BBK DEVELOPMENT CORPORATION

45 Hearns Lake Road Woolgoolga Coastline Hazard Definition and Lake Entrance Processes

Issue No. 3
OCTOBER 2004

Patterson Britton
& Partners Pty Ltd

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Document Amendment and Approval Record

Issue	Description of Amendment	Prepared by [date]	Verified by [date]	Approved by [date]
1	Draft for Client Review	PRH [13/10/04]	GWB [13/10/04]	GWB [13/10/04]
2	Include consideration of 1 Hearns Lake Rd	PRH [21/10/04]	GWB [21/10/04]	GWB [21/10/04]
3	Final	PRH [22/10/04]	GWB [22/10/04]	GWB [22/10/04]

Note: This document is preliminary unless it is approved by a principal of Patterson Britton & Partners.

Document Reference: rp5558prh041022-hearns lake-issue 3.doc
Time and Date Printed 23 July 2008, 6:43 AM

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1 INTRODUCTION

A Masterplan for 45 Hearns Lake Road Woolgoolga (Lot 21, DP 714858) has been prepared by BBK Coastal Development Group (2003), in accordance with *State Environmental Planning Policy No. 71 – Coastal Protection*.

The subject property is located immediately north of the entrance to Hearns Lake, an Intermittently Closed and Open Lake or Lagoon (ICOLL). The beach seaward of the subject property has not been officially named by the Geographical Names Board of NSW, but was denoted as Hearns Lake Beach by Short (1993) and Jones (1981)[1], and Solitary Beach in the Masterplan. The former name has been adopted for the investigation reported herein.

BBK Development Corporation engaged Patterson Britton & Partners to undertake a coastline hazard definition study for the subject property. Given concerns raised by the Department of Infrastructure, Planning and Natural Resources (DIPNR), we were also engaged to comment on lake entrance issues, particularly in relation to the impact of the development on water quality and odours, and possible pressure from future residents to manually open the entrance to Hearns Lake.

Furthermore, a Masterplan for 1 Hearns Lake Road Woolgoolga (Lot 4, DP 612977) has been prepared. This site is located west of the subject property, on the eastern side of the Pacific Highway. Coastline hazard risks are negligible at 1 Hearns Lake Road. However, BBK engaged Patterson Britton & Partners to consider water quality issues in relation to the development at 1 Hearns Lake Road, in conjunction with examination of these issues for the subject property[2].

In the investigation reported herein, the geographical setting of the subject property is outlined in Section 2. A review of relevant literature is given in Section 3, with a discussion on data acquisition in Section 4. Coastal processes acting over the region and at the subject property are discussed in Section 5. In Section 6, the coastline hazards at the subject property are determined, with the coastline hazard zones defined in Section 7.

Estuary classification and processes at Hearns Lake are outlined in Section 8. Water quality issues related to entrance processes are discussed in Section 9, with consideration of both the subject property and 1 Hearns Lake Road. The report conclusions are provided in Section 10, with references listed in Section 11.

Note that all levels given in this report are in metres relative to Australian Height Datum (AHD), unless stated otherwise. Zero metres AHD is approximately equal to mean sea level.

In determining future coastline hazards, results for planning periods of 50 years and 100 years are given, at the years of 2054 and 2104 respectively. In accordance with industry practice, a 50 year

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[1] Jones (1981) actually used the spelling "Hearnes", as did Coffs Harbour City Council on signage observed at the locality in August 2004. This spelling is not recognised as an official or variant name by the Geographical Names Board of NSW.
[2] In the investigation reported herein, 45 Hearns Lake Road is denoted as the "subject property". 1 Hearns Lake Road is always denoted as "1 Hearns Lake Road".

planning period is usually adopted for residential development, and is considered appropriate for the subject property[3]. However, results for the 100 year planning period are also shown for informational purposes, as Coffs Harbour City Council stipulated a 100 year planning period for residential development which may be subject to coastline hazards, in a previous investigation completed by Patterson Britton in the LGA (Patterson Britton & Partners, 1995b)[4].

[3] A 50 year planning period was also adopted in the LGA wide coastal assessment report of PWD (1995a). Furthermore, a 50 year planning period was recommended in a coastal engineering assessment of a development at Campbells Beach (WP Geomarine, 1999a), noting that such a timeframe was applied by Gosford, Warringah and Wyong Councils.

[4] The Development Control Plan applying to Residential Tourist Lands (for land zoned 2e as per the subject property) does not specifically state which planning period should be adopted.

2 GEOGRAPHICAL SETTING

The subject property is located in the suburb of Woolgoolga, within the Coffs Harbour Local Government Area (LGA). It is situated about 20km north of the Coffs Harbour township. The property is located immediately north of the entrance to Hearns Lake, and landward of Hearns Lake Beach. Views of the dune seaward of the property are given in **Figure 1** and **Figure 2**.

Based on a survey undertaken in September 2003 by Resource Design & Management, elevations over and near the subject property (at 1m contour intervals) are shown in **Figure 3**. It is evident that most of the site, except the NE corner, is above 6m AHD, with elevations increasing to over 20m AHD at the northern centre of the property[5].

As shown in **Figure 4**, Hearns Lake Beach faces approximately east and is about 2.0km long, extending between Flat Top Point in the north, and unnamed rocks forming the northern end of Sandy Beach[6] in the south. Sandy Beach extends south to the relatively prominent headland Bare Bluff, also facing east, and being about 1.1km long.

North of Flat Top Point, Woolgoolga Back Beach (as denoted by Short, 1993) extends to another relatively prominent headland, Woolgoolga Headland. The beach is about 2.0km long, and faces ESE. Flat Top Point is usually linked to the mainland via a sandy tombolo, as is evident in Figure 4.

Figure 1: Dune seaward of subject property, looking SSW towards Hearns Lake

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[5] Note that the aerial photography shown in Figure 3 and Figure 4 was taken in June 2000, and was supplied by Coffs Harbour City Council. The subject property boundary shown was derived from cadastral information supplied by DIPNR.

[6] Sandy Beach was the name assigned by the Geographical Names Board of NSW on 17 May 2002. Previously, the official name was Sandys Beach.

Figure 2: Dune seaward of subject property, looking north from Hearns Lake

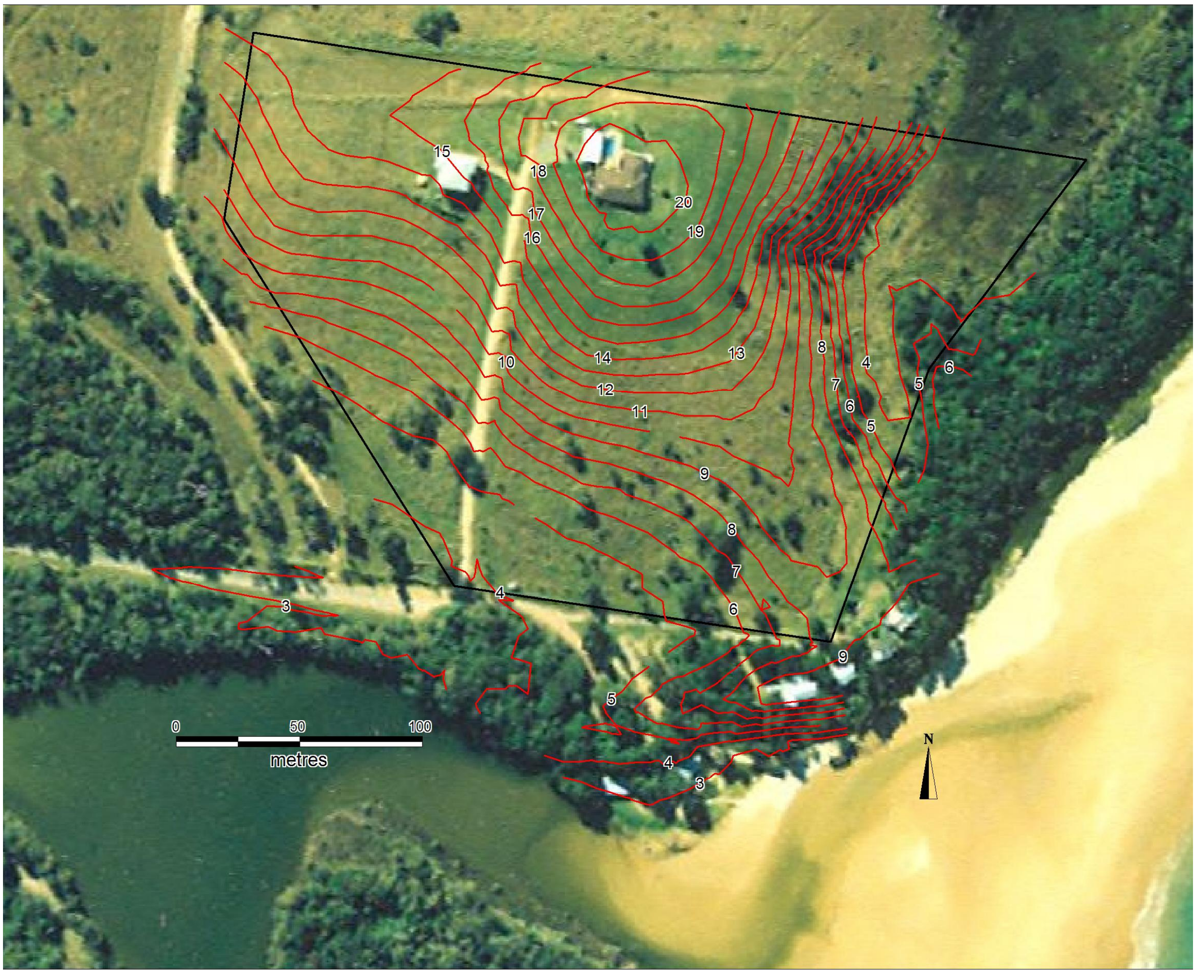


Figure 3: Elevations (m AHD) over and near subject property (1m contour interval)

Figure 4: General view of Hearns Lake Beach in relation to surrounding coastline

3 LITERATURE REVIEW

As far as we could determine, there have been no specific coastline hazard definition studies of Hearns Lake Beach. However, Jones (1981) did provide a brief description of Hearns Lake Beach from a coastal processes perspective as outlined in Section 3.1.

In subsequent Sections, various studies that have been undertaken in Coffs Harbour LGA are reviewed. In particular, the generic "Coffs Harbour City Coastal Assessment Report" (Public Works Department [PWD], 1995a) is reviewed in Section 3.2. A number of photogrammetric studies that fed into the PWD (1995a) study are also outlined. Studies for two of the beaches analysed by PWD (1995a) have been undertaken since the publication of the PWD (1995a) report, namely at Campbells Beach and Park Beach, as described in Sections 3.3 and 3.4 respectively. A study undertaken by Patterson Britton & Partners (1995b) at Emerald Beach is also outlined in Section 3.5. A synthesis of the information presented is given in Section 3.6.

Note that the literature review was mainly focussed on deriving coastal processes and coastline hazard information. Reference to Sections 5 and 6 may assist in understanding the technical discussion. In particular, an understanding of the definition of the "storminess indicator" (Section 5.4.5) would be beneficial. A storminess indicator value less than 1 is indicative of accreted beach states, a value of 1 is indicative of average beach states, and a value greater than 1 is indicative of eroded beach states.

3.1 DESCRIPTION OF HEARNS LAKE BEACH BY JONES (1981)

Jones (1981), in a preliminary study considering coastline hazards in the Coffs Harbour region, stated that dunes were adequately stabilised with vegetation at that time at Hearns Lake Beach. It was noted that sand had been extracted from the tombolo at the northern end of the beach in the past. Glover (2004) stated that this sand extraction occurred from the late 1960's to about 1976. However, this was probably undertaken closer to the entrance than the tombolo[7].

3.2 COFFS HARBOUR CITY COASTAL ASSESSMENT REPORT

For the Coffs Harbour LGA in general, PWD (1995a) prepared the "Coffs Harbour City Coastal Assessment Report". The intended use of the PWD (1995a) document was as an indicative guide only of the coastline hazards in Coffs Harbour LGA, as a planning constraint to development, over a planning period of 50 years.

PWD (1995a) developed coastline hazard estimates based mainly on photogrammetric analyses documented in previous studies. In particular, storm demand and long term recession due to net sediment loss were estimated by measurements over time of the position of a particular contour

[7] The only small scale operations potentially evident in aerial photography (in 1969 and 1972) were being undertaken at the entrance.

level (denoted as a cut level), generally at an elevation of 6m plus or minus 2m AHD[8]. The photogrammetric analysis was based on aerial photography which commenced in the early 1940's.

Storm demand was estimated by measurement of the maximum movement of the cut level position between subsequent photography dates over the period of record. However, although it was assumed that cut level movement was caused only by one major storm or a sequence of closely spaced storms, in reality a period of many years elapsed between most subsequent photography dates in this analysis[9].

Trends in long term recession due to net sediment loss were estimated by measurements over time of the cut level position. In general, the recession rate in m/year for each photogrammetric profile was determined as the positional change between the first and last dates of photography (m), divided by the length of time between the first and last dates (years). The rate for the entire beach was then determined as the average for all profiles. This methodology had a number of limitations, namely:

- volumetric analysis can capture far more information than scarp movement, on changes to the entire subaerial active beach profile[10];
- arbitrarily choosing the first and last dates of photography does not consider the relationship of the photography to coastal storms, in particular whether these profiles are likely to be eroded, average or accreted;
- only considering the first and last dates of photography does not take into account the fluctuations in beach behaviour in between these dates, which provides valid information for the determination of recession trends[11];
- the first date of photography was generally of limited accuracy, making the photogrammetric data unreliable for this date, and hence making recession estimates relying on it questionable[12];
- variations in spatial behaviour were not allowed for, with constant values adopted for entire embayments; and,
- anthropogenic effects that may have influenced the recession rates more than natural processes, such as sand mining, sand extraction, levelling for development, and aeolian losses

[8] PWD (1995a) termed this cut level as the position of the back beach erosion escarpment. However, the latter term is usually used to describe the limit of erosion in a dune caused by storm waves, in particular its crest position. The cut level was not generally at this scarp position. Note however that for Sapphire Beach, the cut level was up to 10m AHD, and that at this location it did correspond to the scarp position (PWD, 1992b).

[9] Therefore, pre-storm and post-storm sequences were not captured, as required for such analysis to be reliable. With such long periods between aerial photography dates, it is more likely that longer term shoreline changes, rather than short-term beach erosion, was being measured. An example given for Campbells Beach indicated that the period from 1942 to 1964 was analysed to determine storm demand, dates that are separated by 22 years. Many storms, and beach recovery in between, would occur over such a long period.

[10] PWD (1995a) stated that measuring the escarpment position was the best available method for determining long term recession. This viewpoint is considered to be arguable as outlined. Volumetric analysis was only undertaken for Sawtell Beach and Macauleys Beach.

[11] Typically, about 5 other dates were available for consideration between the first and last dates.

[12] In general, the 1940's and 1950's photography relied on in the analysis was generally of high flying height (scales exceeding 1:20,000), very poor or poor model control, and usually poor quality. Furthermore, camera calibration coefficients were not available for this photography, meaning that no corrections could be made for lens distortion. As stated by PWD (1995a), "profile information obtained from the [1940's] photography should be treated with caution due to poor photo quality and very poor model control". At some sites, datum shifts in the order of 2m were applied to profiles due to inaccuracies.

associated with vegetation removal (all of which may not continue into the future), were not explicitly considered in determining recession rates[13].

Although there were some limitations to the PWD (1995a) investigation as noted, the storm demand (metres storm cut) and long term recession rates due to net sediment loss adopted by PWD (1995a) for the various beaches analysed in the Coffs Harbour LGA are shown in **Figure 5** (southern end of LGA) and **Figure 6** (northern end of LGA). A total of 12 beaches were analysed. Note that the base mapping for these Figures was taken from PWD (1995a).

