beach

Photogrammetric profiles for Blue Lagoon and Shelly Beach from 1973 and 1974 on one hand and from 2006 and 2008 on the other were examined, to determine the impact of the May 1974 and June 2007 storms on the beach. The most important erosion occurred during the 1974 storm.

Equivalent storm erosion volumes were obtained from the analysis of the beachfront areas along the three blocks at Shelly Beach for both the 1974 and 2007 storms. As shown in Figure B.29, an upper envelope value of 250m^3/m was established for the loss of sand volume for the 1974 and 2007 storms for block 2 and 3 and a value of 200m^3/m was selected for block 1. Several values along the beach do exceed 250m^3/m due to unstabilised dune undergoing strong wind erosion. The presence of wind blown dunes in the 1970's was confirmed with reference to historical aerial photography. However, as the Surf Club is located at the intersection of Blocks 1 and 2 it is outside the zone of influence of the wind-blown sand erosion.

2.4.3 Storm Erosion at Toowoon Bay and Blue Bay

At Toowoon Bay and Blue Bay, close examination of the photogrammetric profiles from 1973 and 1974 was carried out, to determine the impact of the May 1974 storm on the beach.

Equivalent storm erosion volumes were obtained from the analysis of the beachfront areas along the seven blocks of Toowoon and Blue Bays for the 1974 storm. As shown in Figure B.30, an upper envelope value of 70m^3/m was established for the loss of sand volume for the 1974 storm for blocks Q and R, as well as a value of 50 m^3/m for block S, of 140 m^3/m for block T due to the presence of more sand, a value of 110 m^3/m for block U and of 110 m^3/m for block V. The very high value of more than 300 m^3/m for block P is an artefact of the orientation of the profile along the tombolo and is not representative of the storm bite. These different values are reasonable as both bays are very protected.

2.4.4 Storm Erosion at North Entrance Beach

At North Entrance Beach, close examination of the photogrammetric profiles from 1973 and 1974 on one hand and from 2006 and 2008 on the other was carried out, to determine the impact of the May 1974 and the June 2007 storms respectively on the beach. The 1974 storm generally had the most significant impact on the Beach except at the southern end where the 2007 storm had more influence.

Equivalent storm erosion volumes were obtained from the analysis of the beachfront areas along the different blocks of North Entrance Beach for both the 1974 and 2007 storms. As shown in Figures B.31 to B.33, an upper envelope value of 250m^3/m was established for the loss of sand volume for the 1974 and 2007 storms for blocks A to F and a value of 150m^3/m was selected for Block G and H due to the presence of reef and the headland at the northern end of the beach. No value along this section of the beach exceeded 120m^3/m along Block C and exceeded 160m^3/m along Block D. This may have been due to waves from the south-east breaking on fringing reef offshore. However, storm cut values of up to 250 m^3/m were measured further south along the beach, possibly as a result of storm waves penetrating a gap in the offshore reef. If waves were to approach from a more easterly direction, a storm cut of 250m^3/m may be possible at the surf club. For this reason, a conservative estimate of 250m^3/m has been used in the hazard lines calculation for all blocks A to F.

2.4.5 Storm Erosion at Soldiers Beach

At Soldiers Beach surf club, close examination of the photogrammetric profiles from 1973 and 1974 on one hand and from 2006 and 2008 on the other was carried out, to determine the impact of the May 1974 and the June 2007 storms respectively on the beach. The 1974 storm had the most significant impact on the Beach.

Equivalent storm erosion volumes were obtained from the analysis of the beachfront areas along the profiles of the five blocks of Soldiers Beach for both the 1974 and 2007 storms. As shown in Figure B.34, an upper envelope value of 200m^3/m was established for the loss of sand volume for the 1974 and 2007 storms at the level of the surf club. The further south, the more protected the beach is and the less erosion occurs. Hence, storm bites of 160 m^3/m for Block 3, 130 m^3/m for Block 2 and 100 m^3/m for Block 1 were adopted for the hazard line calculation. Two values along the northern end of the beach do exceed 200m^3/m, corresponding to some wind erosion at the top of the dune. This was corroborated with reference to historical photography for the 1974 storm. The upper limit is consistent with the typical storm cut values of 200-250m^3/m measured at open coast beaches along the NSW coastline.

2.4.6 Storm Erosion At Hargraves Beach

At Hargraves Beach, close examination of the photogrammetric profiles from 1973 and 1974 was carried out, to determine the impact of the May 1974 storm on the area of beach which has undergone urban development.

Equivalent storm erosion volumes were obtained from the analysis of the beachfront areas within Blocks I and J along Hargraves Beach for the 1974 storms. As shown in Figure B.35, an upper envelope value of 180m^3/m was established for the loss of sand volume for the 1974 storm for Block I, and around 190m^3/m for Block J. A value exceeded 190m^3/m at the northern end of the beach due to wind blow-out.

2.4.7 Storm Erosion At Lakes Beach

At Lakes Beach surf club, close examination of the photogrammetric profiles from 1973 and 1974 on one hand and from 2006 and 2008 on the other was carried out, to determine the impact of the May 1974 and the June 2007 storms respectively on the beach. The 1974 storm had the most significant impact on the Beach.

Equivalent storm erosion volumes were obtained from the analysis of the beachfront areas within Blocks 1 and 2 along Lakes Beach for both the 1974 and 2007 storms. As shown in Figure B.36, an upper envelope value of 250m^3/m was established for the loss of sand volume for the 1974 storm, and around 120m^3/m for the 2007 storm. Examination of aerial photography taken during the 1974 storm shows a possible rip at the location where 250 m^3/m storm cut was measured (Figure B.37). The value of 250m^3/m is commensurate with typical storm cut values measured along open coast beaches throughout NSW.

3 LONG TERM CHANGES

The photogrammetric data were analysed for volume change to determine trends in beach erosion or accretion over time along the beachfront.

The methods used to examine volume change in the photogrammetric data involved using the software program “Beach Morphology Analysis Package” (BMAP) to quantify changes in profile volumes over time. The results of this analysis are described below.

The digital photogrammetry files were processed and analysed using the software program, Beach Morphology Analysis Package (BMAP). BMAP consists of automated and interactive procedures to analyse morphologic and dynamic properties of beach profiles (Sommerfeld *et al.,* 1994).

For all the beaches in the study area, all the digital profiles along each beach were read into the program BMAP, which is able to calculate volumes under specific beach profiles or the average over multiple profiles.

It should be noted that only the volume above 0.0 m AHD landward of the 2.0m AHD contour was considered in the analysis, as this represents more accurately the volume in the dune and not the volume in the highly variable beach berm area which is subject to frequent fluctuations as a result of tides and normal wave action. It was also considered that the landward boundaries of the profiles extended to just behind the frontal dune, so no adjustment to the profiles on the landward side was considered necessary for the volume calculations.

Table B.1 illustrates the beach recession rates measured for the various beaches in the study area.

Generally, it was found that most of the beaches in the study area are not undergoing significant long term beach recession and that since the storms of May 1974, most of the beaches have been recovering in sand volume as a result of a lack of recent storm activity.

The detailed analysis for each beach in the study area is described below.

Table B.1 – Measured Long-term Beach Erosion Rates at various beaches in the Wyong Shire

Beach	Adopted long term recession rate
Shelly Beach	Nil
Toowoon Bay (Block P-Q-R-S)	0.1
Blue Bay (Block T-U-V)	0.1
South Entrance	Nil
North Entrance (Block A)	Nil
North Entrance (Block B)	0.1
North Entrance (Block C)	0.5
North Entrance (Block D)	0.2
North Entrance (Block E-F-G)	Nil
North Entrance (Block H)	0.1
Soldiers Beach (Block 1-2)	Nil
Soldiers Beach (Block 3-4-5)	0.2
Hargraves Beach (Block I)	Nil
Hargraves Beach (Block J)	0.05
Lakes Beach	0.5

3.1 Blue Lagoon And Shelly Beach

For Blue Lagoon and Shelly Beach, profiles in Block 1 and Block 2 were examined, to determine whether any long term trend in beach profile volumes were evident for the length of beach encompassing the surf club and Blue Lagoon Caravan Park.

From the analysis, it has been found that the location of interest is accreting by up to 0.25m/yr based on an averaged value along the different Blocks. Further details on long term erosion and recession rates can also be found in Table B.2 and Figures B.38 and B.39.

Table B.2 – Long-term recession rates for Shelly Beach

Long term recession rate from erosion volume (m/yr)				
Block 1 P1-8	**Block 1 P9-16**	**Block 1**	**Block 2**	**Block 3**
0.248	-0.010	0.102	0.083	0.287
Dune face movement (m/yr)				
Block 1 P1-8	**Block 1 P9-16**	**Block 1**	**Block 2**	**Block 3**
0.25	0.119	-0.008	0.209	0.158

The beach is mostly accreting with a maximum recession of 0.008m/yr along a couple of profiles. For planning purposes, the long term recession has therefore been neglected for the hazard lines calculation.

3.2 Toowoon Bay And Blue Bay

For Toowoon Bay and Blue Bay, all profiles in each of the photogrammetric blocks were examined, to determine whether any long term trend in beach profile volumes were evident for the length of beach encompassing Toowoon and Blue Bays.

The average dune movement of each profile for each year was plotted in Figures B.40 to B.43, for each of the photogrammetric blocks at Toowoon Bay and Blue Bay. The long term erosion and recession rate for Toowoon and Blue Bays can be found in Table B.3.

From Figures B.40 to B.43, it can be seen that there was little change in beach volumes between 1941 and 2008 at all the photogrammetric blocks along Toowoon Bay and Blue Bay with a maximum long term recession rate of 0.15m/yr. Block P has a significant apparent recession rate, but this is erroneous due to the orientation of the photogrammetric block which was not normal to the beahc profile.

Table B.3 – Long-term recession rates for Toowoon Bay and Blue Bay

Long term recession rate from erosion volume (m/yr)						
Block P	**Block Q**	**Block R**	**Block S**	**Block T**	**Block U**	**Block V**
-0.3407	-0.0365	0.0085	-0.0365	-0.0219	-0.1460	-0.0438
Dune face movement (m/yr)						
Block P	**Block Q**	**Block R**	**Block S**	**Block T**	**Block U**	**Block V**
-0.3285	-0.146	0.01825	-0.0365	-0.1095	-0.1095	-0.02555

As shown in Table B.3, analysis of the movement of the dune face, which is approximately at RL4, has found a recession rate ranging from 0 to 0.15 m/yr for both bays. From both the dune face and dune volume analyses, an average dune recession value of 0.1m/yr has been selected for the hazard lines calculation for both bays.

3.3 South Entrance

From the analysis, it appears that the dune face has been accreting between 1954 and 2001, as shown in Figures B.44 and B.45. This may be due to artificial influences, such as introduction of fill following the 1974 storm and construction of a seawall.

As shown in Figures B.44 and B45, analysis of the movement of the dune face, which is approximately at RL4, has found to accrete at a rate of around 0.44m/yr. As this portion of the beach is partly protected by a seawall, underlain by rock and has been modified by introduction of fill, a long term recession rate could not be established and has been set at zero.

3.4 North Entrance

For North Entrance Beach, profiles in the different blocks were examined, to determine whether any long term trend in beach profile volumes were evident for the length of beach encompassing the existing urban development and at Magenta Shores.

The average dune movement of each profile for each year was plotted in Figures B.46 to B.49, for each of the photogrammetric blocks at North Entrance Beach. The long term erosion and recession rate for North Entrance Beach can be found in Table B.4.

Table B.4 – Long-term recession rates for North Entrance Beach

Long term recession rate from erosion volume (m/yr)							
Block A	**Block B**	**Block C**	**Block D**	**Block E**	**Block F**	**Block G**	**Block H**
-0.1386*	-0.0311	-0.1129	-0.1543	0.0689	-0.1111**	-0.8154**	-0.5464**
Dune face movement (m/yr)							
Block A	**Block B**	**Block C**	**Block D**	**Block E**	**Block F**	**Block G**	**Block H**
0.1841	-0.1084	-0.5383	-0.2041	0.4328	0.3254	0.0818	-0.1103

* *Value non reliable due to high variation in dune height along the profile*

** *Values non reliable due to significant dune height increasing values*

For the areas where there has been no net decrease in sand volume, a beach recession rate of zero was adopted. An average beach recession rate of 0.1m/yr for Block B and H, 0.5m/yr for Block C and 0.2m/yr for Block D were selected. For all other blocks, the recession has been considered as nil.

3.5 Soldiers Beach

From the analysis, it has been found that Soldiers Beach is receding landward by up to 0.19 m/yr based on an average value along the different Blocks at Soldiers Beach. For planning purposes, a conservative beach recession value of 0.20 m/yr has been assumed to determine the location of hazard lines for future planning for Soldiers Beach. Further details on long term erosion and recession rates can also be found in Table B.5 and Figure B.50 to B.53.

Table B.5 – Long-term recession rates for Soldiers Beach

Long term recession rate from erosion volume (m/yr)				
Block 1	**Block 2**	**Block 3**	**Block 4**	**Block 5**
0.0422	0.0175	-0.1918	-0.1452	-0.0226
Dune face movement (m/yr)				
Block 1	**Block 2**	**Block 3**	**Block 4**	**Block 5**
-0.0080	-0.0110	-0.0360	0.0200	0.0398

As shown in Table B.5, analysis of the movement of the dune face, which is approximately at RL5, has found a recession rate of less than 0.04 m/yr for the different Blocks. From both the dune face and dune volume analyses, the highest dune recession value of 0.20m/yr has been selected for the hazard lines calculation for Block 3 to 5 and nil value has been selected for Block 1 and 2.

3.6 Hargraves Beach

From the analysis, it has been found that Hargraves Beach is receding landward by only up to 0.03 m/yr based on an average value along the different Blocks at Hargraves Beach. For planning purposes, a conservative beach recession value of 0.05 m/yr has been assumed to determine the location of hazard lines for future planning for Block J at Hargraves Beach and a nil recession has been selected for Block I. Further details on long term erosion and recession rates can also be found in Table B.6 and Figure B.54 and B.55.

Table B.6 – Long-term recession rates for Hargraves Beach

Long term recession rate from erosion volume (m/yr)	
Block I	**Block J**
0.3192	-0.0284
Dune face movement (m/yr)	
Block I	**Block J**
0.1742	0.3075

As shown in Table B.6, analysis of the movement of the dune face, which is approximately at RL4, has found a recession rate of less than 0.03 m/yr for both blocks. From both the dune face and dune volume analyses, a dune recession value of 0.05m/yr has been selected for the hazard lines calculation for Block J and a value of 0m/yr has been selected for Block I.

3.7 Lakes Beach

From the analysis, it has been found that Lakes Beach is receding landward by 0.25 m/yr based on an averaged value between the two blocks. While Block 1 has been receding by approximately 3.1 m^3/m/year (equivalent to a dune recession of around 0.5 m/year), the recession rate at Block 2 was much lower (0.2 m^3/m/year or less than 0.05 m/year). For planning purposes and to allow a conservative assessment, a long term recession rate of 0.5 m/yr has been assumed to determine the location of hazard lines for future planning for Lakes Beach. The long term recession rates are given in Table B.7 and Figures B.56 and B.57.

Table B.7 – Long-term recession rates for Lakes Beach

Long term recession rate from erosion volume (m/yr)	
Block 1	**Block 2**
-0.53	-0.04
Dune face movement (m/yr)	
Block 1	**Block 2**
-0.17	0.01

As shown in Figures B.58 and B.59, analysis of the movement of the dune face, which is approximately at RL 4, has yielded a recession rate of 0.17 m/yr for Block 1 and close to zero for Block 2. Based on the analysis of both dune translation and dune volume change, a conservative value of 0.50m/yr has been selected for the hazard lines calculation.

4 CONCLUSIONS

The photogrammetric data analysed here was used to quantify storm erosion volume demand quite accurately for the different beaches of along Wyong Shire coastline, as the photographs have been taken within one year before and after the 1974 and 2007 major storms. It has allowed a good estimate of the storm bite as well as long term beach recession rates.

An analysis of the historical aerial photographs has been carried out to better understand the evolution of the coastline at Wyong Shire.

The trend for long term beach change for Wyong Shire was generally a low long term recession all along the coastline. However higher recession (rate of 0.5m/yr) occurs in Lakes Beach and at the southern end of North Entrance Beach. The accuracy of this estimate depended on the horizontal and vertical accuracy of the photogrammetry, as well as the period of time over which the photogrammetry is carried out. This estimate is based on the existing photogrammetric data and may be subject to change in the future as more data is collected.

Hazard mapping for the 2050 and 2100 planning periods has been carried out, using the estimated storm bite and recession rate due to sea level rise. Details of the hazard calculations are given in Appendix D.

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FIGURES

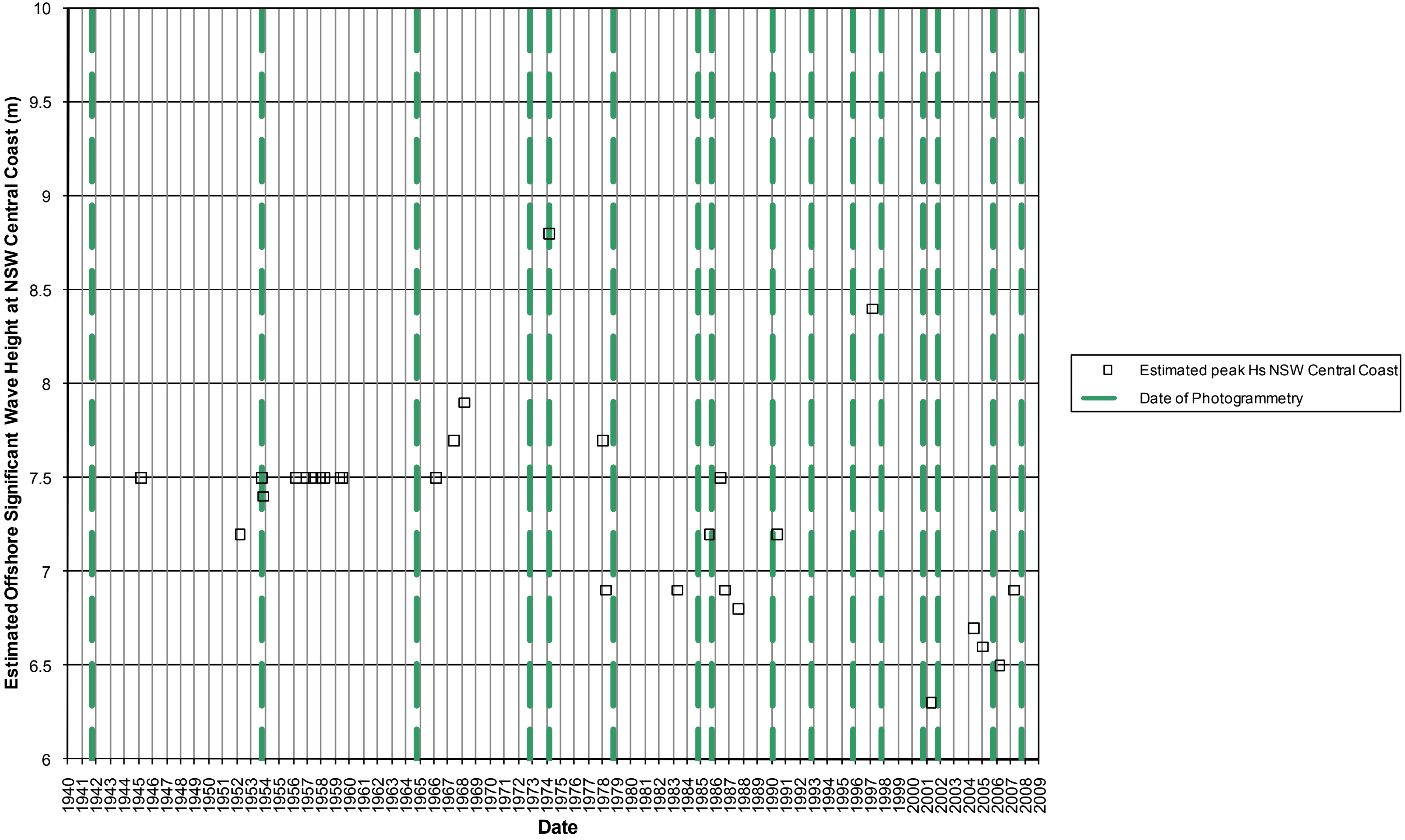


Figure B.1– Extreme Storm events vs. Photogrammetry Dates

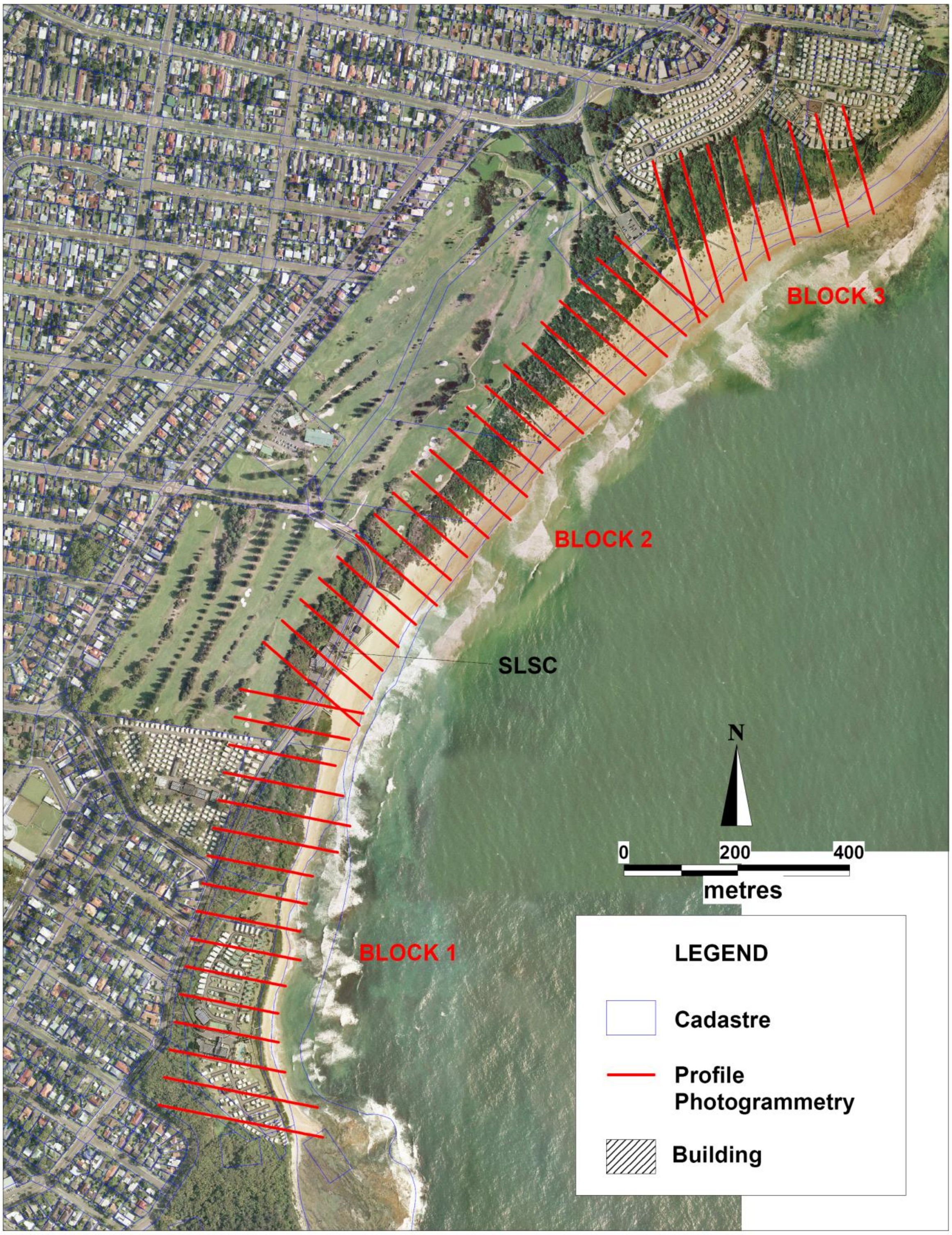


Figure B.2– Blue Lagoon and Shelly Beach – Photogrammetric Block Division

Figure B.3 – Typical view of Blue Lagoon, looking south, at Photogrammetry Block 1

Figure B.4 – Typical view of Shelly Beach, looking north, at Photogrammetry Block 2

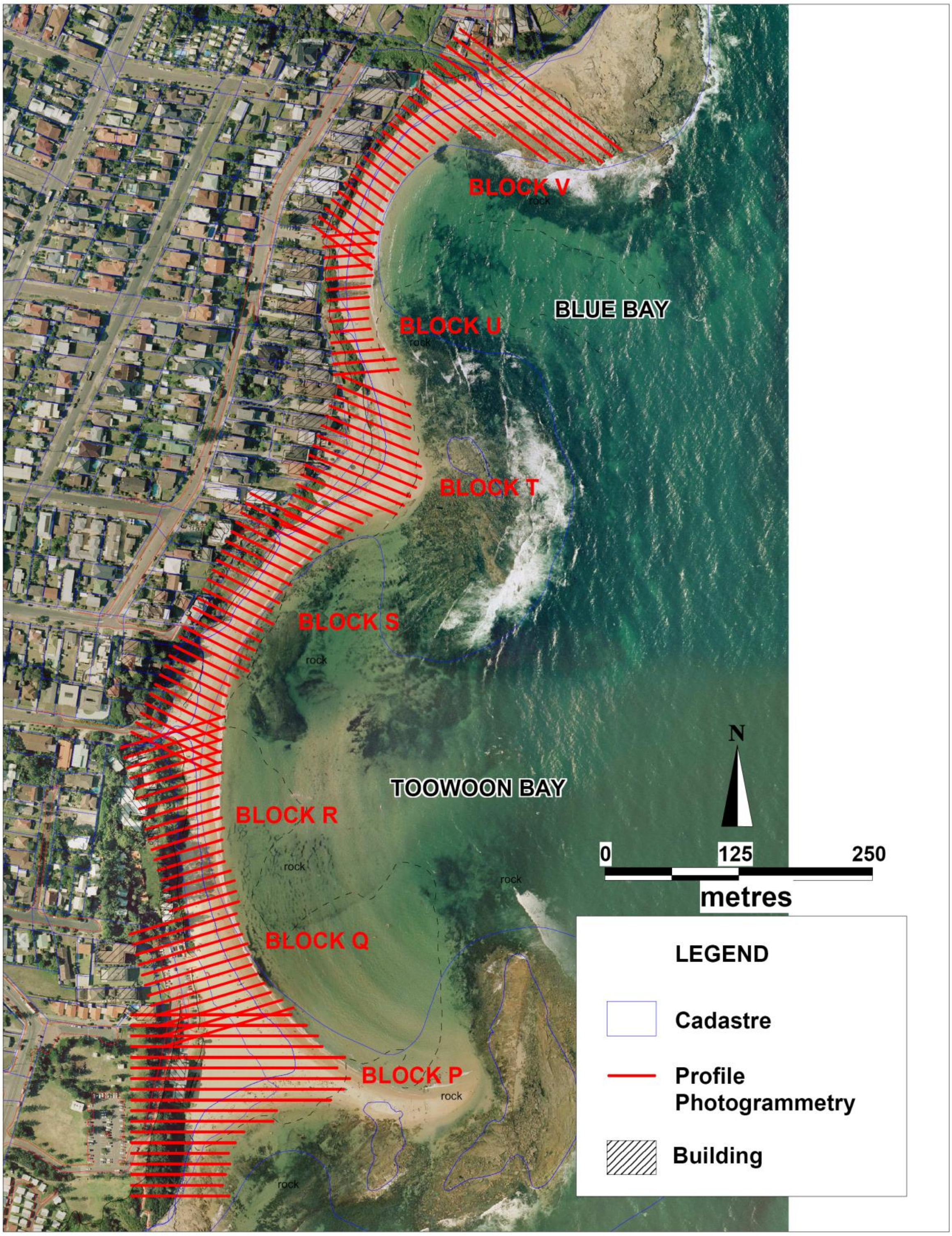


Figure B.5– Toowoon Bay and Blue Bay – Photogrammetric Block Divisions

Figure B.6 – Typical view of Toowoon Bay, at Photogrammetry Block P

Figure B.7 – Typical view of Toowoon Bay, looking south, at Photogrammetry Block R

Figure B.8 – Typical view of Toowoon Bay, at Photogrammetry Block S

Figure B.9 – Typical view of Blue Bay, at Photogrammetry Block T

Figure B.10 – Typical view of Blue Bay, looking north, at Photogrammetry Block U and V

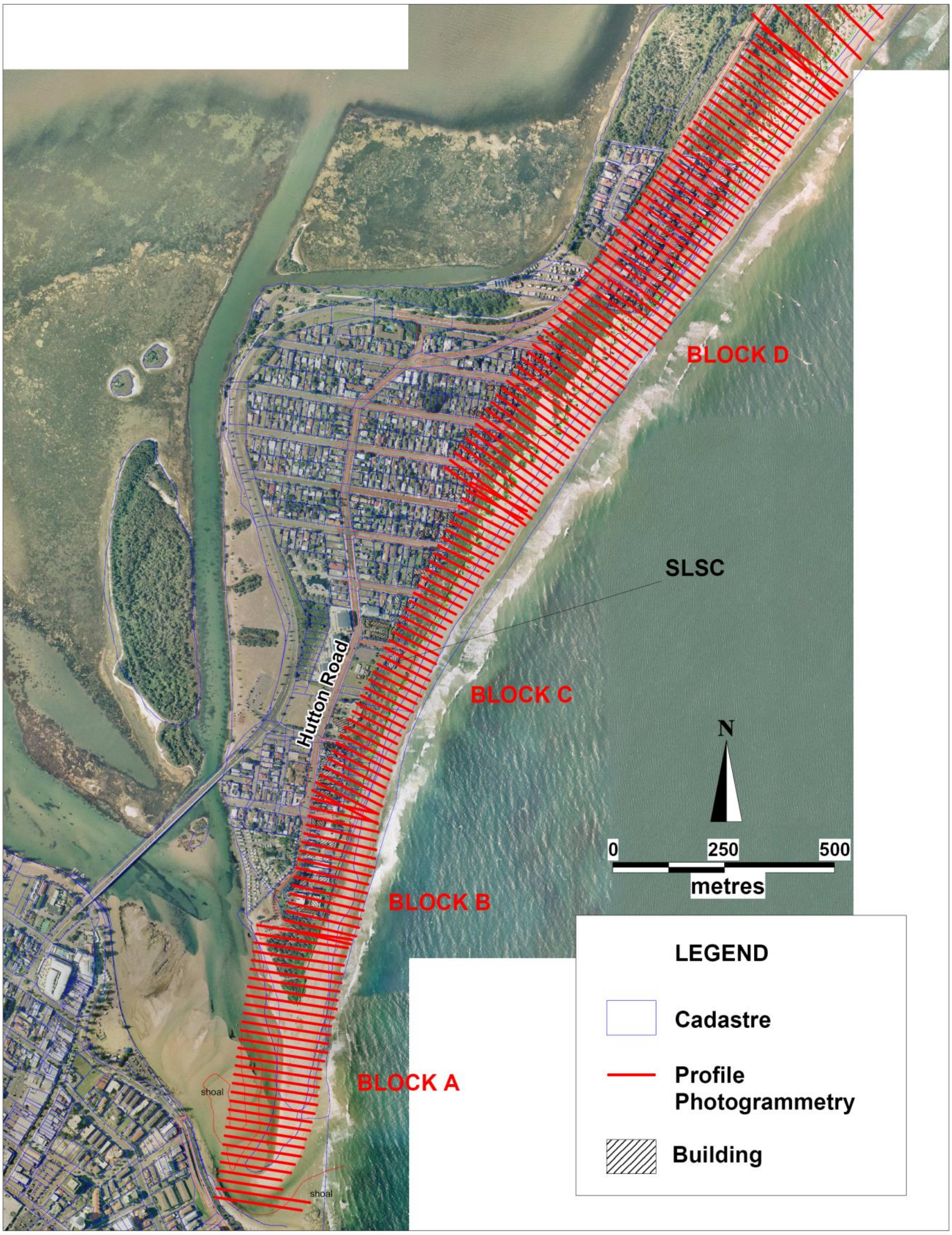


Figure B.11 – North Entrance Beach (south) – Photogrammetric Block Divisions

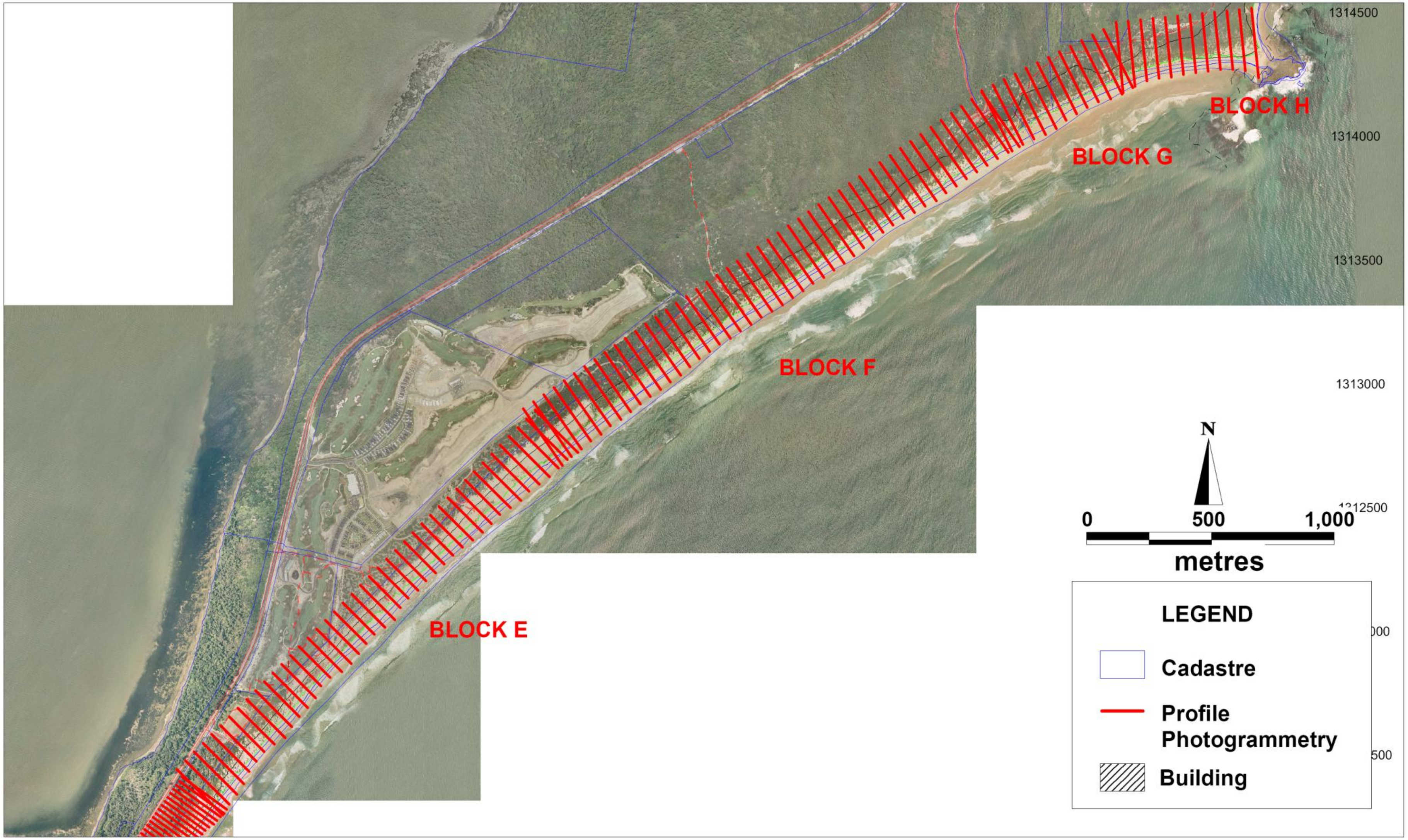


Figure B.12 – North Entrance Beach (north) – Photogrammetric Block Divisions

Figure B.13 – Typical view of North Entrance Beach, at Photogrammetry Block B

Figure B.14 – North Entrance Beach surf club, looking south, at Photogrammetry Block C

