HILLVIEW HEIGHTS PTY LTD

MOONEE WATERS
COASTLINE HAZARD DEFINITION

Issue No. 2
JUNE 2007

Patterson Britton
& Partners Pty Ltd

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Document Amendment and Approval Record

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1 INTRODUCTION

An application for Concept Plan approval of the residential subdivision of Lot 66 DP 551005 (Pacific Highway, Moonee Beach) into 378 lots has been submitted to the NSW Department of Planning. This is to be assessed under Part 3A (major infrastructure and other projects) of the *Environmental Planning and Assessment Act 1979*.

Hillview Heights Pty Ltd engaged Patterson Britton & Partners to undertake a coastline hazard definition study for the subject property, as set out herein. This report forms part of the environmental assessment documentation for the Part 3A application.

Note that a previous issue (Issue No. 1) of the report documented herein was prepared in 2005 on the basis of a different subdivision layout compared to the current proposal. In particular, as part of a previous Draft Masterplan, it was proposed to develop an area Zoned 2e (known as the Beachside Tourist Precinct) at the south-eastern corner of the subject property. This area, now known as the Beachfront Plan Area, <u>is not proposed to be developed as part of the current Concept Plan</u>.

As part of the current Concept Plan, no development is proposed to be closer than about 430m from the seaward property boundary. That is, coastline hazards discussed in the investigation reported herein are not particularly relevant to the current Concept Plan (compared to the previous Masterplan where development was adjacent to the seaward property boundary). However, it was decided that our previous report would be submitted as part of the environmental assessment documentation (with some editorial adjustments as appropriate).

Therefore, references to the Beachside Tourist Precinct in the investigation reported herein include a note that <u>this area is not proposed to be developed as part of the current Concept Plan</u>, and can be considered to be equivalent to the current Beachfront Plan Area.

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 discussion on dune management in Section 7. Coastline hazard zones are defined in Section 8.

The Director-General's requirements for the environmental assessment have been provided by the Department of Planning. Requirements relating to "coastal zone, access and impacts" are addressed in Section 9. 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 2055 and 2105 respectively. In accordance with industry practice, a 50 year planning period is usually adopted for residential development[1]. However, results for the 100 year planning period are also shown for informational purposes, as Coffs Harbour City Council has stipulated a 100 year planning period for residential development which may be subject to coastline hazards, in previous investigations completed by Patterson Britton in the LGA (Patterson Britton & Partners, 1995b, 2005)[2].

The investigation reported herein is consistent with a recent study undertaken by Patterson Britton (2005) for the North Sapphire Beach site (Sapphire Beach Properties Pty Ltd), located immediately south of the subject property[3].

[1] A 50 year planning period was also adopted in the Local Government Area 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.

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

[3] The North Sapphire Beach site incorporated part of Lot 13 DP 882816, Lot 49 DP 861518, Lot 50 DP 881378, and part of Lot 441 DP 1007121. The area of particular interest was the seaward portion of Lot 13 DP 882816.

2 GEOGRAPHICAL SETTING

The subject property is located in the suburb of Moonee Beach, within the Coffs Harbour Local Government Area (LGA). It is situated about 10km north of the Coffs Harbour township. The property is located landward of the sandy Sapphire Beach[4], which extends between Green Bluff in the north and White Bluff (and Lobster Rocks) in the south.

As shown in **Figure 1**, Sapphire Beach faces approximately east-south-east and is about 2.2km long[5]. North of Green Bluff, Moonee Beach extends for about 4.6km to Look at Me Now Headland. South of White Bluff, Campbells Beach extends for about 1.2km past Riecks Point to a small unnamed headland at the northern end of Opal Cove Beach (previously known as Hills Beach).

The area of particular interest in the investigation reported herein is at the south-eastern end of the subject property. This area is zoned 2e (Residential Tourist), and is known as the "Beachside Tourist Precinct" (however, as noted in Section 1, this area is not proposed to be developed as part of the current Concept Plan)[6]. The remainder of land adjoining the seaward property boundary at the subject property, and within the property, is zoned 7a (Environmental Protection Habitat and Catchment), and is not proposed to be developed. Seaward of the subject property, the zoning is 6a (Open Space - Public Recreation). The zonings at the subject property are shown in **Figure 2**.

Road access to the Beachside Tourist Precinct is proposed to be via an existing unsealed road that traverses the southern boundary of the subject property (however, as noted in Section 1, this area is not proposed to be developed as part of the current Concept Plan)[7]. A proposed North Sapphire Beach development (Sapphire Beach Properties Pty Ltd, 2004) is located immediately south of this road. South of this is Split Solitary Caravan Park and the township of Sapphire Beach, in the vicinity of White Bluff.

The township of Moonee Beach is located north of the subject property, which includes a Caravan Park. Moonee Creek flows in a north-south direction and discharges onto the sandy Moonee Beach just north of Green Bluff. Sugar Mill Creek flows in an east-west direction through the subject property, and joins Moonee Creek just upstream of the beach (see Figure 2).

Short (1993) noted that the sandy Sapphire Beach was exposed to slightly less wave energy than the adjacent beach to the north, Moonee Beach, due to the presence of Split Solitary Island offshore. He also found that the adjacent Campbells Beach contained a large proportion of pebble-sized particles, which steepened the beach and narrowed the surf zone.

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[4] Sapphire Beach has been officially named by the Geographical Names Board of NSW, and was also denoted as such by Short (1993). It was previously known as Mid Sapphire Beach.

[5] Note that the aerial photography of the mainland shown in Figure 1 was taken in June 2000, and was supplied by Coffs Harbour City Council. Offshore photography was taken in August 2000, and was supplied by the Department of Infrastructure, Planning and Natural Resources (DIPNR). The subject property boundary shown was derived from cadastral information supplied by DIPNR.

[6] There is also a much larger development area zoned as 2e on the western portion of the subject property.

[7] This road would be upgraded if development was to proceed. The cadastral width of the road is 20.1m.