Long term recession due to climate change was estimated assuming a sea level rise of 0.28m over a 50 year period, as derived from the best estimate of the then current Intergovernmental Panel on Climate Change Working Group 1 Assessment of 1990. The Bruun rule was then utilised with the assumption that the inverse slope of the active beach profile was 50[14]. Therefore, long term recession due to sea level rise was estimated to be 14m for a 50 year planning period.

The three values shown in Figure 5 and Figure 6 for each of the 12 analysed beaches represent the storm demand, long term recession due to net sediment loss, and total setback relative to the cut level position (that is, sum of two former values and 14m long term recession due to sea level rise, equivalent to a coastline hazard line over a 50 year planning period) respectively.

Based on likely beach states related to coastal storms (discussed in more detail in Section 4.2 and in particular Section 5.4.5), the long term recession estimates of PWD (1995a) were more likely to be overestimates for Park Beach, Macauleys Beach, Charlesworth Bay, Hills Beach, and Campbells Beach (due to an initially average or accreted beach state, and ultimately eroded beach state, over the period of analysis) . Conversely, the long term recession estimate for Sawtell Beach was more likely to an underestimate (due to an initially severely eroded beach state, and ultimately average to eroded beach state, over the period of analysis). The long term recession rates for Sapphire Beach, Woolgoolga Beach, Ocean View Beach and Corindi Beach were less likely to be influenced by beach state, as the beaches at the beginning and end of the analysis period would have been expected to be relatively eroded in each case. These observations should be taken into account when interpreting the quoted recession rates[15].

[13] It is recognised that the occurrence of anthropogenic activities was at least noted at most sites.
[14] This slope value was nominally adopted, without consideration of closure depths or offshore bathymetry.
[15] Many of the potential issues associated with relative beach states would have been overcome if the PWD (1995a) analysis was based on trends for all dates, rather than simply the difference between the first and last date.

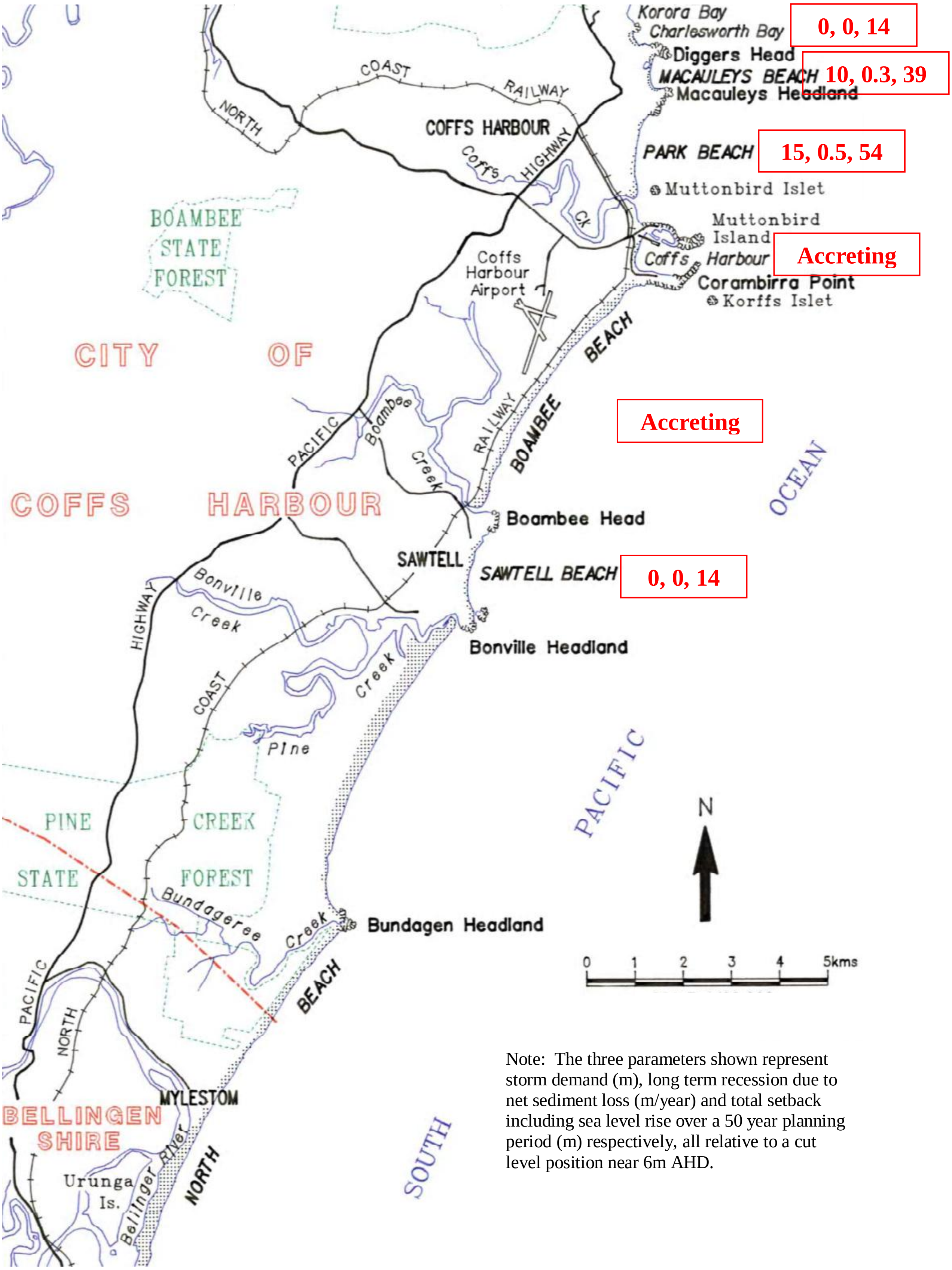
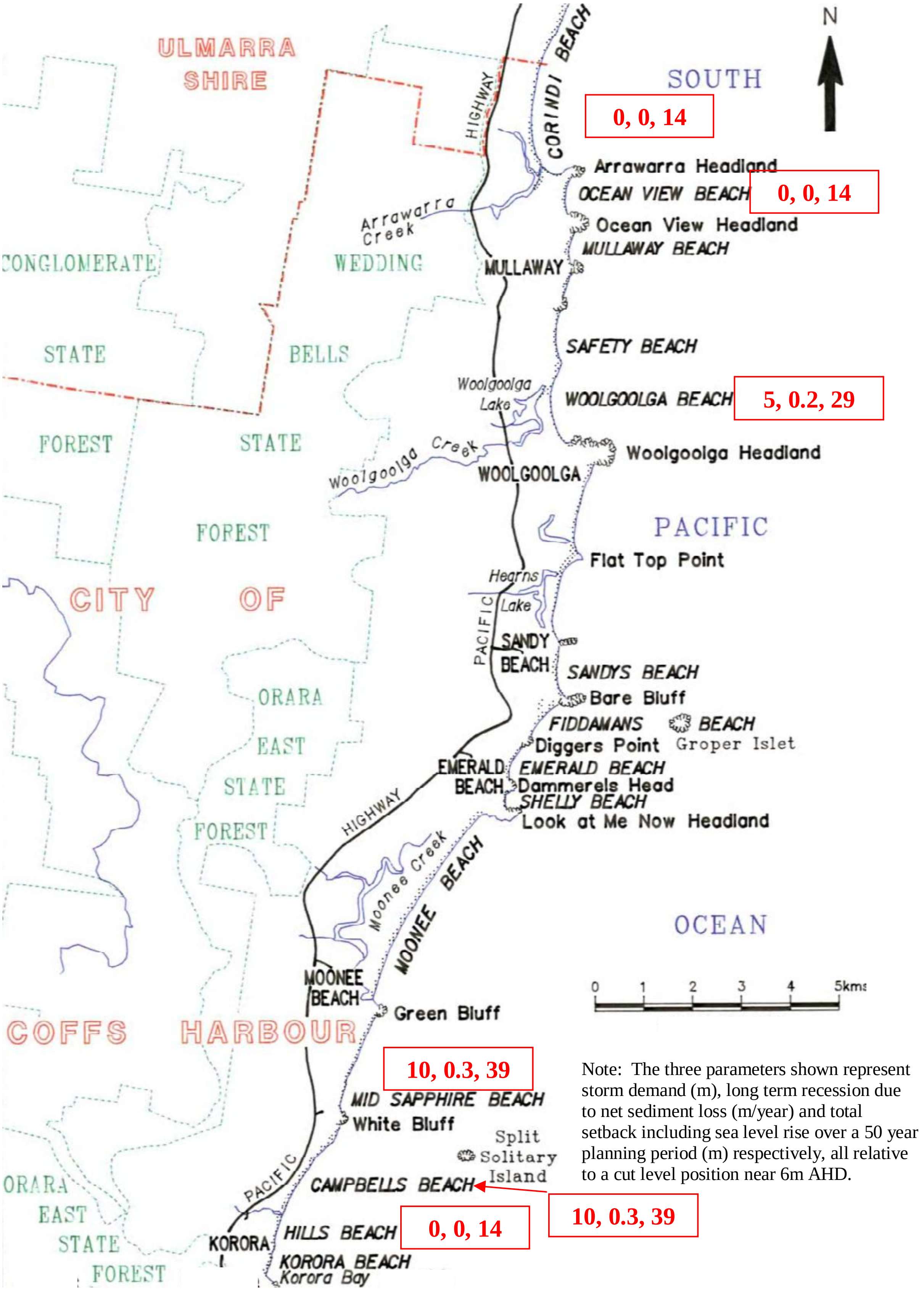


Figure 5: Coastline hazard parameters adopted by PWD (1995a), for beaches at southern end of Coffs Harbour LGA



Note: The three parameters shown represent storm demand (m), long term recession due to net sediment loss (m/year) and total setback including sea level rise over a 50 year planning period (m) respectively, all relative to a cut level position near 6m AHD.

Figure 6: Coastline hazard parameters adopted by PWD (1995a), for beaches at northern end of Coffs Harbour LGA

The references utilised in determining the coastline hazard parameters for each beach are listed in **Table 1**, proceeding from south to north[16]. The photogrammetric analysis period is also shown. Furthermore, the values for the storm demand and long term recession due to net sediment loss, as derived from interpretation of the original references, are listed. Information is also given on photographic accuracy, dates used to estimate storm demand, recession rates for periods other than the analysis period, and other coastal processes.

Table 1: Beaches considered by PWD (1995a), and coastline hazard parameters determined from observation of original references

Beach	Study	Analysis Period	Storm Demand (m)	Recession (m/year)	Comments
Sawtell	PWD (1995b)	1942-1993	See comments	Stable	Volumetric analysis indicated a storm demand 100m³/m (above 0m AHD and landward of 2m AHD contour) and long term accretion of about 3m³/m/yr. 1967 was generally the first date utilised (1942 only covered small area of beach). The 1977-1980 period was used to estimate storm demand.
Park	PWD (1993a)	1942-1989	15	0.5	The 1969-1975 period was used to estimate storm demand. However, 1969 photography was 1:22,000 scale and had poor model control. Recession rate was about 1m/year from 1969-1989.
Macauleys	AWACS (1989)	1942-1986	–	0.6	The 5 dates considered prior to and including 1973 were higher level than 1:21,000 scale. Volumetric analysis was undertaken, but parameters could not be deduced from the reported results. The 1942 and 1954 photography was not included in volume analyses. Recession rate shown was for 1973-1986 period, after sand mining and extraction had ended (these operations commenced in 1959).
Charlesworth Bay	AWACS (1989)	1942-1986	–	–	No useful information presented to determine coastline hazard parameters, except profile plots.
Hills	PWD (1992a)	1943-1989	–	–	No information was presented to determine hazard parameters, except profile plots. The 1943 photography was 1:16,000 scale but of poor quality and control. The 1964 photography was 1:46,000 scale.
Campbells	PWD (1993b)	1942-1988	10	0.3 (S only)	The 1964 photography was 1:46,000 scale. Storm demand was estimated based on 1942-1964 period. Recession rate was about 0.05 to 0.2m/year from 1964-1988, with lower values at the N end.
Sapphire	PWD (1992b)	1943-1988	0-10	0.2	The 1943 photography was 1:16,000 scale but of poor control. The 1964 and 1969 photography were in the order of 1:50,000 scale. Storm demand was estimated based on 1943-1964 period, and was considered equivalent to a volume above 0m AHD of 150 to 280m³/m. Recession rate range of 0.1 to 0.3m/year was stated in PWD (1992b) report, with latter value adopted by PWD (1995a). The variation in rates was spatial, with higher rates in the S and lower rates in the N.
Woolgoolga	PWD (1990)	1943-1986	–	0.2	Recession rate shown only applicable at southern end of beach (northern end was stable).
Ocean View	DLWC (1995)	1943-1993	–	0.1	The 1964 photography was 1:47,000 scale. The recession rate quoted was based on limited data, and only applied at S end (N was stable).
Corindi	PWD (1995c)	1943-1993	–	Accretion	The 1964 photography was 1:47,000 scale. Accretion was noted for most of beach length, with increasing accretion moving north.

[16] Boambee Beach and Jetty Beach were noted as undergoing accretion, with no coastline hazard parameters determined for these two beaches, and therefore these beaches are not included in Table 1. It was stated by PWD (1995a) that Boambee Beach and Jetty Beach were accreting at rates of 38,000m^3/year and 1,800m^3/year respectively (volumes determined above 0m AHD). No specific studies were cited in determining these values.

Note that for Macauleys Beach and Woolgoolga Beach, additional analysis was undertaken by PWD (1995a) subsequent to the original photogrammetric analysis reports, with the inclusion of 1993 photography. For Park Beach, additional dates of photography have been collected since the PWD (1995a) report, namely for the years of 1993, 1994, 1996 and 2000 (Watson, 2004)[17]. Also, for Fiddamans Beach, details on a now stabilised dune blowout at this locality were provided in DLWC (1997b).

For beaches that had not been studied, PWD (1995a) recommended that the parameters adopted for Park Beach, the worst case, should be adopted as a conservative upper limit. These were to be refined as specific investigations were completed. Furthermore, it was recommended that the PWD (1995a) report be reviewed every 5 to 10 years, particularly as climate change estimates evolved.

PWD (1995a) considered that the hazard of coastal inundation could be managed by maintenance of a stabilised dune system of sufficient height (say 6m AHD) to minimise wave overtopping, siting new development sufficiently landward, or setting appropriate design standards.

3.3 CAMPBELLS BEACH

For Campbells Beach, a Coastal Processes and Hazard Definition Study (WP Geomarine, 1998) and Coastline Management Plan (WP Geomarine, 1999b) have been prepared. In these studies, the following parameters were adopted:

- a storm demand above 0m AHD of 140m^3/m, applied as a linear setback of 10m from the back beach erosion escarpment existing at that time;
- long term recession due to net sediment loss of 0.3m/year;
- long term recession due to sea level rise of 4.5m over a planning period of 50 years, based on a sea level rise of 0.23m and inverse slope of the active beach profile of 20[18]; and,
- runup level of 7m AHD[19].

Compared to PWD (1993b), two additional dates of photography were included in the photogrammetric analysis, taken in May 1993 and June 1996.

Storm demand was estimated by considering the maximum envelope of beach volume changes between subsequent dates of photography. As noted previously, given that pre-storm and post-storm sequences were not captured, such analysis need to be treated with some caution. The adopted storm demand value was considered to be within the normal range for storm erosion measured in NSW on open coast beaches with a low dune system.