Figure B.15 – Typical view of North Entrance Beach, looking north, at Photogrammetry Block C

Figure B.16 – Urban Development, Curtis Parade, North Entrance Beach, at Photogrammetry Block D

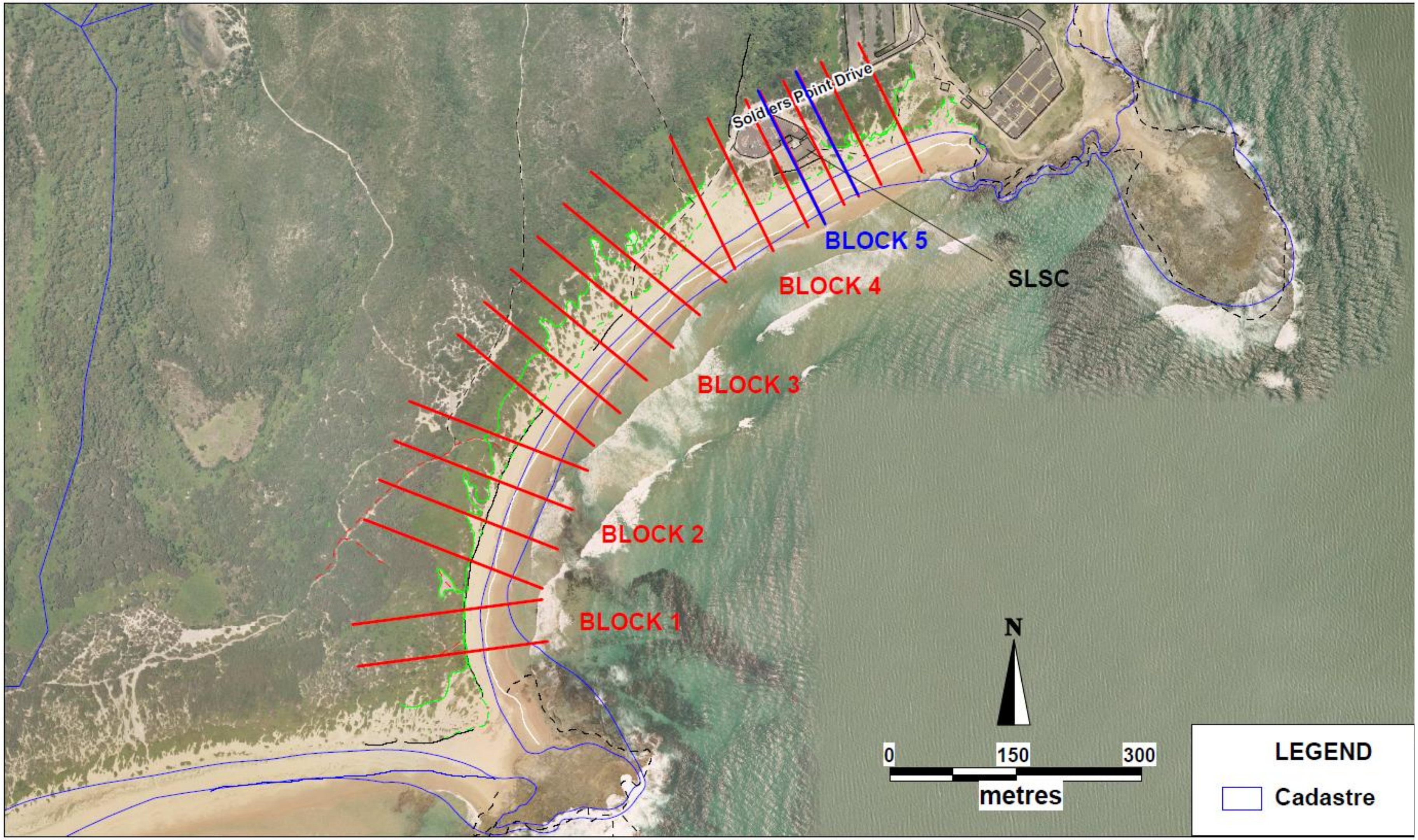


Figure B.17 – Soldiers Beach – Photogrammetric Block Divisions

Figure B.18 – Typical view of Soldiers Beach, looking south, at Photogrammetry Block 4

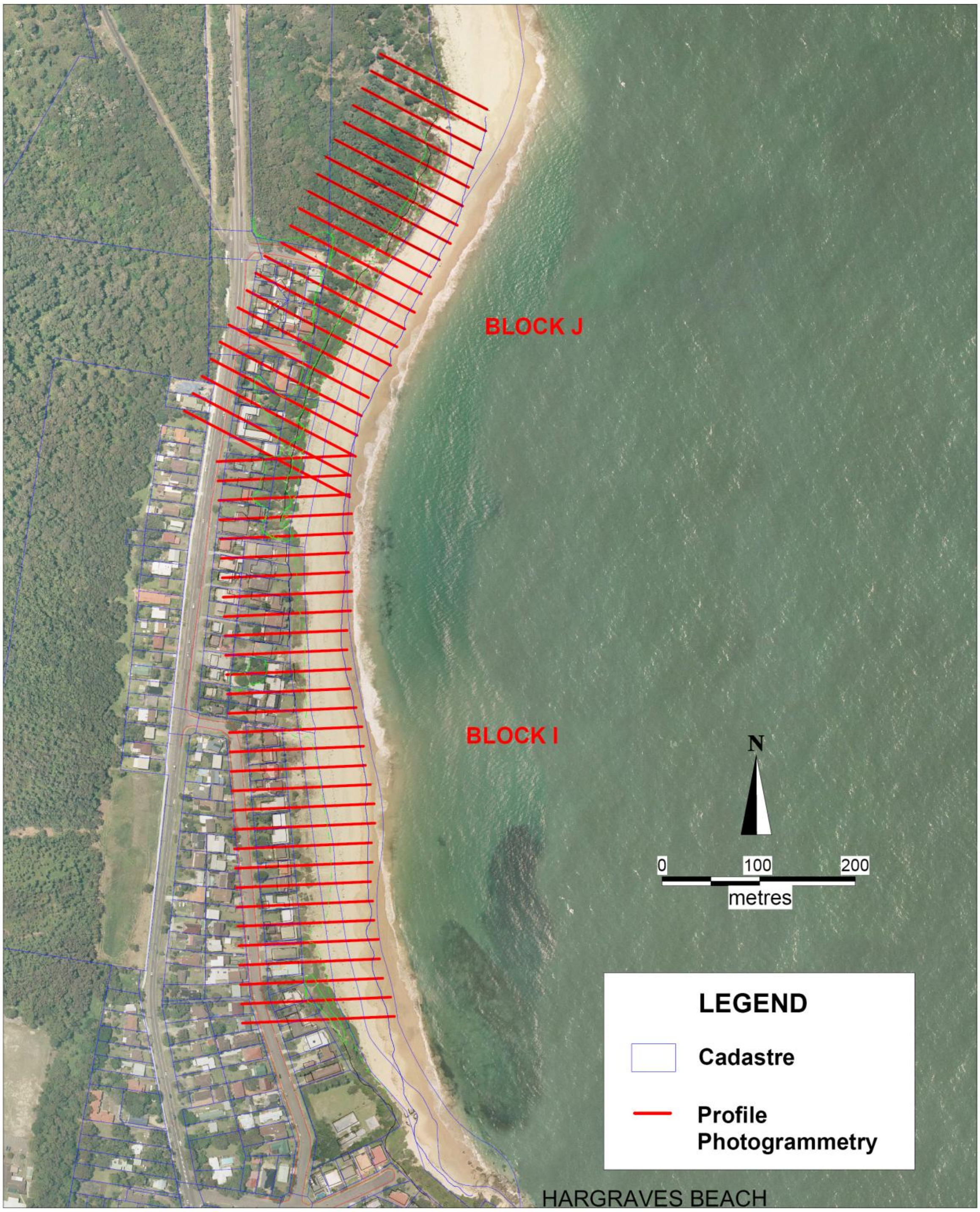


Figure B.19 – Hargraves Beach – Photogrammetric Block Divisions

Figure B.20 – Typical view of Hargraves Beach, looking south, at Photogrammetry Block I

Figure B.21 – Typical view of Hargraves Beach, looking north, at Photogrammetry Block J

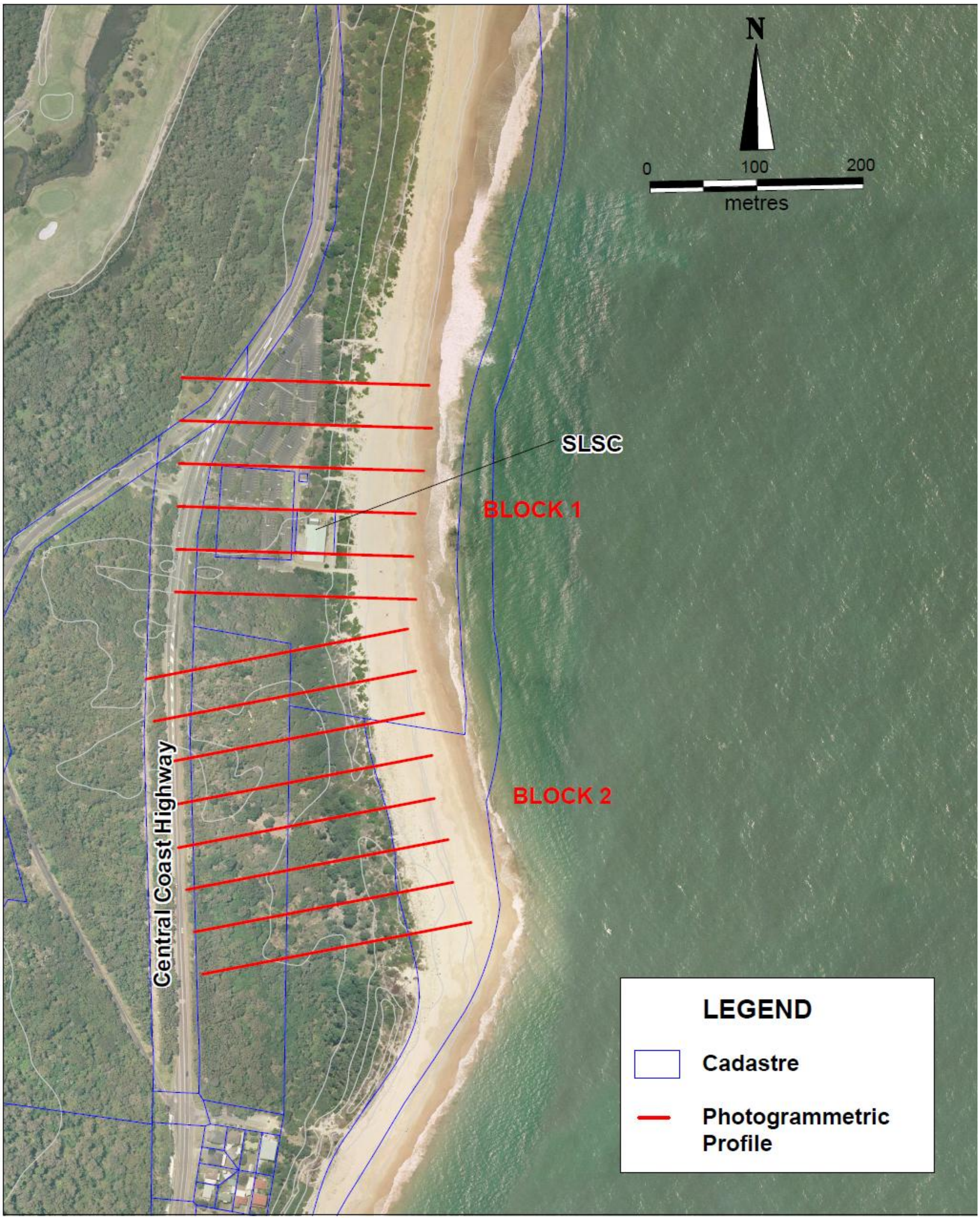
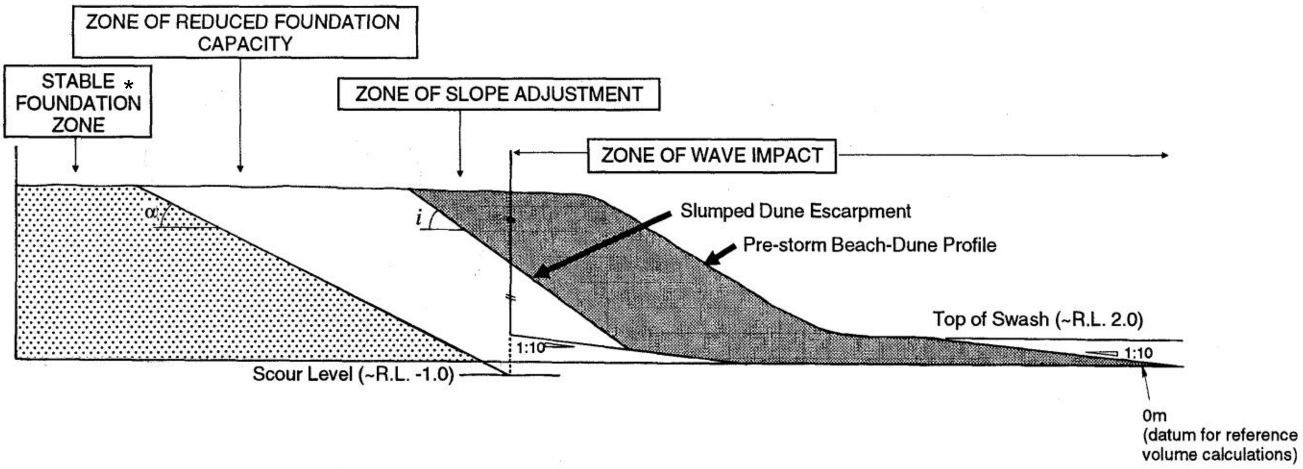


Figure B.22 – Lakes Beach – Photogrammetric Block Divisions

Figure B.23 – Typical view of Lakes Beach surf club, looking south



Angle of repose of dune sand: $i \sim \phi \approx 34^\circ$

Safe angle of repose of dune sand: $\alpha = \tan^{-1}\{(\tan\phi)/1.5\} \approx 24^\circ$

All levels to AHD

Figure B.24 – Dune stability schema (after Nielsen et al., 1992)

**Note – The term "Stable Foundation Zone" refers to a Dune Stable Foundation Zone which does not take into account any land stability, or other geotechnical hazards that may exist in the same area. The identified geotechnical hazards are described in a separate report by SCE (2010).*

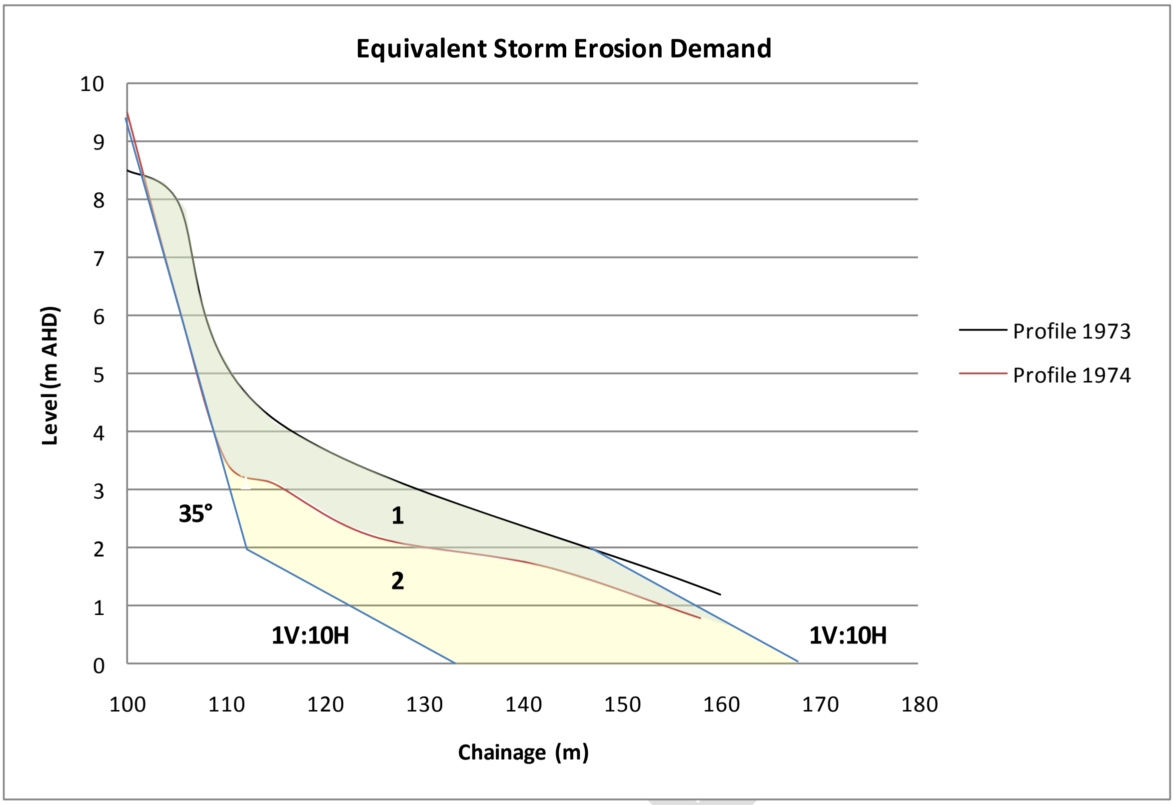


Figure B.25 – Determination of Equivalent storm erosion, 1973 – 1974

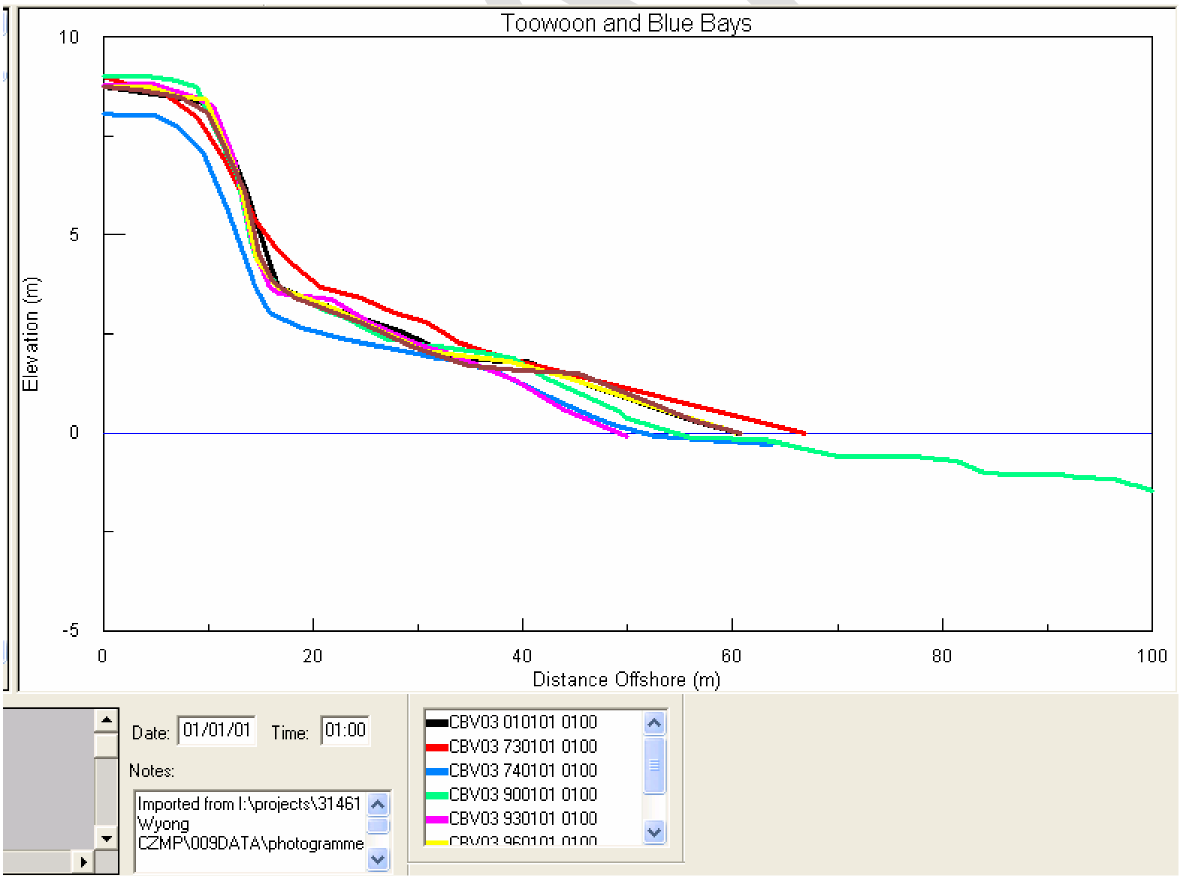


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Figure B.26 – A set of profiles from Blue Bay, indicating datum error (blue = 1974)

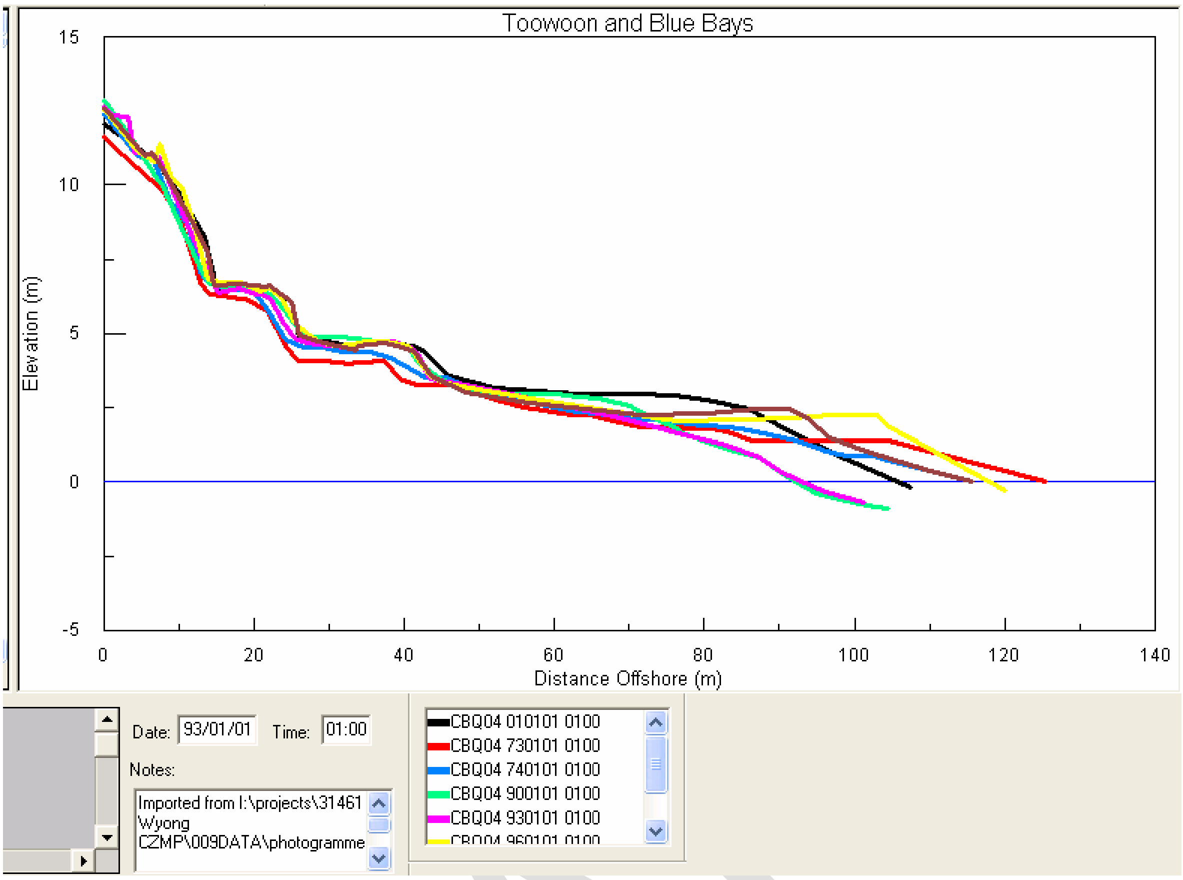

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Figure B.27 – A set of profiles from Toowoon Bay, indicating datum error (red = 1973)

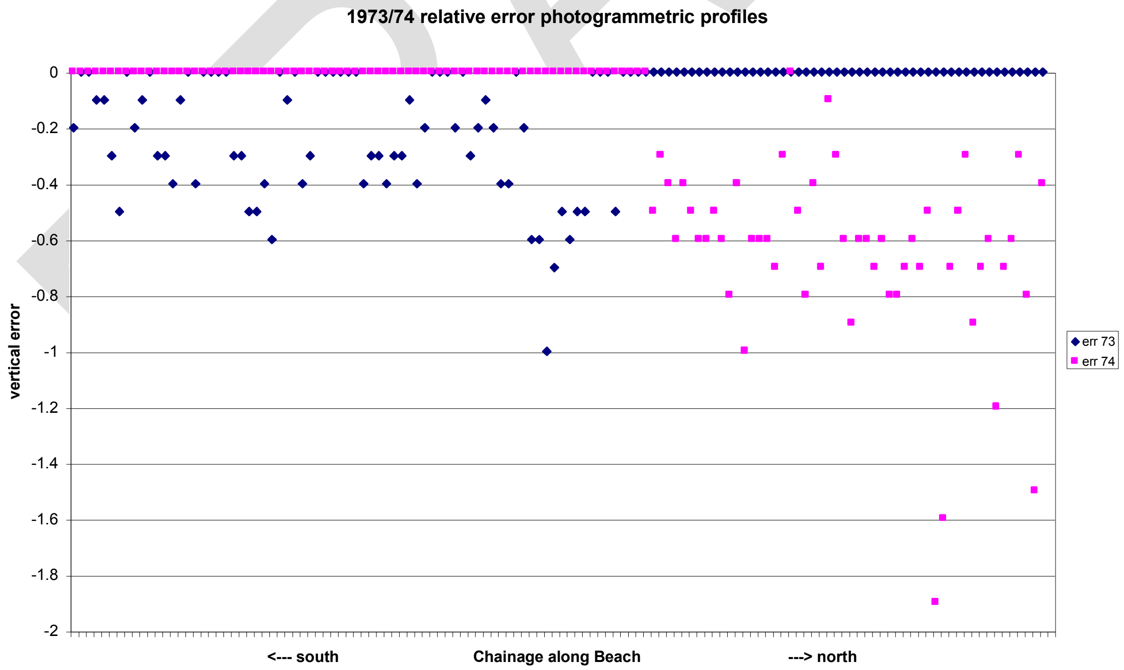


Figure B.28 – Relative Error between 1973 and 1974 photography at Toowoon Bay and Blue Bay