Figure 1: Aerial view of Sapphire Beach and surrounding coastline

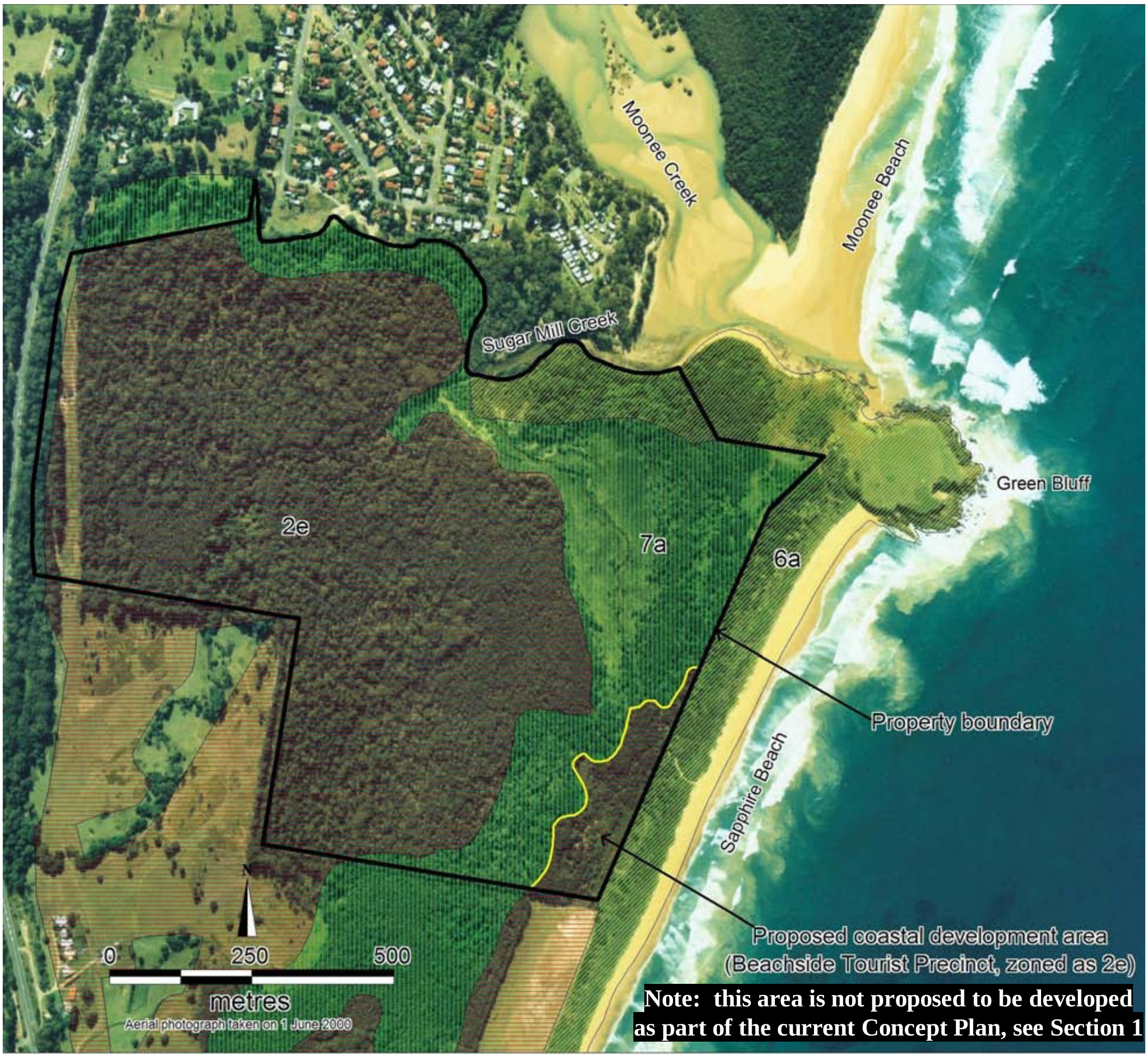


Figure 2: Zonings near subject property, and location of proposed Beachside Tourist Precinct (not proposed to be developed as part of the current Concept Plan)

A view of the well vegetated dune seaward of the property is given in **Figure 3** (from near the southern property boundary) and **Figure 4** (from near the northern end of the Beachside Tourist Precinct), as observed on 31 May 2005.

Figure 3: Dune seaward of subject property, looking north towards Green Bluff

Figure 4: Dune seaward of subject property, looking south towards White Bluff

Based on contours (at 2m intervals) supplied by the then Department of Infrastructure, Planning and Natural Resources (DIPNR), elevations over the subject property are as shown in **Figure 5**. It is evident that seaward of the dune, which has an elevation of about 10m AHD, elevations reduce from about 6m AHD to about 2m AHD moving landward within the Beachside Tourist Precinct.

Based on a survey undertaken in 2003 and 2004 by Blair & Lanskey[8], elevations over and near the Beachside Tourist Precinct are as shown in **Figure 6**. The position of the observed sand/vegetation interface at the time of the survey is also noted.

Figure 5: Elevations (m AHD) over and near subject property (2m contour interval)

[8] Survey was undertaken on at least 19 March 2003 and 17 September 2004, with the drawing denoted as "Proposed Subdivision of Lot 66 DP 551005", January 2005, Drawing No. 01, Revision A, Job No 6867, for RB Mercer.