[17] Inclusion of the 1994 and 1996 photography was documented in DLWC (1996) and DLWC (1997a) respectively. Despite beach nourishment having been undertaken in 1988 and 1993, the recession rates from 1942-1994 and 1969-1994 were similar to those reported in PWD (1993a) for the periods ending at 1989.

[18] The inverse slopes varied along the beach, being 10 in the south, 20 in the centre and 50 in the north. The value in the centre of the beach was adopted. Note that bedrock in the surf zone was considered to act as a control, in determining slopes (that is, the slope inshore from the edge of bedrock was used).

[19] The calculation of runup was seemingly in error as wave setup was included in the still water level, and a numerical error was also potentially made (without these miscalculations, the value would have been 6.6m AHD).

The actual average long term recession rates measured between 1942 and 1996 at Campbells Beach were 0.21m/year in the south, 0.08m/year in the centre, and 0.11m year of accretion in the north (based on volumetric analysis for these two dates only)[20]. The beach-averaged recession rate was only 0.08m/year, much less than the 0.3m/year adopted by PWD (1995a).

Fortunately, the dates chosen as the beginning and end of the photogrammetric analysis period were likely to have relatively average beach states in each case. Therefore, the influence of beach state on recession rates was considered most likely to be minor. This may partly explain why the recession estimates of WP Geomarine (1998) were lower than those of PWD (1995a)[21].

A coastal engineering investigation of a property at the southern end of Campbells Beach was undertaken by WP Geomarine (1999a). A storm demand above 0m AHD of $80m^3/m$ was adopted for this property, applied as a linear setback of 4m from the back beach erosion escarpment. The reason that a smaller storm demand was adopted compared to WP Geomarine (1998) was that it was considered that the southern end of the beach had a decreased exposure to waves, and the beach sands seaward of the subject property were interspersed with bedrock.

3.4 PARK BEACH

For Park Beach, a Coastal Hazard Definition and Management Study (Resource Design and Management [RDM], 1998a) and Coastline Management Plan (RDM, 1998b) have been prepared. In these studies, the following parameters were adopted as per PWD (1995a):

- storm demand given by a linear setback of 15m from the back beach erosion escarpment existing at that time;
- long term recession due to net sediment loss of 0.5m/year;
- long term recession due to sea level rise of 14m over a planning period of 50 years, based on a sea level rise of 0.28m and inverse slope of the active beach profile of 50; and,
- recommended minimum dune level of 6m AHD.

3.5 EMERALD BEACH

Patterson Britton & Partners (1995b) identified coastline hazards for a proposed development at Emerald Beach, which almost traversed the entire length of beach. In particular, long term recession due to net sediment loss was estimated by reference to aerial photography, taken in 1943, 1956, 1964, 1973, 1981, 1986 and 1993 (generally corresponding or close to the dates shown in Section 4.2, Table 2, for each of these years[22]).

By plotting the position of the sand/vegetation interface for each date of photography, it was evident that Emerald Beach had accreted between 1943 and 1993 (assuming that this interface was indeed representative of long term beach changes). At the south, centre and northern ends of

[20] These values were derived from Table 2 of WP Geomarine (1998). It is uncertain why different values were reported in Section 2.5 of the same report (0.35, 0.13 and 0m/year respectively), and adopted in WP Geomarine (1999b).

[21] As noted in Section 3.2, the PWD (1995a) analysis of Campbells Beach may have overestimated recession rates with the selection of a likely initially average and ultimately relatively eroded beach profile.

[22] The only exception to this was the photography taken on 26 October 1981. The storminess indicator for this date was 0.1.

Emerald Beach, accretion rates from 1943 to 1993 were found to be 0.1, 0.5 and 0.9m/year respectively. In the centre and north, the vegetation interface moved monotonically seaward from 1943 to 1988, then was landward of the 1981 position in 1993. The largest accretion rates were found to be from 1943 to 1956.

Note that in terms of likely beach states, 1943 and 1993 would both be expected to be relatively eroded, meaning that selection of these two dates in isolation would be unlikely to skew natural recession rates. The seaward progression of the vegetation line for 1981 relative to 1993 is explainable in that the former date had a storminess indicator of 0.1, indicative of a very accreted beach state, whereas 1993 had a storminess indicator of 1.7, indicative of an eroded beach state.

However, it was conservatively assumed by Patterson Britton & Partners (1995b), as an upper bound, that Emerald Beach was receding at a rate of 0.2m/year, taking account of the average recession rate of 0.2m/year noted in PWD (1995a) for 10 beaches in the Coffs Harbour LGA.

3.6 SYNTHESIS

The literature review provided some useful information with regard to coastal processes. In particular, strong evidence for reducing recession rates moving north along individual beaches in the vicinity of Hearns Lake Beach was obtained, as well as relatively low recession rates in the region. The evidence for this included:

- accretion at the northern end of Campbells Beach from 1942-1996, and beach-averaged recession rate only 27% of the value quoted by PWD (1995a);
- recession rates at the northern end of Sapphire Beach being about 33% of those at the southern end;
- increasing accretion rates from 1943-1993 moving north along Emerald Beach (based on vegetation lines);
- northern end of Woolgoolga Beach being stable from 1943-1986;
- northern end of Ocean View Beach being stable from 1943-1993; and,
- accretion along most of Corindi Beach, with accretion rates generally increasing moving north.

For the six beaches nearest to Hearns Lake Beach, the average recession rate quoted by PWD (1995a) was 0.13m/year. However, of the only three beaches actually considered to be receding, two of these were either accreting or stable at the northern end. Furthermore, there was evidence that Emerald Beach has been accreting.

The relatively high recession rate of 0.5m/year quoted for Park Beach was not considered to be applicable at Hearns Lake Beach, as recession of Park Beach has predominantly been caused by construction of Coffs Harbour, 20km south of the subject property. Furthermore, the dates used in the photogrammetric analysis for this site may have caused recession rates to be overestimated.

Unfortunately, the dates of available photography and methodology employed by PWD (1995a) did not generally allow much data to be gathered on likely storm demands in the region, and no other known studies have considered the issue rigorously. In general, the storm demand values presented were considered to be unconservative. Furthermore, little data was presented on likely slopes of the active beach profile for use in the Bruun Rule.

4 DATA ACQUISITION

Three key items of data that were acquired as part of the investigation reported herein were:

- a land based survey of Hearns Lake Beach seaward of the subject property;
- historical aerial photography of Woolgoolga Back Beach and Hearns Lake Beach; and,
- photogrammetric data for Sandy Beach.

These data items are discussed in Sections 4.1 to 4.3 respectively below.

4.1 SURVEY OF HEARNS LAKE BEACH

A survey of Hearns Lake Beach was undertaken seaward of the subject property on 27 August 2004. The work was carried out by Reg Walters and Partners, Consulting Engineers, Surveyors and Planners. As part of this, four shore-normal beach profiles were obtained, as shown in **Figure 7**, overlaying aerial photography taken in June 2000 (refer Footnote 5, Page 3). The profiles were denoted as Profile 1 to Profile 4, proceeding from north to south. The location of features such as vegetation lines and lake edges were also noted, and are labelled in Figure 7**.**

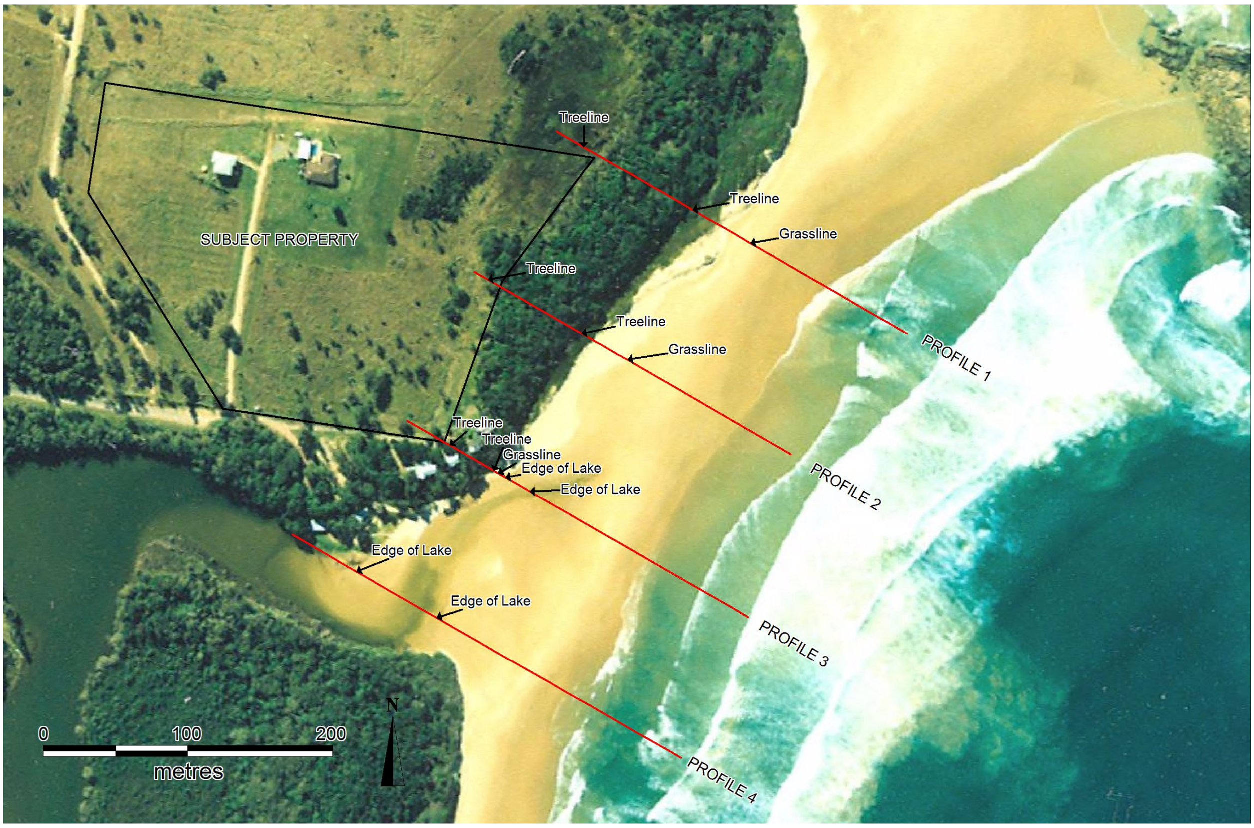


Figure 7: Location of profiles obtained seaward of subject property in August 2004

Denoting the landward end of each profile as zero chainage, a plot of elevation versus chainage for each profile is given in **Figure 8**.

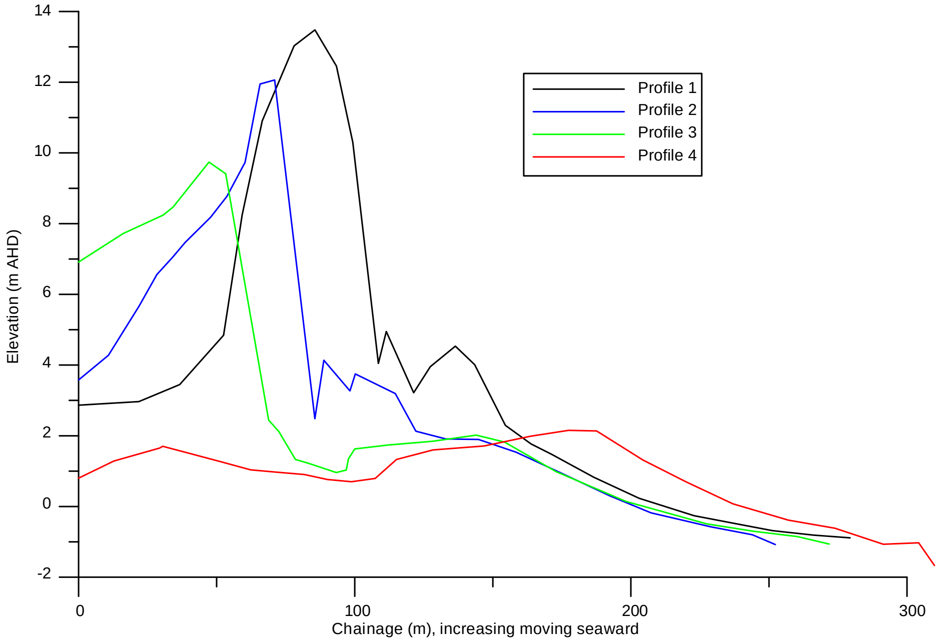


Figure 8: Elevation versus chainage for Profiles 1 to 4

4.2 REVIEW OF HISTORICAL AERIAL PHOTOGRAPHY

Aerial photography of Woolgoolga Back Beach and Hearns Lake Beach was obtained from the Department of Lands and Roads and Traffic Authority (RTA). The collection of aerial photography held at DIPNR in Newcastle was also perused. A summary of the dates and scales of each set of photography examined is given in **Table 2**[23].

Photography that was obtained from the Department of Lands and RTA was approximately registered to real world coordinates by matching consistent features[24] in a June 2000 orthorectified aerial photograph supplied by Council, within a GIS package. The approximate accuracy of each registered photograph (based on image pixel distances from control points, converted to metres) is also shown in Table 2, as the maximum and average errors (based on four control points). Other photography was qualitatively viewed at DIPNR in Newcastle[25].

Based on the photography, it was evident that the subject property was forested until 1969, and cleared some time between 1969 and 1972. The site of the present Caravan Park (located just west of Figure 7, adjacent to Hearns Lake) was also similarly initially forested, and cleared in the 1969-1972 period. The Caravan Park was developed some time between 1976 and 1980.

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[23] The storminess indicator shown in Table 2 was derived as discussed in Section 5.4.5, and is indicative of eroded beach states if less than 1, average beach states if close to 1, and eroded beach states if greater than 1.

[24] Such features included rocky outcrops on Woolgoolga Headland, Flat Top Point, and at the northern end of Sandy Beach; road intersections; structure outlines; and creek junctions. In all cases, it was determined that the location of these features were consistent between the date of photography being examined and the June 2000 base photography.

[25] An 11 November 2003 aerial photograph taken by Asquith and de Witt was also viewed, which covered the southern end of Hearns Lake Beach (south of the entrance).

Table 2: Aerial photography examined as part of investigation reported herein

Date	Scale (1 to)	Source	Registration error (m)		Storminess Indicator[23]
			Maximum	Average	
9 March 1943	16,000	DIPNR	N/A	N/A	1.6
11 March 1943	18,900	Department of Lands	4.8	3.6	1.6
23 March 1943	18,900	DIPNR	N/A	N/A	1.6
26 April 1956	32,230	Department of Lands	2.8	1.6	0.8
12 August 1964	46,610	DIPNR	N/A	N/A	1.1
19 August 1964	80,000	DIPNR	N/A	N/A	1.1
7 February 1966	15,980	DIPNR (permission from Lands)	6.4	5.1	0.3
6 April 1969	58,590	Department of Lands	9.9	9.9	0.4
8 October 1972	18,400	RTA	3.9	2.9	0.8
14 April 1973	40,010	DIPNR	N/A	N/A	0.2
3 May 1973	26,460	Department of Lands	2.8	2.0	0.2
28 March 1974	26,000	DIPNR	N/A	N/A	1.5
23 June 1974	40,250	Department of Lands	2.7	1.3	1.7
18 August 1974	44,280	Department of Lands	2.8	1.4	1.3
2 December 1976	40,050	DIPNR	N/A	N/A	1.4
19 March 1980	10,150	RTA	2.6	1.3	0.4
29 January 1983	10,060	DIPNR	N/A	N/A	0.4
31 August 1983	10,060	DIPNR	N/A	N/A	0.8
22 June 1986	9,954	Department of Lands	5.7	3.4	1.3
9 May 1988	10,200	DIPNR	N/A	N/A	1.7
17 June 1993	10,280	Department of Lands	0.4	0.3	1.4
28 June 1996	10,150	DIPNR	N/A	N/A	1.0
17 May 2000	9,950	Department of Lands	0.8	0.4	1.8
1 June 2000	15,000	Coffs Harbour City Council	0.0	0.0	1.8
7 September 2002	25,000	Department of Lands	2.0	1.0	–

4.3 ANALYSIS OF SANDY BEACH PHOTOGRAMMETRIC DATA

Photogrammetric data for Sandy Beach was obtained from DIPNR. This data comprised shore-normal beach profiles, based on aerial photography as detailed in **Table 3** (also see Table 2).