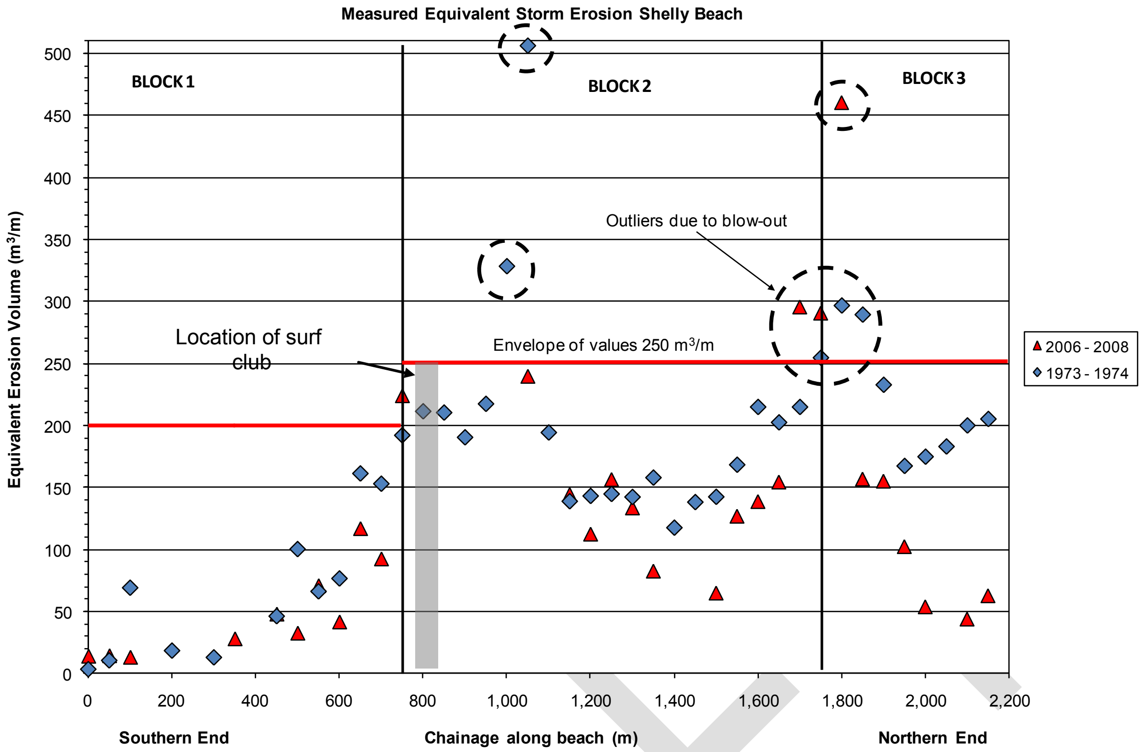
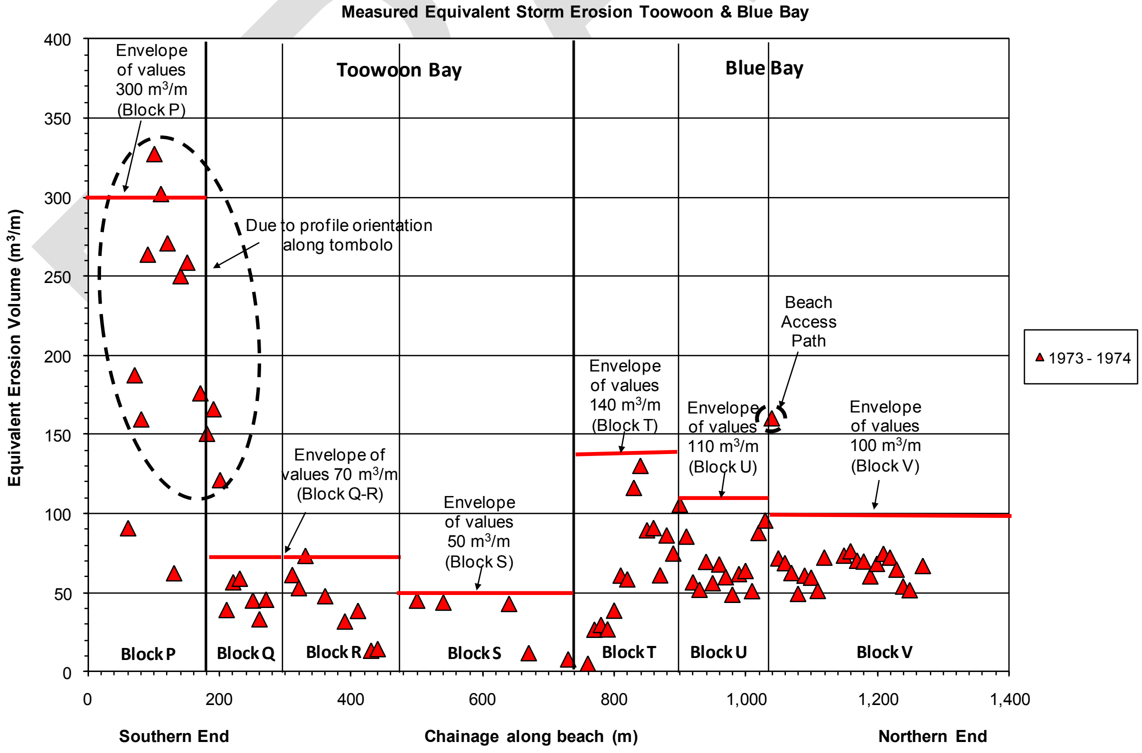


Figure B.29 – Upper envelope for storm bite, Shelly Beach



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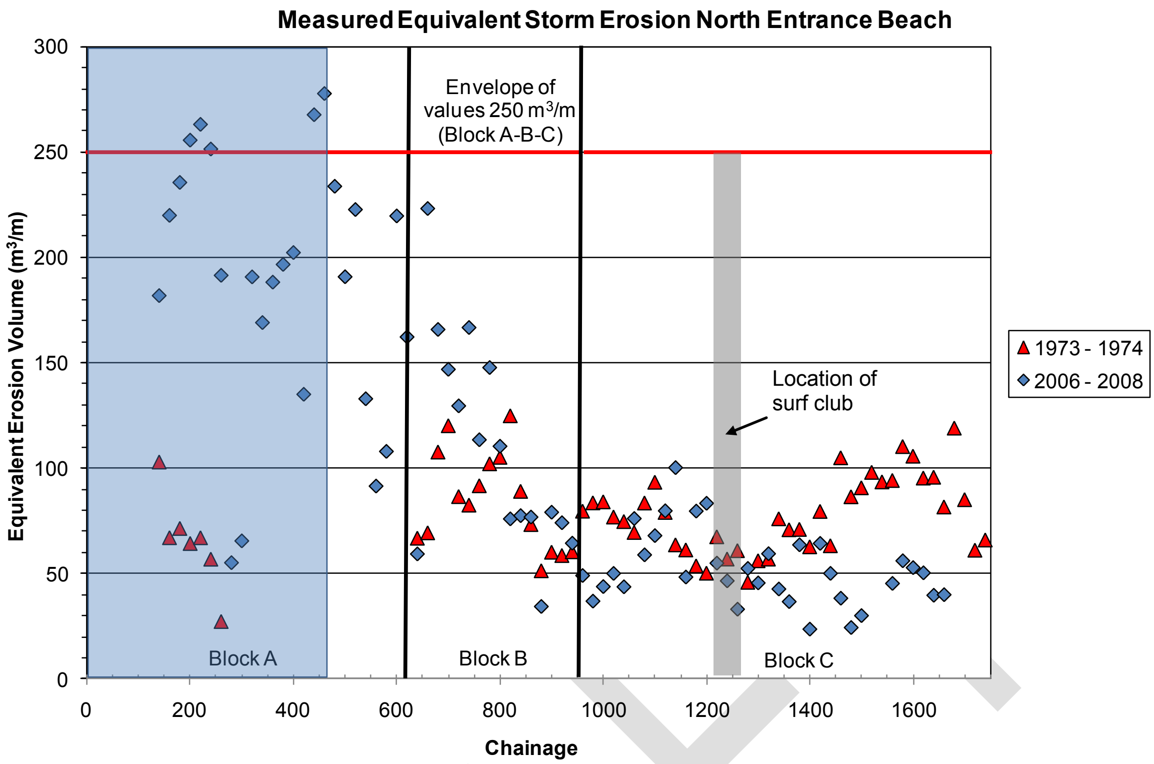

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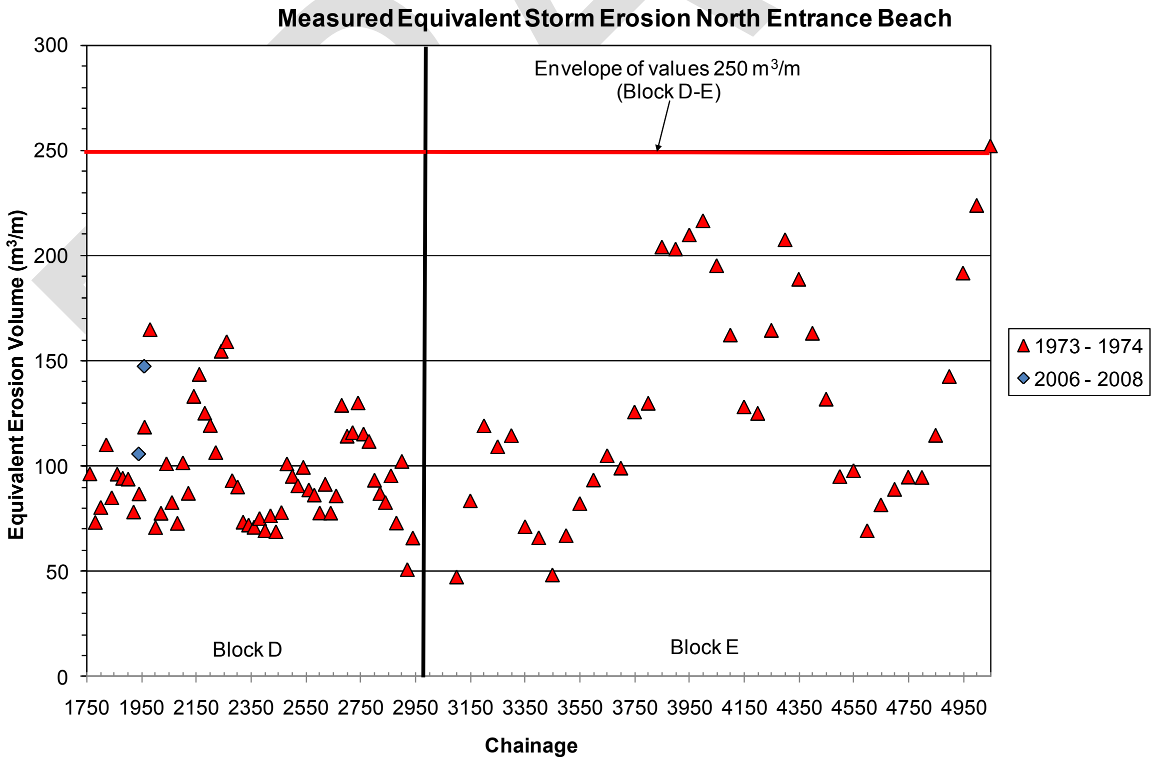

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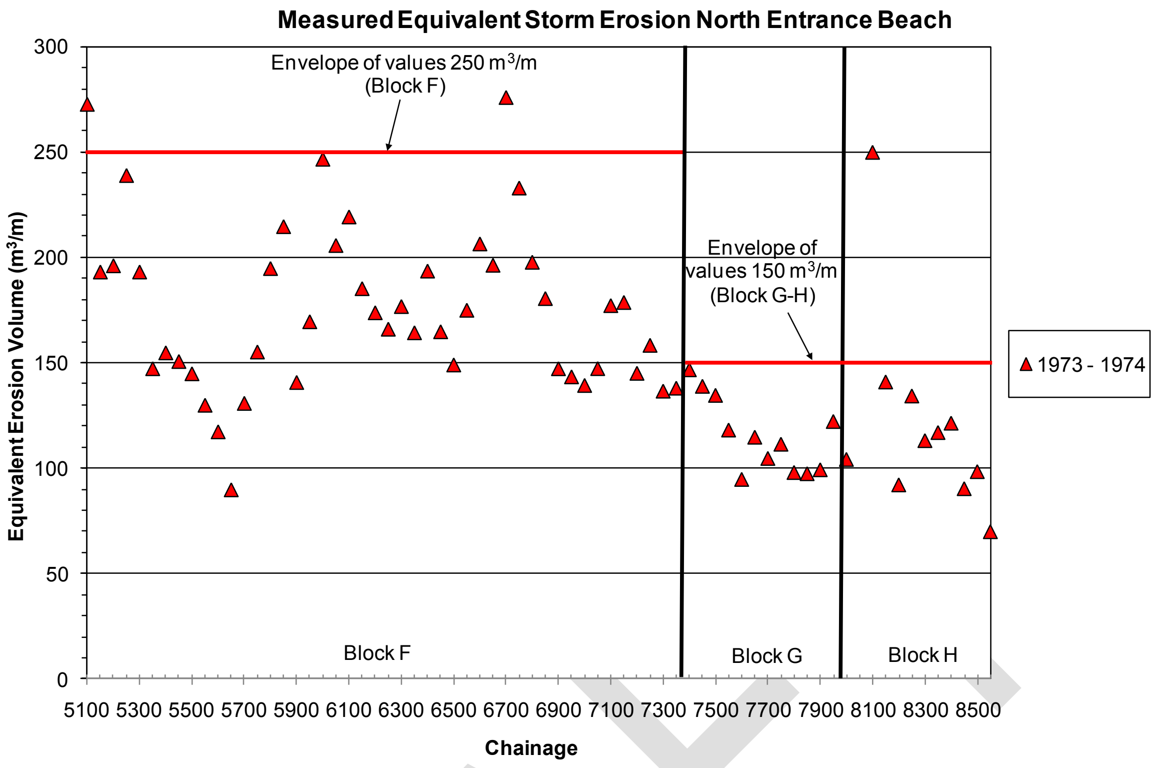
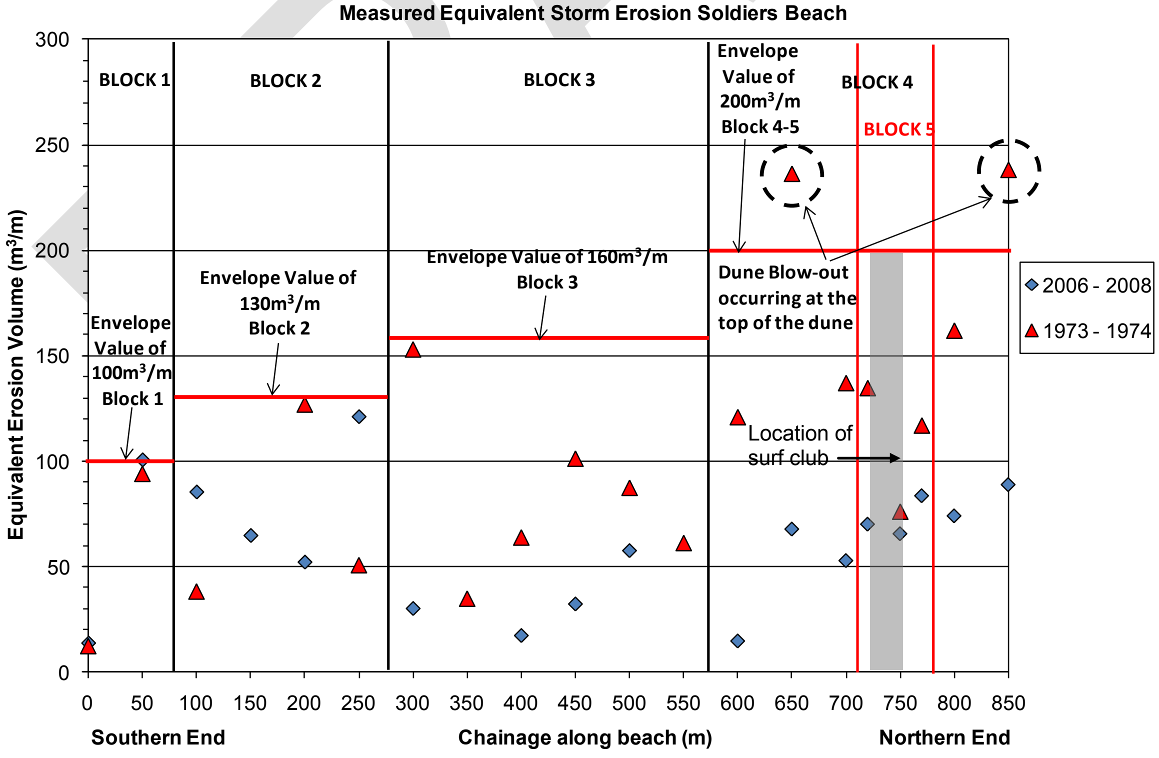


Figure B.33 – Upper envelope for storm bite, North Entrance (Block F-H)



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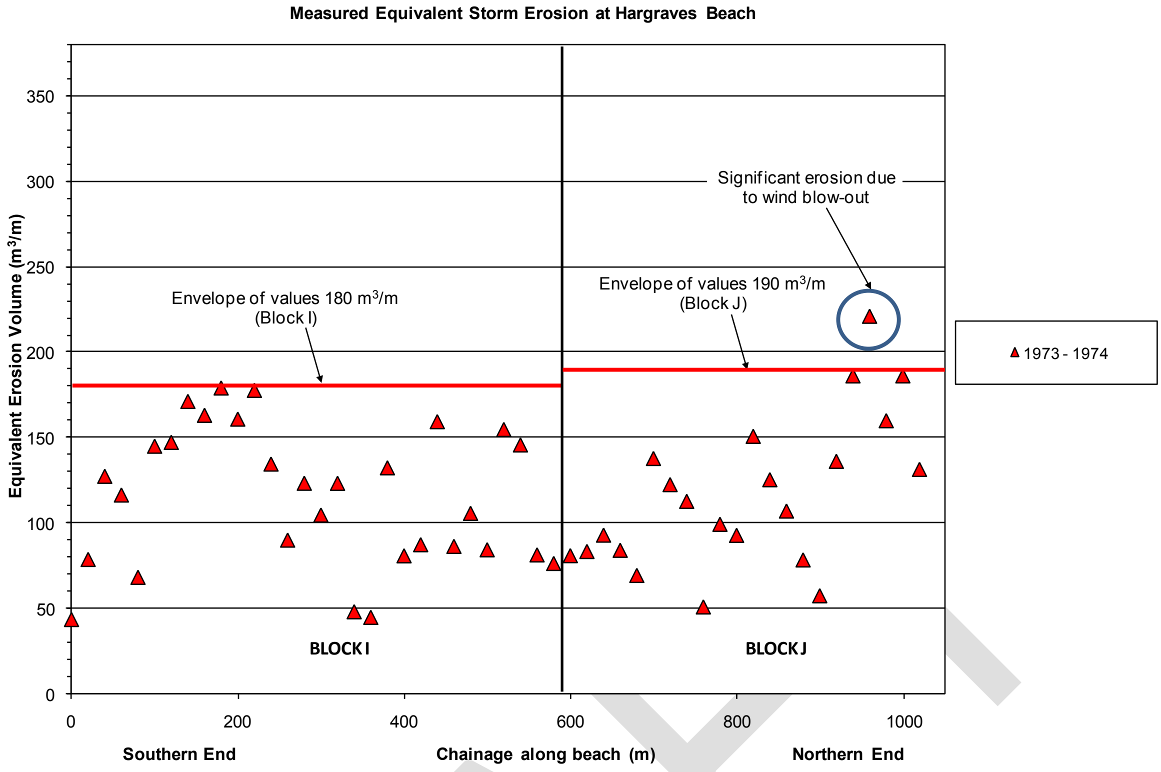
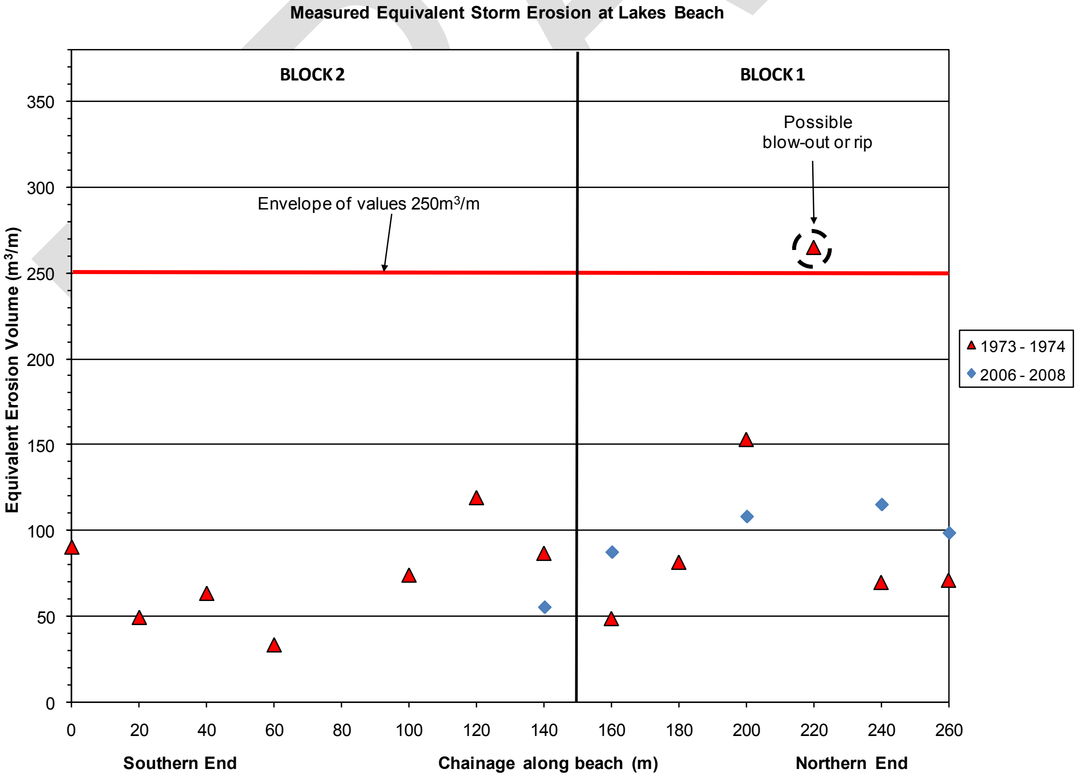


Figure B.35 – Upper envelope for storm bite, Hargraves Beach



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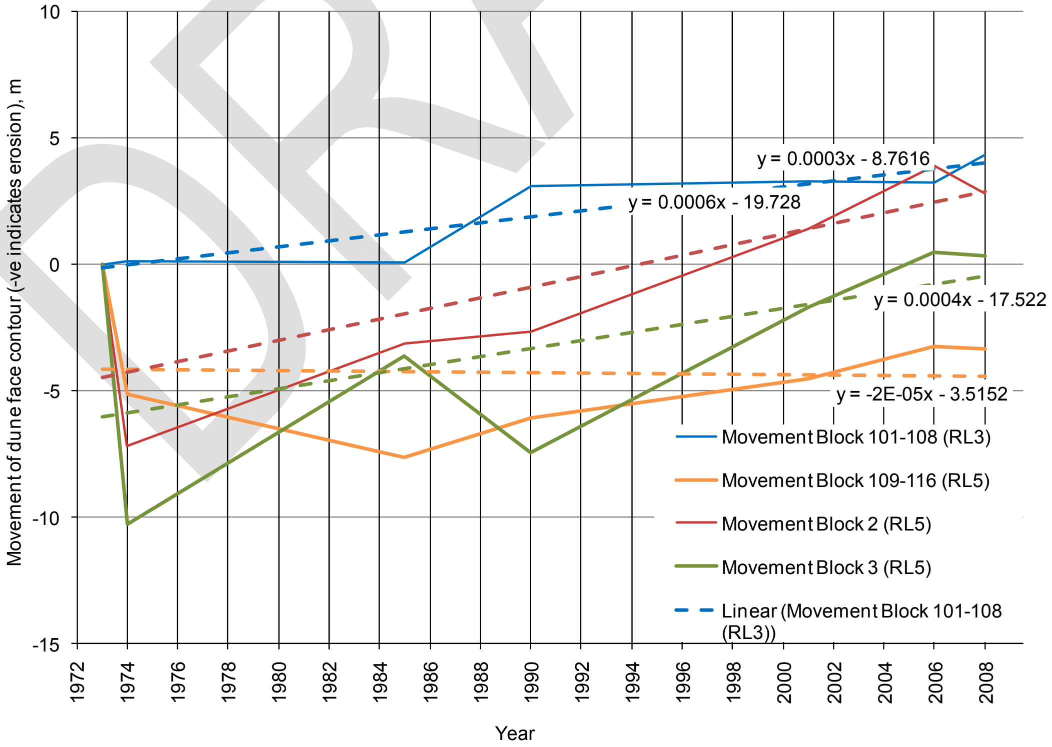


Figure B.38 – Average dune face movement, Shelly Beach

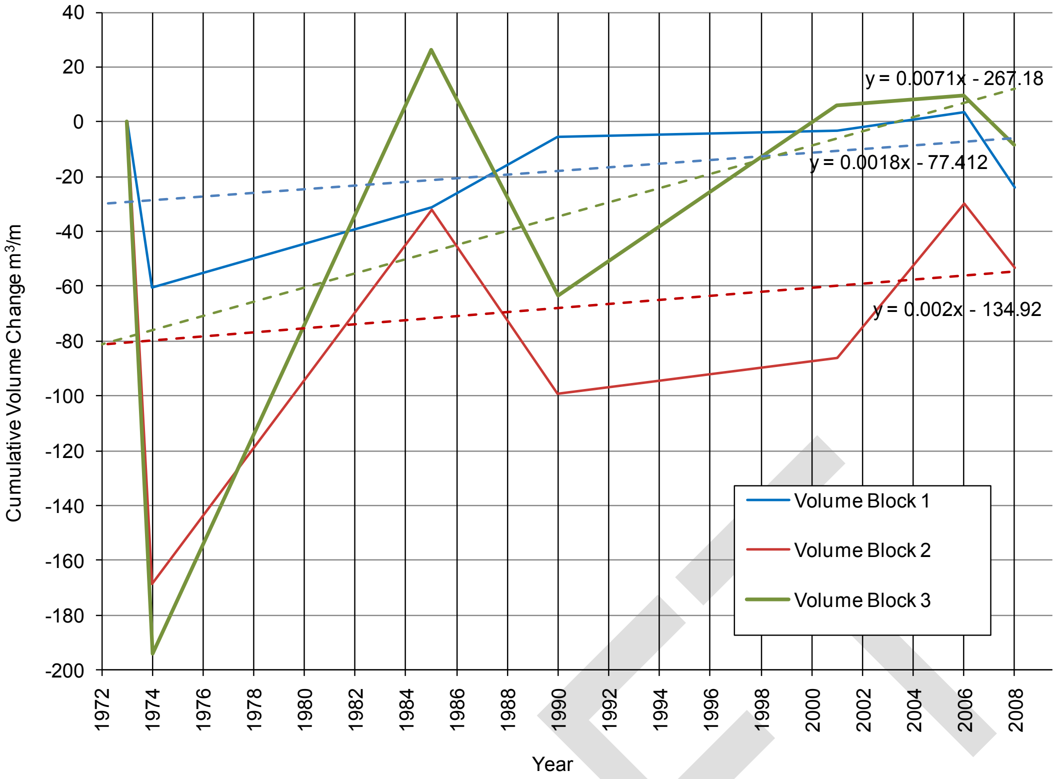
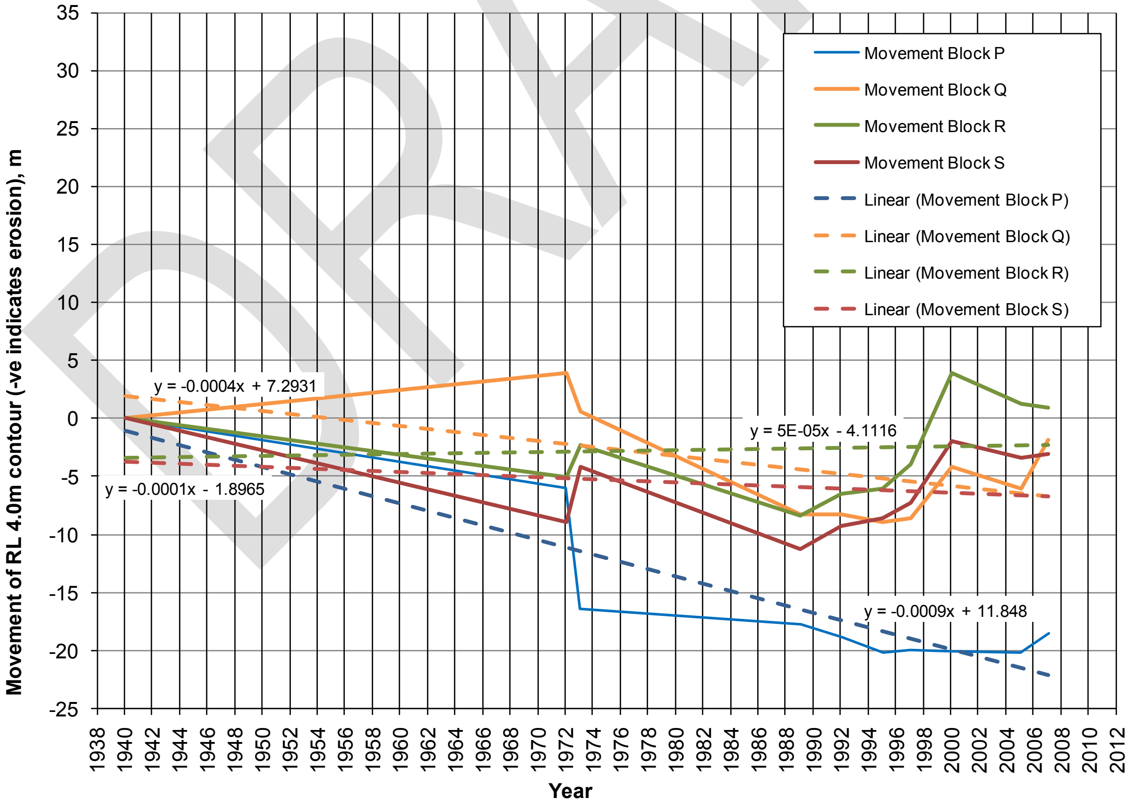


Figure B.39 – Average volume change, Shelly Beach



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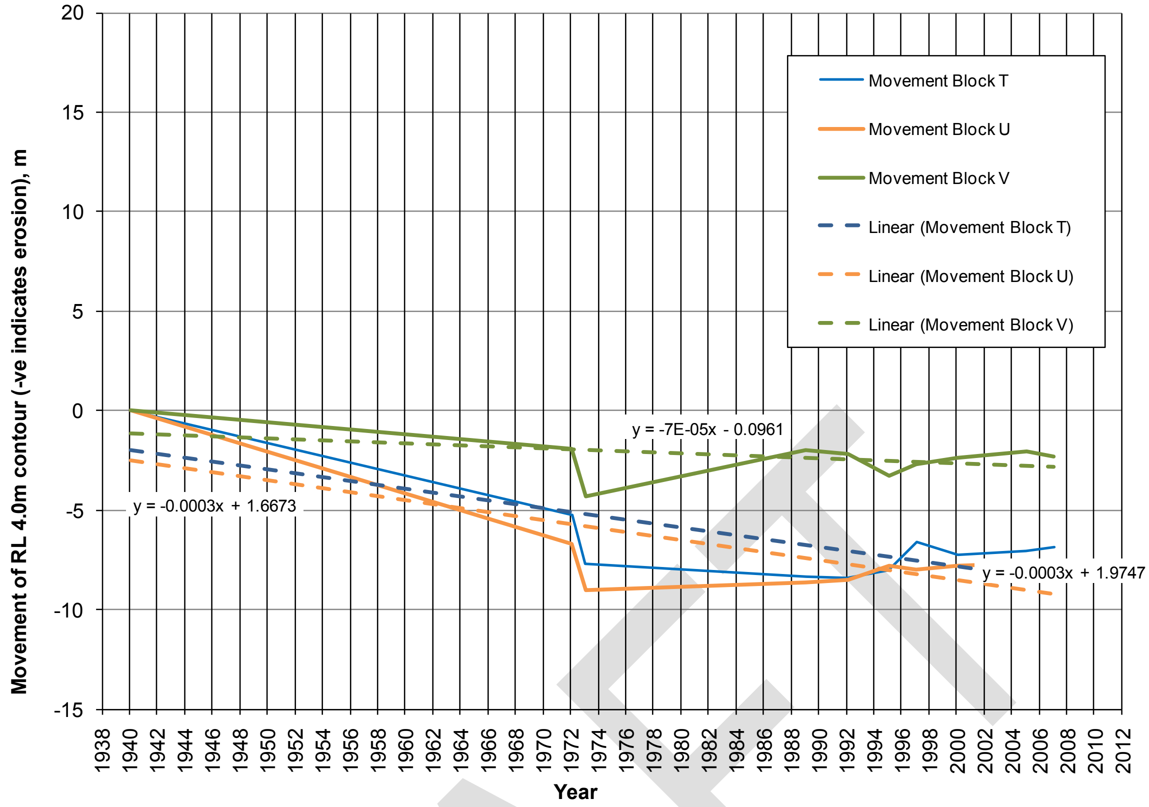

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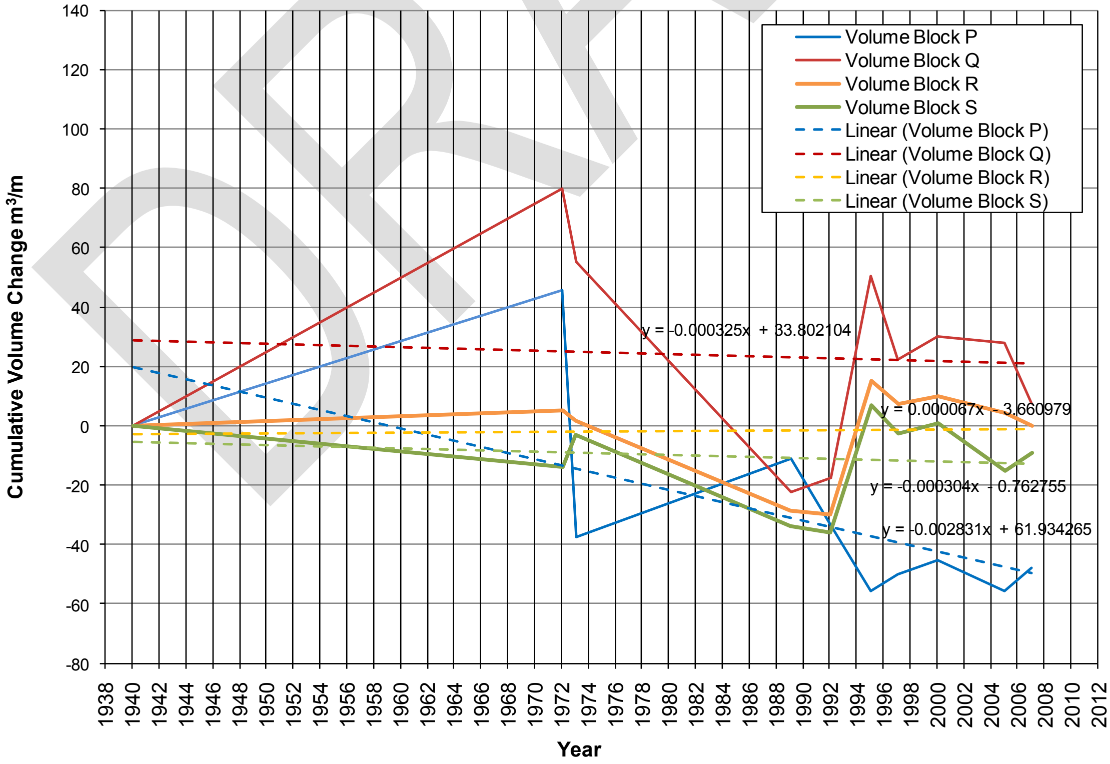