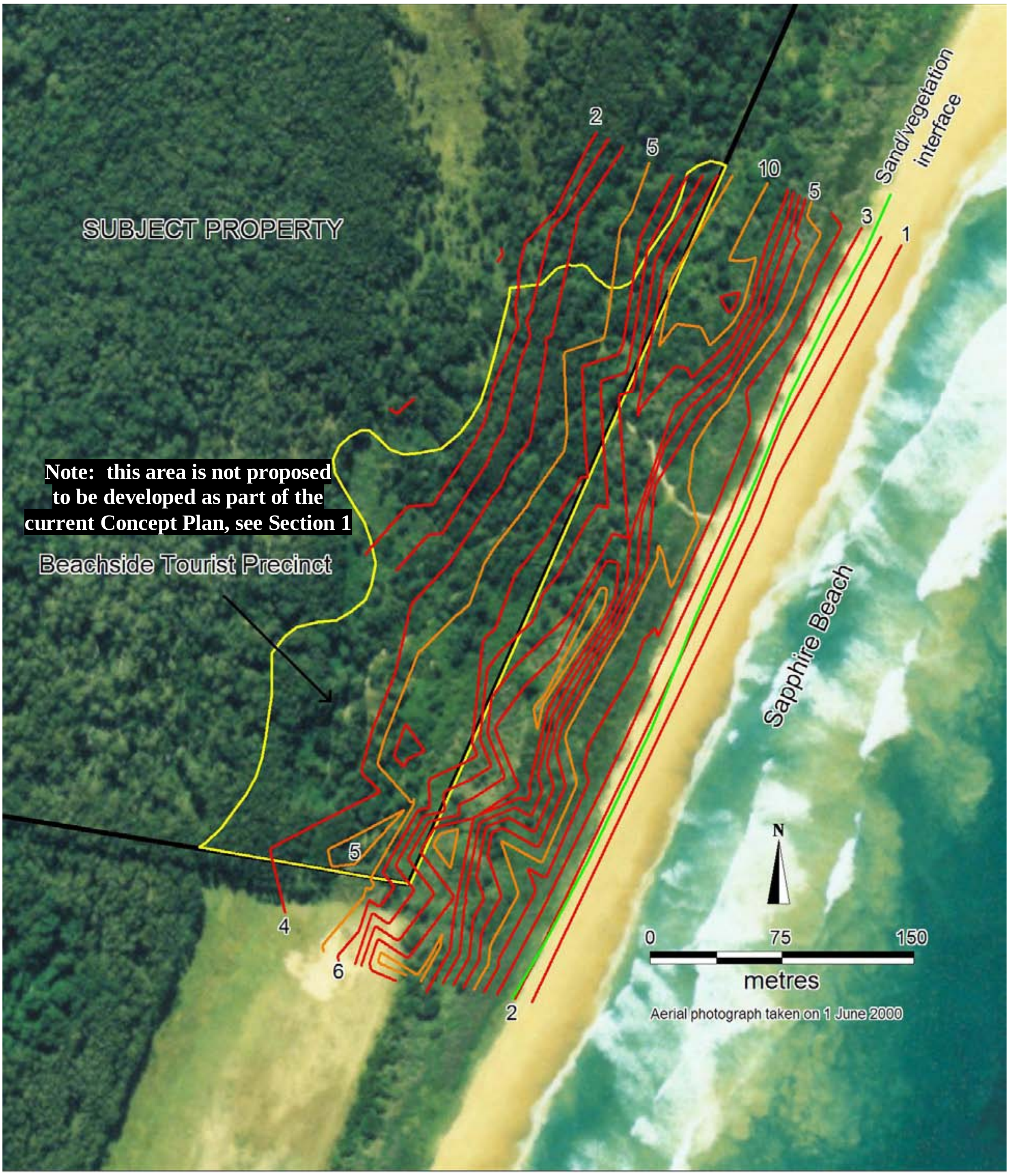


Figure 6: Elevations (m AHD) in vicinity of Beachside Tourist Precinct (1m contour interval)

3 LITERATURE REVIEW

In subsequent Sections, various coastal studies that have been undertaken in Coffs Harbour LGA are reviewed.

Jones (1981) has provided a brief description of the Sapphire Beach area from a coastal processes perspective, as outlined in Section 3.1. In Section 3.2, there is a discussion on heavy mineral sand mining that was undertaken at Sapphire Beach in 1971.

The generic “Coffs Harbour City Coastal Assessment Report” (Public Works Department [PWD], 1995a) is reviewed in Section 3.3. A number of photogrammetric /coastline hazard definition studies that fed into the PWD (1995a) study are also outlined in Section 3.3. The particular photogrammetric / coastline hazard definition study undertaken at Sapphire Beach (PWD, 1992b) is discussed in more detail in Section 3.4, given its relevance for the investigation reported herein.

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 3.5 and 3.6 respectively. Studies undertaken by Patterson Britton & Partners (1995b, 2004b) at Emerald Beach and Hearns Lake Beach (the latter which included analysis of Sandy Beach photogrammetric data) are also outlined in Section 3.7 and Section 3.8 respectively. A synthesis of the information presented is given in Section 3.9.

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 SAPPHIRE BEACH BY JONES (1981)

Jones (1981), in a preliminary study considering coastline hazards in the Coffs Harbour region, noted that the area north of White Bluff, including Sapphire Beach[9], was characterised by relatively long beaches, extensive sand barriers, offshore sediment deposits, and generally low-lying hinterland. Look at Me Now Headland was considered to be a dominant coastal feature in the area.

Mineral sand mining was noted as having been undertaken in the general area, and it was acknowledged that this mining had altered the dunal structure, although stabilising vegetation cover now existed over most dune areas. This sand mining is discussed further in Section 3.2. Jones (1981) also made reference to extraction of sand and gravel from the active beach zone and

[9] Jones (1981) actually denoted Sapphire Beach to be south of White Bluff, at the northern end of Campbells Beach. The beach seaward of the subject property was denoted as “Green Bluff”.

back dune areas, and noted that these operations were still active at Sapphire Beach. No further details were supplied on the nature, duration and specific location of these operations.

3.2 SAND MINING

Sand mining, also known as heavy mineral sand mining or black sand mining, has played an important part in the development of the North Coast of NSW. Prior to the late 1920's, black sands were mined for their small gold, tin and platinum content only. After this, heavy mineral mining began to be considered, although extensive mining operations did not commence in NSW until 1941. The heavy mineral fraction consists mainly of rutile (titanium dioxide), zircon (zirconium silicate) and ilmenite (titanium iron oxide). For further information, see Morley (1981).

As alluded to by Jones (1981), Sapphire Beach has been sand mined (PWD, 1992b). PWD (1992b) noted that the face of the erosion escarpment was unaltered by the mining, and that the mining took place in 1971[10]. With reference to Morley (1981), it is most likely that Cudgen R-Z was the company that undertook the mining operations at Sapphire Beach. Furthermore, a prospectus of Cudgen R-Z (1967) indicated that mining for rutile and zircon was proposed in the Sapphire Beach area as Private Lands Lease (PLL) 1070 in the south, PLL 1080 in the north, and Special Lease of Crown Lands (SL) 219 (ML6) along the shoreline.