Table 3: Photogrammetric data obtained for Sandy Beach

Date	Scale (1 to)	Likely Beach State	Comments
23 March 1943	18,900	Eroded	Very poor photography, with incorrect datum (could not be used)
12 August 1964	46,610	Average	High level photography, only to be used with caution
3 May 1973	26,460	Accreted	
9 May 1988	10,200	Eroded	
17 June 1993	10,280	Eroded	
28 June 1996	10,150	Average	

The likely beach state for each date of photography was derived by referring to the storminess indicators in Table 2.

The photogrammetric profiles were arranged into 3 blocks, namely Blocks 1, 2 and 3 proceeding from south to north. There were 12 profiles in Block 1 and 8 profiles in each of Blocks 2 and 3. For the investigation reported herein, each profile was numbered from 1 to 28, with Profiles 1-12 in Block 1, Profiles 13-20 in Block 2, and Profiles 21-28 in Block 3. The arrangement of the profiles (based on the 1996 data extents and June 2000 aerial photography) is shown in **Figure 9**.

Figure 9: Arrangement of photogrammetric profiles at Sandy Beach

Given the proximity of Sandy Beach to Hearns Lake Beach, and similar orientation, the photogrammetric data was analysed to determine if there were any long term recession trends[26]. There had been no known analysis of this data undertaken previously[27].

It was beyond the scope of the investigation reported herein to consider in detail the anthropogenic influences on historical profile changes. However, it was evident that there had been dune vegetation clearing, and perhaps sand extraction (Glover, 2004), and levelling for development over the period covered by the photogrammetry[28]. Based on examination of the photogrammetric profiles, the largest changes to dune heights appeared to have occurred between Profiles 7 and 13, where the dune height of about 6m AHD in 1964 had been reduced to around 4m AHD by 1973[29].

To determine long term recession rates, changes in volume in profiles over time can be determined. This procedure is often denoted as Profile Area Volume (PAV) analysis. To determine the volumes for each profile, the Beach Morphology Analysis Package (BMAP) of the US Army Corps of Engineers was used (Sommerfeld et al, 1994). BMAP allows the calculation of profile volumes with respect to any specified reference elevation and/or segment along the profile. For the study reported herein, volumes above 0m AHD are reported[30]. BMAP also allows the position (chainage) of a particular elevation to be determined. For the study reported herein, the positions of the 3m AHD contour are reported[31].

For each of the 28 profiles, the rate of change of the volume above 0m AHD, and the rate of change of the position of the 3m AHD contour, was determined. The rates were calculated for the 1964-1996, 1973-1996 and 1988-1996 periods, and derived by linear regression, that is by determining the line of best fit (least squares error) in each case[32]. The results of this analysis are summarised into longitudinal plots of the variation of these parameters, that is versus the position along the beach, in **Figure 10** and **Figure 11**.

For calculation purposes, a landward limit was applied to the profiles. That is, not all data from 0m chainage was used, given that part of the profiles would be landward of natural coastal processes. Referring to Figure 9, it is evident that some profiles extended landward of the vegetated dune into a level open space area, for example. The landward limit was defined by determining a continuous line along the beach (in plan) that would logically represent a landward limit to coastal processes, with reference to vegetation lines[33].

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[26] Given the number of years between each photography date, analysis to determine storm demand was not possible.
[27] Christine Gray, Mohammed Hanif and Phil Watson of DIPNR were not aware of analysis that had been undertaken.
[28] It was evident from aerial photography that Sandy Beach was virtually devoid of dune vegetation (other than grasses) between 1956 and 1980 (restoration appeared to be underway in 1980). Roads had been established by 1969.
[29] There was also a large change at Profiles 27 and 28 between 1973 and 1988, where the dune height was reduced from about 9.5m to 5m AHD at Profile 27, and from about 12.5m to 10.5m AHD at Profile 28.
[30] The volume above 0m AHD was used as it was defined in many profiles (72%) without necessity for extrapolation (and 86% and 96% of profiles extended below 0.5m AHD and 1m AHD respectively), and is the typical datum level used in the method of Nielsen et al (1992). Selecting a higher level would have discarded relevant data.
[31] The position of the 3m AHD contour was used as it was both defined in every profile, and also high enough to minimise unwanted noise. If a higher level was selected, although data noisiness may have been reduced, rates would not have been able to be defined at some profiles with low dune heights.
[32] This does not imply that there were uniform rates of volume or positional change between dates of photography.
[33] However, some aeolian processes may still be have been occurring in areas landward of the applied landward limit, such as at Profiles 12-14. Further, by applying a landward limit, the 3m contour position could not be defined at a number of profiles (Profiles 10 and 18 for 1964-1996, Profile 22 for 1964-1996 and 1973-1996, and Profiles 12-16, 19, and 26-27 for all periods).

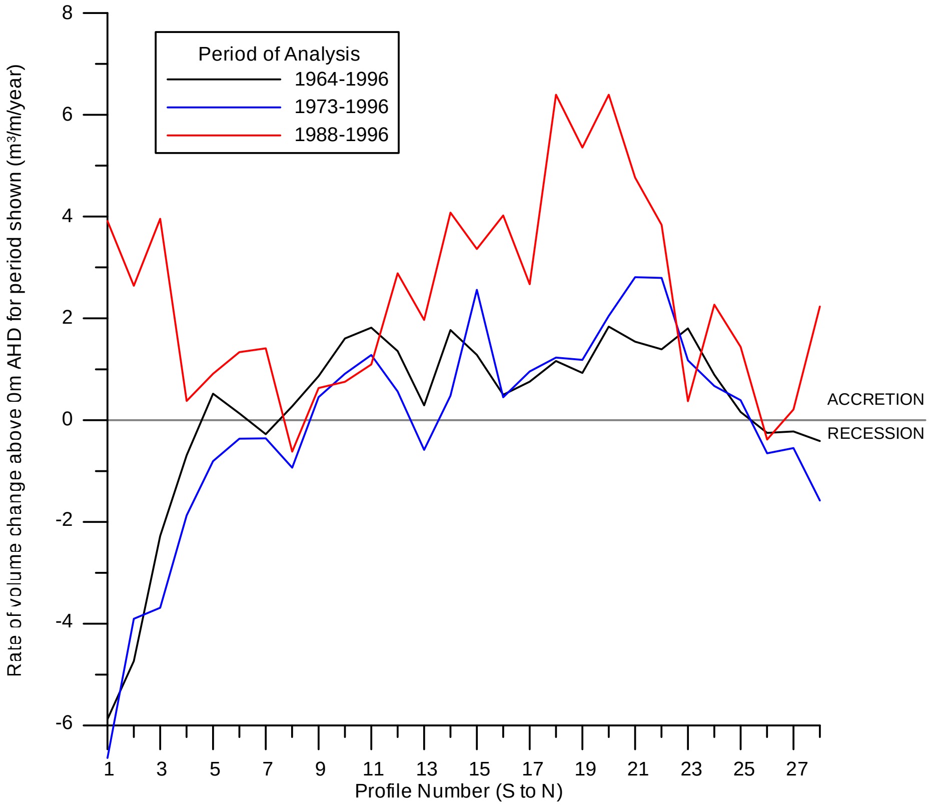

Figure 10: Rate of change of volume above 0m AHD at Sandy Beach

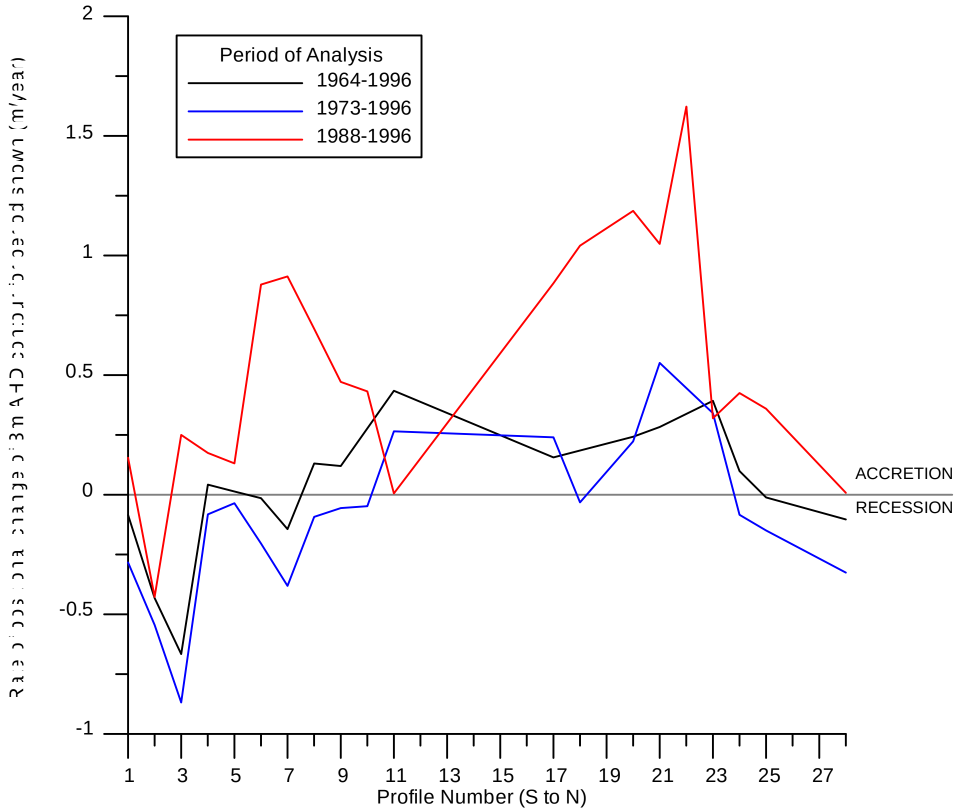

Figure 11: Rate of positional change of 3m AHD contour at Sandy Beach

It is evident that the section of Sandy Beach actively influenced by coastal processes had generally accreted over the period of photogrammetry. The volumetric and positional rates of change, averaged over the entire beach, are summarised in **Table 4**. Note that recession was greatest at the southern end of the beach.

Table 4: Average accretion rates at Sandy Beach based on photogrammetric analysis

Period	Rate of change of volume above 0m AHD (m^3/m/year)	Rate of positional change of 3m AHD contour (m/year)
1964-1996	0.2	0.03
1973-1996	-0.07	-0.08
1988-1996	2.4	0.5

As noted previously, all analysis was undertaken using linear regression, rather than simple differences between the first and last dates of photography. Therefore, errors due to variations in beach states were likely to have been minimised. However, in a relative sense, accretion rates based on the analysis periods to 1996, commencing in 1964, 1973 and 1988, were more likely to be reasonable, underestimates, and overestimates respectively. This observation matches the variation in rates, with the 1964 estimate in between the 1973 (low) and 1988 (high) estimates. Overall, it can be realistically concluded that small accretion rates have occurred at Sandy Beach between 1964 and 1996.

The Sandy Beach accretion rates are further evidence of the observations made in Section 3.6, that recession rates generally reduce moving north along beaches in the vicinity of Hearns Lake Beach, and that these recession rates are relatively low. In fact, six beaches near to Hearns Lake Beach appeared to be either stable or accreting at their northern ends, over a period of record of 30 to 50 years, namely Campbells Beach, Emerald Beach, Sandy Beach, Woolgoolga Beach and Corindi Beach.

5 COASTAL PROCESSES

In this Section, the coastal processes operating in the vicinity of the subject property at Hearns Lake Beach are outlined. In particular, details are provided on:

- wave climate (Section 5.1);
- elevated water levels (Section 5.2);
- wave runup (Section 5.3);
- coastal storms (Section 5.4);
- net sediment transport (Section 5.5), which is caused by longshore sediment transport (Section 5.6) and onshore/offshore sediment transport (Section 5.7);
- geotechnical conditions (Section 5.8);
- Hearns Lake entrance processes (Section 5.9); and,
- climate change (Section 5.10).

5.1 WAVE CLIMATE

Manly Hydraulics Laboratory (MHL), part of the NSW Department of Commerce, operates a network of Waverider buoys in deep water along the NSW coast. Waverider buoys are spherical floating accelerometers which determine sea level surface displacement based on the double integration of measured vertical accelerations. Analysis of the collected data allows (amongst other things) the significant wave height (H_s) and peak spectral wave period (T_p) to be determined[34]. For the NSW network, records are collected for 2048s bursts (about 34 minutes) every hour at 0.5s intervals (Lord and Kulmar, 2001).

Waverider buoys can be non-directional or directional. Directional buoys allow the predominant wave direction to be determined.

In the vicinity of Hearns Lake Beach, Waverider buoys are located offshore of Byron Bay and Coffs Harbour, about 150km north and 20km south respectively from the subject property[35]. The Byron Bay Waverider buoy has been operating since 14 October 1976, being directional since 26 October 1999. The non-directional Coffs Harbour Waverider buoy has been operating since 26 May 1976.

Based on all data collected at Byron Bay and Coffs Harbour to 31 December 1999, the probability of exceedance of a particular offshore deepwater significant wave height (H_s) is as shown in **Figure 12**. It can be seen that H_s values exceeding 4m occur less than 1% of the time[36]. Storm conditions with H_s exceeding 5m occur on average once or twice a year, with H_s exceeding 3m for about 5% of the time, and the average H_s being about 1.6m (MHL, 1997). The average T_p at

[34] The significant wave height is the average height of the highest one-third of the waves in a particular record. The peak spectral wave period is determined by the inverse of the frequency at which the wave energy spectrum reaches its maximum.
[35] MHL also operates Waverider buoys at Crowdy Head, Sydney, Port Kembla, Batemans Bay and Eden. The Sydney and Batemans Bay Waverider buoys are directional, with the other sites non-directional.
[36] Note that this is not the same as saying the 1% annual exceedance probability wave height is 4m.

Byron Bay and Coffs Harbour from 1 January 1985 to 31 December 1999 was 9.6s, with about 92% of records having a T_p between 6s and 14s (Lord and Kulmar, 2001).