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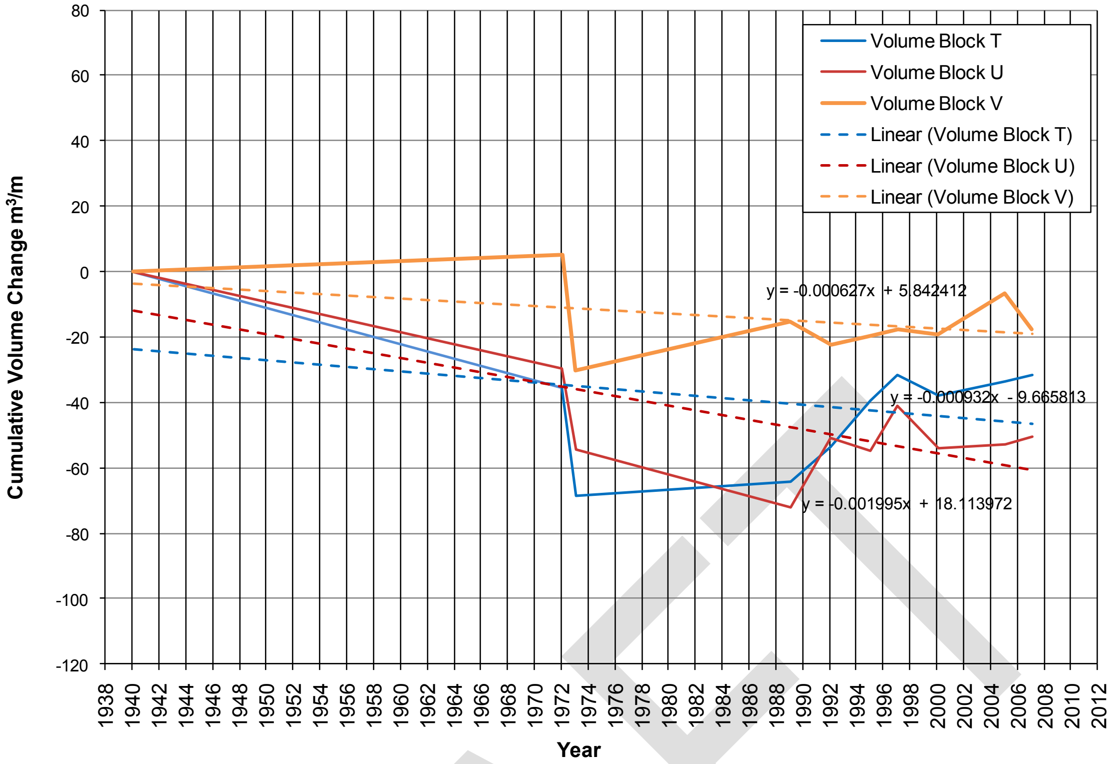


Figure B.43 – Average volume change, Blue Bay

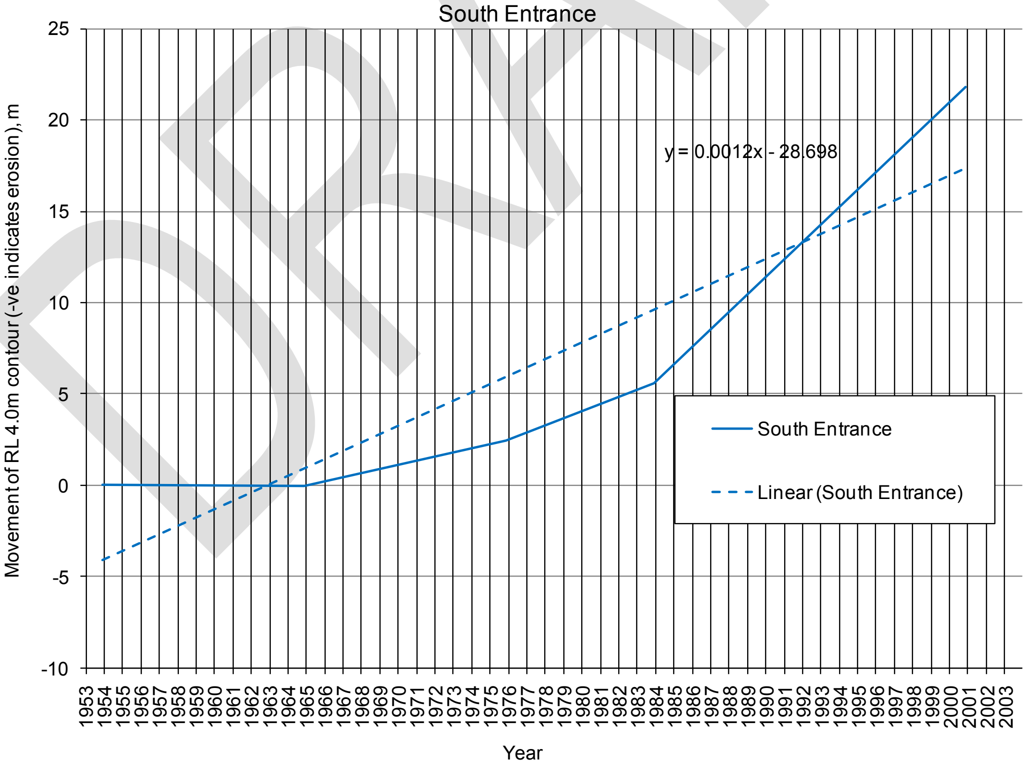
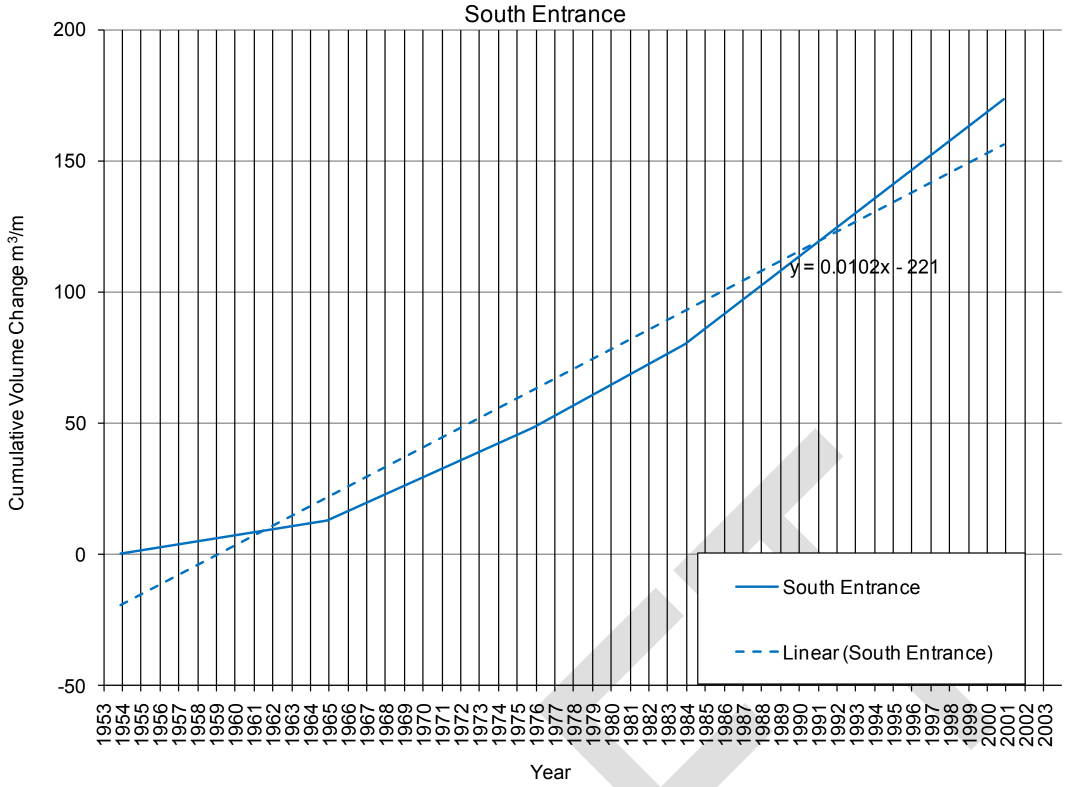


Figure B.44 – Average dune movement, South Entrance Beach



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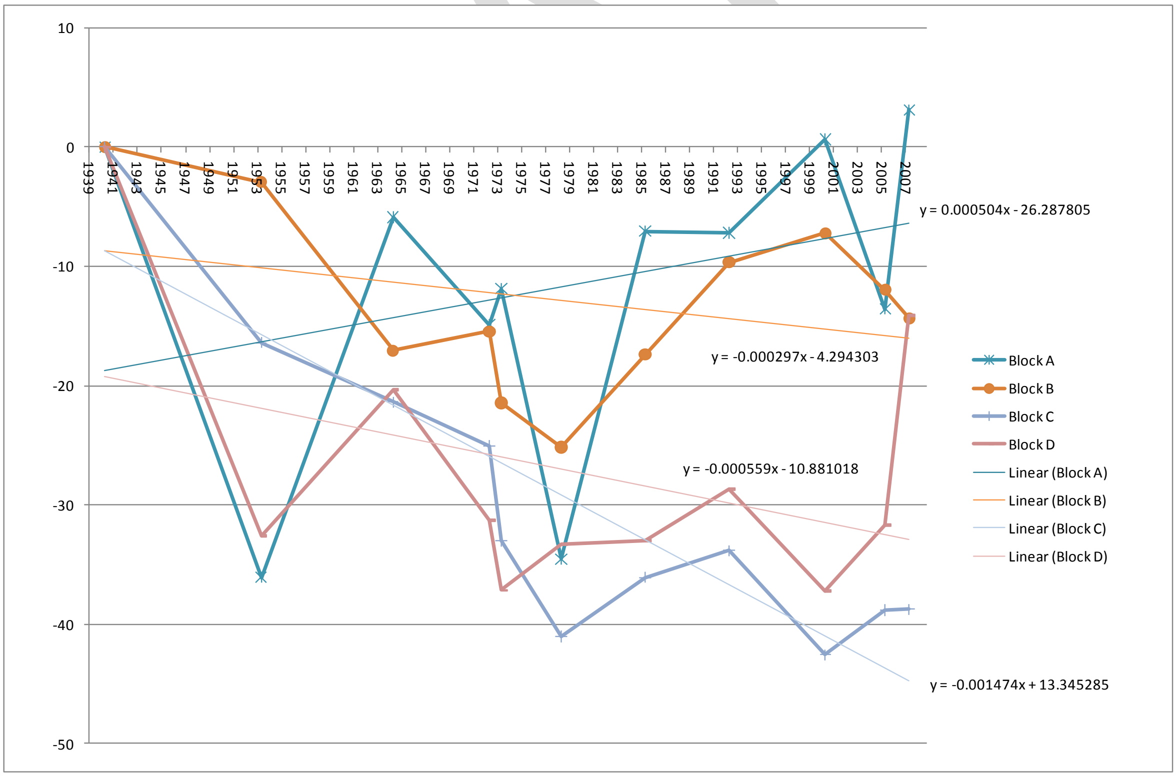
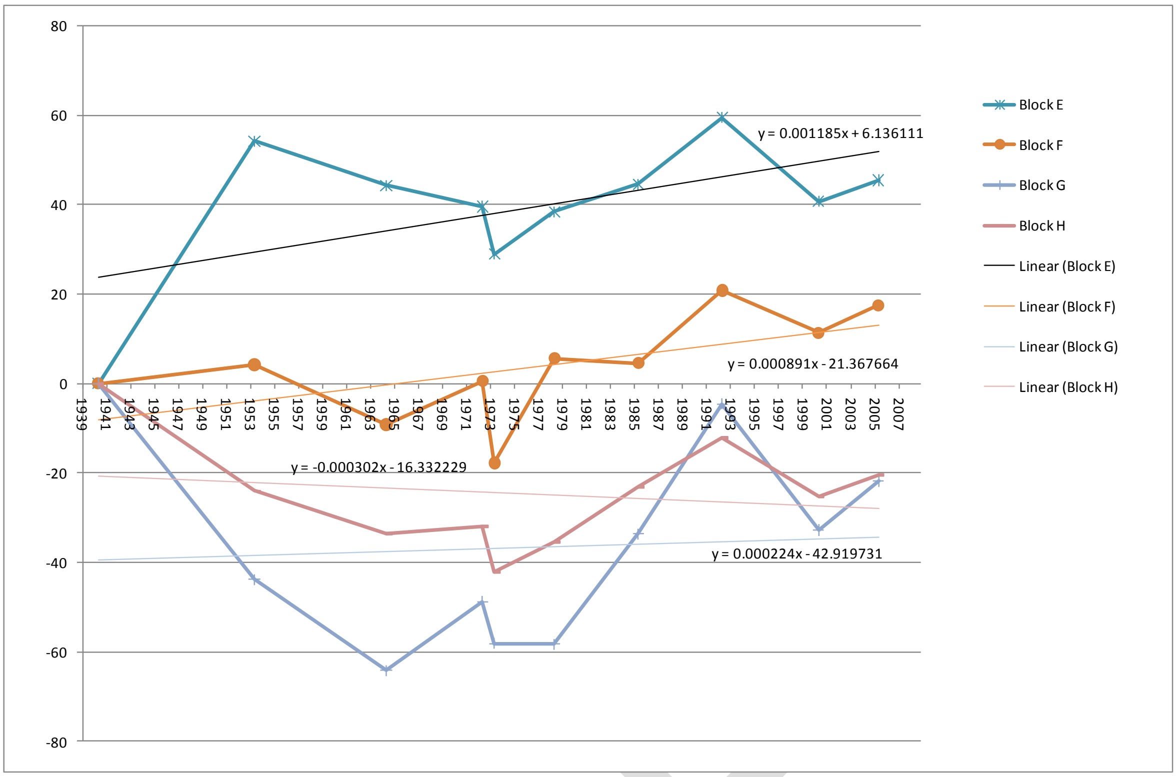


Figure B.46 – Average dune movement, North Entrance Beach (Block A-D)



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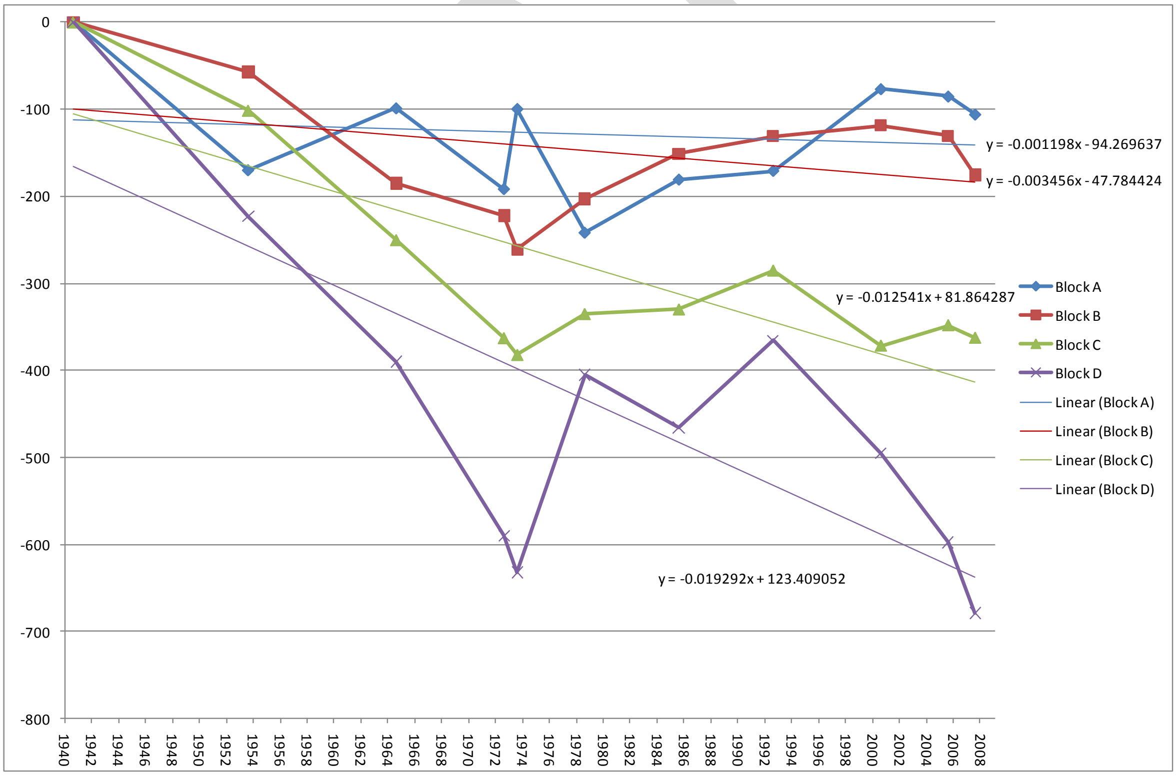
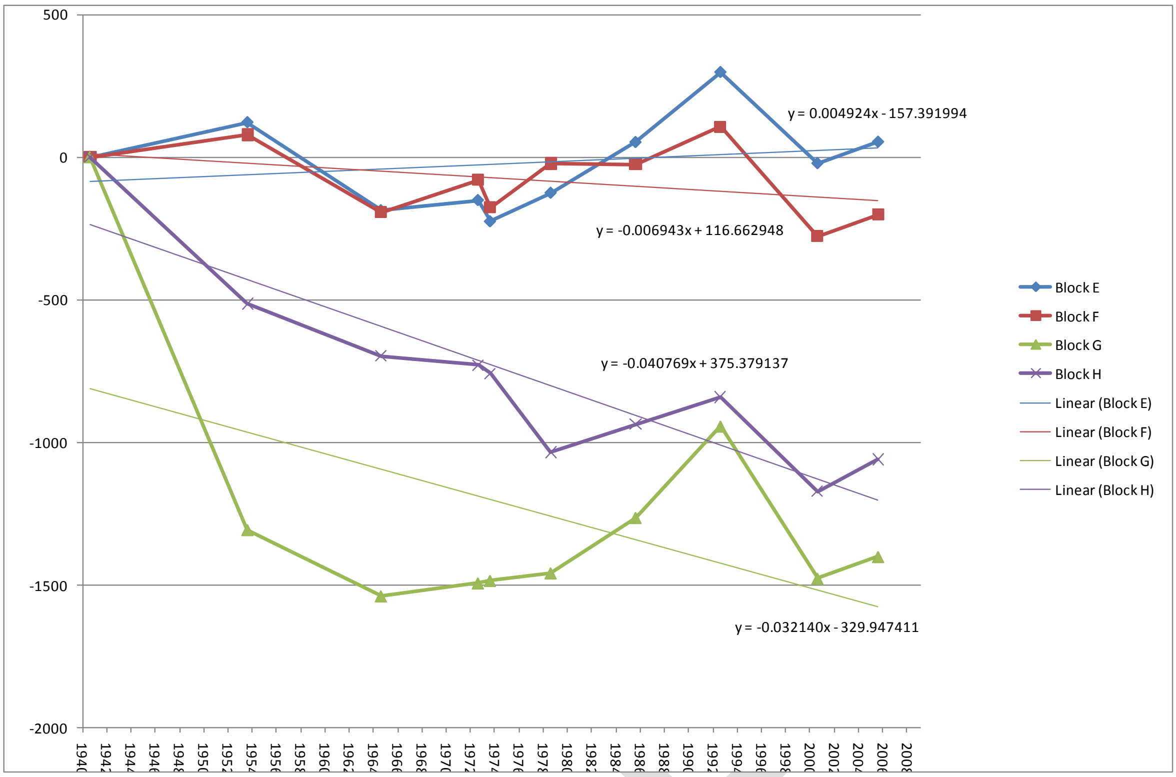


Figure B.48 – Average volume change, North Entrance Beach (Block A-D)



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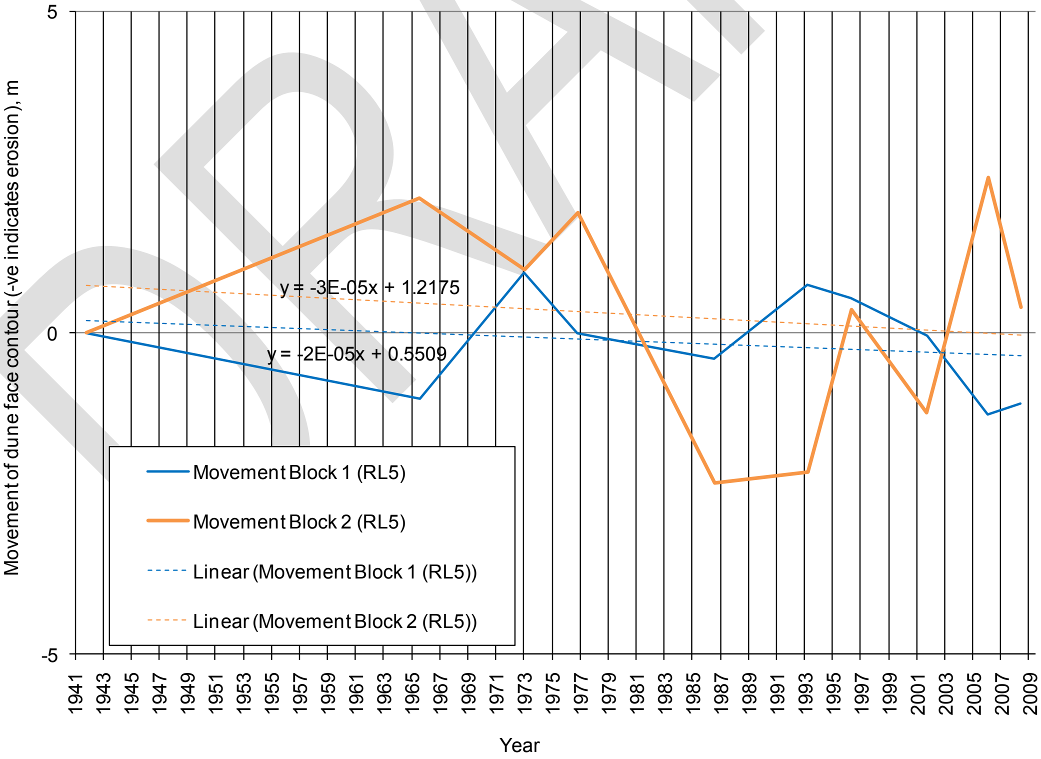

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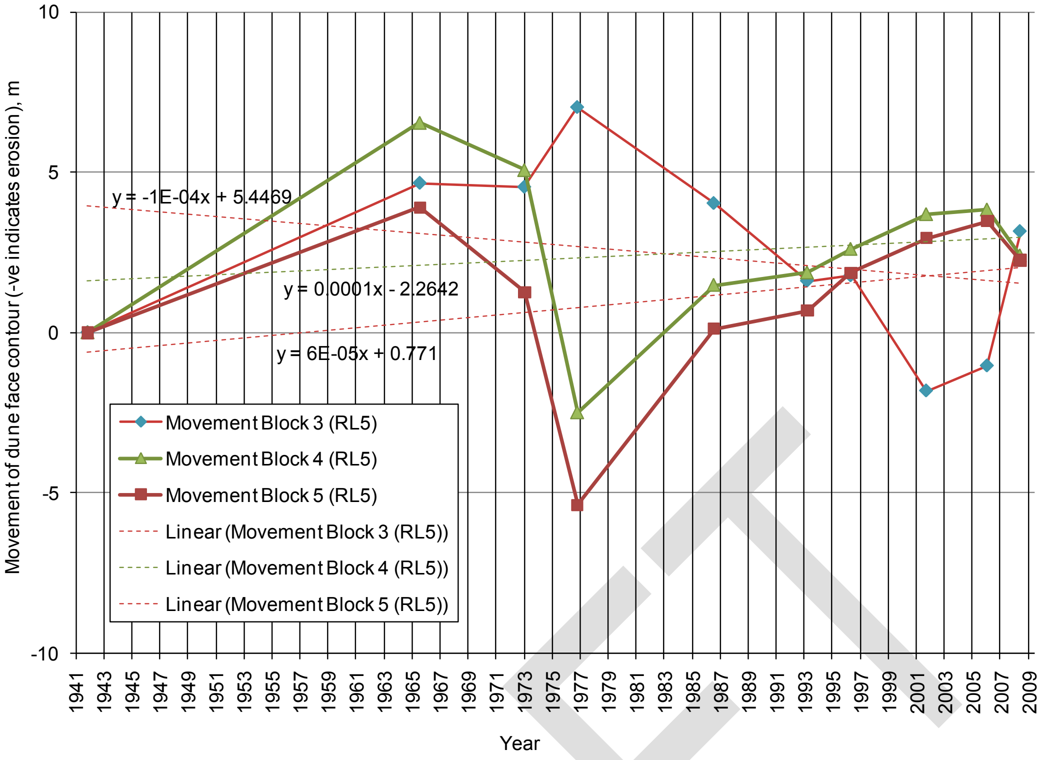

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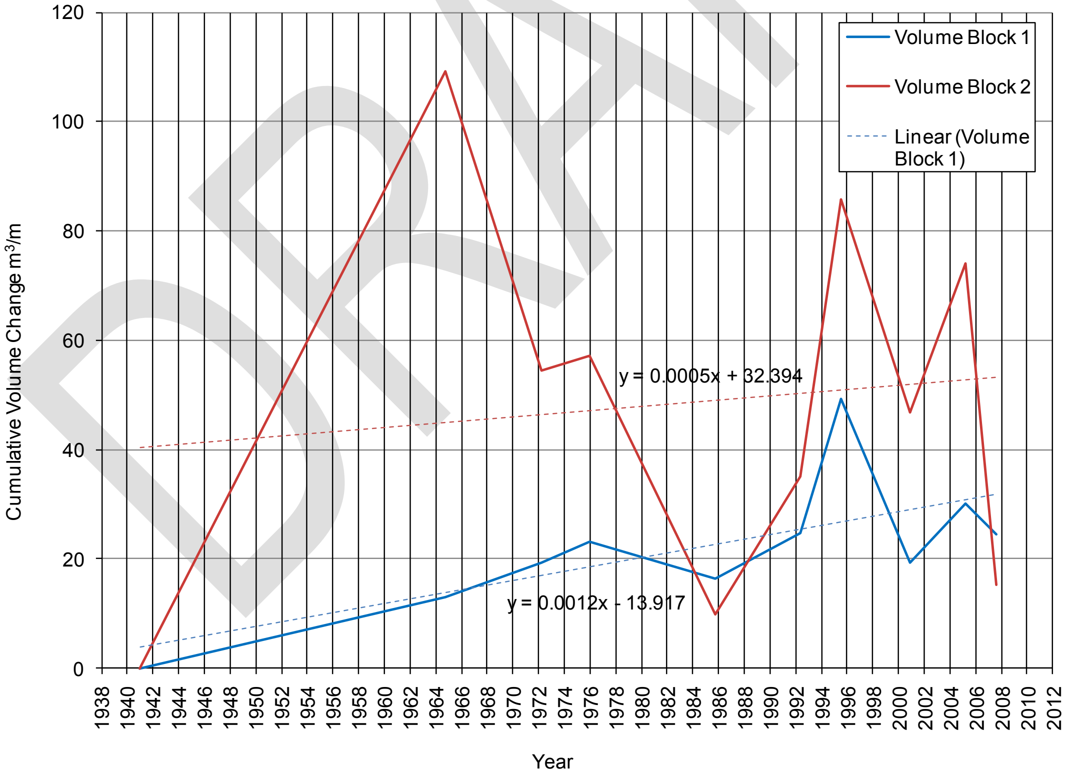

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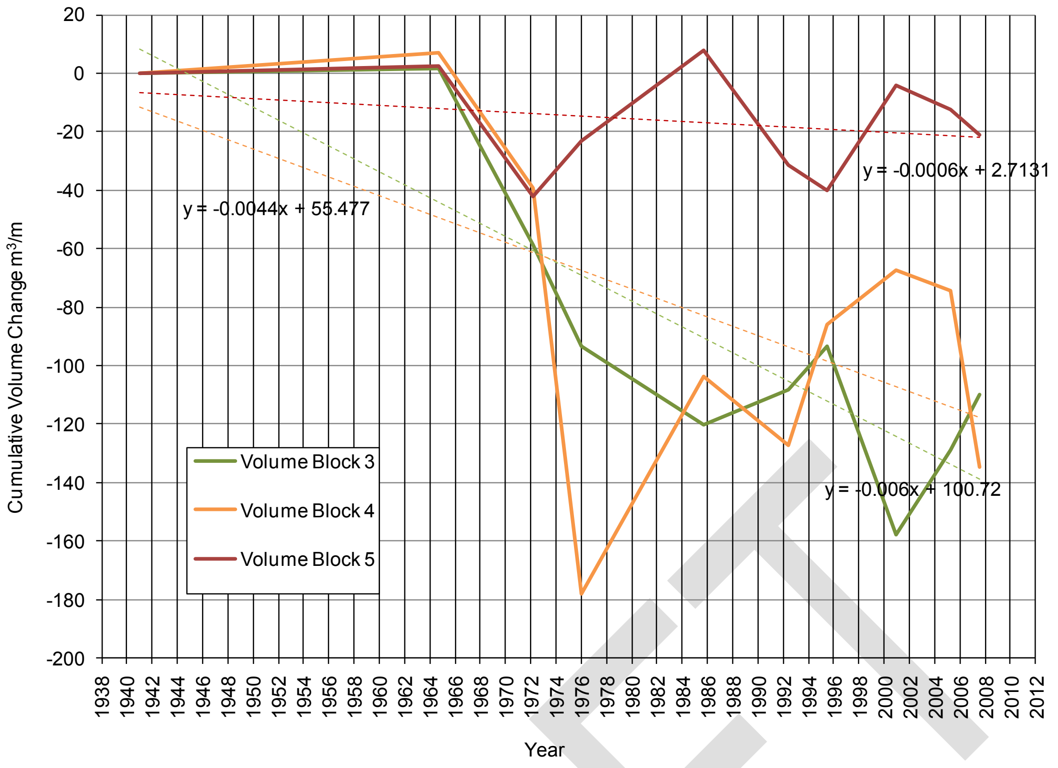
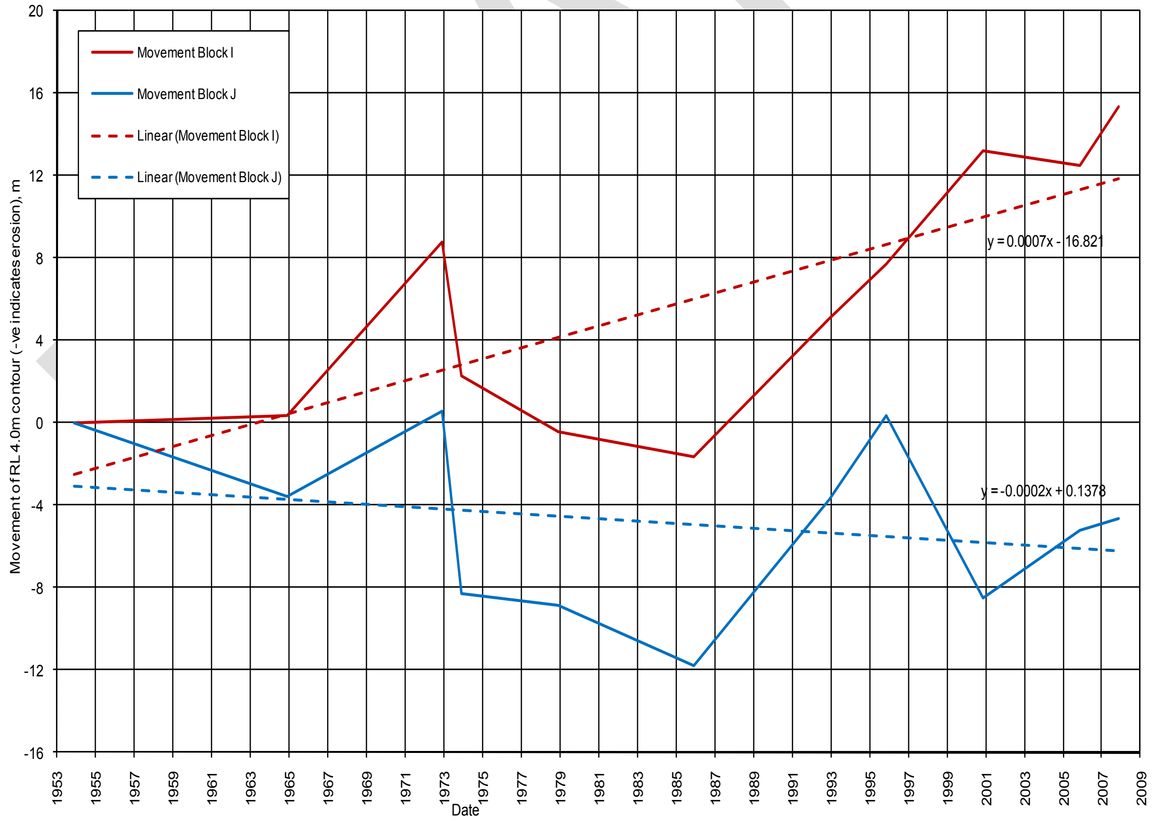