The extent of mining operations in 1971 is shown in **Figure 7**. This extent was derived from PWD (1992b), and was confirmed by examination of aerial photography taken in 1972. An inspection of November 1975 noted that the mining had finished, rehabilitation was very satisfactory, and cancellation of the lease was pending (Mine Inspector, 1975)[11]. The location of Private Mining Lease (PML) 24, as derived from the Blair & Lanskey survey, is also shown in Figure 7. The significance of this lease is uncertain, although reference to NSW Mines Department (1975) would suggest that PML 24 covered the PLL 1080 area. There was also PML 23 covering the PLL 1070 area. However, NSW Mines Department (1975) noted that PML 23 and PML 24 were recommended for refusal in 1974[12].

Based on the extent of mining indicated in Figure 7, it is evident that the mining did not generally alter the dunal structure seaward of the subject property. However, virtually the entire Beachside Tourist Precinct was mined. That is, the vegetation now established in the Beachside Tourist Precinct has only been in existence since the completion of the mining.

[10] The NSW Mines Department (1975) indicated that the work commenced in late 1971.

[11] Since the early 1960's, mining companies were required to restore sand-mined areas under legislation administered by the Department of Mineral Resources. This involved reformation of the sand mass to the original or otherwise specified shape and elevation, replacement of the surface layer of sand and organic matter, and propagation of the vegetative cover (Morley, 1981).

[12] Martin Pundyk of Blair & Lanskey advised that PML 24 was created in May 1960, but that he had no further information on the lease.

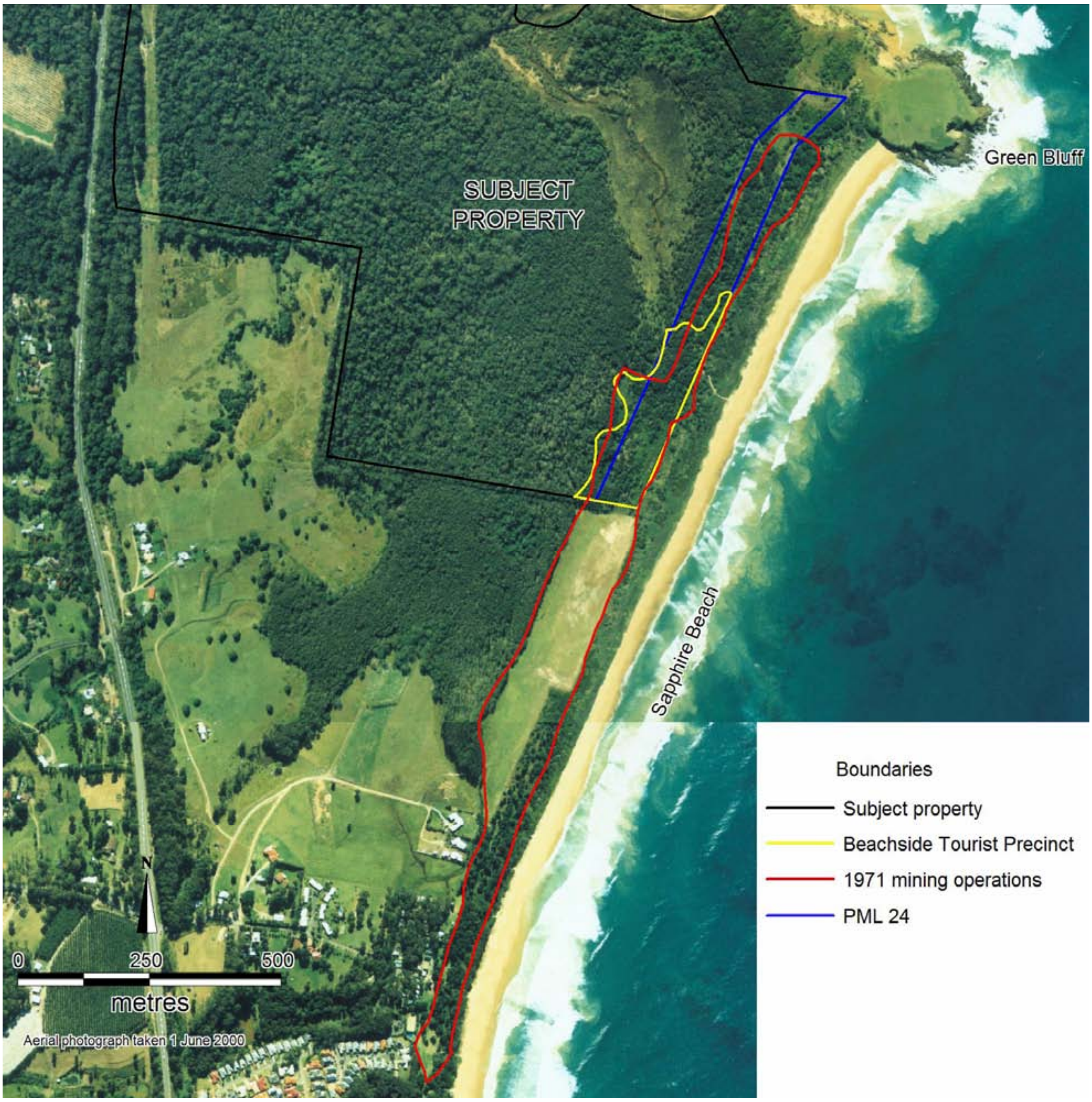


Figure 7: Location of sand mining operations in 1971 (based on PWD, 1992b), and PML 24 boundary

3.3 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 only as an indicative guide to 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 level (denoted as a cut level), generally at an elevation of 6m plus or minus 2m AHD[13]. 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[14].

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[15];
- 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[16];
- 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[17];
- variations in spatial behaviour were not allowed for, with constant recession values adopted for entire embayments; and,

[13] 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. Also, at Sapphire Beach, the cut level was up to 10m AHD, above the elevation of wave-driven coastal processes (see Section 3.4 for further discussion on this cut level).