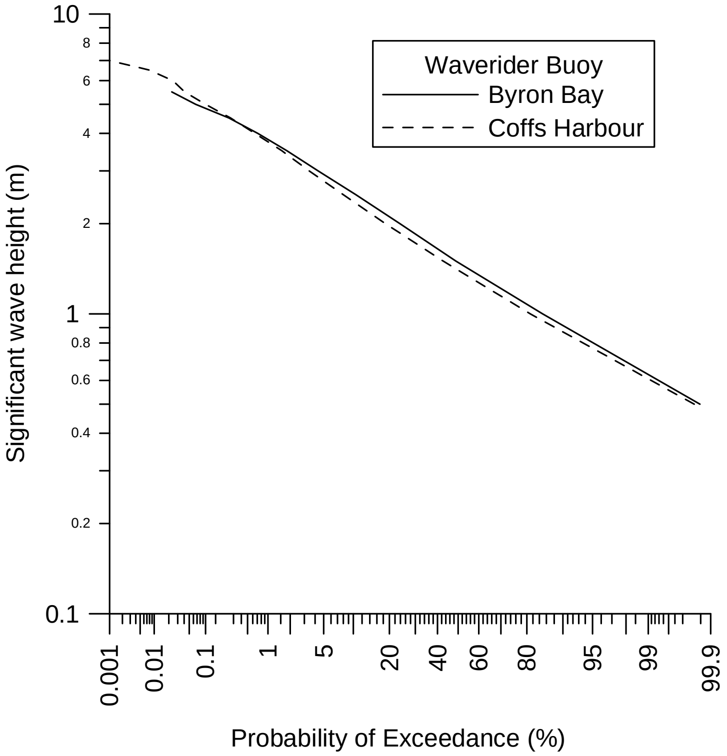

Figure 12: Significant wave height exceedance for Byron Bay and Coffs Harbour, based on data collected from 1976 to 1999 (after Lord and Kulmar, 2001)

Beach erosion is strongly linked to the occurrence of high wave conditions with elevated ocean water levels (the latter are discussed in Section 5.2). Therefore, inclusion of duration is likely to more accurately describe the severity of a storm in terms of beach erosion, rather than using ARI alone (Lawson and Youll, 1977). Erosion is more likely to be significant when the large waves coincide with a high tide. In general, storms with a duration in excess of 6 hours are likely to coincide with high tide on the NSW coast (Lord and Kulmar, 2001). The relationship between H_s, duration and average recurrence interval (ARI), at the Byron Bay Waverider buoy (for all data collected up to 31 December 1999), is shown in **Figure 13**[37].

[37] Note that Lord and Kulmar (2001) did not present this relationship for the closer site to the subject property, Coffs Harbour.

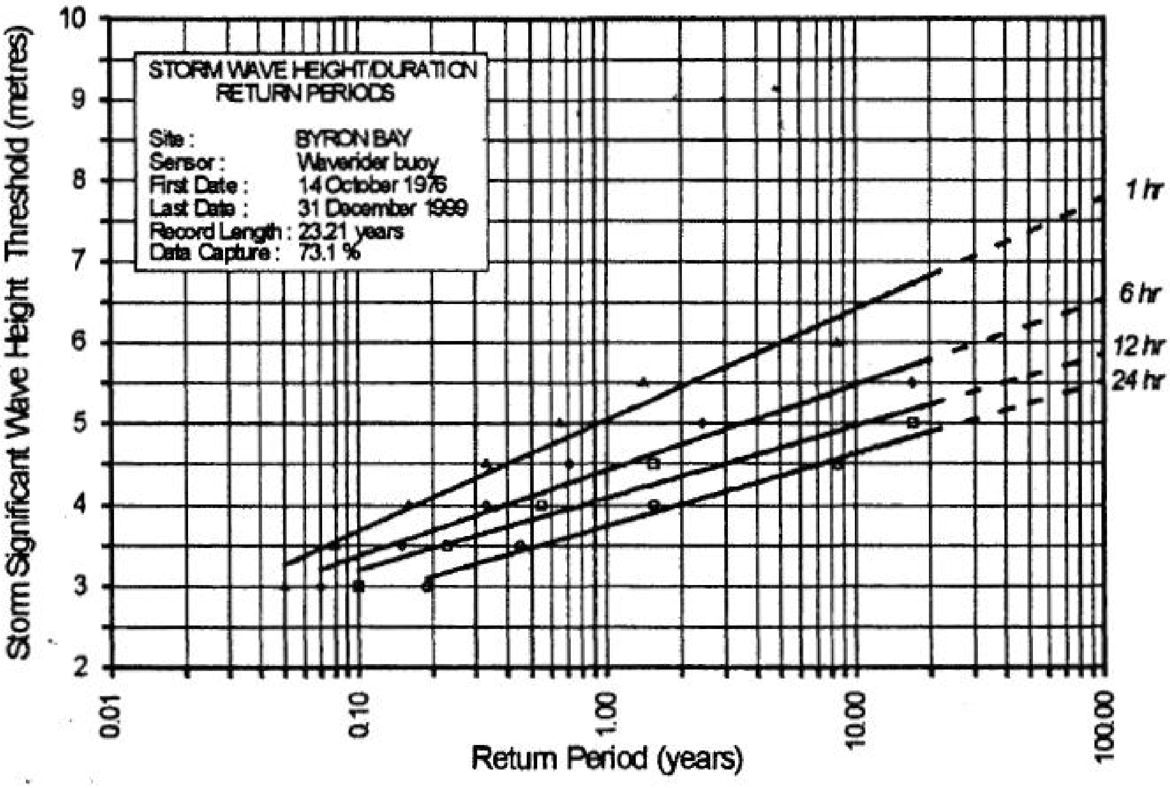

Figure 13: Relationship between significant wave height, duration and ARI for the Byron Bay Waverider buoy, 1976-1999 (from Lord and Kulmar, 2001)

It is evident that the 100 year ARI significant wave height exceeded for a duration of 6 hours at Byron Bay is about 6.5m. Note that the corresponding wave height in Sydney estimated by Lord and Kulmar (2001) is about 7.5m, indicating the larger wave climate experienced on the NSW Central Coast compared to the Far North Coast.

WP Geomarine (1998) reported that the 100 year ARI significant wave height exceeded for a duration of 6 hours at Coffs Harbour was 7.5m[38]. Although it is surprising that this value is 15% larger than the corresponding value for Byron Bay[39], the value of 7.5m was adopted as the design 100 year ARI significant wave height for the investigation reported herein.

Installation of directional Waverider buoys (since 1992 in Sydney) has indicated that the predominant wave climate along the NSW coast is from the SSE[40]. Analysis of the Sydney directional data from 1992 to 1999 indicated that 34% of waves came from the SSE, with 17% of waves from the SE and 14% of waves from the S. Furthermore, the SSE direction was dominant for larger waves (Lord and Kulmar, 2001).

[38] The corresponding 1 hour duration wave height was estimated as 8.4m. Nielsen et al (2001) estimated a similar value of 8.3m.
[39] The 1 hour duration value is only 6% larger at Coffs Harbour compared to Byron Bay.
[40] Prior to installation of the directional Waverider buoy, wave directions were hindcast (that is, estimated by prediction of wind fields from reference to synoptic weather charts). Hindcast directions overestimated the NNE and NE directions and underestimated the S and SSE directions. It was previously considered, based on hindcasting, that the dominant wave direction on the NSW coast was from the SE.

5.2 ELEVATED WATER LEVELS

The potential factors which contribute to elevated still water levels on the NSW coast comprise:

- astronomical tide[41];
- storm surge (barometric setup[42] and wind setup[43]); and,
- wave setup (caused by breaking waves[44]).

Individual waves also cause temporary water level increases above the still water level due to the process of wave runup or uprush (see Section 5.3). Note that sea level is also predicted to rise due to climate change (the Greenhouse Effect). This is discussed further in Section 5.10.1.

In NSW, open coast still water levels (within the wave breaking zone) can increase by up to about 2.1m above normal levels in storms due to storm surge and wave setup, with components approximately as large as follows:

- storm surge of 0.6m (barometric setup of up to 0.3m to 0.4m and wind setup of up to 0.2m to 0.3m); and,
- wave setup of up to 1.5m (typically about 10-15% of the significant wave height).

This increase in water level is superimposed on the astronomical tide, which typically varies between about –1m AHD (Indian Springs Low Water or Lowest Astronomical Tide, LAT) and 1m AHD (Highest Astronomical Tide, HAT) along the NSW coast, with 0m AHD close to mean sea level[45]. On the NSW coast, Mean High Water Springs is about 0.6m AHD, Mean High Water is about 0.5m AHD, and Mean High Water Neaps is about 0.4m AHD[46]. If a severe storm continued for a day, it would be expected that two high tides would occur during this time. Ignoring wave effects, the highest absolute water level that might be experienced in a storm would be if the maximum storm surge occurred at the same time as the HAT.

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[41] Astronomical tide is the regular rise and fall of sea level in response to the gravitational attraction of the sun, moon and planets, and the rotational effect due to the spin of the earth on its axis. Tides along the NSW coastline are semi-diurnal, with high and low water approximately equally spaced in time and occurring twice daily (that is, on average, there are two high tides and two low tides in any 24 hour period). There is also significant diurnal inequality in NSW coast tides, a difference in height of the two high waters or the two low waters of each tidal day.

[42] Barometric setup is a localised vertical rise in the still water level due to a reduction in atmospheric pressure. The increase in water level is approximately 0.1m for each 10 hectopascal drop below normal barometric pressure of 1013 hPa (MHL, 1992). Note that hectopascals are approximately equivalent to millibars.

[43] Wind setup is the vertical rise in the still water level on the leeward side of a body of water caused by wind stresses on the surface of the water.

[44] Wave setup is defined as the superelevation of the mean water level caused by wave action alone. The phenomenon is related to the conversion of the kinetic energy of wave motion to quasi-steady potential energy. It is manifested as a decrease in water level prior to breaking, with a maximum set down at the break point; from the break point the mean water surface slopes upward to the point of intersection with the shore (Coastal Engineering Research Center, 1984).

[45] HAT at Coffs Harbour is 1.2m AHD (Nielsen et al, 2001).

[46] Spring tides occur twice per month (during new or full moons) and result in higher high tides and lower low tides (that is, a larger tidal range, compared to the average). Neap tides also occur twice per month (during quarter moons) and result in lower high tides and higher low tides (that is, a smaller tidal range, compared to the average). The height of the spring tide also varies throughout the year and due to the lunar Metonic cycle, the 18.6 period over which the moon returns to the same position relative to the earth (MHL, 1992).

Water levels have been recorded at Fort Denison in Sydney Harbour for over 100 years, and are representative of NSW open coast water levels near Sydney in the absence of waves[47]. The data from 1914 onwards is considered to be reliable. Based on a joint probability analysis of tide and storm surge (assumed as independently occurring events), for the May 1914 to December 1991 data set, MHL (1992) predicted that the 100 year, 50 year and 20 year ARI water levels at Fort Denison were 1.49m, 1.46m and 1.41m AHD respectively[48]. The highest recorded water level at Fort Denison was 1.48m AHD in May 1974[49]. These levels are representative of astronomical tide and storm surge, but exclude wave setup.

Assuming extreme water levels in Sydney were representative of conditions at Hearns Lake Beach, then the 100 year ARI water level, including astronomical tide and storm surge, was adopted as 1.5m AHD. With a 100 year ARI offshore significant wave height of 7.5m (Section 5.1), and assuming wave setup as 15% of this wave height, then the 100 year ARI wave setup value was determined as 1.1m. Therefore, a 100 year ARI total design still water level (astronomical tide plus storm surge plus wave setup) of 2.6m AHD was adopted for the investigation reported herein[50].

5.3 WAVE RUNUP

Wave runup is site specific, but typically is about 3m to 6m above the elevated still water level (Section 5.2) on the open coast. The height of wave runup on beaches depends on many factors including (NSW Government, 1990):

- wave height and period;
- the slope, shape and permeability of the beach;
- the roughness of the foreshore area; and,
- wave regularity.

Wave runup can be difficult to predict accurately due to the many factors involved. Anecdotal evidence and the surveying of debris lines following a storm event usually provide the best information on wave runup levels.

Hanslow and Nielsen (1995) provide guidance on calculating wave runup. They found that the runup above the still water level (excluding wave setup) was given by:

$$R = 0.9H_s\left(\frac{L_s}{H_s}\right)^{0.5}\tan\beta \qquad (1)$$

where R is the runup exceeded by 2% of waves, H_s is the significant wave height, L_s is the significant wave length, and $\tan\beta$ is the beach slope. The significant wave length is given by:

[47] An analysis of tidal anomalies at five NSW water level recording stations (between Crowdy Head and Batemans Bay from 1987 and 1991) indicated that there was a strong correlation between Sydney and the other stations (MHL, 1992). The 100 year ARI water level predicted at Sydney for this analysis period was 1.45m AHD, whereas at Crowdy Head the predicted level was 1.46m AHD.

[48] Lord and Kulmar (2001) revised these elevated water level estimates, with values slightly reducing. However, they did not include a correction for sea level rise adopted in MHL (1992).

[49] For this event, the peak storm surge was 0.59m (MHL, 1997).

[50] PWD (1986a) determined the same value of 2.6m AHD, for Coffs Harbour.

$$L_s = \frac{gT_s^{\ 2}}{2\pi} \qquad (2)$$

where g is the gravitational acceleration ($9.8ms^{-2}$) and T_s is the significant wave period.

At Hearns Lake Beach, H_s is 7.5m (Section 5.1), and T_s can be assumed to be equal to 12s, as is commonly used in coastal engineering design. Assuming that the beach face slope is equal to 1 in 10, as is common in a eroded profile[51], the predicted runup above the still water level (excluding wave setup) is 3.7m. With a still water level (excluding wave setup) of 1.5m AHD (Section 5.2), the predicted 100 year ARI wave runup level exceeded by 2% of waves is 5.2m AHD[52]. For planning purposes, it is considered that a runup level of 5.8m AHD should be adopted for the subject property, which conservatively takes account of predicted future sea level rise over a 100 year planning period[53].

In the long term, as a beach receded, it could be postulated that the present dunal barrier would disappear, with the new dune taking on the existing topography landward of the present dune. This is considered to be unlikely from an understanding of the morphological response of beaches. The existing dune crest levels are a complex response to a variety of factors including beach sand characteristics, exposure to wind and wave action, and local topographic controls, all of which are likely to be relatively constant irrespective of the shoreline position in the long term.

5.4 COASTAL STORMS

5.4.1 General

The NSW coastline is subject to intense tropical and non-tropical storms at irregular intervals. The drop in atmospheric pressure and the winds and waves that accompany these storms can cause the ocean to rise above its normal level (see Section 5.2). If this occurs concurrently with high astronomical tides, there is the potential for:

- coastal erosion (in particular as the storm waves dissipate energy closer to the shoreline with the increased water levels); and/or
- overwash into low-lying coastal areas (PWD, 1985).

PWD (1985, 1986b) categorised coastal storms in NSW, to indicate the potential of a storm to generate abnormal water levels along the NSW coastline. The categories were discretised on the basis of offshore significant wave heights[54], as shown in **Table 5**.

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[51] Hearns Lake Beach is actually much flatter than this at present. Survey completed as part of the investigation reported herein indicated that the beach slope in the vicinity of a few metres of mean sea level was about 1 in 40. That is, the value of 1 in 10 chosen is conservative.
[52] This value is comparable to estimates made in nearby studies, such as 5m AHD for Ballina Shire (WBM, 2003), and 5.1m AHD for exposed areas at Brooms Head (Nielsen et al, 2001). WP Geomarine (1998) estimated a runup level of 7m AHD for Campbells Beach, which should have been calculated as 6.6m AHD (Section 3.3)
[53] Refer to Section 5.10.1 for discussion on sea level rise. The 5.8m AHD runup level includes the predicted sea level rise of 0.5m over a planning period of 100 years, plus an allowance for waves breaking closer to the shore with increased water levels (and thereby increasing runup levels). Furthermore, a 50 year planning period is considered to be more appropriate (Section 1).
[54] In PWD (1985), where a sequence of synoptic patterns was available, the wind field was used to estimate an effective wind velocity and duration over a fetch for each pattern. Significant wave heights were then calculated

Table 5: Categorisation of coastal storms in NSW by PWD (1985, 1986b)

Category	Offshore significant wave height (H_s), m
X	$H_s \geq 6$
A	$5 \leq H_s < 6$
B	$3.5 \leq H_s < 5$
C	$2.5 \leq H_s < 3.5$

Category X and A storms were those expected to lead to coastal erosion and damage to coastal facilities. According to PWD (1985, 1986b), Category X storms were characterised by damage to coastal installations, severe erosion, and serious disruption to shipping. Category A storms were characterised by erosion or other damage to coastal installations and disruption to shipping.