Figure B.53 – Average volume change for Blocks 3, 4 and 5, Soldiers Beach



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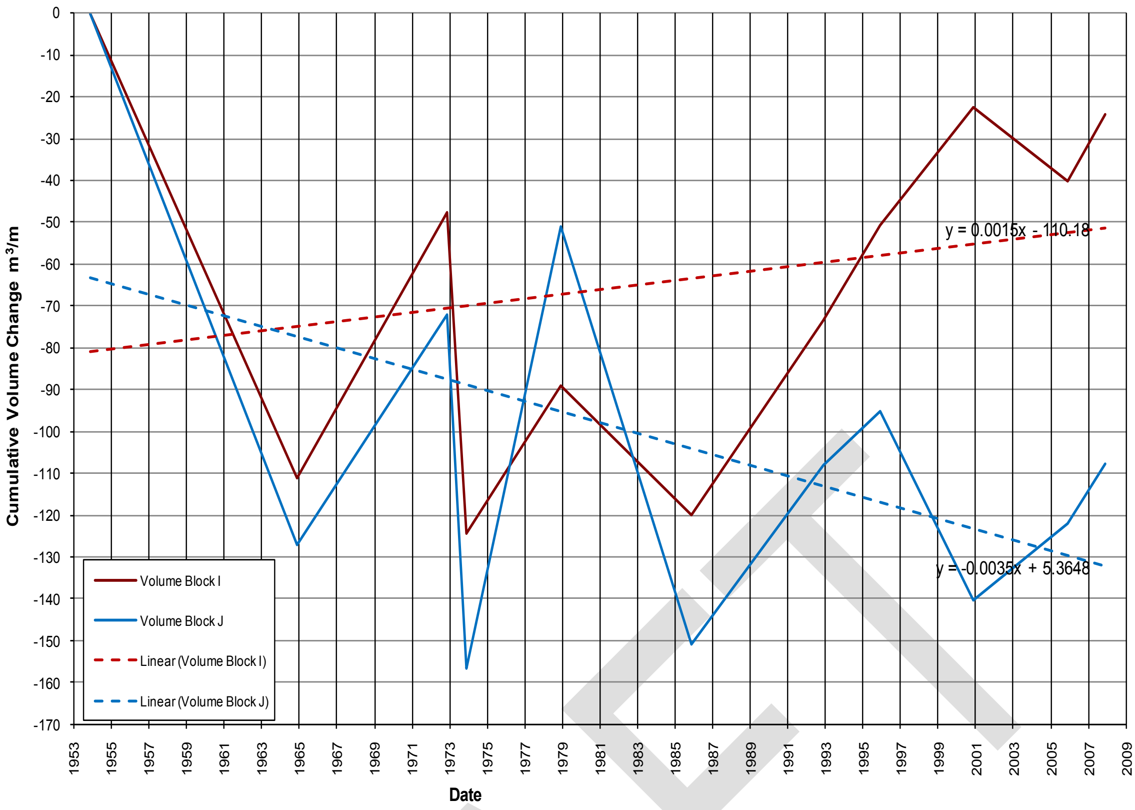

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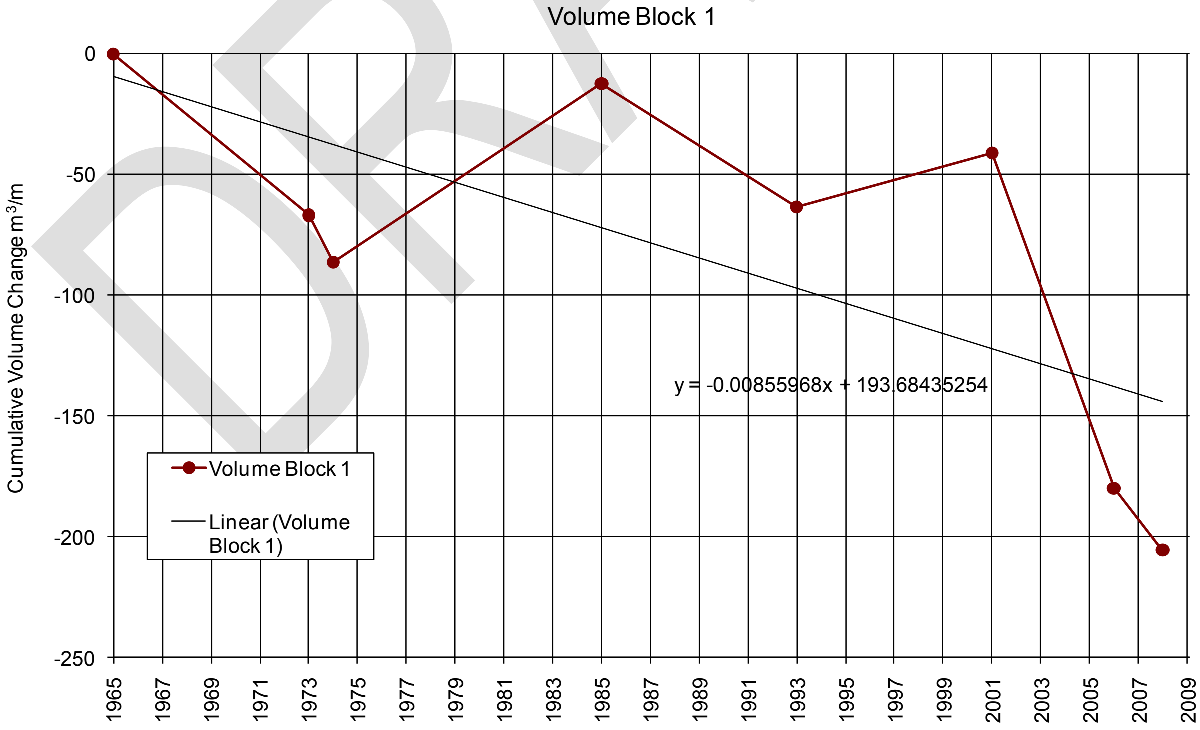

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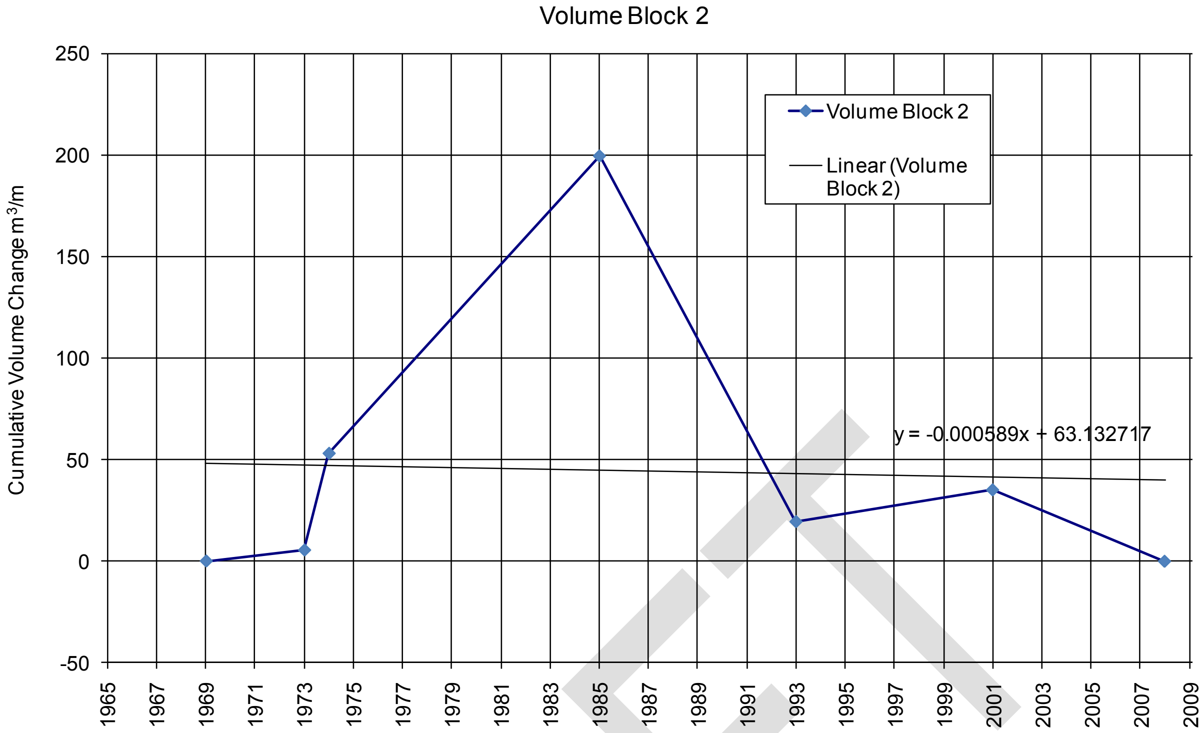

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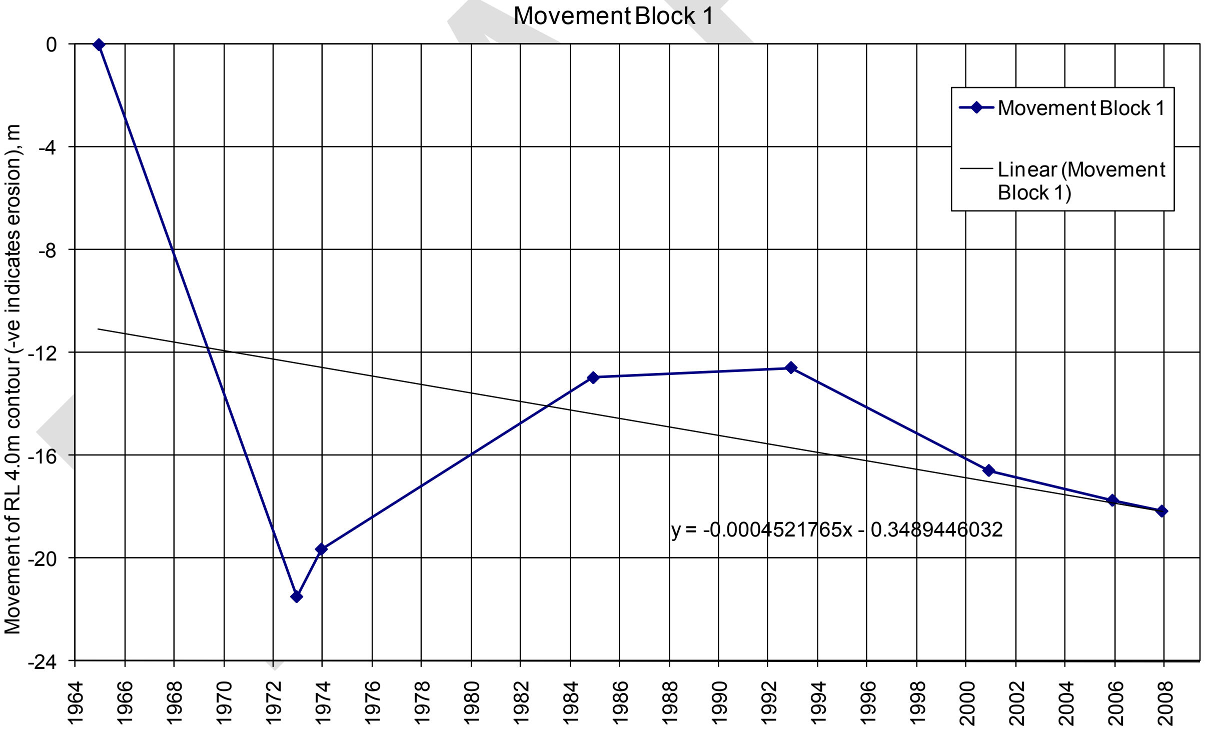

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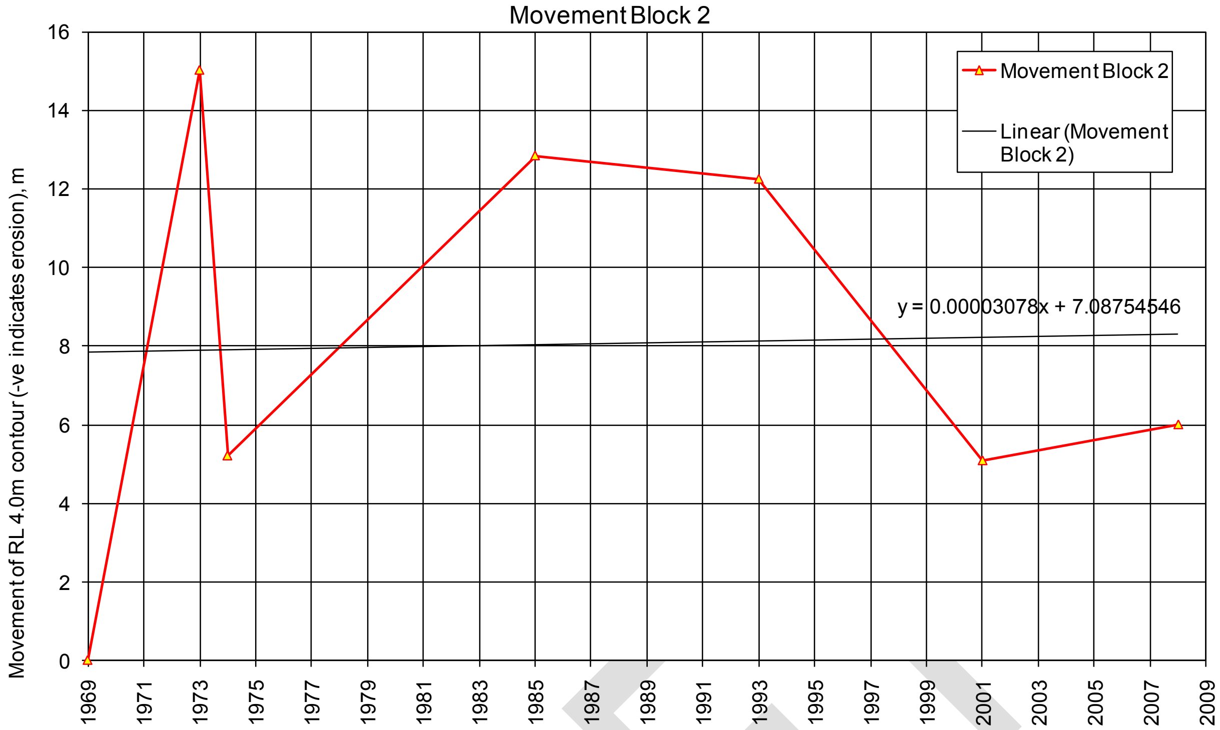

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Project Name:	Wyong Coastal Hazard Study – Final Draft
Project Number:	3001053
Report for:	Umwelt Australia

PREPARATION, REVIEW AND AUTHORISATION

Revision #	Date	Prepared by	Reviewed by	Approved for Issue by
1	26/02/10	M. Glatz	C. Adamantidis	C. Adamantidis
2	28/05/10	M. Glatz and C. Adamantidis	C. Adamantidis	C. Adamantidis
3	1/10/10	M. Glatz and C. Adamantidis	C. Adamantidis	C. Adamantidis

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Appendix C

Climate Change

For: Umwelt Australia

TABLE OF CONTENTS

1 INTRODUCTION

Climate is the pattern or cycle of weather conditions, such as temperature, wind, rain, snowfall, humidity, clouds, including extreme or occasional ones, over a large area and averaged over many years. Changes to the climate and, specifically, changes in mean sea levels, wind conditions, wave energy and wave direction, can be such as to change the coastal sediment transport processes shaping beach alignments.

Climate change had been defined broadly by the Intergovernmental Panel on Climate Change (IPCC, 2001) as any change in climate over time whether due to natural variability or as a result of human activity. Apart from the expected climate variability reflected in seasonal changes, storms, *etc.*, climate changes that are considered herein refer to the variability in average trends in weather that may occur over time periods of decades and centuries. These may be a natural variability of decadal oscillation or permanent trends that may result from such factors as changes in solar activity, long-period changes in the Earth's orbital elements (eccentricity, obliquity of the ecliptic, precession of equinoxes), or man-made factors such as, for example, increasing atmospheric concentrations of carbon dioxide and other *greenhouse* gases.

The signature of climate variability over periods of decades is seen in the Southern Oscillation Index (SOI), a number calculated from the monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin. Sustained negative values of the SOI usually are accompanied by sustained warming of the central and eastern tropical Pacific Ocean, a decrease in the strength of the Pacific Trade Winds and a reduction in rainfall over eastern and northern Australia. This is called an *El-Niño* episode. During these episodes, a more benign south-easterly wave condition is expected on the NSW coast. Positive values of the SOI are associated with stronger Pacific trade winds and warmer sea temperatures to the north of Australia, popularly known as a *La-Niña* episode. Waters in the central and eastern tropical Pacific Ocean become cooler during this time. Together, these give an increased probability that eastern and northern Australia will be wetter than normal and, during these episodes, severe storms may be expected on the Australian Eastern seaboard.

Over much longer time frames, the Intergovernmental Panel on Climate Change (IPCC 2001) has indicated that the global average surface temperature has increased over the 20th century by 0.6°C and that this warming will continue at an accelerating rate. This warming of the average surface temperature is postulated to lead to warming of the oceans, which would lead to thermal expansion of the oceans and loss of mass from land-based ice sheets and glaciers. This would lead to a sea level rise which, in turn, would lead to recession of unconsolidated shorelines.

2 SEA LEVEL RISE

2.1 Historic Sea Level Rise

Tidal gauge data show that over the 20th century global average sea level rose between 0.1 m and 0.2 m; that is, at an average rate of between 1 mm/y to 2 mm/y (IPCC, 2001). Mitchell *et al.* (2001) summarised observed sea level rise in Australia and the Pacific. Analysis of data from Fort Denison in Sydney showed that, between 1914 and 1997, the underlying trend in sea level rise has been an average increase in relative sea level of 0.86 mm/year (and 1.18 mm/year in Newcastle). However, it was noted that there was considerable variation in the data, which was due to processes acting at inter-decadal scales, such as the *El-Niño* Southern Oscillation phenomenon. Part of this (25 mm) was due to isostatic rebound inducing a rise of the land mass, which is occurring at a rate of 0.3 mm/year. Mitchell *et al.* (2001) corrected sea-level changes at Fort Denison to an average increase of 1.16 mm/year to account for this rate of post-glacial rebound.

Satellite altimetry data has recently been employed to measure changes in global sea level – this has allowed a more accurate measurement of changes in Mean Sea Level around the globe since around 1993. From these measurements, it is apparent from Figure C.1 that the rate of sea level rise has accelerated in the later part of the 20th century, with sea level in Australia rising by around 3.1 mm/year between 1993 and 2004 (White and Church, 2006).

2.2 Projected Sea Level Rise

The National Committee on Coastal and Ocean Engineering of Engineers Australia has issued *Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering* (NCCOE, 2004). These *Guidelines* indicated a range of engineering estimates for global average sea level rise from 1990 to 2100 of 0.1 m to 0.9 m with a central value of 0.5 m. The *Guidelines* indicated also that global average sea level rise scenarios must be converted to estimated local relative sea level movement for each site. In this regard, reference has been made to the IPCC projections for global and regional sea level change.

Using various climate models for different climate change scenarios, the Third Assessment Report (TAR) of the IPCC (2001) projected a range of sea level rises for the 21st century. It was projected that global average sea levels could rise from between 0.09 m and 0.90 m by 2100 (Figure C.2; and from between 0.05 m and 0.30 m by around 2055).

From the IPCC Fourth Assessment Report (2007), the 5% to 95% confidence limit ranges of sea level rise predictions for the 21st century are shown in Figure C.3 and summarised in Table C.1, for the various scenarios and based on the spread of model results.

It can be seen from Table C.1 that the 95% confidence interval for global average sea level rise in the worst case scenario (Scenario A1FI) is 0.59 m for the 2100 planning period. This is made up of various components, including thermal expansion of the oceans (the largest component), melting of the Greenland and Antarctic ice sheets and melting of land-based glaciers. There is considerable uncertainty also in the level of ice-sheet discharge, which could contribute, at a maximum, an additional 0.17 m to the worst-case scenario global average sea level rise (refer Table C.2). This would give an upper bound sea level rise of 0.76 m for the 2100 planning period.

There is also a local effect due to the East Australian Current, which could add around 10-14 cm to the global average sea level rise (McInnes et al.,2007).

In addition to the effects of climate change, there is also an existing underlying rate of sea level rise. Mitchell et al. (2001) quantified underlying rates of existing sea level rise at various tide gauge locations around Australia. Factors other than global warming that contribute to the underlying rate of sea level rise include (Walsh *et al*., 2004):

- geological effects caused by the slow rebound of land that was covered by ice during the last Ice Age (isostatic rebound);
- flooding of continental shelves since the end of the last Ice Age, which pushes down the shelves and causes the continent to push upwards in response (hydroisostasy);
- changes in land height in tectonically or volcanically active regions;
- changes in atmospheric wind patterns and ocean currents; and
- local subsidence due to sediment compaction or groundwater extraction.

This underlying rate has been estimated at 0.12 metres for 2100 in NSW.

Combining the relevant global and local information indicates that sea level rise on the NSW coast is expected to reach up to **0.90 m** for the 2100 planning period. For 2050, the sea level rise benchmark advocated by the NSW Sea Level Rise Policy (2009) is 0.40 m.

It should be noted also that sea level rise is subject to considerable regional variation, with the southern ocean in general forecast to undergo less sea level rise than the Arctic, due to regional climatic variations and local changes in salinity and ocean density. In the region off the east coast of Australia, the IPCC (2007) report indicates that the expected sea level rise would be close to the geographic global average.

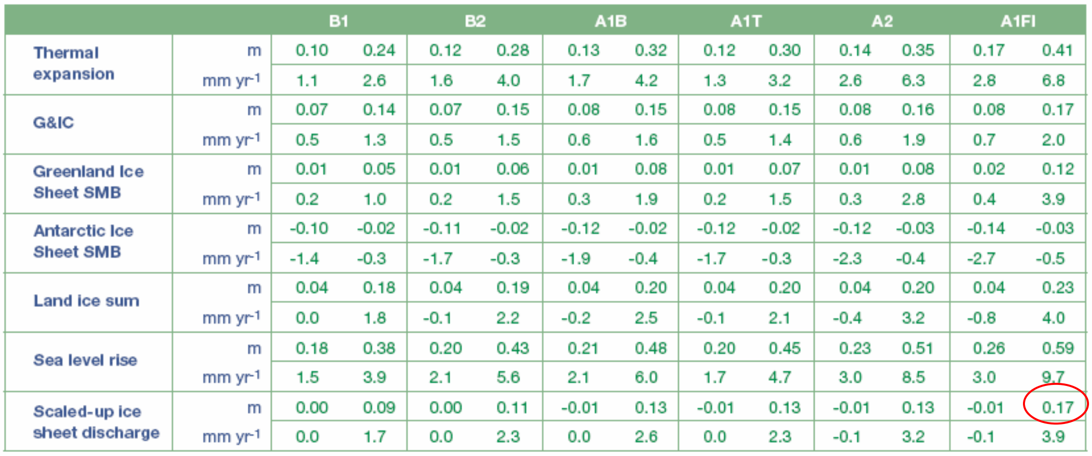
The NSW Department of Environment and Climate Change and Water (DECC&W) has recently been advocating sensitivity analyses using a range of sea level rise scenarios for various planning horizons. As the 5% lower bound estimate from the IPCC report has a 95% probability of being exceeded for the 2100 planning period it is generally excluded from the sensitivity analysis for planning purposes.

Table C.1 - Range of Sea Level Rise Predictions (IPCC 2007)

Scenario	5% (Lower bound) predicted sea level rise 1980-1999 to 2090-2099 (m)	Assumed median predicted sea level rise 1980-1999 to 2090-2099 (m)*	95% (upper bound) predicted sea level rise 1980-1999 to 2090-2099 (m)
B1	0.18	0.28	0.38
B2	0.20	0.32	0.43
A1B	0.21	0.35	0.48
A1T	0.20	0.33	0.45
A2	0.23	0.37	0.51
A1F1	0.26	0.43	0.59

*The IPCC (2007) report does not provide median values for predicted sea level rise. Median values have been assumed by adopting the central value between the 5% and 95% confidence interval limits.

*Table C.2 - Contributions to global average sea level rise for various scenarios, 1990 – 2095 (source: IPCC 2007).**



		B1		B2		A1B		A1T		A2		A1FI	
Thermal expansion	m	0.10	0.24	0.12	0.28	0.13	0.32	0.12	0.30	0.14	0.35	0.17	0.41
	mm yr^{-1}	1.1	2.6	1.6	4.0	1.7	4.2	1.3	3.2	2.6	6.3	2.8	6.8
G&IC	m	0.07	0.14	0.07	0.15	0.08	0.15	0.08	0.15	0.08	0.16	0.08	0.17
	mm yr^{-1}	0.5	1.3	0.5	1.5	0.6	1.6	0.5	1.4	0.6	1.9	0.7	2.0
Greenland Ice Sheet SMB	m	0.01	0.05	0.01	0.06	0.01	0.08	0.01	0.07	0.01	0.08	0.02	0.12
	mm yr^{-1}	0.2	1.0	0.2	1.5	0.3	1.9	0.2	1.5	0.3	2.8	0.4	3.9
Antarctic Ice Sheet SMB	m	-0.10	-0.02	-0.11	-0.02	-0.12	-0.02	-0.12	-0.02	-0.12	-0.03	-0.14	-0.03
	mm yr^{-1}	-1.4	-0.3	-1.7	-0.3	-1.9	-0.4	-1.7	-0.3	-2.3	-0.4	-2.7	-0.5
Land ice sum	m	0.04	0.18	0.04	0.19	0.04	0.20	0.04	0.20	0.04	0.20	0.04	0.23
	mm yr^{-1}	0.0	1.8	-0.1	2.2	-0.2	2.5	-0.1	2.1	-0.4	3.2	-0.8	4.0
Sea level rise	m	0.18	0.38	0.20	0.43	0.21	0.48	0.20	0.45	0.23	0.51	0.26	0.59
	mm yr^{-1}	1.5	3.9	2.1	5.6	2.1	6.0	1.7	4.7	3.0	8.5	3.0	9.7
Scaled-up ice sheet discharge	m	0.00	0.09	0.00	0.11	-0.01	0.13	-0.01	0.13	-0.01	0.13	-0.01	0.17
	mm yr^{-1}	0.0	1.7	0.0	2.3	0.0	2.6	0.0	2.3	-0.1	3.2	-0.1	3.9

*The additional 0.17 m sea level rise allowed for uncertainties in ice-sheet discharge is the upper bound range under the A1FI scenario, as indicated in the Table. This needs to be added to the sea level rise attributed to the other sources of sea level rise indicated in Table 2, which include thermal ocean expansion, melting of glaciers and ice caps, melting of the Greenland Ice Sheet and changes in the Antarctic Ice Sheet.

The IPCC Fourth Assessment Report (2007) does not provide estimates of sea level rise for the 2050 planning horizon. However, the IPCC Third Assessment Report (2001) provides projections over the 21st century (Figure C.2), with a median value of around 0.2 m and a maximum value of around 0.35 m. Adding the underlying rates of sea level rise yields a maximum value of around 0.4 m for the 2050 planning period.

The projections of future sea level rise for the Wyong coastal hazard study are in line with those in the NSW Sea Level Rise Policy and presented in Table C.3.

Table C.3 – Projected Greenhouse sea level rise scenarios for Wyong Shire coastline

Scenario Range	2050	2100
Maximum	0.40 m	0.90 m

2.2.1 NSW Sea Level Rise Policy Statement

The IPCC were unable to exclude larger values and there is emerging evidence in the current measurements and observations, suggesting the IPCC's 2007 report may have underestimated the future rate of sea level rise. The NSW Government through the NSW Sea Level Rise Policy Statement have set the NSW Sea Level Rise Planning benchmark at the upper bound levels of a 0.40 m increase above 1990 levels by 2050 and 0.90 m by 2100. The rationale behind the NSW Government's adoption of the respective planning benchmark allowances for SLR are detailed in the DECCW publication "Derivation of the NSW Government's sea level rise planning benchmarks – Technical Note (DECCW, 2009a). The benchmarks are based on the sea level rise developed by Australian and international experts and include globally averaged sea level rise, accelerated ice melt, and regional sea level rise variations.

2.3 Impacts Of Sea Level Rise

2.3.1 Bruun Rule

The most widely accepted method of estimating shoreline response to sea level rise is the Bruun Rule (Bruun, 1962; 1983). Bruun (1962, 1983) investigated the long term erosion along Florida's beaches, which was assumed to be caused by a long term sea level rise. Bruun (1962, 1983) hypothesised that the beach assumed an *equilibrium profile* that kept pace with the rise in sea level without changing its shape, by an upward translation of sea level rise (S) and shoreline retreat (R).

Figure C.4 illustrates the concept of the Bruun Rule. The Bruun Rule equation is given by:

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

where: R = shoreline recession due to sea level rise;

S = sea level rise (m)

h_c = closure depth

B = berm height; and

L = length of the active zone.

The Bruun model assumes that the beach profile is in an equilibrium state.

Berm height is taken to be the average height of the dune along the beach, and closure depth is the depth at the seaward extent of measurable sand movement. The length of the active zone is the distance offshore along the profile in which sand movement still occurs.

2.3.2 Determination Of Bruun Rule Parameters

Several schemas exist, based on analytical and laboratory studies, to determine closure depth and length of the active zone, including those of Swart (1974) and Hallermeier (1981, 1983).

Hallermeier (1981, 1983) defines a simple zonation of an onshore-offshore beach profile consisting of a *littoral* zone, *shoal* zone or buffer zone, and offshore zone where surface wave effects on the bed are negligible.

Based on an analytical approach, supported by laboratory data and some field data, the two water depths bounding the shoal zone, defined by d_s and d_o are given by:

$$d_s = \frac{2.9H}{\left(S-1\right)^{0.5}} - \frac{110H^2}{\left[\left(S-1\right)gT^2\right]}$$

where d_s = water depth bounding the littoral and shoal zones

H = significant wave height *exceeded 12 hours per year*

T = associated wave period

S = specific gravity of the sediment, and

G = acceleration due to gravity; and

$$d_o = 0.018 H_{med} T_{med} \left[\frac{g}{(S-1)D_{50}} \right]^{0.5}$$

where d_o is the depth at the boundary of the offshore zone and H and T are the median *significant* wave height and period parameters and D_{50} is the median grain size. For Wyong Shire, H_{med} = 1.5 m; T_{med} = 9.0 s; H_s = 9.5 m and T_p = 12 s (*"Future Directions for Wave Data Collection in New South Wales"*, Kulmar & Lord, 2005).

Typical beach sand characteristics give S = 2.65, a median grain size value of 0.25mm has been assumed for Wyong Shire.

Use of these values gives:

d_s = 16.50 m and

d_o = 39.60 m.

Nielsen (1994) reviewed these, other analytical methods and a large body of field data to define subaqueous fluctuations of open coast beaches in NSW. Nielsen (1994) found that the absolute limit of offshore sand transport under cyclonic or extreme storm events occurred at a depth of 22m. Use of the Hallermeier (1981, 1983) formulation for estimating the closure depth gives an inner limit for the depth of closure of around 16.50 m and an outer limit of around 40 m.