[14] 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. Similarly, the 1943 to 1964 period was used to estimate the storm demand at Sapphire Beach, dates that are separated by 21 years. Many storms, and beach recovery in between, would occur over such long periods.

[15] 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.

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

[17] 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.

- 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 associated with vegetation removal (all of which may not continue into the future), were not explicitly considered in determining recession rates[18].

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 8** (southern end of LGA) and **Figure 9** (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[19]. 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 8 and Figure 9 for each of the 12 analysed beaches represent the storm demand, long term recession rate due to net sediment loss, and total setback relative to the cut level position (that is, the sum of the two former values plus 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 4.1 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[20].

[18] It is recognised that the occurrence of anthropogenic activities was at least noted at most sites.
[19] This slope value was arbitrarily adopted, without consideration of closure depths or offshore bathymetry.
[20] 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.

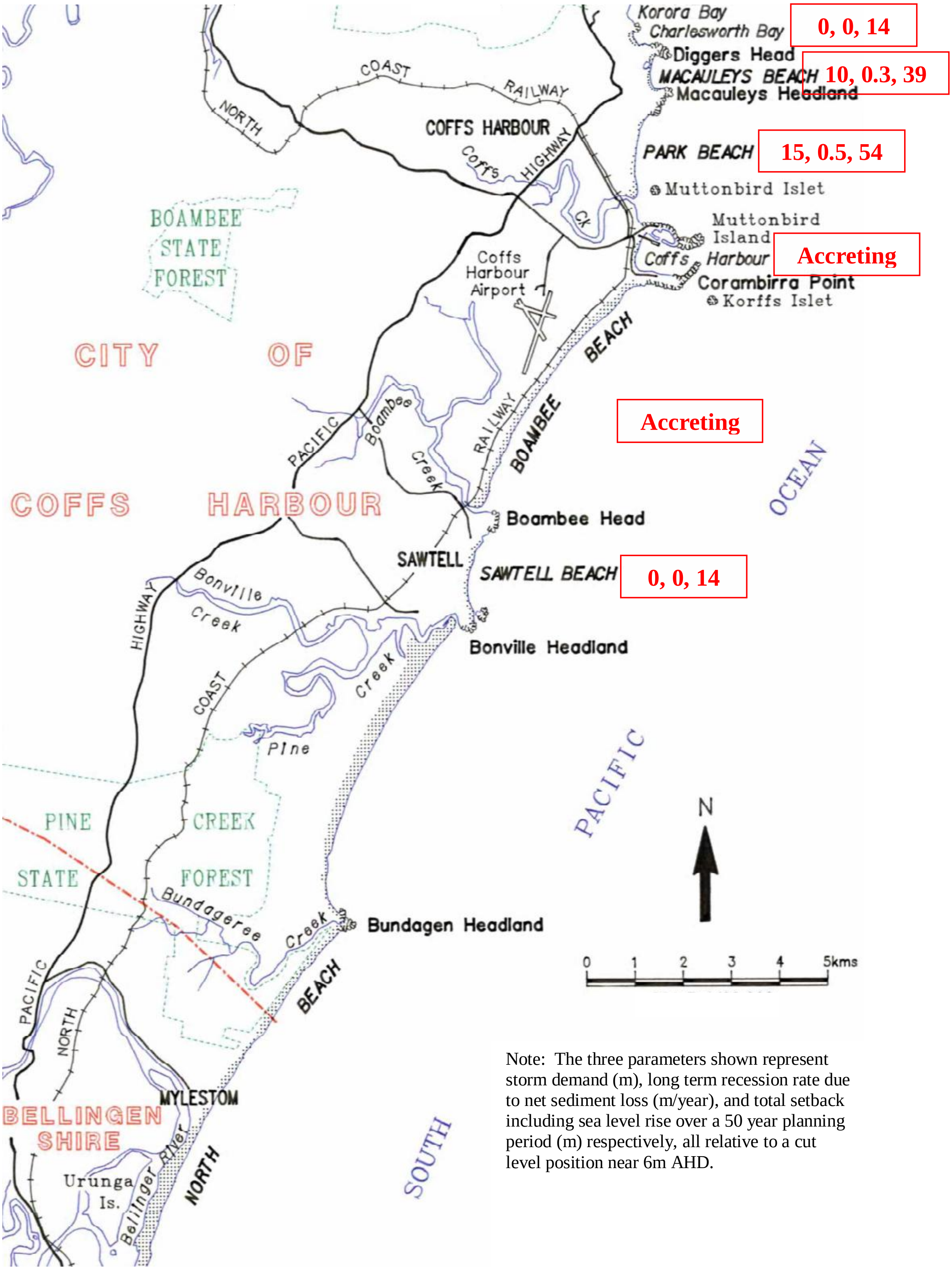
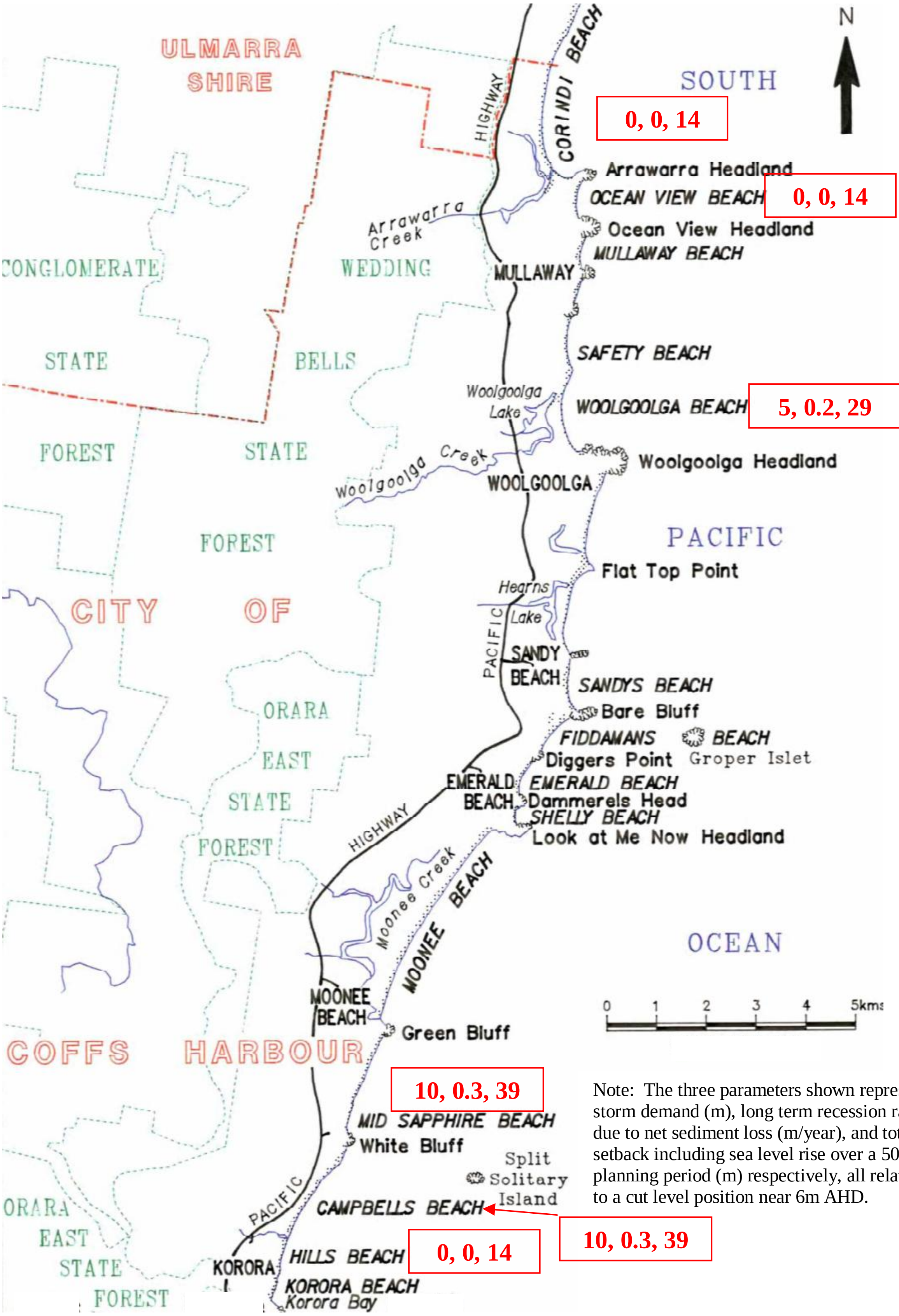