In PWD (1985), all Category X, A, B and C storms that were predicted to have occurred between 1880 and May 1980 were listed[55], along with a description of the storm generating mechanism and characteristics, and wave heights and periods (for selected storms). Estimates were given for each of four coastal sectors in NSW, namely North, Mid-North, Central and South. The North sector covered Hearns Lake Beach, with the sector including all of NSW north of Smoky Cape (which is near South West Rocks, about 90km south of the subject property)[56].

Similarly, in PWD (1986b), all Category X, A, B and C storms that were predicted to have occurred between May 1980 and December 1985 were listed.

5.4.2 Storm Types

PWD (1985) recognised 6 different major storm types which impacted on the NSW coast, namely:

- tropical cyclones;
- easterly trough lows;
- inland trough lows;
- continental lows;
- southern secondary lows; and,
- anticyclonic intensification.

Typical synoptic patterns for tropical cyclones, easterly trough lows, inland trough/continental lows, and southern secondary lows are shown in **Figure 14**.

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using the Sverdup, Munk, Bretschneider (SMB) formula for wave hindcasting. Where records were not as comprehensive, storm categorisation was based on comparing "reference" storms. In PWD (1986b), the availability of offshore wave data allowed storm events to be directly identified from the measured wave heights, with meteorological records then examined to identify the nature of the source; the reverse had been the case in PWD (1985).

[55] However, the only reliable data for statistical analysis was from 1920 to 1944 and 1957 to 1980.

[56] The Mid-North Coast extended south of Smoky Cape to Sugarloaf Point (near Seal Rocks). The Central Coast extended south of Sugarloaf Point to just south of Jervis Bay. The South Coast extended from just south of Jervis Bay to the Victorian border.

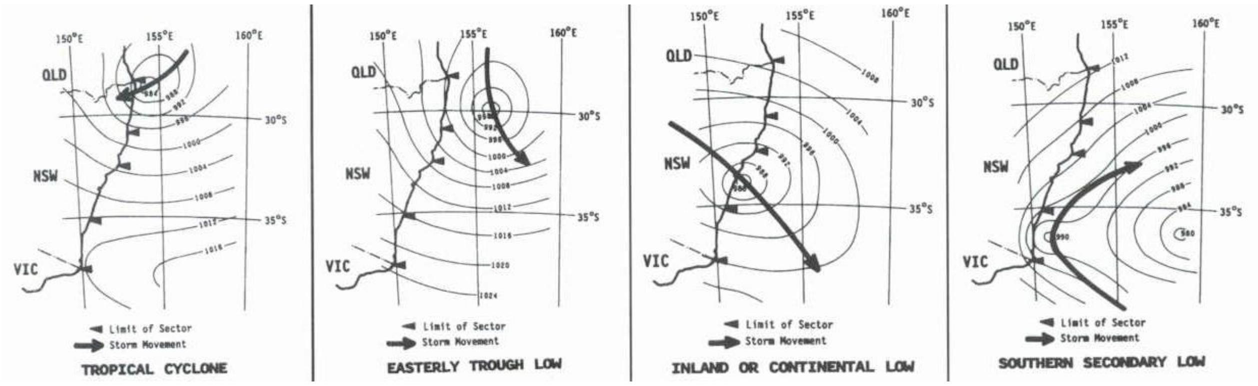

Figure 14: Typical synoptic patterns for tropical cyclones, easterly trough lows, inland trough / continental lows, and southern secondary lows (after NSW Government, 1990)

Based on PWD (1985, 1986b), the spatial variation in occurrence of these six storm types along the NSW coast is shown in **Figure 15**, with monthly variations in storm occurrence on the North Coast shown in **Figure 16**. It is evident that, on average:

- the North Coast has less storms than areas further south in NSW;
- easterly trough lows and tropical cyclones are the dominant storm types on the North Coast[57], as well as southern secondary lows[58]; and,
- most storms on the North Coast occur in Summer, Autumn and Winter, with June and February-March being the most prevalent months for storms (tropical cyclones generally only occur between January and April, with easterly trough lows dominating between April and July).

PWD (1985) also noted that the North Coast can have relatively long periods of time without any significant storm activity.

[57] These storm types are predominantly weather systems that come from the north.
[58] Note that the NSW Government (1990) presented the information in Figure 16 based only on data to 1980. By using the more accurate data set from 1980-1985, a large number of southern secondary lows, and other Category B and C events, were picked up that were not in the PWD (1985) study.

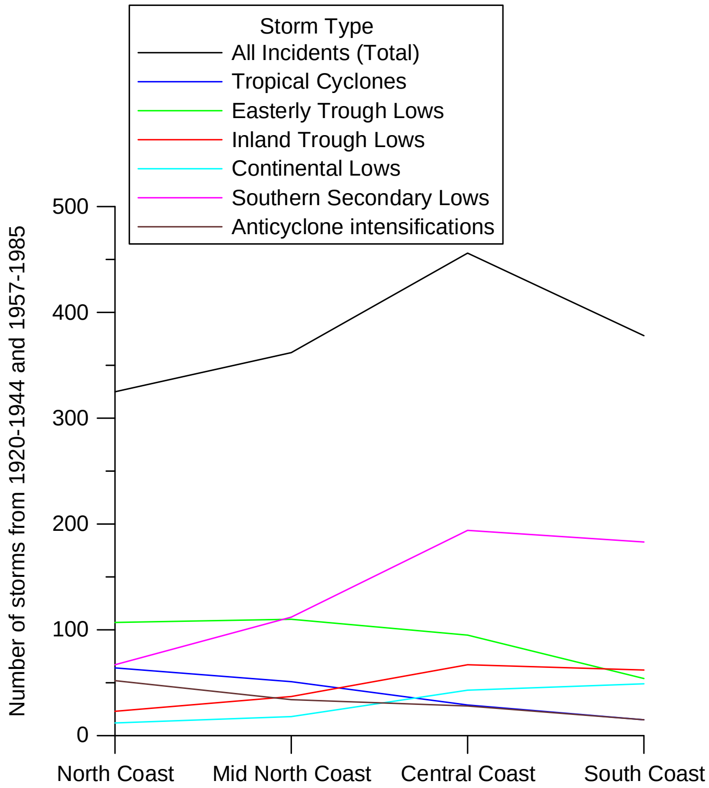

Figure 15: Variation in occurrence of different major storm types (significant wave height exceeding 2.5m) along the NSW coast (based on PWD 1985, 1986b)

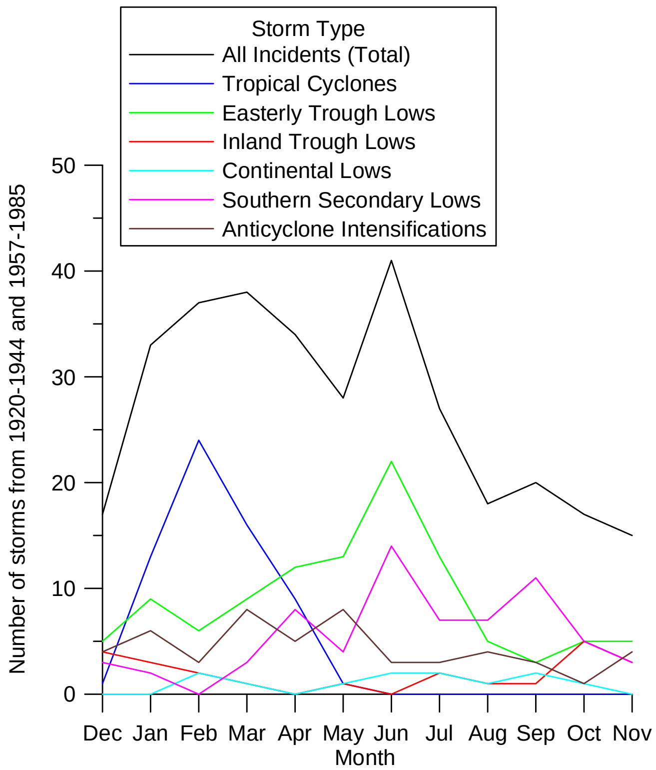

Figure 16: Monthly variation in storm occurrence (significant wave height exceeding 2.5m), North Coast of NSW (based on PWD 1985, 1986b)

5.4.3 Storm History

As noted in Section 5.4.1, PWD (1985, 1986b) listed all Category X, A, B and C storms that were predicted to have occurred between 1880 and 1985.

Wave data collected in deep water offshore of Coffs Harbour and Byron Bay was also obtained from Manly Hydraulics Laboratory, NSW Department of Commerce (MHL, 2003). DIPNR is acknowledged as the owner of this data. The data was provided as storm histories for each site (events where the significant wave height exceeded 3m) since the commissioning of the Waverider buoys in 1976. Further information on this data is given in Section 5.1.

Based on the PWD (1985) and MHL (2003) data, a total of 93 Category A events were hindcast from January 1880 to May 1976, with 35 Category A events recorded from June 1976 to December 2001[59], a total of 128 events. This represents an average of 1.05 Category A events per year, in the 122 years of record. However, the time period between storms was not uniform. For example, there were no Category A storms in 1935-1936, 1943-1944, 1949-1950 and 1952-1953, and four Category A storms in 1998.

A total of 19 Category X events were hindcast from January 1880 to May 1976, with 9 Category X events recorded from June 1976 to December 2001[60]. This represents an average of 1 Category X event every 4.4 years, in the 122 years of record. However, the time period between storms was not uniform. For example, there were no Category X storms from 1930-1936 and 1972-1983, and 3 Category X storms in 1967.

A listing of the predicted Category X storms from 1880 to 1976 is given in **Table 6**, including the estimated significant wave height (H_s) and significant wave period (T_s) calculated by hindcasting (for some storms). The Category X storms measured at the Coffs Harbour Waverider buoy from June 1976 to December 2001 are listed in **Table 7**, with the recorded H_s and T_s values also shown.

Table 6: Occurrences of Category X storms on the North Coast from 1880 to 1976 (based on PWD, 1985)

Date	Storm Type	H_s (m)	T_s (s)
30 January – 3 February 1890	Tropical cyclone		
1-7 January 1893	Inland trough		
26 April - 2 May 1902	Easterly trough low		
16-20 May 1926	Easterly trough low / anticyclone intensification	7.8	11.2
29-30 June 1929	Easterly trough low	7.1	10.6
16-20 February 1937	Tropical cyclone	8.1	11.3
12-15 October 1942	Easterly trough low	9.1	12.1

[59] The 4 events exclusively noted by PWD (1985, 1986) are not included in the 37 events from 1976 to 2001, given that they were not recorded to be Category A at either the Byron Bay or Coffs Harbour Waverider buoys.
[60] There were 7 Category X events recorded at Coffs Harbour from 1976 to 2001, and 2 Category X events at Byron Bay which were lower Category events at Coffs Harbour.

Date	Storm Type	H_s (m)	T_s (s)
10-13 June 1945	Easterly trough low		
24-26 March 1946	Tropical cyclone		
18-19 January 1950	Inland trough low	6.6	10.3
23-26 June 1950	Easterly trough low		
19-22 February 1954	Tropical cyclone	9.1	12.1
18-23 February 1957	Tropical cyclone		
20-24 January 1959	Tropical cyclone	7.5	10.9
27 June 1963	Easterly trough low		
29-31 January 1967	Tropical cyclone	9.9	12.6
21-22 February 1967	Tropical cyclone	6.1	9.8
25-28 June 1967	Easterly trough low	10.1	12.7
22-25 July 1971	Continental low	6.1	9.8

Table 7: Category X storms measured at Coffs Harbour from 1976 to 2001

Date	Peak H_s (m)	Mean T_s (s)
8-11 April 1984	6.2	9.8
9 July 1985	6.6	8.9
7-12 August 1986	6.4	11.0
9-11 February 1988	6.4	10.9
20-25 June 1989	7.4	9.2
6-8 March 1995	6.2	9.7
13-17 July 1999	6.8	10.2

5.4.4 Historical Information on Coastal Storms

There were three Category X storms on the North Coast in 1967, in January, February and June (PWD, 1985), see Section 5.4.3. The June 1967 storm would be likely to have caused the most damage, as it had the largest predicted wave height, was accompanied by a noted elevated water level, and was acting on a beach that was most probably already in an eroded state due to previous recent storms. However, Chapman et al (1982) noted that most damage was caused north of Coffs Harbour, at the Gold Coast in Queensland, and New Brighton, Byron Bay, Lennox Head, and Ballina in NSW.

WBM (2003) rated the June 1967 storm as one of the three most notable major erosion events on record for northern NSW and southern Queensland. The other significant events reported by WBM (2003) occurred in:

- February 1954, noted as Category X by PWD (1985); and,
- February 1974, noted as Category A by PWD (1985), followed by another Category A event in March 1974.

These three storms (February 1954, June 1967 and February 1974) were particularly severe as they occurred during high spring tides, most probably with accompanying elevated water levels due to storm surge[61]. Another storm highlighted by WBM (2003) was in February 1972, noted as Category A by PWD (1985).

Chapman et al (1982) provided information on the effects of coastal storms on North Coast beaches due to the May-June 1974 storms (it was claimed), which are generally considered to be the most severe coastal storms to have been recorded on the Central Coast of NSW[62]. However, it is considered that Chapman et al (1982) may have incorrectly combined a separate storm event, in February 1974, with the May-June storms. That is, the description of effects of coastal storms on North Coast beaches given by Chapman et al (1982) applied to the February 1974 event, or at least a combination of the February and May-June 1974 events[63]. Evidence for this conclusion included that:

- the major May-June 1974 storms did not receive any storm rating on the North Coast from PWD (1985), as noted in Footnote 62;
- review of historical newspaper articles in 1974 and literature has indicated that the effects from the May-June 1974 events were mainly in the Sydney and Central Coast areas, with the February 1974 event the main focus of reporting on the North Coast (Patterson Britton & Partners, 2004).

Coastal erosion depends on far more than just wave height, with factors such as storm duration, water level, wave direction and storm history being important. In particular, the May 1974 storm coincided with the highest recorded water level along the NSW coast[64]. Therefore, it is acknowledged that erosion on the North Coast was possible in the May-June 1974 events due to elevated water levels, even if wave heights were not particularly severe.

MHL (1998) described the effects of a coastal storm that occurred in May 1997. This event caused significant erosion of beaches along the NSW coast, and the eastern breakwater at Coffs Harbour was damaged during the storm. The storm was particularly severe as the peak wave height (H_s of 5.6m) coincided with an elevated water level 0.7m above the predicted tide[65]. In terms of wave energy (Section 5.4.5), which takes storm duration and wave period into account (as well as wave height), the storm was the seventh largest to be measured from 1976 to 2001[66].

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[61] The February 1974 storm coincided with the highest ever recorded water level at Brisbane Bar in Moreton Bay, of 1.89m AHD, or 0.42m above Highest Astronomical Tide (WBM, 2003).

[62] The 25-26 May 1974 storm was noted as being Category X on the Central Coast by PWD (1985), but not given a rating on the North or Mid-North Coast (and Category A on the South Coast). This was followed by a Category B storm on the North and Mid-North Coast from 3-5 June 1974 (Category C on the Central and South Coast). Again, this was followed by a Category X storm on the South Coast from 8-14 June 1974 (Category A on the Central Coast and Category B on the Mid-North Coast, but not rated on the North Coast).

[63] In the Coffs Harbour area, Chapman et al (1982) particularly noted that extensive erosion at Woolgoolga (with the Surf Club damaged) and Park Beach (with a car park threatened) occurred in 1974.

[64] In terms of wave height and duration at Sydney, the May 1974 storm was approximately a 20 year to 70 year ARI event, for storm durations between 1 and 24 hours (Lord and Kulmar, 2001).

[65] This was the largest anomaly over the predicted tide recorded at Coffs Harbour since records began in 1986.