A depth of closure of around 1m has been estimated by applying the method of Nielsen (1994) for Toowoon and Blue Bay due to the presence of the reef along the shore. A closure depth of 16.50 m has been used for South Entrance Beach after study of the bathymetric data and of the equilibrium profile of the beach. A depth of closure of 9-15m was measured for the southern end of North Entrance Beach, 15-25m for the centre of the beach and 7-8 for the northern end. A closure depth of 6-8m has been estimated for Soldiers Beach and 7-19m for Shelly Beach. A depth of closure of around 26m was used for Lakes Beach and of less than 7m for Hargraves.

Bruun (1954) proposed a simple power law to describe the relationship between water depth, h, and offshore distance, x, measured at the mean sea level:

$$h = Ax^{\frac{2}{3}}$$

where A is a dimensional shape factor, mainly dependent on the grain size. Figure C.5 (from Dean, 1987) gives an empirical relationship between A and grain size, D. This gives a value of A for the different beaches along the Wyong Shire coast, based on an assumed median grain size of around 0.25 mm, of approximately 0.1 to 0.15. These closure depths were estimated by analysing the data from the digitised soundings on an approximately 1 km grid as provided by Geoscience Australia, as well as closely spaced depth soundings from detailed bathymetric survey and topographic data from the Aerial Laser Survey (ALS) provided by Wyong Shire Council.

The equilibrium profile lengths were measured for the different beaches. Equilibrium profile lengths of 100-150m were measured for Toowoon and Blue Bay and of around 1050m for South Entrance. Lengths of 450-750m were estimated for the southern end of North Entrance Beach, 700-1200m for the centre of the beach and 500-600m for the northern end. The equilibrium profile length was of 600-1000m for Soldiers Beach and

500-1200m for Shelly Beach. An equilibrium profile length of around 2400m was used for Lakes Beach and one of less than 400m for Hargraves Beach.

The closure depths and the equilibrium profile lengths have been assessed from the beach profile graph. These two characteristics are the coordinates of the last point fitting with the equilibrium profile.

These results have been used to determine the recession and the erosion along Wyong Shire coastline as the application of the Bruun Rule is limited to the portion of the profile in equilibrium. The computed nearshore profile slope is within the range of 1:11 to 1:13 for Toowoon and Blue Bays due to the presence of a reef along the shoreline, 1:48 to 1:52 for South Entrance, 1:29 to 1:45 for North Entrance and Soldiers Beach. 1:35 to 1:42 for Shelly Beach, 1:15 and 1:32 for Hargraves Beach and was around 1:70 for Lakes Beach. Most of these slopes are relatively common along NSW coastline. However, some slopes are steeper due to the presence of offshore reefs.

A comparison plot of the shore-normal profile at Wyong Shire and the estimated equilibrium profile is given in Figure C.6. It should be noted that the nearshore profile is based on limited data.

2.3.3 Beach Response

2.3.3.1 Shelly Beach

Results of the Bruun analysis for Shelly Beach are given in Table C.7.

Table C.4 - Predicted beach erosion due to sea level rise, Shelly Beach

Block	Total Predicted Sea Level Rise (m)		Nearshore Equilibrium Slope (1:X)	Total Beach Recession (m)		Total Beach Erosion (m^3/m)	
	2050	2100		2050	2100	2050	2100
1	0.40	0.90	35	15.2	34.2	72.9	164.0
2			42	17.4	39.2	189.8	426.9
3			37	14.8	33.3	128.8	289.7

For an upper-range sea level rise scenario in line with the NSW Sea Level Rise Policy Statement, the total beach recession relative to 1990 levels expected would be **14.8-17.4 metres by 2050** and **34.2-39.2 metres by 2100** for Shelly Beach.

2.3.3.2 Toowoon And Blue Bays

Results of the Bruun analysis for Toowoon and Blue Bays are given in Table C.4.

Table C.5 - Predicted beach erosion due to sea level rise, Toowoon Bay

Block	Total Predicted Sea Level Rise (m)		Nearshore Equilibrium Slope (1:X)	Total Beach Recession (m)		Total Beach Erosion (m^3/m)	
	2050	2100		2050	2100	2050	2100
Toowoon Bay	0.40	0.90	13	5.2	11.7	52.0	116.9
Blue Bay			11	4.4	9.8	39.5	88.8

For an upper-range sea level rise scenario in line with the NSW Sea Level Rise Policy Statement, the total beach recession relative to 1990 levels expected would be **5.2 metres by 2050** and **11.7 metres by 2100** for Toowoon Bay and **4.4 metres by 2050** and **9.8 metres by 2100** for Blue Bay.

It should be noted that these recession rates assume that the dune is composed of erodible material. Where a superficial layer of sandy beach overlies bedrock the erosion would be limited. Most of Toowoon and Blue Bays' coastline is underlain by rocks.

2.3.3.3 South Entrance

The Bruun calculation would not be valid for the South Entrance Surf Club or Boatshed, as these sites are underlain by rock and the Bruun Rule does not apply.

2.3.3.4 North Entrance

Results of the Bruun analysis for North Entrance Beach are given in Table C.5.

Table C.6 - Predicted beach erosion due to sea level rise, North Entrance

Block	Total Predicted Sea Level Rise (m)		Nearshore Equilibrium Slope (1:X)	Total Beach Recession (m)		Total Beach Erosion (m³/m)	
	2050	2100		2050	2100	2050	2100
A	0.4	0.9	30	11.8	26.6	73.3	164.9
B			29	11.6	26.1	104.4	234.9
C			45	18.0	40.4	152.7	343.7
D			31	12.6	28.3	104.8	236.0
E			35	14.1	31.5	105.8	237.9
F			39	15.4	34.5	92.0	207.0
G			37	14.6	33.0	102.5	230.7
H			45	14.8	33.3	128.5	283.1

For an upper-range sea level rise scenario in line with the NSW Sea Level Rise Policy Statement, the total beach recession relative to 1990 levels expected would be **11.6-18.0 metres by 2050** and **26.1-40.4 metres by 2100** for North Entrance Beach.

2.3.3.5 Soldiers Beach

Results of the Bruun analysis for Soldiers Beach are given in Table C.6.

Table C.7 - Predicted beach erosion due to sea level rise, Soldiers Beach

Block	Total Predicted Sea Level Rise (m)		Nearshore Equilibrium Slope (1:X)	Total Beach Recession (m)		Total Beach Erosion (m³/m)	
	2050	2100		2050	2100	2050	2100
1	0.4	0.9	29	11.6	26.1	143.7	323.4
2			32	12.9	29.0	149.4	336.1
3			44	17.4	39.2	123.8	278.6
4-5			39	15.4	34.7	155.7	350.3

For an upper-range sea level rise scenario in line with the NSW Sea Level Rise Policy Statement, the total beach recession relative to 1990 levels expected would be **11.6-17.4 metres by 2050** and **26.1-39.2 metres by 2100** for Soldiers Beach.

2.3.3.6 Lakes Beach

Results of the Bruun analysis for Lakes Beach are given in Table C.8.

Table C.8 - Predicted beach erosion due to sea level rise, Lakes Beach

Block	Total Predicted Sea Level Rise (m)		Nearshore Equilibrium Slope (1:X)	Total Beach Recession (m)		Total Beach Erosion (m^3/m)	
	2050	2100		2050	2100	2050	2100
Lakes Beach	0.40	0.90	72	28.9	65.0	190.8	429.2
Budgewoi Lake	0.40	0.90	29	11.5	25.9	81.7	183.8

For an upper-range sea level rise scenario in line with the NSW Sea Level Rise Policy Statement, the total beach recession relative to 1990 levels expected would be **28.9 metres by 2050** and **65 metres by 2100** for Lakes Beach and **11.5 metres by 2050** and 25.9 **metres by 2100** for Budgewoi Lake.

2.3.3.7 Hargraves Beach

Results of the Bruun analysis for Hargraves Beach are given in Table C.9.

Table C.9 - Predicted beach erosion due to sea level rise, Hargraves Beach

Block	Total Predicted Sea Level Rise (m)		Nearshore Equilibrium Slope (1:X)	Total Beach Recession (m)		Total Beach Erosion (m^3/m)	
	2050	2100		2050	2100	2050	2100
I	0.4	0.9	25	10.2	22.9	58.7	132.1
J			16	6.7	15.0	45.9	103.3

For an upper-range sea level rise scenario in line with the NSW Sea Level Rise Policy Statement, the total beach recession relative to 1990 levels expected would be **6.7-10.2 metres by 2050** and **15.0-22.9 metres by 2100** for Hargraves Beach.

2.3.4 Estuary Entrance Response

Sea level rise is likely to cause an increase in the tidal prism of Tuggerah Lake entrance, leading to an increase in the volume of sand trapped in the ebb-tide and flood-tide deltas within the entrance (US National Research Council, 1987). This increased volume of sand trapped within the entrance is sourced from the adjacent beach, leading to erosion of the beach on either side of the entrance. For natural entrances, a larger ebb and flood tide delta means that longshore drift has a reduced capacity to bypass the entrance, and sediment infilling of the entrance occurs.

Further, an increased tidal prism would lead to the entrance offshore bar moving further offshore into deeper water, thus increasing the wave energy that can reach the beach and causing erosion. This has occurred at trained estuary entrances on the NSW coast, such as at Town Beach at Port Macquarie following construction of the breakwater on the northern bank of the Hastings River (SMEC, 2003). An increased tidal prism due to sea level rise could eventually send the estuary into an unstable scouring mode, which could lead to further beach erosion around the lake entrance. This may be occurring at a number of estuaries along the NSW coast, such as Lake Macquarie and Wallis Lake, due to an increased tidal prism caused by construction of entrance training walls at these estuaries (Nielsen and Gordon, 2007).

The lake entrance dynamics would likely also be influenced by changes in wave climate brought about by climate change, including changes in the frequency of *El-Niño* and *La-Niña* events.

Potential for a new entrance to the estuary at Lakes Beach, Budgewoi also exists due to long term recession of the narrow dune here as a result of sea level rise. This new entrance would dramatically change the estuarine dynamics of Budgewoi Lake, causing the lake to have a higher tidal range and become more marine. This could threaten infrastructure fringing the lake with more frequent coastal inundation.

3 INCREASED STORMINESS

Hennessy *et. al.* (2004) predicts no increase in winter storm wind speeds for the NSW coast as a result of climate change. Mean wind-speed projections show a tendency for increases across much of the state in summer, with decreases in the north-east. In autumn, there is a tendency toward weaker winds in the south and east, and stronger winds in the north-west. The tendency in winter is toward increases in the far north-west and south and decreases elsewhere. A tendency for stronger winds is evident in spring, with greatest increases across central NSW.

Projected changes in extreme monthly winds (strongest 5%) showed similar patterns to the mean wind changes in summer and autumn, except that the magnitude of the increases and decreases tended to be larger. In winter, changes in extreme winds differed from changes in mean winds in that most of the state and the ocean in the far south showed a tendency for increasing extreme winds with, only the north-east indicating decreasing winds. However, as shown in Figure C.7, for the north coast the tendency was for little change or decrease in extreme wind speeds. In spring, extreme winds tended to increase, in agreement with the mean wind speed changes, except in a small area on the southern half of the coast where there was a tendency towards decreasing extreme winds.

In the winter half-year, the modelling has indicated that Tasman Lows contributing to extreme winds increased in frequency from 26% at present to 31% by 2070. Frontal systems also increased from 25% of extreme wind days at present to 29% by 2070.

4 SUMMARY AND CONCLUSIONS

Climate change has the potential to affect the beaches at Wyong Shire in two ways:

- erosion/recession resulting from beach rotation, longshore drift and lake entrance behaviour at decadal time scales; and
- overall beach recession resulting from sea level rise.

The IPCC (2007) projections for sea level rise caused by climate change have been synthesised with tectonic changes relevant for the NSW coast. The predicted shoreline response due to sea level rise along Wyong Shire has been examined using a Bruun analysis. Sea level rise may also increase the volume of the tidal prism of Tuggerah Lake entrance. This would further increase beach erosion by causing an increase in lake entrance infilling by beach sand.

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FIGURES

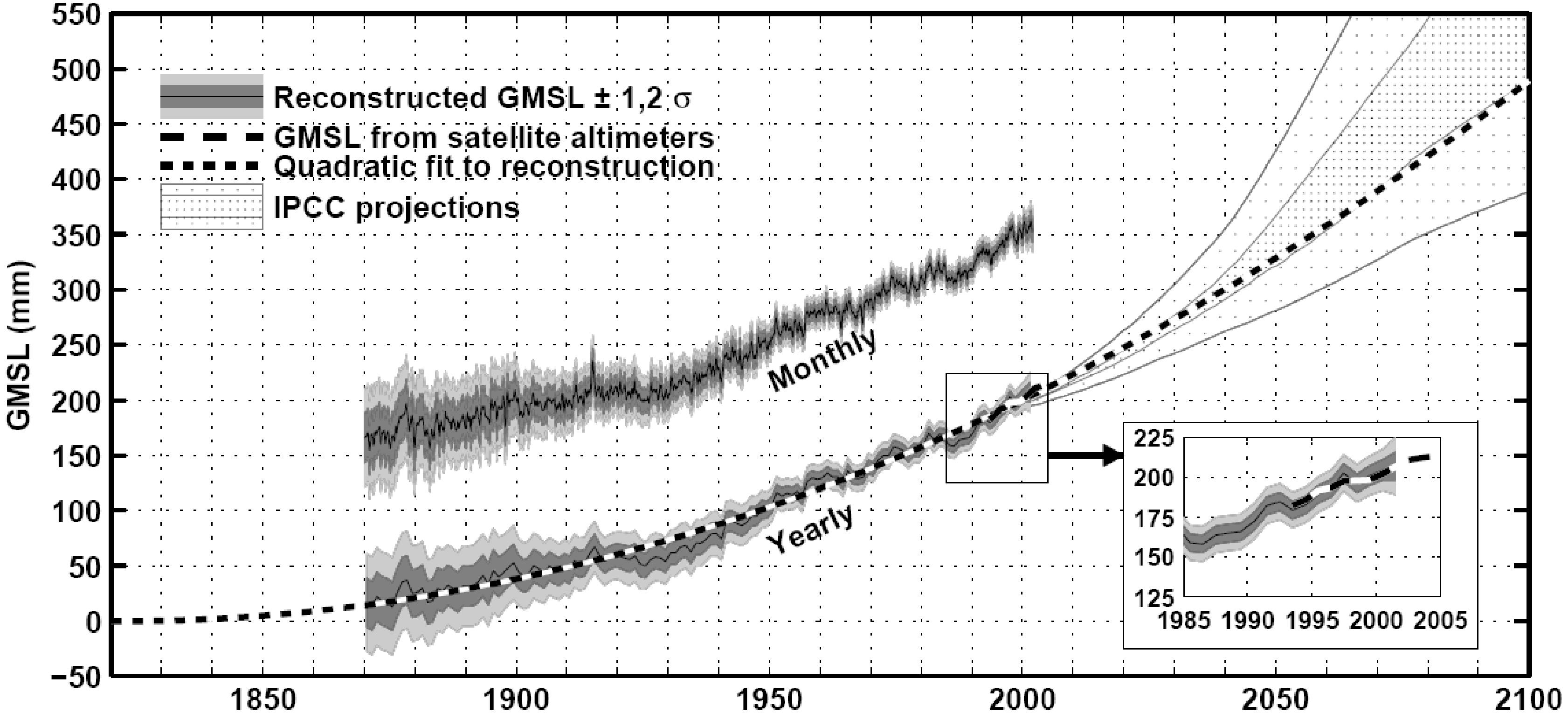


Figure C.1 – Measured global mean sea level 1870 – 2002 (White and Church, 2006)

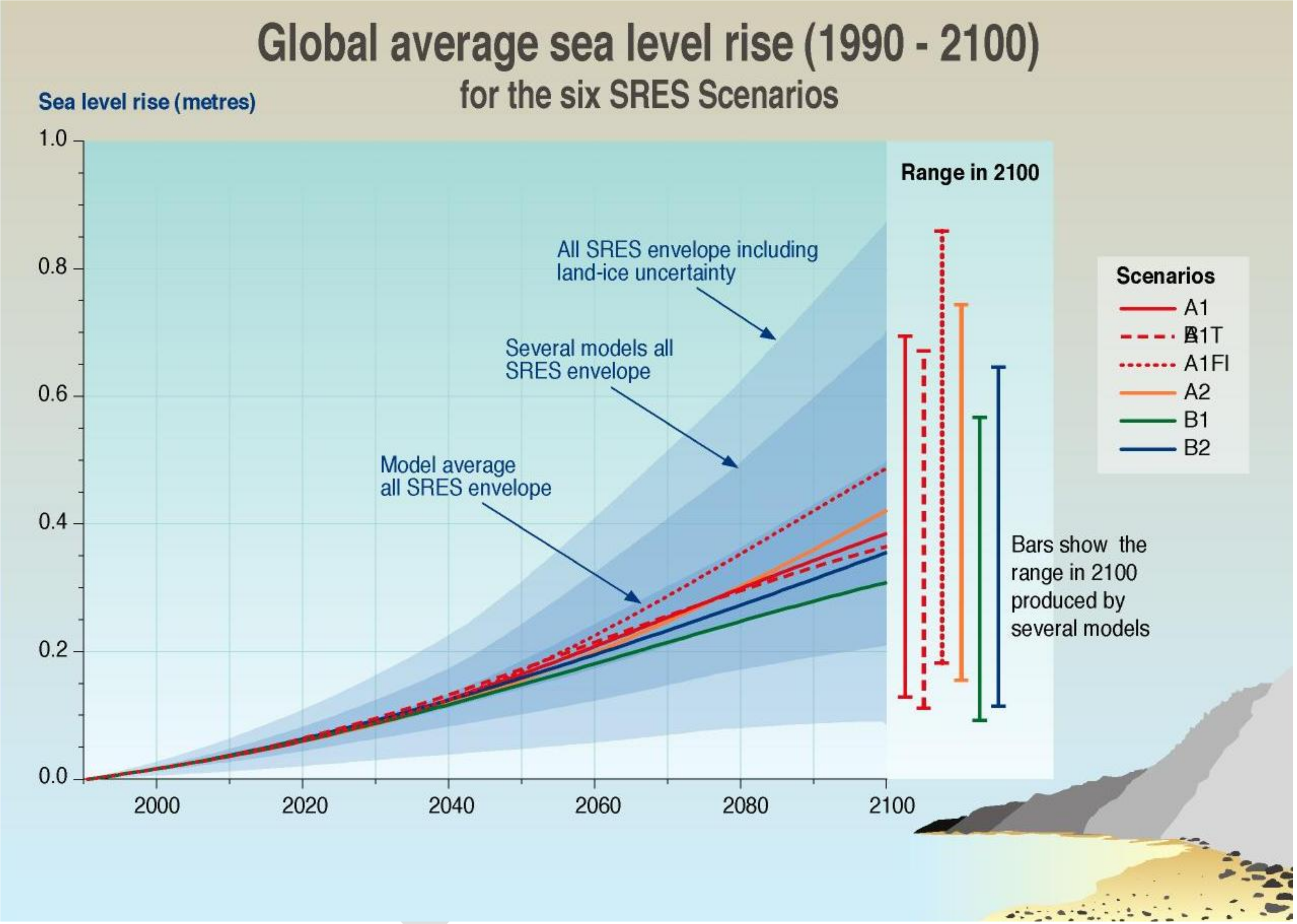


Figure C.2 – IPCC (2001) Sea level rise estimates

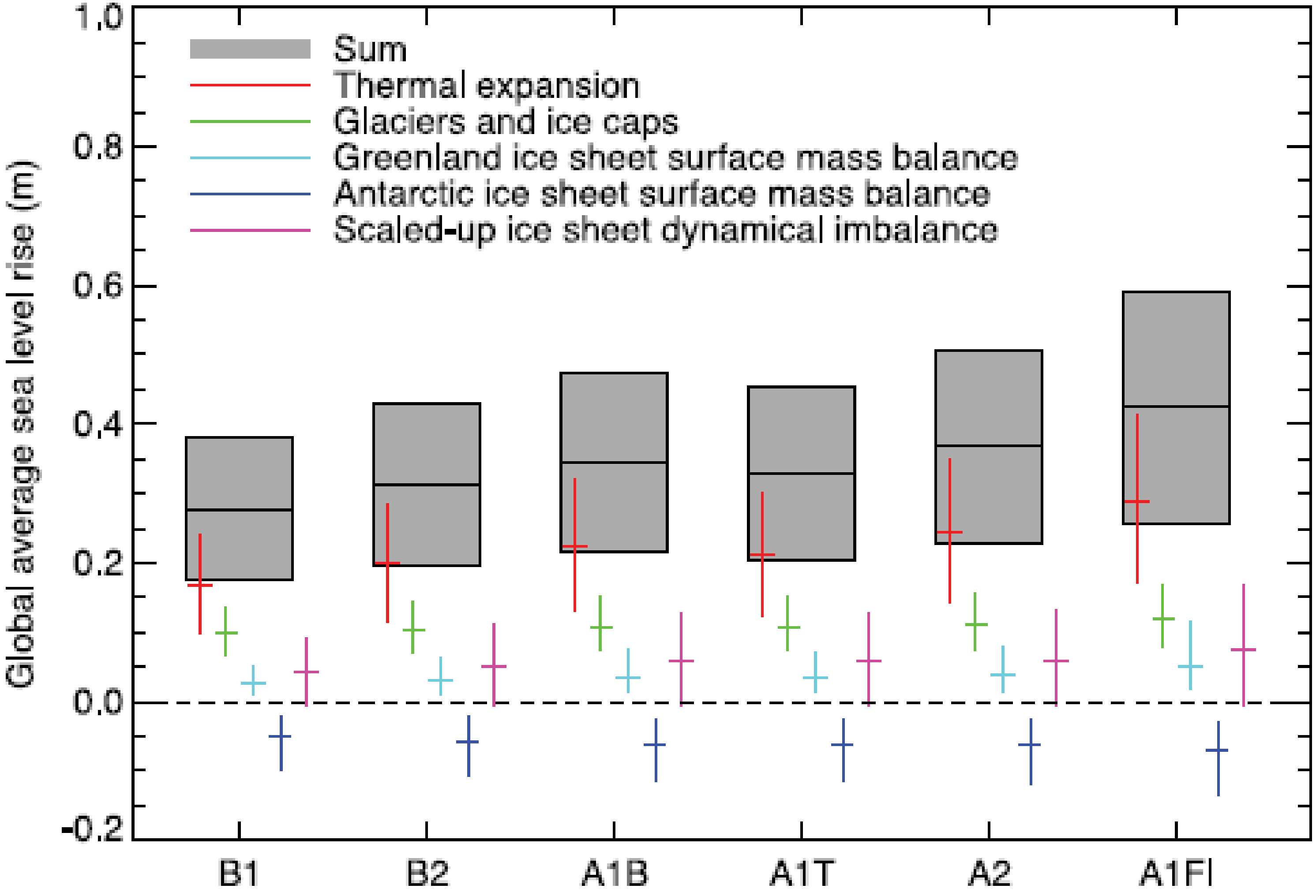
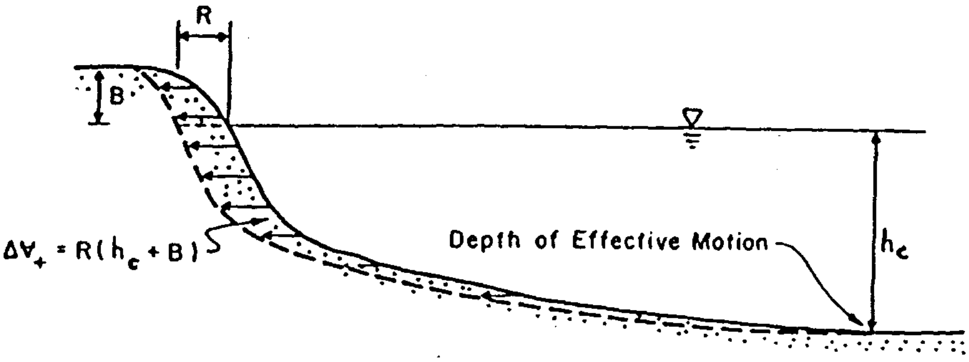
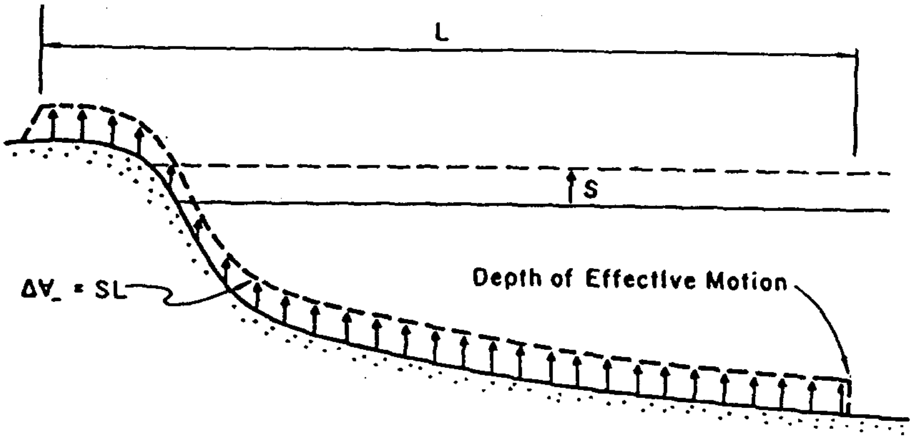


Figure C.3 – IPCC (2007) Global average sea level rise estimates



(a) Volume of Sand "Generated" by Horizontal Retreat, R, of Equilibrium Profile Over Vertical Distance ($h_c + B$)



(b) Volume of Sand Required to Maintain An Equilibrium Profile of Active Width, L, Due to a Rise, S, in Mean Water Level.

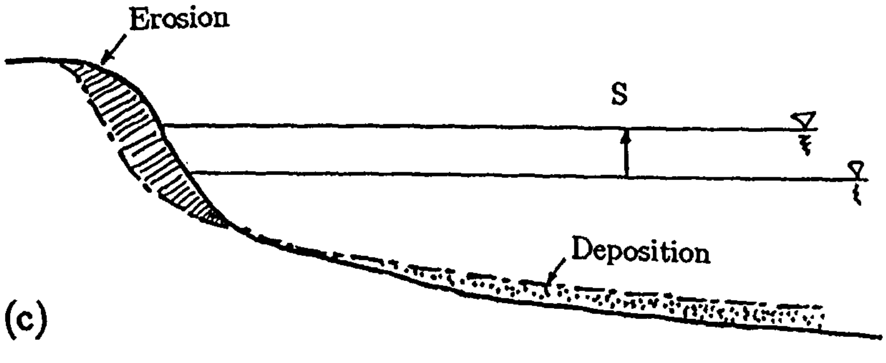


Figure C.4 - Concept of shoreline recession due to sea level rise

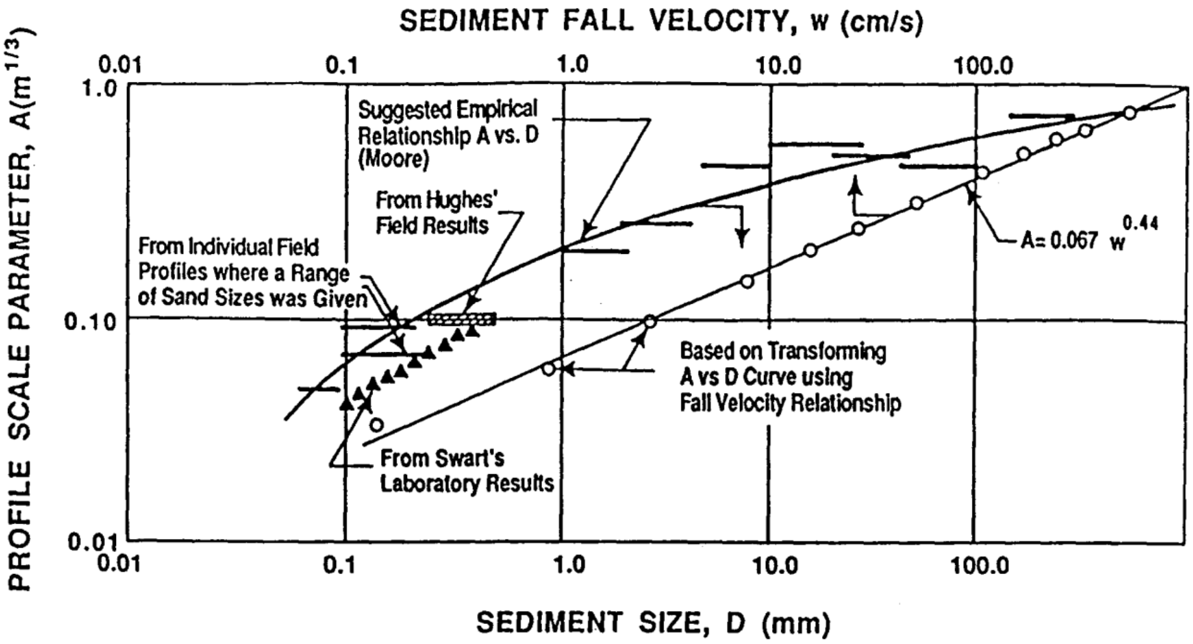


Figure C.5 – Suggested relationship for shape factor A vs. grain size D

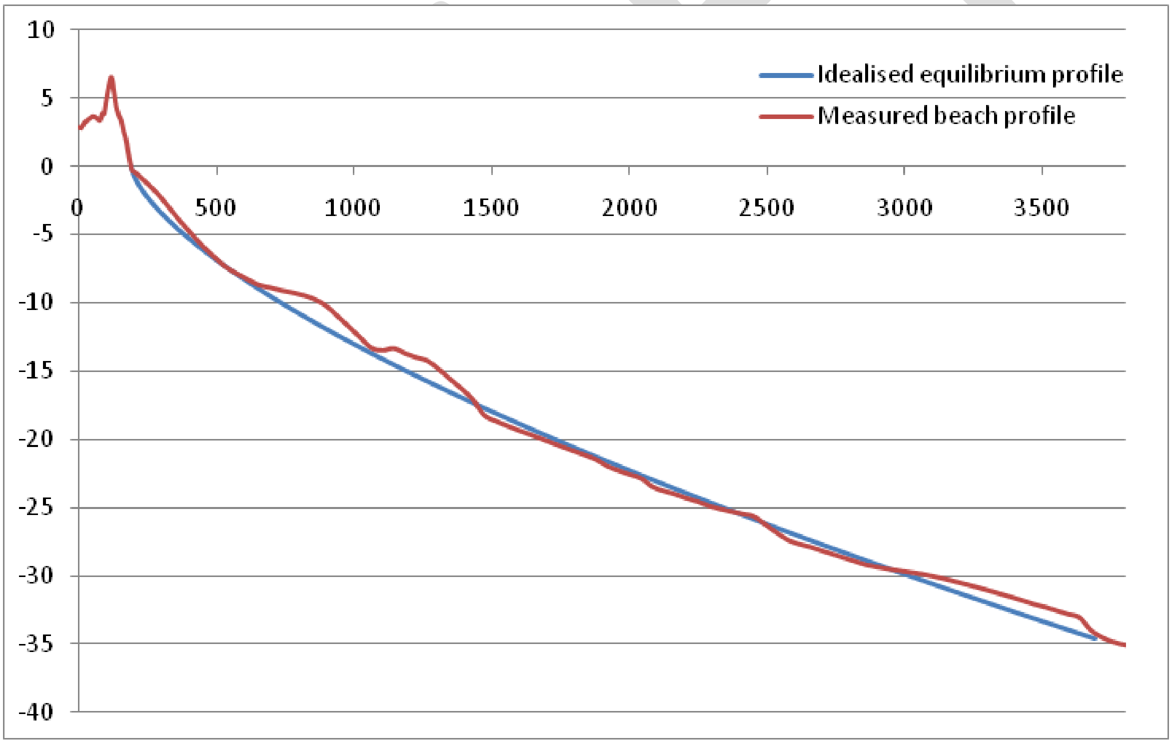


Figure C.6 – Nearshore profile at Lakes Beach vs. idealised equilibrium profile

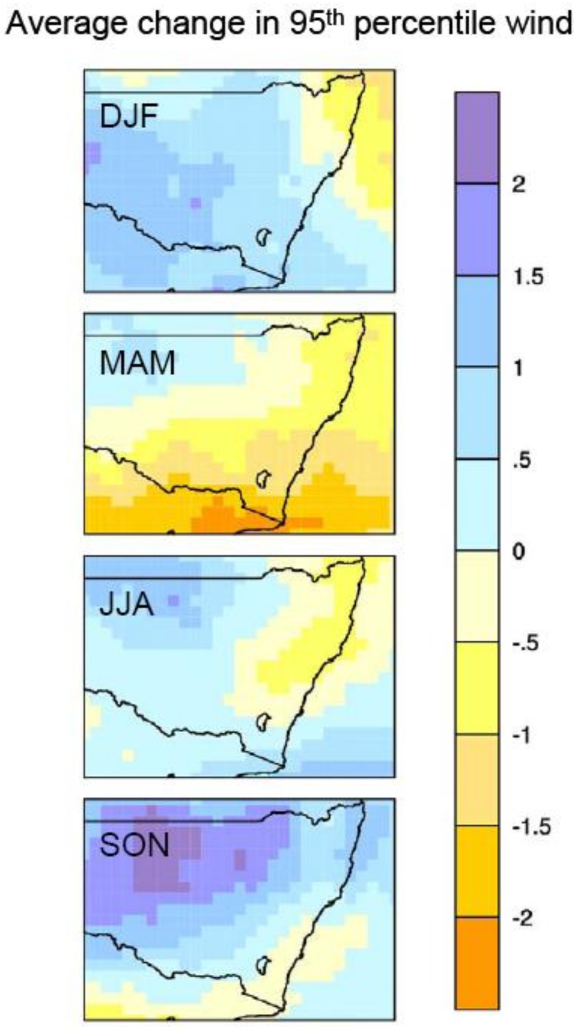


Figure 5.6. The change in the 95th percentile of monthly wind speed derived by averaging the 12 models results. Units are % change per °C of global warming.