Figure 8: Coastline hazard parameters adopted by PWD (1995a), for beaches at southern end of Coffs Harbour LGA



Note: The three parameters shown represent storm demand (m), long term recession rate 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 9: 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[21]. 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 100m^3/m (above 0m AHD and landward of 2m AHD contour) and long term accretion of about 3m^3/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 280m^3/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.

[21] 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)[22]. 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.

3.4 PWD (1992B) ANALYSIS OF SAPPHIRE BEACH

The investigation of Sapphire Beach undertaken by PWD (1992b) has been summarised in Section 3.3. Further details are given below.

The seven dates of photography that were analysed by PWD (1992b) were as listed in **Table 2**. Photogrammetric profiles and planform information (such as water marks, vegetation lines, scarps, structures, roads, fences and tracks) were produced for all dates except 1981. All dates were considered to have good photo quality, but good model control only for 1973 onwards. The likely beach state, shown in Table 2 for each date of photography, was derived by referring to the storminess indicators listed in Section 4.1 and discussed further in Section 5.4.5.

Root mean square (RMS) errors (residuals) for the plan (horizontal) position and elevation are also shown in Table 2. Plan RMS errors were determined as the square root of the sum of the squares of the easting and northing RMS errors. Where varying residuals were given at different locations along the beach, these were averaged[23].

[22] 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.

[23] Spatially varying residuals were given for 1943 and 1981 (north and south), and 1983 and 1988 (north, centre and south).

Table 2: Dates of photography analysed at Sapphire Beach by PWD (1992b)

Date	Scale (1 to)	Likely Beach State	RMS Error (m)		Comments
			Plan	Elevation	
9 March 1943	18,900	Eroded	1.5	1.0	There was poor model control. No camera lens calibration information was available. PWD (1992b) stated that the scale was 1:16,000.
12 August 1964	46,610	Average	0.9	0.3	There was fair model control.
6 April 1969	58,590	Accreted	0.7	0.6	There was poor model control.
15 April 1973	25,000	Accreted	0.4	0.2	
26 October 1981	16,000	Accreted	0.4	0.2	Only used for model control, no photogrammetric profiles were produced.
31 August 1983	10,060	Average-Accreted	0.3	0.2	
9 May 1988	10,200	Eroded	0.3	0.2	

Given the relatively large residuals using the 1943, 1964 and 1969 photography, PWD (1992b) attempted to correct for possible systematic errors. It was decided to lower the 1943 profiles by up to 2.6m[24], translate the 1943 profiles by a distance of 8m landward, and raise the 1964 profiles by 0.6m. Examination of the actual profiles as part of the investigation reported herein (see Section 4.2) indicated that the 1943 data was distinctly different to the profiles for the other five years (beyond which could logically be explained by coastal processes), and that it therefore could not be confidently used for analysis purposes, even with the shifts applied.

Shore-normal photogrammetric profiles were derived for the entire length of Sapphire Beach and arranged into 3 blocks, namely Blocks 1, 2 and 3 proceeding from south to north. There were 10 profiles in Block 1, 18 profiles in Block 2, and 28 profiles in Block 3. For the investigation reported herein, each profile was numbered from 1 to 56, with Profiles 1-10 in Block 1, Profiles 11-28 in Block 2, and Profiles 29-56 in Block 3. The arrangement of the profiles (based on the 1988 data extents and June 2000 aerial photography) is shown in **Figure 10**. Within each Block, the alongshore profile spacing was 40m.