[66] A number of other storms were examined by MHL (1998), including the Category X storms in August 1986 and June 1989 (Table 7), and a Category A storm in April 1989. In terms of wave energy, these storms were ranked 1, 2, and 4th largest to be measured from 1976 to 2001. For these three storms, water levels at the storm peak were 1.2m to 1.9m below the water level recorded at the peak of the 1997 storm, so they were less erosive and damaging.

It is apparent that virtually no aerial photography (Section 4.2), and certainly no photogrammetry (Section 4.3), was captured immediately after the significant storms in February 1954, June 1967, February 1972, February 1974 and May 1997[67]. This further emphasises that storm demand cannot be readily estimated from the available data (also refer to Sections 3.2, 3.3, 3.6 and 5.7.2).

5.4.5 Storminess Indicator

Particular dates of aerial photography and photogrammetric data can be referenced against dates of coastal storms. This provides an approximate measure of the likely beach state (accreted, average or eroded) at the time of photography, which can assist in the interpretation of photogrammetry and other observations.

Shoreline erosion can be expected to correlate with wave energy, more so than wave height or wave period alone[68]. According to Airy theory, the total wave energy in one wavelength per unit crest width is given by (in deep water):

$$E = \frac{\rho g H^2 L_o}{8} \qquad (3)$$

where (in SI units) ρ is the water density (kg/m^3), g is the gravitational acceleration (m/s^2), H is the wave height (m) and L_o is the deepwater wavelength (m), given by:

$$L_o = \frac{gT^2}{2\pi} \qquad (4)$$

Therefore, E has units of kgms^{-2}, equivalent to N or J/m. It can be seen that E is proportional to H^2T^2.

For the PWD (1985) record from 1880 to 1976 (Section 5.4.3), significant wave heights (H_s) and periods (T_s) were estimated for many storms. For other storms, H_s could be assumed to be the median value in the Category range. That is, if the storm was Category C, H_s was assumed to be 3.0m. Similarly, for Category B and A storms, H_s was assumed to be 4.3m and 5.5m respectively. For Category X events without estimated wave heights, H_s was assumed to be the average H_s of all other Category X events from 1880 to 1976 with estimated wave heights, namely 8.0m.

For storms where T_s was not estimated, the T_s value was assumed to be equal to the average T_s of all other events in that Category from 1880 to 1976, where T_s was estimated. For Categories C, B, A and X, the T_s values estimated were 6.9, 8.0, 9.1, and 11.2s respectively.

For the 1880 to 1976 period, H^2T^2 was determined for each storm as described above. A storminess indicator was determined for each year of record as the sum of H^2T^2 for the year

[67] However, registered photography was available 8 months and 4 months after the 1972 and 1974 storms respectively, but substantial beach recovery would have been expected over this time.
[68] This has been shown to be particularly true in the assessment of erosion caused by boat wakes, especially if significant rather than peak parameters are used (Patterson Britton & Partners, 1995a). It has also been applied in open coast studies such as at Bate Bay (Patterson Britton & Partners, 2001), and at sheltered beaches such as Fishermans Beach at Collaroy (Geomarine, 1991).

divided by the average yearly H^2T^2 for the data set. Therefore, a storminess indicator value less than 1 is indicative of accreted beach states, a value of 1 is indicative of average beach states, and a value greater than 1 is indicative of eroded beach states. The storminess indicators determined for each of the calendar years from 1940 to 1976 inclusive are shown in **Figure 17**.

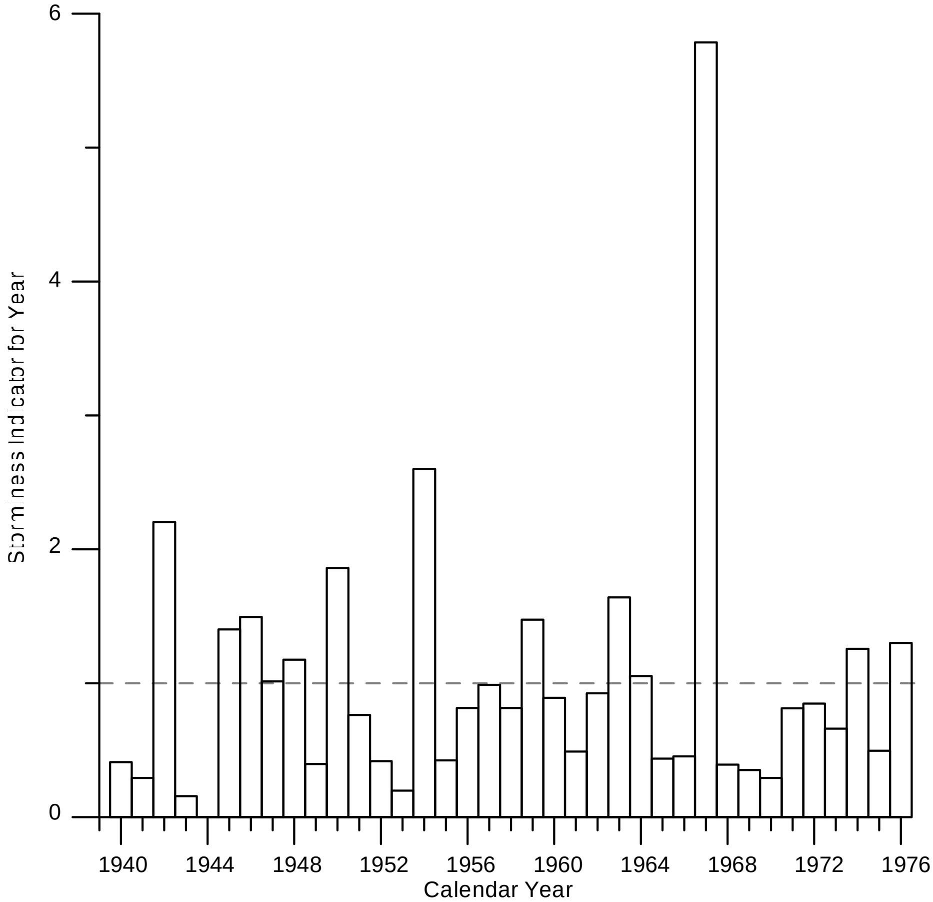

Figure 17: Yearly storminess indicators for 1940-1976

It is evident that 1967 was a particularly stormy year, followed by 1954 and 1943. Conversely, the 1968 to 1973 period was particularly calm.

The relationship between the cumulative H^2T^2 for 1940-1976 (from which the storminess indicator was derived) and dates of aerial photography listed in Section 4.2[69] is shown in **Figure 18**. The slope of the cumulative H^2T^2 line is indicative of storminess, with flat slopes indicating calm periods and steep slopes representative of erosive periods.

[69] The date of 23 April 1942 was also included as it was the first date (or close to it) analysed in the Sawtell, Park, Macauleys, and Campbells Beach photogrammetry (Section 3.2). The date of 12 December 1967 was included as it was also utilised in the Sawtell Beach photogrammetric analysis.

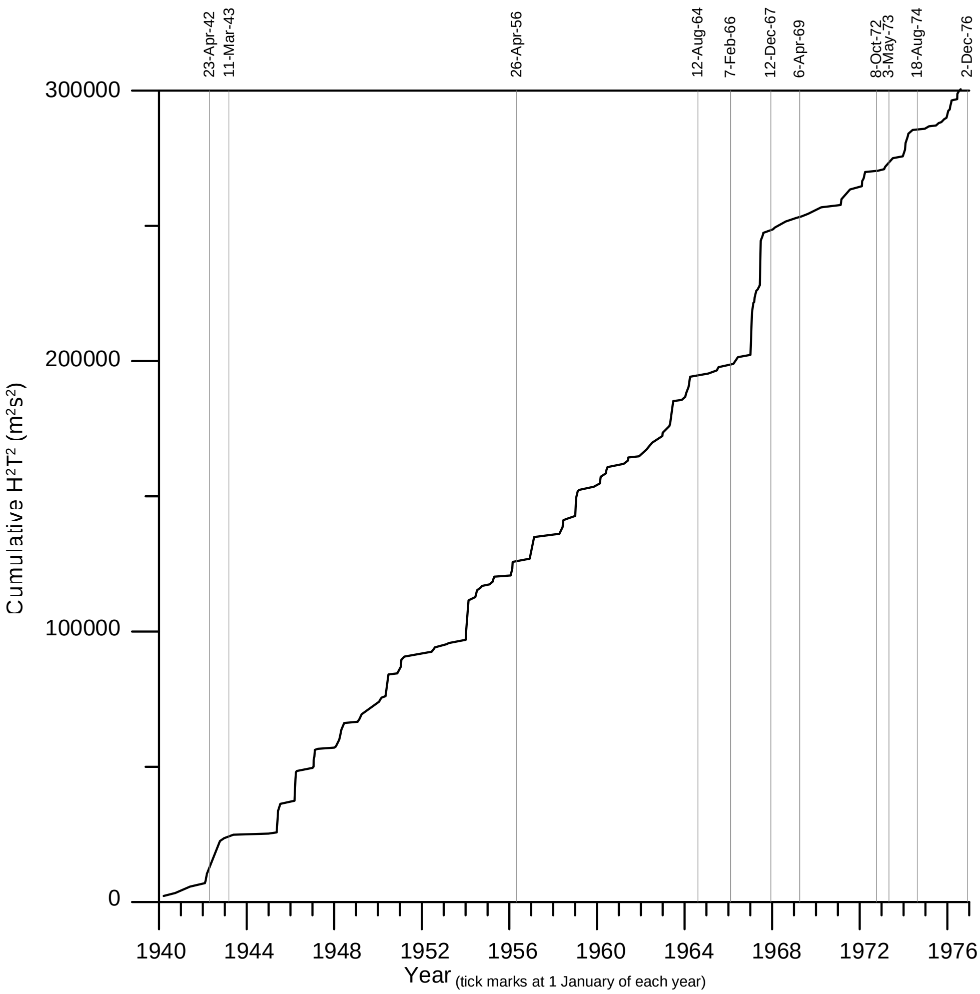

Figure 18: Cumulative sum of squares of H times T for 1940-1976

For the 1977 to 2001 period, which had measured wave data, the storminess indicator was calculated in a more rigorous manner. The data included the duration that H_s exceeded 3m to 8m, in 0.5m increments. Therefore, duration could be considered as well as wave height and period. Inclusion of duration in the analysis would be expected to provide a better measure of the wave energy or power associated with a storm.

In deep water, wave power (P) for an individual wave is given by:

$$P = \frac{E}{L_o}\frac{gT}{2\pi} \quad (5)$$

where all variables have been previously defined (refer to Equation 3). In the SI system, the units of P are $kgms^{-2}$/s, or N/s, or W/m (Watts per metre wave crest width). Including duration as a multiplier, the units become Ws/m, or J/m, thus representing total storm energy per unit wave crest width (denoted as E_s)[70].

[70] The various durations and wave heights for each 0.5m increment range were summed as the median H_s of each range, multiplied by the duration that the wave height was in that range.

For the 1977 to 2001 period, E_s was determined for each storm as described above. A storminess indicator was determined for each year of record as the sum of E_s for the year divided by the average yearly E_s for the data set, as previously for the 1880-1976 data set. The storminess indicators determined for each of the calendar years from 1977 to 2001 inclusive are shown in **Figure 19**.

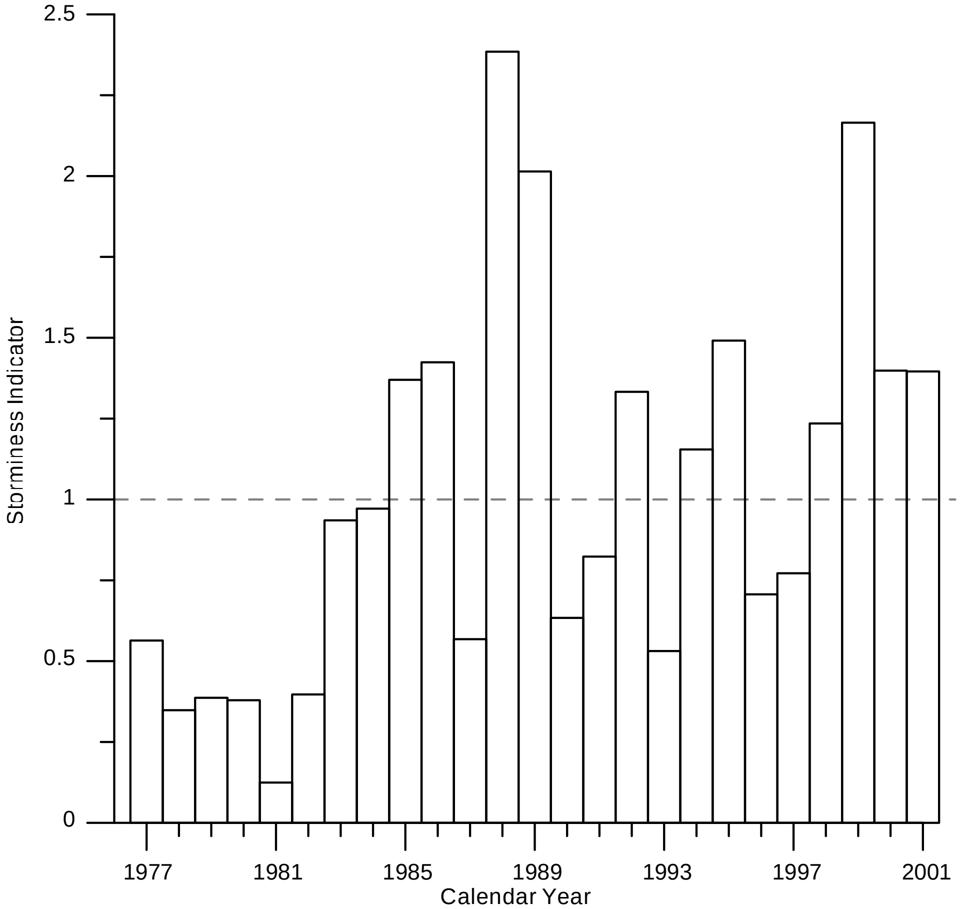

Figure 19: Yearly storminess indicators for 1977-2001

It is evident that 1988, 1999 and 1989 were the most stormy years, with the 1998 to 2001 period notably stormy. Conversely, the 1977 to 1984 period was particularly calm.

The relationship between the cumulative storm energy per unit wave crest width (E_S) for 1977-2001 (from which the storminess indicator was derived) and dates of aerial photography listed in Section 4.2[71] is shown in **Figure 20**.

[71] The date of 26 October 1981 was also included as it was included in the Emerald Beach analysis (Section 3.5). The date of 28 August 1989 was included as it was also utilised in the Park and Hills Beach photogrammetric analyses (Section 3.2).