Figure C.7 – Impact of climate change on wind speeds along NSW coast (Hennessy, 2004)

Project Name:	Wyong Coastal Hazard Study
Project Number:	3001053
Report for:	Umwelt Australia

PREPARATION, REVIEW AND AUTHORISATION

Revision #	Date	Prepared by	Reviewed by	Approved for Issue by
1	22/01/10	M. Glatz	C. Adamantidis	C. Adamantidis
2	28/05/10	M. Glatz & C. Adamantidis	C. Adamantidis	C. Adamantidis
3	1/10/10	M. Glatz & C. Adamantidis	C. Adamantidis and DECCW	C. Adamantidis

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Appendix D

Hazard Analysis

For: Umwelt Australia

TABLE OF CONTENTS

1 INTRODUCTION

The principal hazards induced by the coastal processes that are relevant for a coastal hazard risk assessment of the beaches along the Wyong Shire coastline include:

- short-term coastal erosion including that resulting from severe storms, the behaviour of river entrances and slope instability;
- long term coastline recession including that resulting from aeolian sand transport and climate change; and
- oceanic inundation of low lying areas.

In this Appendix, the coastal hazards are synthesised and applied for the present day, 2050 and 2100 planning periods along the Wyong Shire coastline. A sensitivity analysis is carried out to examine the relative impact of sea level rise on the locations of the coastal hazard zones.

2 HAZARD ASSESSMENT

2.1 Introduction

The delineation of the coastal hazard at Wyong Shire has been determined in accordance with the stability criteria in Nielsen *et al*. (1992), as described in Appendix B and illustrated in Figure D.1.

2.2 Short Term Erosion

2.2.1 Design Storm Erosion Demand

The design storm erosion demand has been based empirically on the measured erosion caused by the 1974 storms. The storms of May-June 1974 caused widespread damage to coastal structures and beaches along the central coast of New South Wales (Foster *et al.*, 1975). These storms were associated with an intense low pressure cell adjacent to the coast south of Sydney. A Waverider buoy in deep water offshore of Port Kembla recorded a wave height history for the event, which lasted between 25 May and mid June 1974. Over this time, the maximum *significant* offshore wave height reached a peak of 6.4 m 24 hours into the storm, with a second peak of Hs = 6.8 m reached 60 hours into the storm. Figure D.2 illustrates the time series of the May and June 1974 events as measured at the Port Kembla Waverider buoy. As these storms occurred within a short timeframe of each other, they have been combined and considered as a single storm event.

Because nearshore waves causing dune erosion are depth-limited, wave duration of moderate wave heights becomes a more important factor for dune erosion than peak offshore wave heights of short duration. It was the long duration of moderately high waves that made this particular 1974 storm so destructive.

The 1974 storm event was coincident with maximum spring tides, with a maximum tidal anomaly measured at Fort Denison of 0.59 m and a maximum ocean water level of 1.48 m on AHD (Kulmar and Nalty, 1997). The individual measurable attributes of the storm include wave height, duration, wind speed and water level. The combined exceedance probability of all these parameters makes it difficult to ascribe an Annual Exceedance Probability (AEP) to the storm event, though recent extreme value analysis of the Fort Denison record (Watson and Lord, 2008) indicates that the water level reached on 25 May 1974 had an ARI in the order of 300 years.

At other locations in NSW, a relationship between beach erosion and whether an adjacent estuary entrance is open or closed has been found – such a relationship was found at Shoalhaven Heads on the NSW south coast (SMEC Australia, 2007). It was found that more beach erosion occurred when a coastal storm event coincides with an open entrance.

From this analysis, an envelope of values for the loss of sand volume was calculated for each of the different beaches along the Wyong Shire coastline and the result is shown in Table D.1.

Table D.1 – Selected storm bites for the different beaches along Wyong Shire coastline

Location	Adopted Storm bite (m3/m)
Shelly Beach (Block 1)	200
Shelly Beach (Block 2-3)	250
Toowoon Bay (Block P-Q-R)	70
Toowoon Bay (Block S)	50

Location	Adopted Storm bite (m3/m)
Blue Bay (Block T)	140
Blue Bay (Block U)	110
Blue Bay (Block V)	100
South Entrance Beach	N/A
North Entrance Beach (Block A-F)	250
North Entrance Beach (Block G-H)	150
Soldiers Beach (Block 1)	100
Soldiers Beach (Block 2)	130
Soldiers Beach (Block 3)	160
Soldiers Beach (Block 4-5)	200
Lakes Beach	250
Hargraves Beach (Block I)	180
Hargraves Beach (Block J)	190

2.2.2 Estuary Entrance Instability Hazard

Short term beach fluctuations can be enhanced at natural estuary entrances, such as at Tuggerah Lake entrance. Estuary entrance instability has been examined in Appendix B, and it was found that this hazard is currently restricted to the zone along the beach berm at the entrance at the southern end of North Entrance Beach.

2.3 Long Term Recession

2.3.1 Measured Long Term Changes

Table D.2 illustrates the beach recession rates measured for the various beaches in the study area.

Generally, it was found that most of the beaches in the study area are not undergoing significant long term beach recession and that since the storms of May 1974, several beaches have been recovering in sand volume as a result of a lack of recent storm activity.

The detailed analysis for each beach in the study area is described below.

Table D.2 – Measured Long-term Beach Erosion Rates at various beaches in the Wyong Shire

Beach	Adopted long term recession rate (m/yr)
Shelly Beach	Nil
Toowoon Bay (Block P-Q-R-S)	0.1
Blue Bay (Block T-U-V)	0.1
South Entrance	Nil
North Entrance (Block A)	Nil
North Entrance (Block B)	0.1
North Entrance (Block C)	0.5
North Entrance (Block D)	0.2
North Entrance (Block E-F-G)	Nil
North Entrance (Block H)	0.1
Soldiers Beach (Block 1-2)	Nil
Soldiers Beach (Block 3-4-5)	0.2

Beach	Adopted long term recession rate (m/yr)
Hargraves Beach (Block I)	Nil
Hargraves Beach (Block J)	0.05
Lakes Beach	0.5

2.3.2 Climate Change

The possibility of increased storm wave heights has been investigated as part of this study. Hennessy *et al.* (2004) do not predict any increase in winter storm wind speeds for the NSW coast. The background to this is provided in Appendix C.

Foreshore recession resulting from a *Greenhouse*-induced sea level rise has been assessed using the *Bruun Rule* (Appendix C). The results are shown in Table D.3.

Table D.3 – Predicted beach erosion due to sea level rise

Beach	Block	Total Predicted Sea Level Rise (m)		Equilibrium Nearshore Slope (1:X)	Total Beach Recession (m)		Total Beach Erosion (m3/m)	
		2050	2100		2050	2100	2050	2100
Shelly Beach	1	0.40	0.90	35	15.2	34.2	72.9	164.0
	2			42	17.4	39.2	189.8	426.9
	3			37	14.8	33.3	128.8	289.7
Toowoon Bay	Whole Bay	0.40	0.90	13	5.2	11.7	52.0	116.9
Blue Bay	Whole Bay	0.40	0.90	11	4.4	9.8	39.5	88.8
South Entrance	Whole Beach	0.40	0.90	N/A*	N/A*	N/A*	N/A*	N/A*
North Entrance	A	0.4	0.9	30	11.8	26.6	73.3	164.9
	B			29	11.6	26.1	104.4	234.9
	C			45	18.0	40.4	152.7	343.7
	D			31	12.6	28.3	104.8	236.0
	E			35	14.1	31.5	105.8	237.9
	F			39	15.4	34.5	92.0	207.0
	G			37	14.6	33.0	102.5	230.7
	H			45	14.8	33.3	128.5	283.1
Soldiers Beach	1	0.4	0.9	29	11.6	26.1	143.7	323.4
	2			32	12.9	29.0	149.4	336.1
	3			44	17.4	39.2	123.8	278.6
	4-5			39	15.4	34.7	155.7	350.3
Lakes Beach	Whole Beach	0.40	0.90	72	28.9	65.0	190.8	429.2
Budgewoi Lake	Dune Arm	0.40	0.90	29	11.5	25.9	81.7	183.8
Hargraves Beach	I	0.4	0.9	25	10.2	22.9	58.7	132.1
	J			16	6.7	15.0	45.9	103.3

*South Entrance Beach is underlain by rock all along its length.

It should be noted that these recession rates assume that the dune is composed of erodible material and that the nearshore beach profile is in equilibrium with the wave climate. Where a superficial layer of sandy beach overlies bedrock or if there is presence of bedrocks seaward of the beach, erosion would be limited (i.e. Toowoon Bay, Blue Bay and Blue Lagoon).

2.3.3 Oceanic Inundation

Design incident wave conditions for the assessment of wave runup were determined for a storm event assuming a 1-in-100-year (1% Annual Exceedance Probability or AEP) significant wave height combined with a 1-in-100-year (1% AEP) water level. This is a conservative assumption, as it is unlikely that a 1% AEP wave height would occur concurrently with a 1% AEP water level. As the Wyong Shire coastline is fairly exposed to swell waves, it can be assumed that the peak wave height reached offshore at the different beaches along this coast would be similar to what could be expected at Sydney.

Wave runup levels along Wyong Shire coastline were estimated using the Automated Coastal Engineering Software (ACES) using the value of the nearshore significant wave height calculated with SBEACH software. The wave runup module of ACES was used to determine the levels, which assumes a smooth slope, linear beach.

SBEACH (Storm-induced BEAch CHange 32) is an empirically based, two-dimensional, morphological, numerical model. The model is founded on extensive large wave tank and field data measurements and analysis (Larson *et al*., 1990; Rosati *et al*., 1993). The model accepts as data:

- surveyed beach profiles;
- time-varying water levels;
- regular or irregular wave heights and periods;
- wave angles;
- wind speeds and wind directions; and
- an arbitrary grain size in the fine-to-medium sand range.

The nearshore boundary conditions for ACES that have been adopted for various locations along the beach are shown in Table D.4. The assumed nearshore beach profile is measured from approximately 2 m below AHD to the top of the dune, to obtain a beach slope for use in the wave runup calculation. The runup was added to the nearshore water level, which included an allowance for wave setup and wind setup. The maximum expected wave runup and 2% wave runup (runup level exceeded by 2% of waves) is given in Table D.4. The runup level has been calculated by adding up the runup calculated by ACES to the nearshore water level and the maximum recorded ocean water level at Sydney of 1.48 m on AHD (Kulmar and Nalty, 1997).

From these results, it can be seen that the maximum expected wave runup level along Wyong Shire coastline is generally around 6 to 7m AHD with higher values for North Entrance where the run-up may reach up to around 8.1m AHD. From the Aerial Laser Scan data, this indicates that some overtopping could occur at Shelly Beach caravan park, at the southern end of Blue Bay, at South Entrance swimming pool, along Curtis Parade at North Entrance and along Hargraves Beach. However, the impact would be limited due to absorption of the wave run-up along the dune and if the houses and roads are affected, the impact would not be significant as the energy would be very low. The map of the maximum wave runup levels are represented in Figures D.3 and D.10.

Table D.4 – Wave Runup levels for Wyong Shire, 1% AEP water level combined with 1% AEP wave height

Beach	Profile Location (Block-Profile)	Water Level	Maximum Wave RunUp Level from ACES	2% Wave RunUp Level from ACES	Significant Wave RunUp Level from ACES	Maximal Offshore Water Level	Maximal Run Up
		m	m	m	m	m AHD	m AHD
Shelly Beach	1-3	1.207	4.62	4.18	3.17	1.48	7.307
	1-8	0.99	4.35	3.96	3.00	1.48	6.820
	2-2	1.005	4.44	3.96	3.00	1.48	6.925
	2-19	1.051	4.27	3.89	2.95	1.48	6.801
	3-5	1.05	4.19	3.82	2.90	1.48	6.720
Toowoon and Blue Bays	Q-8	1.111	2.96	2.77	2.11	1.48	5.551
	R-12	1.202	2.92	2.74	2.09	1.48	5.602
	S-15	1.184	3.03	2.84	2.16	1.48	5.694
	T-7	1.144	3.07	2.87	2.18	1.48	5.694
	U-7	1.192	3.84	3.53	2.68	1.48	6.512
	V-9	1.18	3.91	3.58	2.72	1.48	6.570
South Entrance	SLSC	1.315	3.56	3.29	2.50	1.48	6.355
	Boatshed	1.172	3.78	3.48	2.64	1.48	6.432
North Entrance	A-32	1.17	3.78	3.48	2.64	1.48	6.430
	B-13	0.958	3.72	3.43	2.60	1.48	6.158
	C-18	1.272	3.97	3.64	2.76	1.48	6.722
	C-37	1.11	4.62	4.18	3.17	1.48	7.210
	D-15	1.164	4.93	4.44	3.36	1.48	7.574
	D-40	1.186	5.43	4.86	3.67	1.48	8.096
	D-56	1.187	5.43	4.86	3.67	1.48	8.097
	E-14	1.153	5.17	4.64	3.51	1.48	7.803
	E-34	1.234	5.43	4.86	3.67	1.48	8.144
	F-11	1.212	5.17	4.64	3.51	1.48	7.862
	F-28	1.153	5.17	4.64	3.51	1.48	7.803
	G-12	1.069	4.19	3.82	2.90	1.48	6.739
	H-2	1.058	1.69	1.45	1.09	4.48	7.228
Soldiers Beach	1-2	1.058	4.19	3.82	2.90	1.48	6.728
	2-4	1.153	4.12	3.76	2.85	1.48	6.753
	3-5	1.168	4.27	3.89	2.95	1.48	6.918
	SLSC	1.224	4.44	4.03	3.05	1.48	7.144
Lakes Beach	SLSC	0.95	2.77	2.61	1.99	1.48	5.200
Budgewoi Lake	Dune Arm	0.925	3.45	3.2	2.43	1.48	5.855
Hargraves Beach	I-1	1.043	3.5	3.24	2.46	1.48	6.023
	I-5	1.042	3.14	2.93	2.23	1.48	5.662
	I-10	1.298	3.07	2.87	2.18	1.48	5.848
	I-15	1.399	3.23	3	2.28	1.48	6.109
	I-20	1.208	3.84	3.53	2.68	1.48	6.528
	I-25	1.091	4.12	3.76	2.85	1.48	6.691
	J-1	1.033	4.55	3.7	2.76	1.48	7.063
	J-6	0.954	4.39	3.58	2.66	1.48	6.824
	J-12	1.092	4.35	3.96	3.00	1.48	6.922
	J-17	1.171	4.44	4.03	3.05	1.48	7.091

Beach	Profile Location (Block-Profile)	Water Level	Maximum Wave RunUp Level from ACES	2% Wave RunUp Level from ACES	Significant Wave RunUp Level from ACES	Maximal Offshore Water Level	Maximal Run Up
	J-22	1.157	4.19	3.82	2.90	1.48	6.827

2.4 Additional Analysis for Bateau Bay, Pebbly Beach and Cabbage Tree Harbour

Several additional sandy dune areas have been identified within the study area which were not included in the full analysis due to lack of photogrammetric data and/or a lack of nearby infrastructure. Some of these areas are adjacent to coastal slopes where SCE (2010) have conducted geotechnical analyses. The areas considered included:

- The sandy beach berm at Bateau Bay
- The dune at Pebbly Beach (the embayment north of Soldiers Beach adjacent to Norah Head), and
- The sandy beach berm at the southern end of Cabbage Tree Harbour.

As there was little photogrammetric data available to undertake a full analysis of these areas, a qualitative dune hazard assessment for these areas is presented below.

2.4.1 Storm Erosion Demand

Insufficient data was available to ascertain storm erosion demand for the sandy portions of Bateau Bay, Pebbly Beach and the southern end of Cabbage Tree Harbour as photogrammetry data before and after a suitable storm event were not available. However, a qualitative assumed storm erosion demand for these areas based on the degree of their exposure has been proposed – these are presented below.

- Bateau Bay – the sandy portion of this beach is exposed to a high wave climate from the south but is fronted by extensive rock reef which would limit the nearshore wave heights – storm erosion demand is likely to be between 100 and 200 m^3/m. An analysis of photogrammetric data for this beach shows that the changes in available sand store on the beach have fluctuated by less than 100 m^3/m between 1965 and 2001 and that the total sand store is approximately 200 m^3/m.
- Pebbly Beach – this beach directly north of Soldiers Beach is exposed to a full open coast wave climate. No photogrammetry data was available here but it is likely that storm erosion demand would be commensurate with that measured at other open coast beaches throughout NSW at around 250 m^3/m.
- Southern end of Cabbage Tree Harbour – this area is fronted by areas of extensive reef, and is well protected from southerly swells by Norah Head. It is likely that the storm erosion demand would be lower than 50 m^3/m at this location. However, from analysis of LiDAR data it is apparent that there is less than 50 m^3/m of available sand store on the beach here.

2.4.2 Long Term Recession

From photogrammetric data between 1965 and 2001, the volume of the beach berm at Bateau Bay beach had increased. No data were available to determine long term beach behaviour at the other two locations. However, from aerial photography provided for this project it appears that a recent dune blow-out had occurred at Pebbly Beach which could represent a mechanism for continuing loss of sand from this area.

2.4.3 Climate Change

An analysis of aerial photography and LiDAR data has allowed nearshore slopes for use with the Bruun Rule to be estimated for Bateau Bay, Pebbly Beach and the southern portion of Cabbage Tree Harbour.

At Bateau Bay, the nearshore equilibrium profile slope was estimated at 1:20, and at Pebbly Beach and the southern end of Cabbage Tree Harbour this slope was estimated at 1:10. These nearshore equilibrium slopes are steeper than for many open coast beaches in NSW due to the presence of extensive areas of nearshore reef.

Adopting the sea level rise benchmarks in accordance with the NSW Sea Level Rise Policy (0.4 m by 2050 and 0.9 m by 2100), the total predicted dune recession due to sea level rise is as follows:

- Bateau Bay – 8 m by 2050 and 20 m by 2100
- Pebbly Beach and southern end of Cabbage Tree Harbour – 4m by 2050 and 10 m by 2100

2.4.4 Overall hazard assessment

At Bateau Bay an indicative hazard assessment for the dune area was carried out which showed that approximately 200 m^3/m of sand store is available on the beach and that by 2100 storm erosion could encroach into the foreshore bluff.

At Pebbly Beach there was insufficient data to determine whether there was long term recession though it was noted from aerial photography that a recent dune blow-out had occurred. The dune is very high here and there is no infrastructure currently at threat from dune erosion. It is not likely that any infrastructure would be at threat in this location prior to 2100.

At the southern end of Cabbage Tree Harbour there is very little available sand store on the beach berm. While storm erosion demand is expected to be relatively low in this location due being relatively protected, it is likely that a large storm would result in erosion of all the sand from the beach berm. Insufficient data relating to underlying strata is available to determine dune hazard locations here. However, a sensitivity analysis has been carried out here using available LiDAR data and storm erosion demand volumes of 50 m^3/m and 100 m^3/m assuming that the underlying strata is sandy.

3 CALCULATION OF HAZARD LIMITS

The limits of the *Zone of Wave Impact and Slope Adjustment* and the *Zone of Reduced Foundation Capacity* have been calculated using the values for design storm erosion demand, with reference to Figures D.11 to D.18, for the 2050 and 2100 planning periods, adding the estimated recession allowed for as a result of upper range sea level rise prognoses as advocated by the NSW Sea Level Rises Policy and measured long term recession.

To obtain the location of the various zones, average values of the different profiles would normally have been used as the different beaches are accreting. However, the several anthropogenic influences (sand mining, dune stabilisation, etc.) would have distorted the average result. Therefore, the most recent profile (2007) has been used for the determination of the hazard lines. These have been checked using the ALS data, which provides a greater density of data (although this data is dated from 2007).

The immediate hazard limits due to the design storm erosion volume are shown in Figures D.19 to D.25, for the different beaches along Wyong Shire coastline. They have been calculated in terms of chainage along each profile.

For the 2050 and 2100 planning periods, long term beach recession and sea level rise limits were added to the design storm recession for several locations along the beach, to determine the seaward limits of the *Zone of Reduced Foundation Capacity* and *Dune Stable Foundation Zone*.

Figures D.26 to D.32 illustrate the hazard limits for 2050 and Figures D.33 to D.39 illustrate the hazard limits for 2100.

A special area located north of Lakes Beach has been studied to determine if Budgewoi Lake can become an open lake over the next 100 years. The immediate, 2050 and 2100 hazard limits are illustrated on Figure D.40 to D.42 respectively and the maximum runup on Figure D.43.

Additional assessment was carried out at Bateau Bay, Pebbly Beach and the southern end of Cabbage Tree Harbour. The immediate, 2050 and 2100 hazard limits for the sandy portion of Bateau Bay are provided in Figures D.44 to D.46.

Immediate hazard lines for the sandy portion of Pebbly Beach are provided in Figure D.47 but 2050 and 2100 hazard lines could not be determined at this location due to the lack of historical photogrammetric data.

A sensitivity analysis of the *Zone of Slope Adjustment* assuming storm erosion demand values of 50 m^3/m and 100 m^3/m was carried out for the southern end of Cabbage Tree Harbour, assuming that the underlying strata is composed of sand. This sensitivity analysis is shown in Figure D.48. The analysis showed that four buildings were seaward of these lines. However, there is insufficient data to determine whether the buildings are at risk from storm erosion as the storm erosion demand is unknown. Further, it is unknown whether their foundations extend into the underlying bedrock.

4 SUMMARY AND CONCLUSIONS

The assessment of coastal hazards has concluded that regarding an immediate risk:

- No private dwelling is at immediate risk of storm damage at Shelly Beach. A small section of the caravan park located at the southern end of Shelly Beach will be impacted. A narrow section of the caravan park north of Shelly Beach lies within the *Zone of Reduced Foundation Capacity*.

- Around five dwellings are at immediate risk at Toowoon and Blue Bays as well as around 25 lots. Additional 19 dwellings and two lots lie within the *Zone of Reduced Foundation Capacity*. Some houses along the coast may potentially be at geotechnical risk.

- Some 18 dwellings and 28 lots lie within the *Zone of Slope Adjustment* and some additional 17 dwellings, the surf club and one lot will be subject to reduced foundation capacity along North Entrance Beach.

- Soldiers Beach SLSC lies within the *Zone of Reduced Foundation* Capacity.

- Along Hargraves Beach, some 30 dwellings and nine lots are at immediate risk and additional four lots and five dwellings lie within the *Zone of Reduced Foundation Capacity*.

- Lakes Beach Surf Club partially lies within the *Zone of Slope Adjustment*.

Assessment of the runup along the Wyong Shire coastline concluded that:

- Most of the caravan park south of Shelly Beach would be impacted by wave run-up as well as a section of the caravan park located along Toowoon Bay.

- Some low-lying houses along the southern half of Blue Bay could also be affected by wave run-up.

- South Entrance surf club, boatshed and swimming pool would also be impacted.

- Several dwelling along Curtis Parade at North Entrance as well as most houses located .

- Hargraves Beach could be affected by wave run-up.

For the 2050 planning period:

- A larger section of the caravan park south of Shelly Beach lies within the *Zone of Slope Adjustment* and the SLSC will suffer from *Reduced Foundation Capacity*.

- Along Toowoon and Blue Bays, some 27 dwellings and three lots will be at immediate risk and an additional dwelling and five lots will lie within the *Zone of Reduced Foundation Capacity*.

- Some 38 dwellings and 25 lots will be at immediate risk at North Entrance and additional 21 dwellings and 6 lots will lie within the *Zone of Reduced Foundation Capacity*.

- Soldiers Beach and Lakes Beach SLSCs will completely lie within the *Zone of Slope Adjustment*.

- At Hargraves Beach, some 36 dwellings and 8 lots will be at immediate risk and three additional dwellings will lie within the *Zone of Reduced Foundation Capacity*.

For the 2100 planning period:

- A larger section of the caravan park south of Shelly Beach lies within the *Zone of Slope Adjustment* and the SLSC will be at immediate risk.

- At Toowoon and Blue Bays 27 dwellings and 6 lots will be at immediate risk. However, this risk depends on the foundation of the houses. Some of the dwellings located along Toowoon Bay which are based on rock may not be affected as illustrated on the maps.

- At North Entrance, most dwellings and lots along Curtis Road as well as most of the building seaward of Hutton Road south of the SLSC will be at immediate risk. Some additional 30 dwellings and six lots would be at immediate risk and 20 buildings and three lots will lie within the *Zone of Reduced Foundation Capacity*.

- At Hargraves Beach, some 40 dwellings and seven lots will be at immediate risk and some additional six dwellings and four lots will lie within the *Zone of Reduced Foundation Capacity*.

This risk assessment assumes that the coast is only composed of sand and that the sand is not underlain by rocks which may not be the case at Toowoon Bay. South Entrance is underlain by bedrock along most of its length. Hence only the run-up at this beach has been mapped. However, the entire sandy portion of the beach is under threat from erosion in a large storm event.

The study of the sand arm separating Budgewoi Lake from the ocean showed that some overtopping may occur in the future due to the generally low height at this location. For the 2050 planning period, Central Coast Highway might be at risk due to the landward movement of the dune which might reach the road. For the 2100 planning period, a section of Central Coast Highway will lie within the *Zone of Reduced Foundation Capacity* if no regular beach nourishment is undertaken.

Assessment of additional locations using available data was undertaken at Bateau Bay, Pebbly Beach and the southern end of Cabbage Tree Harbour. Insufficient data was available to determine definitive dune erosion hazards at these locations. However, it was considered that by 2100, dune erosion at Bateau Bay could occur over the entire sandy portion of the beach. At Pebbly Beach, it was considered unlikely that any infrastructure would come under threat from dune erosion prior to 2100. At the southern end of Cabbage Tree Harbour, insufficient data was available to undertake a coastal hazard analysis, but a sensitivity analysis using storm erosion demand values of 50 m^3/m and 100 m^3/m was undertaken assuming that the underlying strata consisted of sand. This sensitivity analysis showed that four buildings may lie partially within the present day *Zone of Slope Adjustment*.

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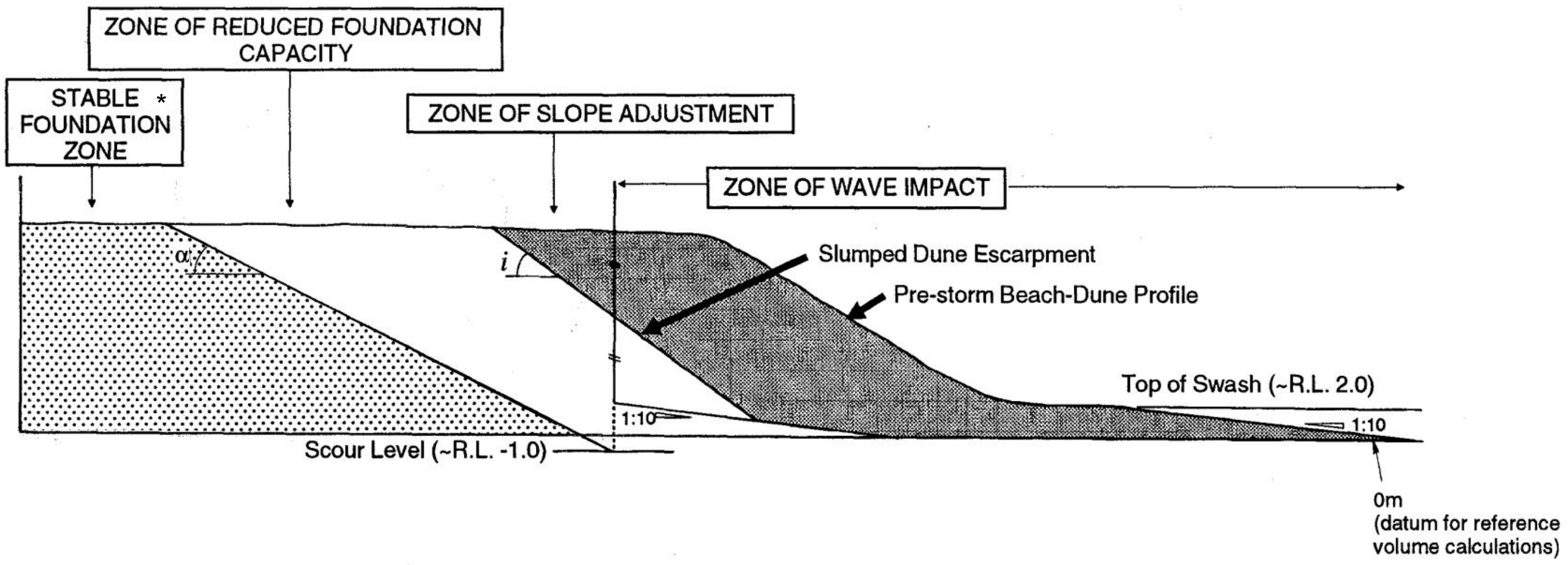
FIGURES



Angle of repose of dune sand: $i \sim \phi \approx 34^{\circ}$

Safe angle of repose of dune sand: $\alpha = \tan^{-1}\{(\tan\phi)/1.5\} \approx 24^{\circ}$

All levels to AHD

Figure D.1 – Dune stability schema (after Nielsen et al., 1992)

**Note – The term "Stable Foundation Zone" refers to a Dune Stable Foundation Zone which does not take into account any land stability, or other geotechnical hazards that may exist in the same area. The identified geotechnical hazards are described in a separate report by SCE (2010).*

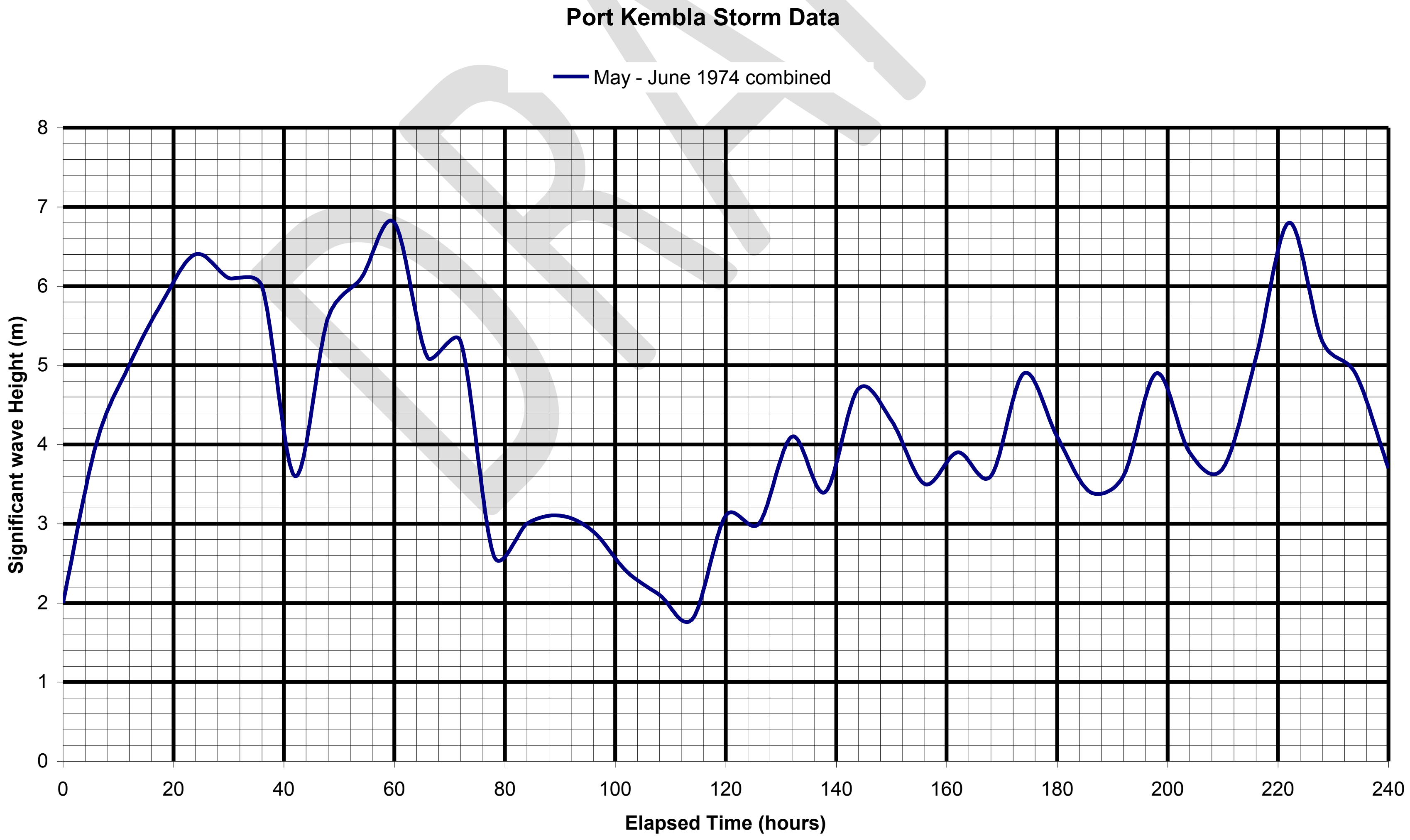


Figure D.2 – Combined storm time series at Port Kembla, May-June 1974 storm event