[24] PWD (1992b) stated that the maximum lowering in 1943 was 2m, but examination of the actual photogrammetric data indicated a maximum lowering of 2.6m. For 1943, Profiles 1, 6-7, 11, and 53-56 were not lowered; Profiles 2-5, 8, 23, and 27-28 were lowered by 1m; Profiles 10, 12, and 24 were lowered by 1.5m; Profiles 9, 13-18, 20-22, 25-26 and 29-52 were lowered by 2m; and Profile 19 was lowered by 2.6m. It is difficult to see, based on the method by which photogrammetric data is collected, how such a wide variation in elevation shifts between adjacent profiles could be supported. Whatever the case, it is hard to use the 1943 data with any confidence.

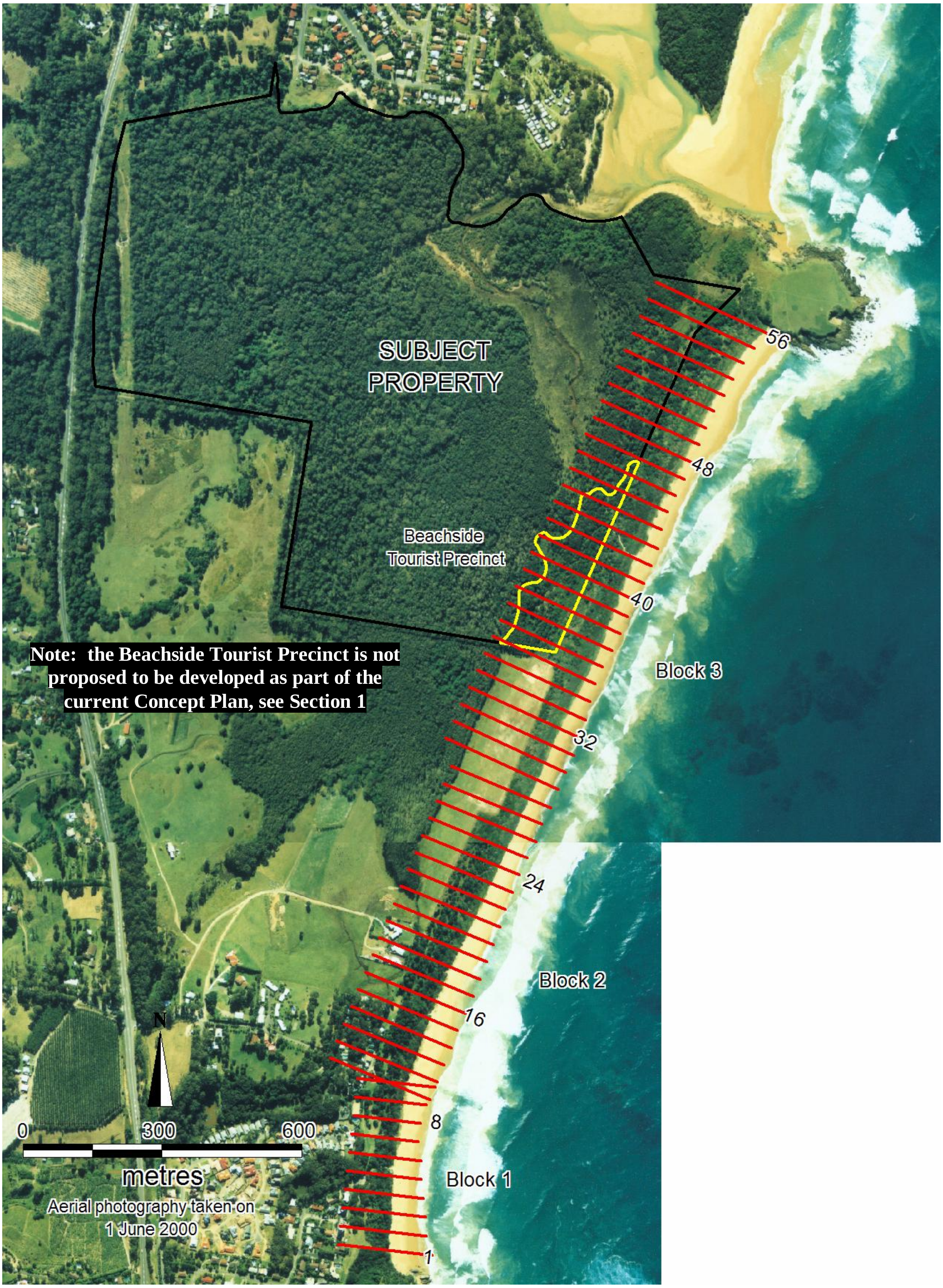


Figure 10: Arrangement of photogrammetric profiles at Sapphire Beach

PWD (1992b) used the photogrammetric data to estimate storm demand. This was estimated as a landward translation of the back beach erosion escarpment, based on the difference between the 1943 and 1964 profiles. However, the methodology used cannot be considered to be appropriate for a number of reasons, namely:

- A period of 21 years does not represent the effect of a single storm or group storms. As discussed in Section 3.3, pre-storm and post-storm sequences should be captured for such analysis to be reliable.
- The 1943 data cannot be used with any confidence, and the 1964 data also had significant potential errors.
- The scarp locations chosen were not necessarily at equivalent positions along the beach profile for each year. That is, incipient and back-beach scarp positions were sometimes used interchangeably.
- Scarp movements were estimated at locations where distinct scarps had not been determined as a planform feature.
- The back beach erosion escarpment position used in the analysis was sometimes at an elevation above 10m AHD, above wave-driven coastal processes that would have been expected to occur in the last few hundred years. In general, the only changes that would be expected at this elevation would be wind driven or anthropogenic, although it is recognised that erosion at lower elevations can influence movement at this level in relatively high dunes, due to slumping[25].

Using this limited methodology, PWD (1992b) considered that a 10m setback from the back beach erosion escarpment was appropriate. Based on the position of the back beach erosion escarpment in 1988, PWD (1992b) estimated that a setback of 10m was equivalent to volumes above 0m AHD of 150m^3/m in the south and 280m^3/m in the north[26].

PWD (1992b) also used the photogrammetric data to estimate long term recession due to net sediment loss. This was achieved by measuring the movement of a particular cut level (elevation) between 1943 and 1988, and 1964 and 1988 (with no dates considered in between). It was stated that cut levels between 4m AHD and 10m AHD were used.