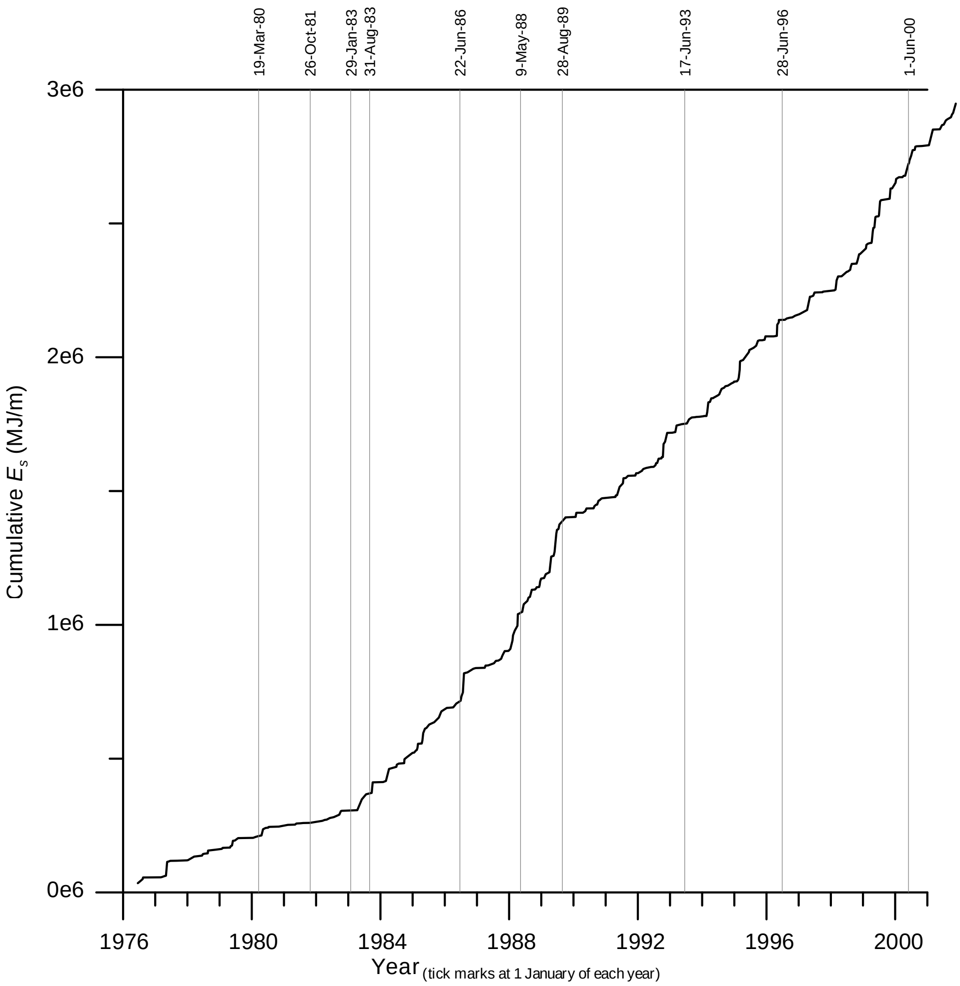

Figure 20: Cumulative storm energy per unit wave crest width for 1977-2001

Note that despite the different methodologies employed from 1940-1976 compared to 1977-2001, there was still a reasonable correlation between the storminess indicators calculated in each period. This can be illustrated by comparing the storminess indicators determined using the more rigorous E_s methodology (as applied for 1977-2001) to those determined using the H^2T^2 methodology (as applied for 1940-1976), using the 1977-2001 data set. The correlation is shown in **Figure 21**. Given the reasonable correlation, it can be accepted that storminess indicators before and after 1976 are comparable.

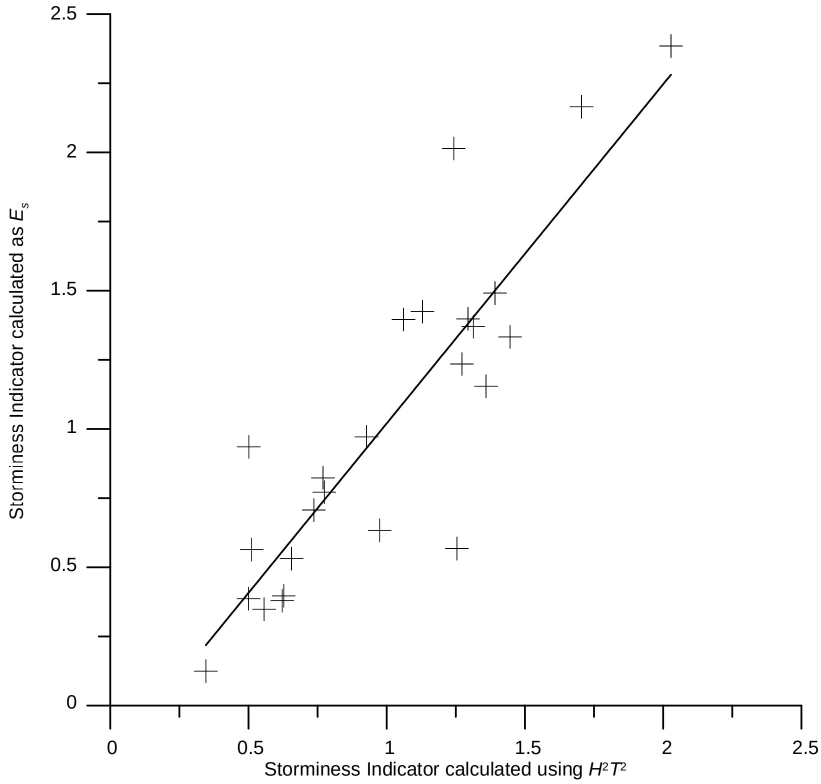

Figure 21: Correlation between storminess indicators calculated for 1977-2001 period, using simple and rigorous methodologies

Note that the storminess indicator is only an approximate measure of beach state, as water level is a very significant factor in defining the erosiveness of storms. Furthermore, for the 1940-1976 period, storm duration was not included, and the storms were only predicted and not measured. With an understanding of these limitations, the "storminess indicator" is still considered to be a reasonable measure of the likely beach state for each date of photography.

5.5 NET SEDIMENT TRANSPORT

Two processes within the surf zone can result in net sediment transport, namely (NSW Government, 1990):

- longshore sediment movement; and,
- onshore / offshore sediment movement.

These transport processes are discussed in Section 5.6 and Section 5.7 respectively.

5.6 LONGSHORE SEDIMENT TRANSPORT

5.6.1 Regional Processes

Longshore sediment transport is associated with longshore currents. Longshore currents occur within the breaker zone and the surf zone[72], and are generated by:

- waves breaking at an angle to the shoreline;
- feeder currents to rip cells; and,
- longshore variations in water level resulting from nearshore wave conditions and wind stress (NSW Government, 1990).

Longshore currents essentially move parallel to the shoreline. These currents cause movement of sediment along the shoreline, commonly referred to as littoral drift[73]. Due to the variability in wave approach direction at beaches (and other wind and wave conditions), there may be times when the littoral drift is in one direction and at other times when it is in the opposite direction.

There is a strong net south to north longshore movement of littoral sand within the surf zone of all NSW North Coast and southern Queensland beaches, in particular those beaches north of Woody Head, which is located about 6km north of the Clarence River and the township of Yamba (about 75km north of Hearns Lake Beach)[74]. As such, North Coast beaches are generally supplied by sand from the south and are the source of sand for beaches to the north. This net northward movement of sand is caused by the dominant SSE wave climate (Section 5.1) in relation to the general NSW coast orientation of NNE to SSW, and is particularly pronounced in northern NSW as headlands are less prominent. Storm waves can also carry sand around headlands[75].

Where there is a longshore variation in the rate of longshore sand transport, there will be a net gain or loss of sand from the beach compartment. That is, where more sand is transported out of a beach area than is being brought in over an extended period of time, the beach will erode with the shoreline gradually realigning itself. The erosion will occur initially in the surf zone where sand

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[72] The surf zone is coastal waters between the breaker zone (where swell waves break, typically in the shallower waters over an offshore bar) and the swash zone (the area of shoreline characterised by wave uprush and retreat), characterised by broken swell waves moving shorewards in the form of bores (NSW Government, 1990).

[73] Littoral means of or relating to the shore of a lake, sea, or other body of water (Harcourt Academic Press, 2001). The littoral transport rate (or littoral drift rate) is the rate of transport of sedimentary material parallel or perpendicular to the shore in the littoral zone. If this movement is parallel to the coastline, it is often denoted as the longshore transport rate.

[74] WBM (2003) noted that the northward net longshore transport of sand along beaches north of Woody Head was continuous, although spatially and temporally variable, along the whole coastal system extending some 300 kilometres to Moreton Bay in Queensland. Longshore transport rates tend to increase moving northwards along the NSW North Coast, particularly north of Byron Bay.

[75] As noted by WBM (2003), sand movement past headlands tends to occur as episodic slugs of relatively large quantities of sand during short term storm events with large waves, whereas longshore transport at adjacent beaches tends to be more continuous at lower rates. This was considered to lead to large accumulations of sand on the downdrift side of headlands during major storms; and long term extensive erosion of the downdrift beach, in which potentially large quantities of sand moved away by longshore transport are not immediately replaced at the beach itself by sand bypassing the headland. van Kerkvoort (1985), using dye sand tracing to measure sand transport rates around Diggers Head (north of Macauleys Beach), determined that sand could bypass a major headland under ideal energy conditions. Diggers Head was considered to be most likely headland in the area that would interrupt longshore sediment transport.

transport is greatest, and manifest as beach retreat (recession) following onshore/offshore readjustment of the nearshore profile (WBM, 2003).

On a dominant northwards longshore transport coastline, based on Stephens et al (1981), shoreline evolution was predicted to occur as recession commencing at the southern end of the compartment forming an embayment between controlling headlands/features. Within each embayment, recession was also expected to be highest in the southern hook, reducing northwards to negligible rates immediately south of each headland/feature. Long term recession rates were expected to be minimal within small pocket beaches contained between controlling headlands/features. The evolution of zeta form embayments[76] between controlling headlands was considered to be the result of this longshore transport process (see **Figure 22** and **Figure 23**).

The coastline in the vicinity of Hearns Lake Beach does indicate some embayment (Figure 4), consistent with northwards longshore transport leading to zeta form coastlines as per Stephens et al (1981). That is, it is considered that the highest rates of recession at Hearns Lake Beach would be most likely occurring near the southern end of the beach, at the "hook" of the zeta spiral. At the subject property, it could be postulated that recession rates would be relatively small (the minimum recession values at the embayment would be expected at the northern end)[77].

As the shoreline realigned within each compartment, the longshore transport rate was expected by Stephens et al (1981) to reduce, with an ultimate reduction in the supply of sand to the next compartment. This would induce a greater transport differential in the next compartment, and cause progressive recession from south to north. The increasing sediment transport rates moving north along the NSW North Coast are consistent with the compartmentisation and zeta form model of Stephens et al (1981). It is not possible to determine at what stage Hearns Lake Beach may be in this process[78].

It has been postulated that the construction of the eastern breakwater at Coffs Harbour, completed in 1939 (MHL, 1998)[79], caused a completion cessation of south to north longshore sediment transport at this location (Lord and van Kerkvoort, 1981a, b). It was estimated that the 75,000m^3/year longshore transport rate was intercepted by the harbour and either deposited at Boambee Beach to the south, within the harbour entrance, or on to Jetty Beach within the harbour. It was considered that beaches to the north of Coffs Harbour, at least as far north as Campbells

[76] Many sections of coastline which are situated in the lee of a natural or artificial headland, feature a curved shoreline geometry. Where sections of coastline are situated between two headlands, and particularly when there is a single, dominant wave direction, the shoreline may likewise assume a curved or "scalloped" shape. In both cases, the curved portion of the shoreline related to the headland(s) is termed a crenulate or "spiral bay". Because of their geometries, these shorelines are also sometimes termed "parabolic," "zeta-bay", or "log-spiral" shorelines. The shape results from longshore transport processes which move sediment in the downdrift direction along the down-wave section of the shoreline, and from processes associated with wave diffraction which move sediment in the opposite direction in the immediate lee of the up-wave headland (Rosati et al, 2002).

[77] In making these postulations, it is implicitly assumed that there are not other coastal processes leading to net sediment transport, such as aeolian losses or entrance effects. Neither of these effects is considered likely to be significant at Hearns Lake Beach.

[78] It is very difficult to see any evidence of progressive compartmentalisation commencing at the beaches immediately south of Hearns Lake Beach.

[79] Construction of the eastern breakwater commenced in 1919. The gap between the southern island (now Corambirra Point) and the mainland was filled in between 1915 and 1927. The northern breakwater, connecting Muttonbird Island to the mainland, was constructed between 1914 and 1924 (PWD, 1984). It was considered that Coffs Harbour had been a complete barrier to longshore transport since at least 1924.

Beach, were still adjusting to this loss of sediment supply from the south (WP Geomarine, 1998). Park Beach, to the immediate north of Coffs Harbour, has particularly shown accelerated long term recession as a result of the breakwater construction.

It is uncertain if there has been a reduction in sediment supply from the south as a result of the construction of training walls at Coffs Harbour, at Hearns Lake Beach (which is about 20km north). However, it is possible that there are naturally lower rates of longshore transport bypassing Look at Me Now Headland, Bare Bluff and Woolgoolga Headland, meaning that the section of coastline including Hearns Lake Beach is accustomed to relatively low supply rates of sand from the south.

Note: Vector arrows indicate magnitude of net longshore transport bypassing headlands (no vector indicates the headland is a barrier to transport)

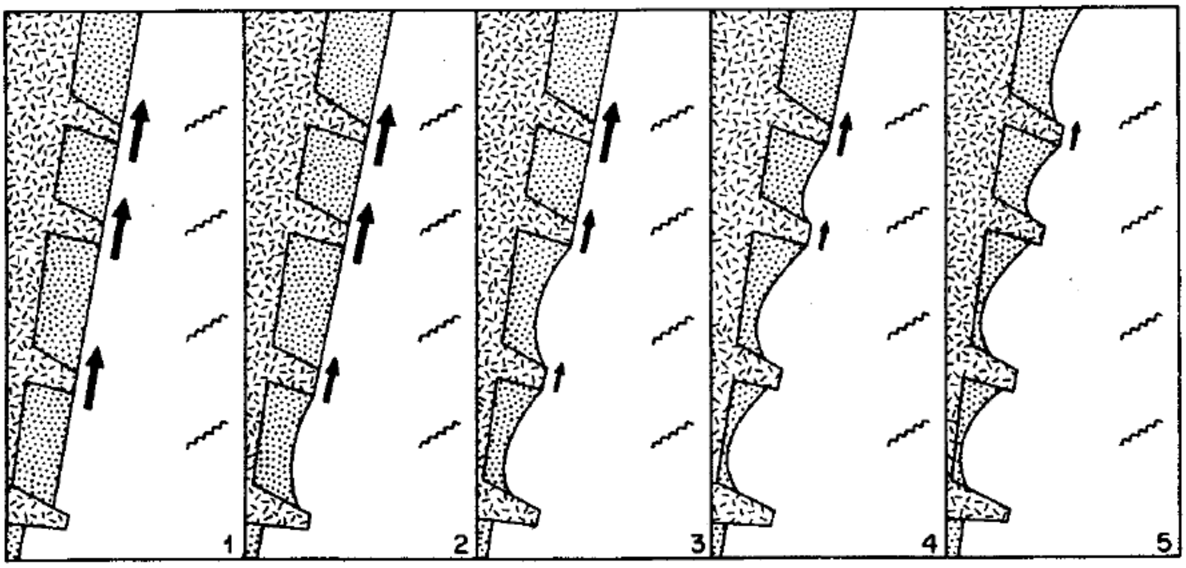
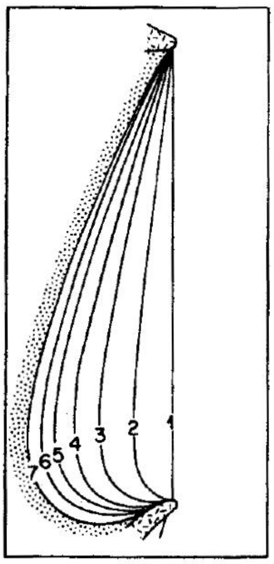


Figure 22: Successive stages in the evolution of coast with net northwards longshore sediment transport and progressive compartmentisation (after Stephens et al, 1981)



Note: Numbers indicate shoreline configurations at successive equal time periods. The numbers are located in the zone of most rapid erosion at each stage.

Figure 23: Evolution of a zeta form bay by coastal erosion (after Stephens et al, 1981)