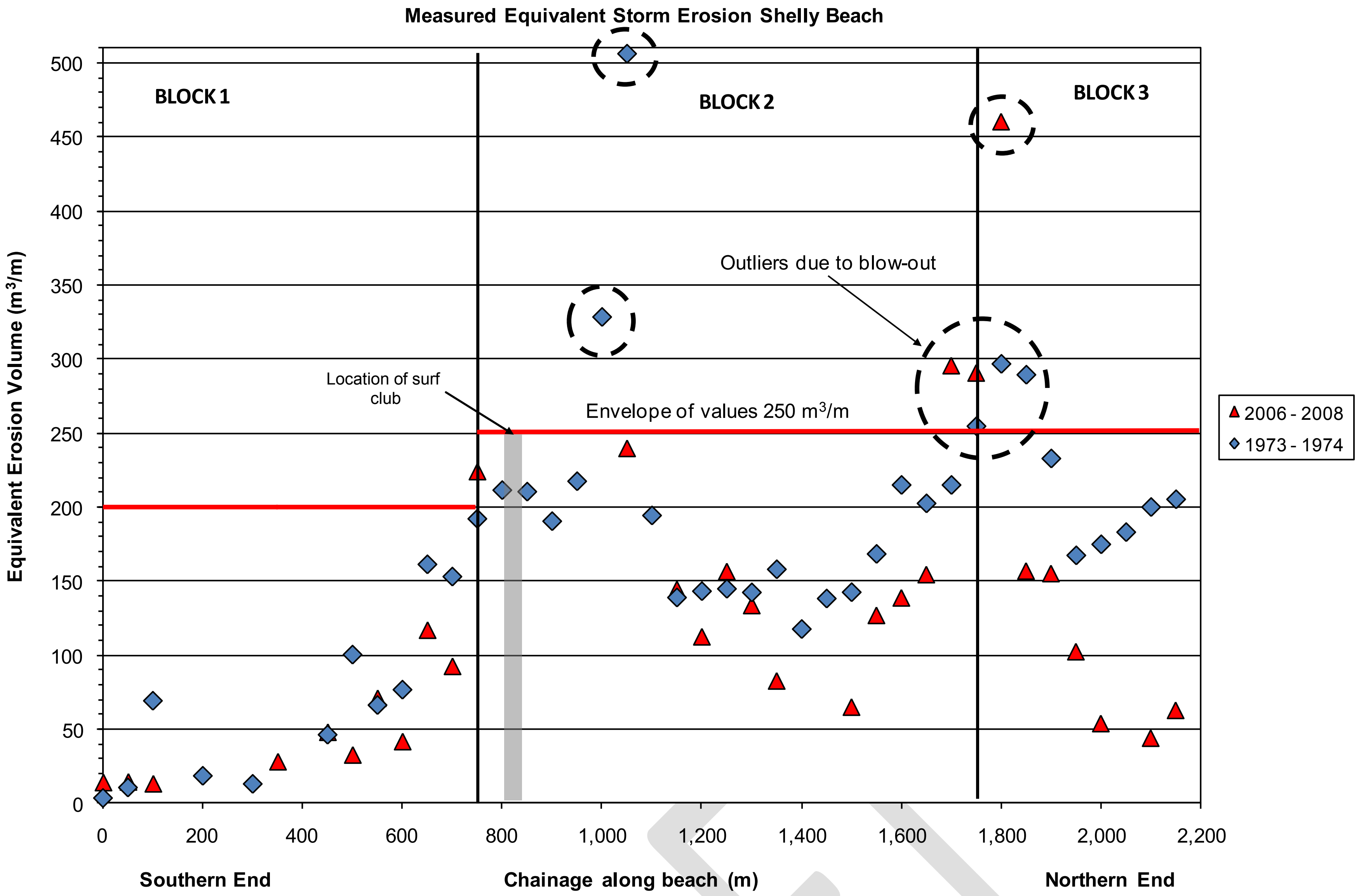


Figure D.3 – Upper envelope for storm bite, Shelly Beach

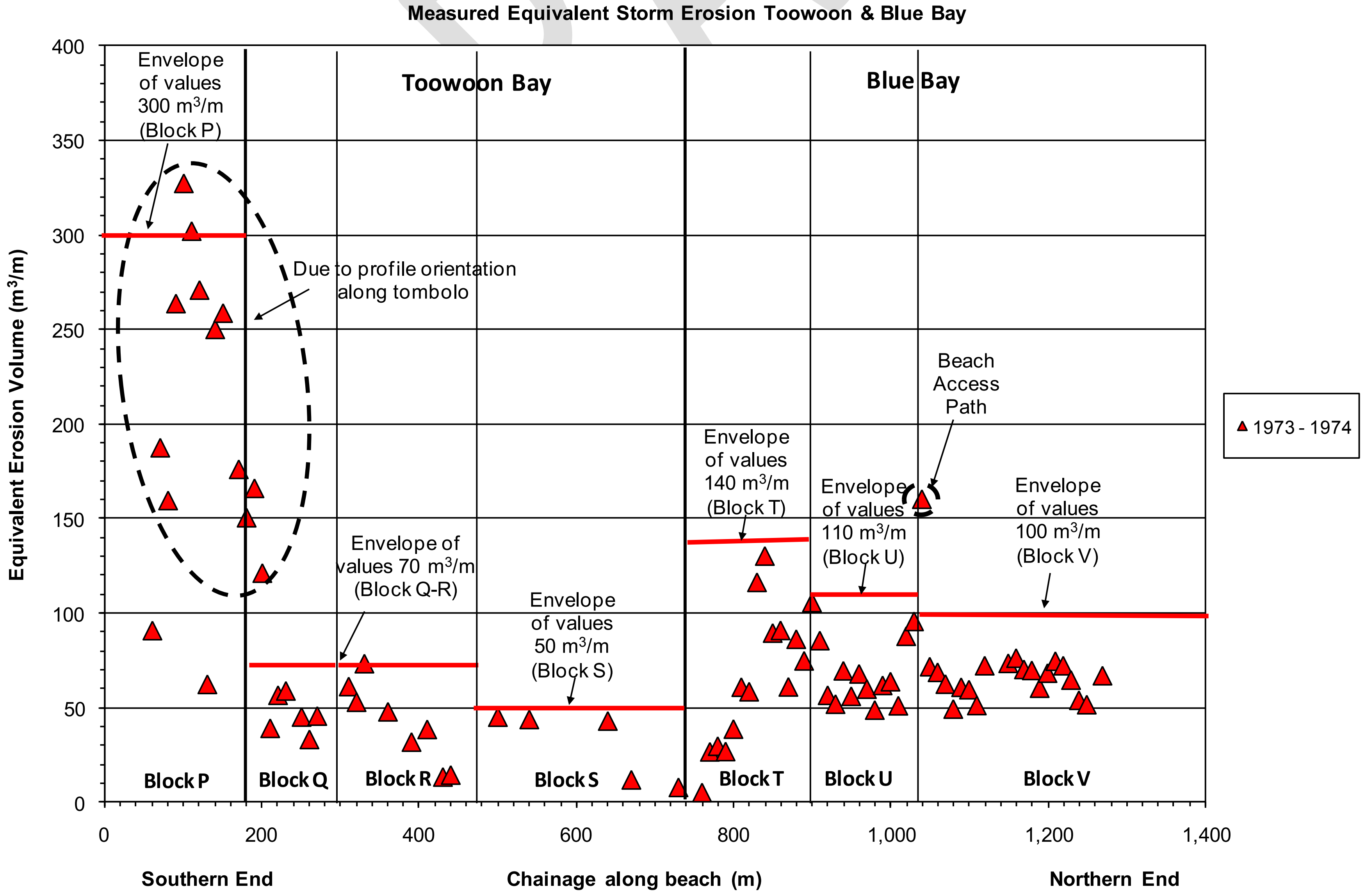


Figure D.4 – Upper envelope for storm bite, Toowoon and Blue Bays

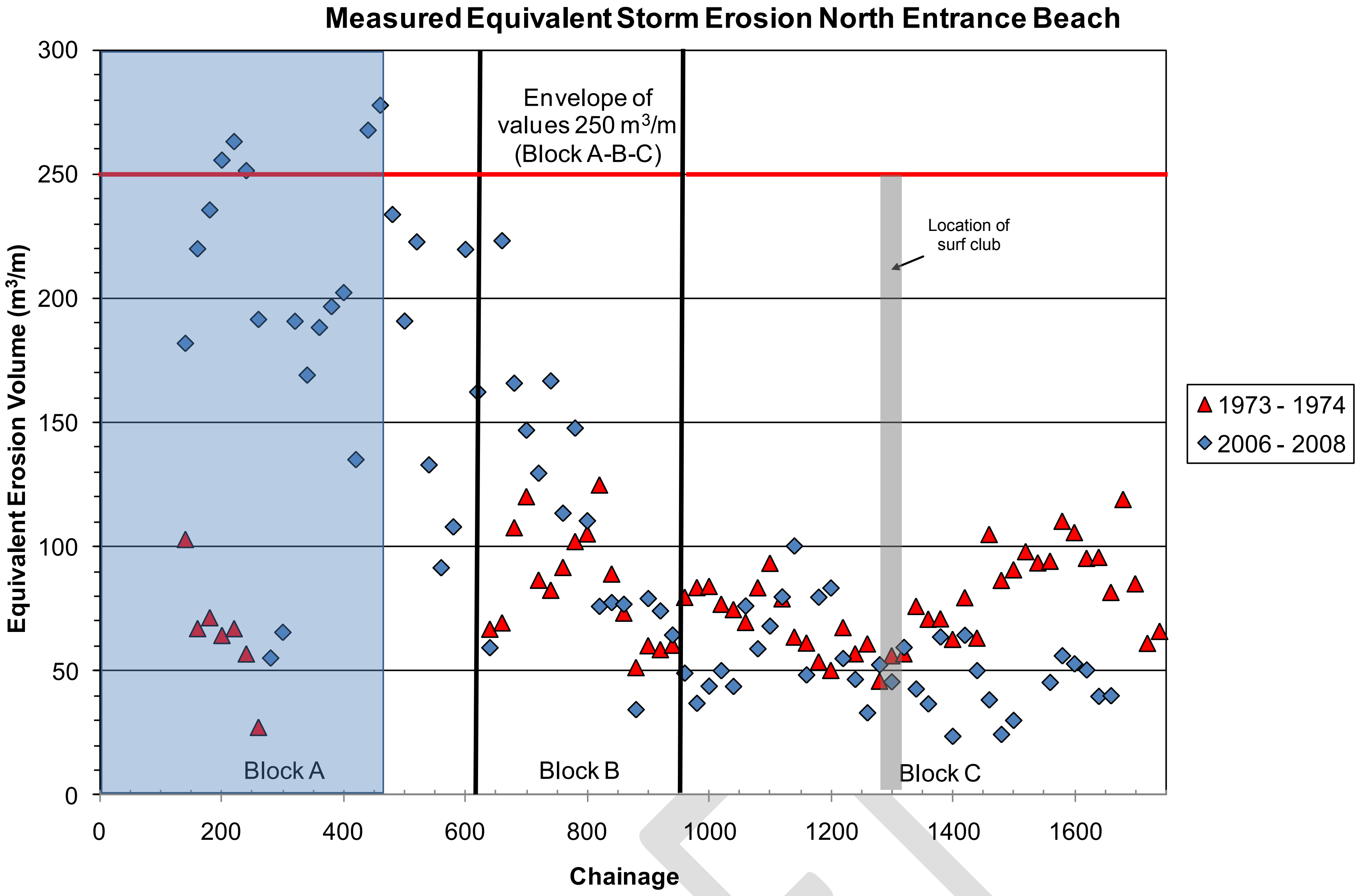


Figure D.5 – Upper envelope for storm bite, North Entrance (Block A-C)

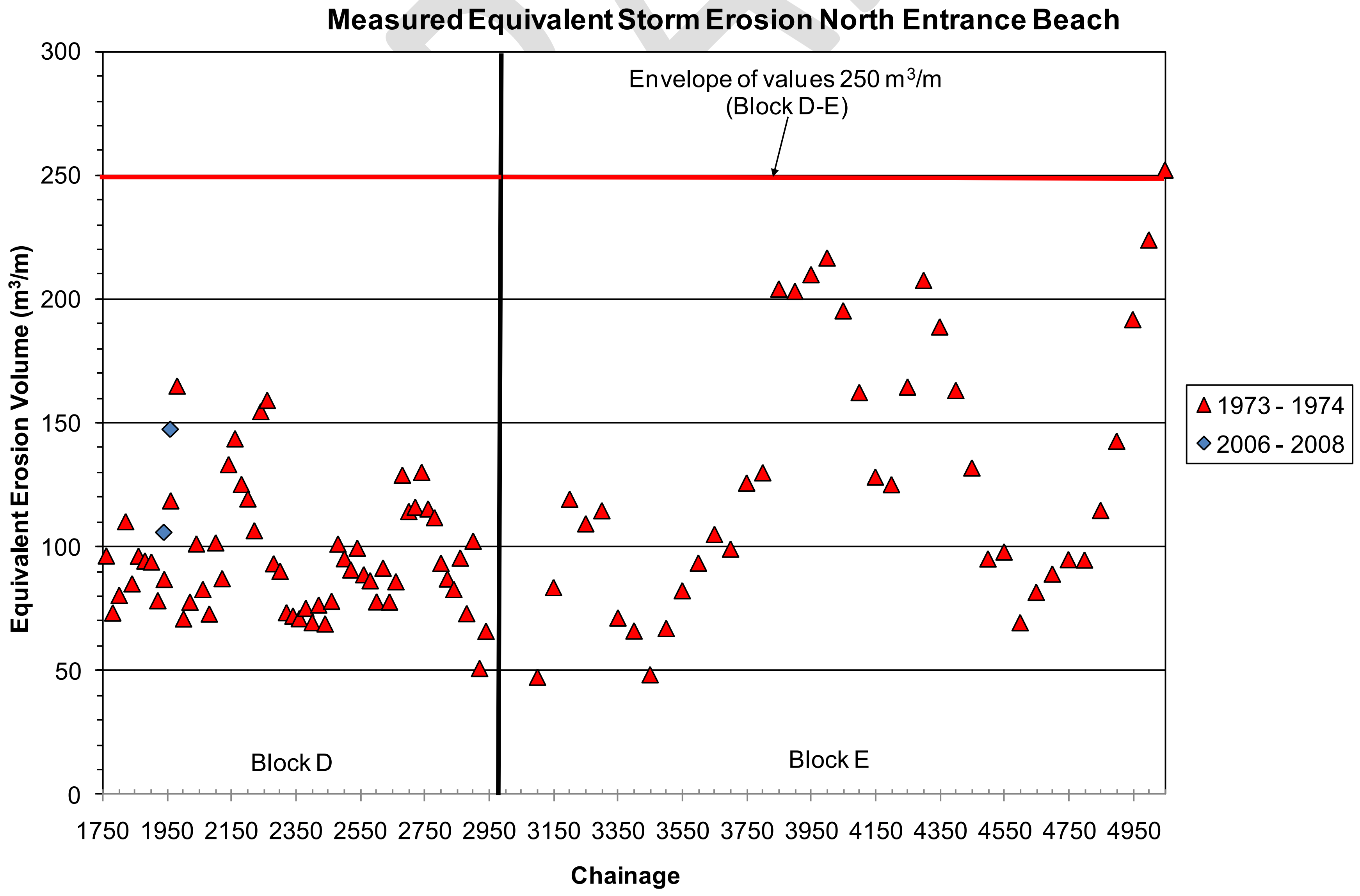


Figure D.6 – Upper envelope for storm bite, North Entrance (Block D-E)

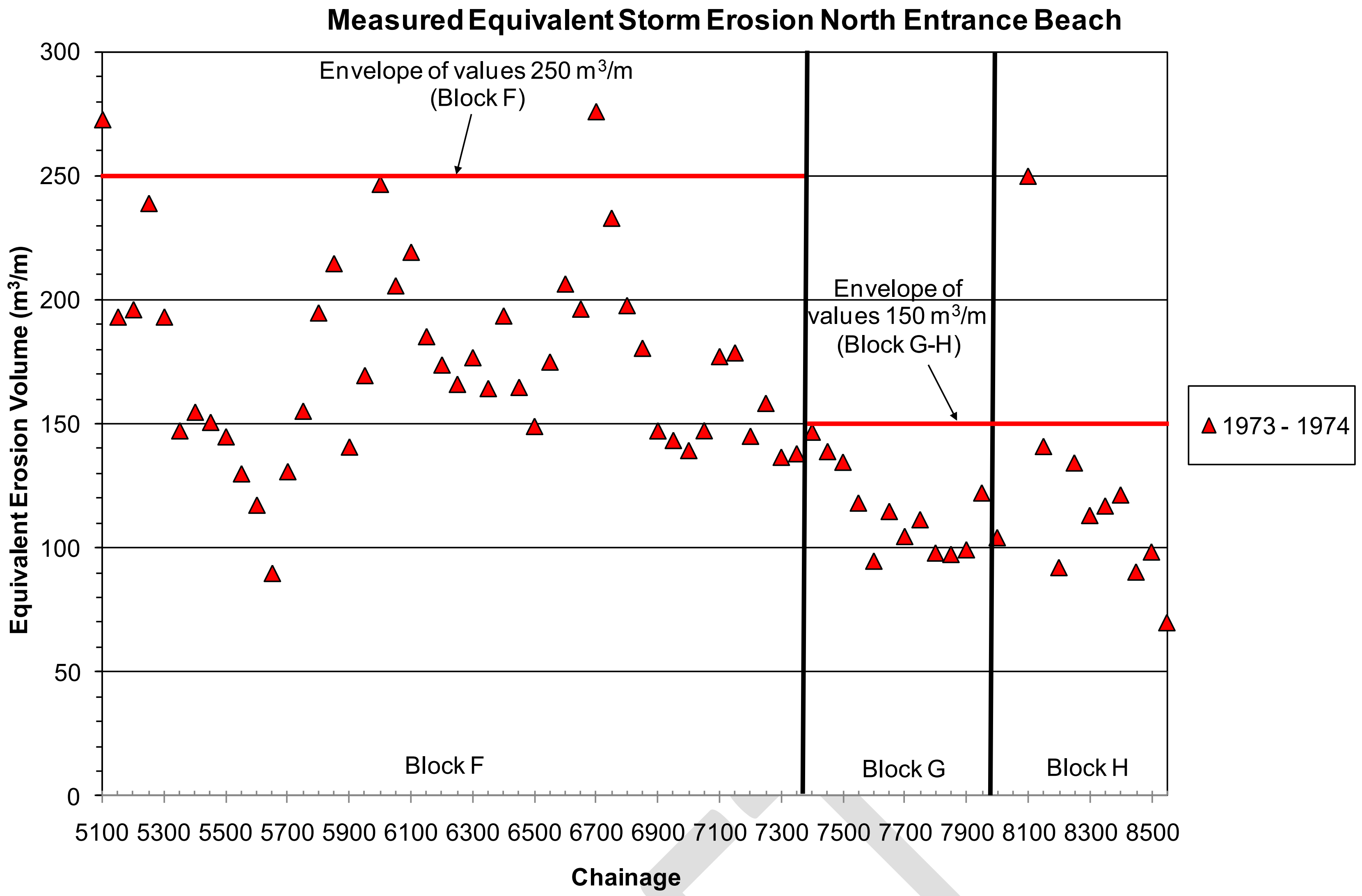


Figure D.7 – Upper envelope for storm bite, North Entrance (Block F-H)

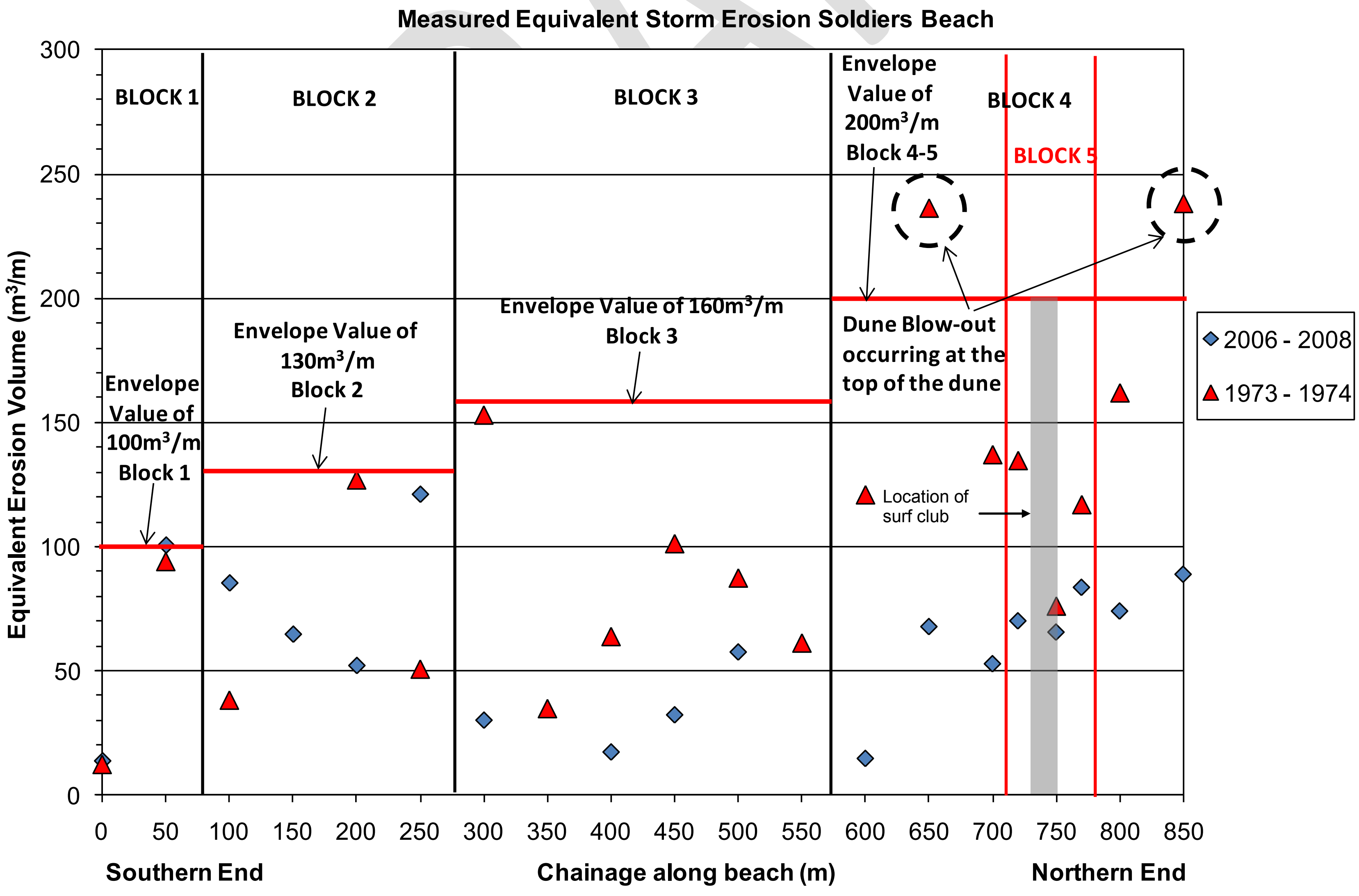


Figure D.8 – Upper envelope for storm bite, Soldiers Beach

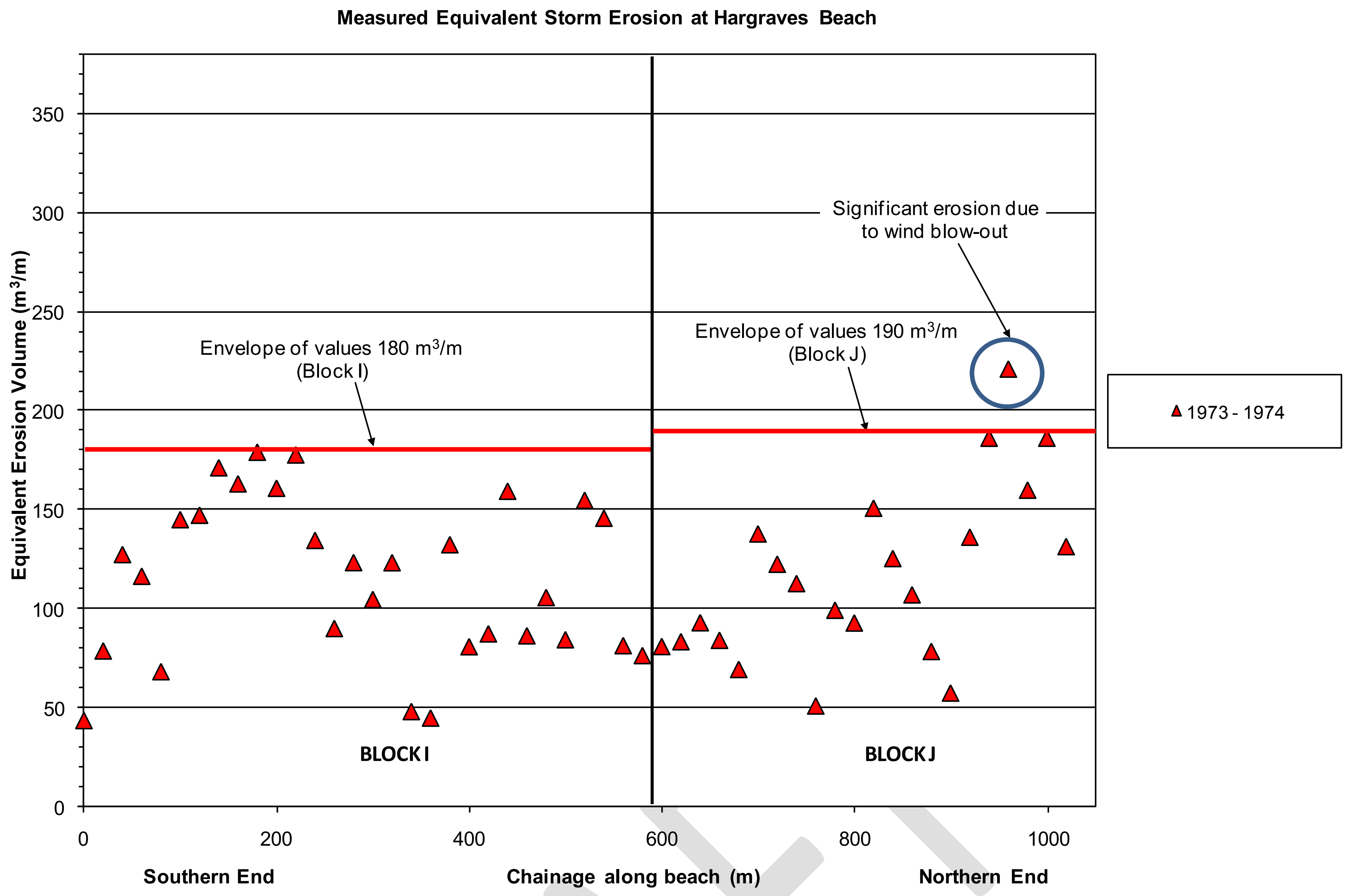


Figure D.9 – Upper envelope for storm bite, Hargraves Beach

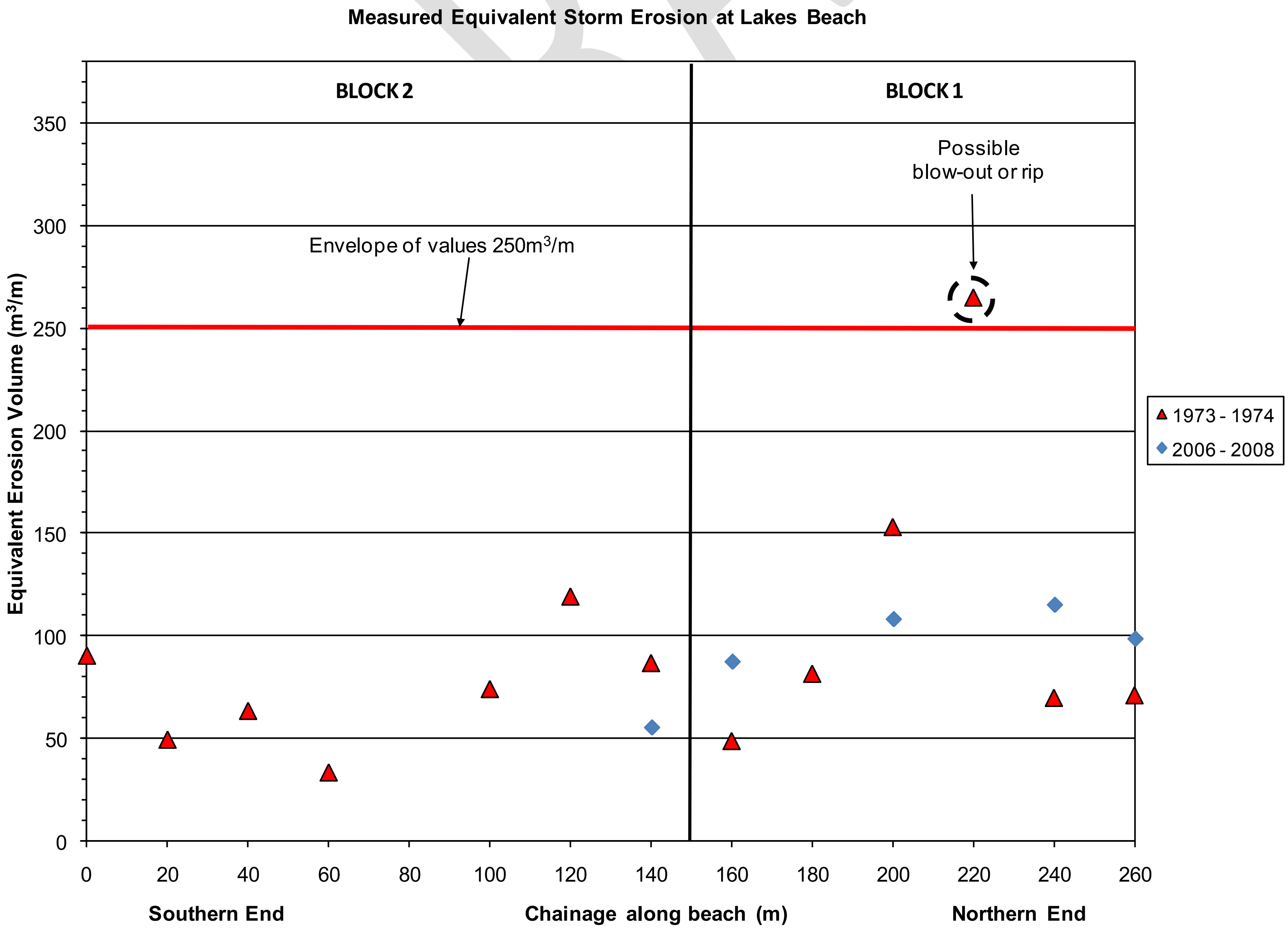


Figure D.10 – Upper envelope for storm bite, Lakes Beach