As discussed in Section 3.3, it is more appropriate to consider recession trends by examining all dates of photography, particularly when the 1943 data is unreliable, and the 1964 data has limitations. It is also uncertain why a constant cut level was not adopted. Whatever the case, cut levels in the order of 10m are not appropriate as they are generally above wave-driven coastal processes, and overly influenced by other effects.

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[25] However, at Sapphire Beach, there was no evidence that any storms would have actually caused the scarp movements observed.

[26] However, at many locations, the 1988 scarp position was not actually observed in plan, but derived as the location of a profile maxima. This was particularly the case at the northern end of the beach, with no scarps observed north of Profile 31. By doing this, the scarp location was often placed at elevations above 10m AHD, well landward of wave-driven coastal processes, which is not an appropriate baseline scarp unless it would be expected that erosion would extend this far landward. This caused the relatively large volumes of 280m^3/m to be determined at the northern end of the beach.

PWD (1992b) found that recession rates were highest at the southern end of Sapphire Beach, with the average recession rate south of Profile 18, from 1943 to 1988, being determined as 0.3m/year (and 0.2m/year from 1964 to 1988). North of this, the average recession rate was about 0.1m/year from 1943 to 1988, but there was high variability[27]. PWD (1992b) considered that recession rates varying from 0.1 to 0.3m/year should be adopted along the beach.

With regard to coastal inundation hazards, PWD (1992b) found that these could be minimised by the maintenance of a stabilised frontal dune system to a height of about 6m AHD. It was considered that the dune south from Profile 15 was mostly below 6m AHD, and therefore may experience minor overtopping for short periods during major storm events (in conjunction with elevated ocean levels), very infrequently. No existing development was considered to be at threat due to coastal inundation, which included the Caravan Park at that time.

Given the limitations of the PWD (1992b) analysis, the photogrammetric data was re-analysed as part of the investigation reported herein, as discussed in Section 4.2.

3.5 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[28]; and,
- a runup level of 7m AHD[29].

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 needs 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.

[27] PWD (1992b) considered that the high variability was caused by the fact that the dune was wind-blown and unstable during the 1960's. Stabilisation of the dune commenced in the 1970's, after sand mining operations had ceased. However, note that the dune was largely stable and well vegetated by 1983. The high variability is considered to be predominantly due to the high elevation chosen for analysis, and errors in the early photography dates.

[28] 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).

[29] The calculation of runup was seemingly in error as wave setup was included in the still water level (the formulation used to calculate runup includes wave setup implicitly), and a numerical error was also potentially made (without these miscalculations, the value would have been 6.6m AHD, based on a slope of 0.13).

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)[30]. 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)[31].

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.

3.6 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.

3.7 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 4.1, Table 3, for each of these years[32]).

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

[30] 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).
[31] As noted in Section 3.3, 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.
[32] The 1973 photograph was taken on 3 May.

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 1.4, indicative of a more 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.

3.8 HEARNS LAKE BEACH AND SANDY BEACH

Patterson Britton & Partners (2004b) recently completed a coastline hazard definition study for a proposed development at the northern end of Hearns Lake Beach, which is located about 9km north of Sapphire Beach.

The study included analysis of dune vegetation lines evident in aerial photography of the beach. It was evident that the sand/vegetation interface migrated seaward between 1943 and 2004, typically by over 20m. This was considered to be evidence that the northern end of Hearns Lake Beach had been accreting over the last 61 years.

Photogrammetric data for Sandy Beach, the next beach to the south of Hearns Lake Beach, was also analysed by Patterson Britton & Partners (2004b). It was evident that the section of Sandy Beach actively influenced by coastal processes had generally accreted over the period of photogrammetry, from 1964 to 1996.

3.9 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 Sapphire 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 of only 0.08m/year (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);
- a general trend of accretion at Sandy Beach from 1964 to 1996;
- accretion at the northern end of Hearns Lake Beach from 1943-2004;

- northern end of Woolgoolga Beach being stable from 1943-1986, with southern end receding at 0.2m/year;
- northern end of Ocean View Beach being stable from 1943-1993, with southern end receding at 0.1m/year; and,
- accretion along most of Corindi Beach, with accretion rates generally increasing moving north.

Therefore, there is strong evidence that the beaches in the vicinity of Sapphire Beach are relatively stable, particularly moving north along the individual embayments.

The relatively high recession rate of 0.5m/year quoted for Park Beach was not considered to be applicable at Sapphire Beach, as recession of Park Beach has predominantly been caused by construction of Coffs Harbour, 10km 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 (except Patterson Britton & Partners, 2004b, 2005) have considered the issue rigorously. Furthermore, little data was presented on likely slopes of the active beach profile for use in the Bruun Rule, to determine recession due to sea level rise.

4 DATA ACQUISITION

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

- historical aerial photography of Sapphire Beach; and,
- photogrammetric data for Sapphire Beach.

These data items are discussed in Sections 4.1 and 4.2 respectively below. Note also that a land based survey of Sapphire Beach seaward of the Beachside Tourist Precinct has been undertaken as shown in Figure 6 (page 8).

4.1 REVIEW OF HISTORICAL AERIAL PHOTOGRAPHY

Aerial photography of Sapphire Beach was obtained from Coffs Harbour City Council, the Department of Lands, DIPNR, GHD, the Roads and Traffic Authority (RTA), and United Photo and Graphic Services Pty Ltd (United). A summary of the dates and scales of each set of photography examined is given in **Table 3**[33].

Photography that was obtained was approximately registered to real world coordinates by matching to consistent features in a June 2000 orthorectified aerial photograph, or photogrammetric landform (planform) data, within a GIS package[34]. The approximate accuracy of each registered photograph (based on image pixel distances from control points, converted to metres) is also shown in Table 3, as the maximum and average errors (based on a minimum of four control points).

[33] The storminess indicator shown in Table 3 was derived as discussed in Section 5.4.5, and is indicative of accreted beach states if less than 1, average beach states if close to 1, and eroded beach states if greater than 1.

[34] Such features included rocky outcrops, 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. For years with photogrammetric data, images were registered to landform features derived photogrammetrically for that particular year (this was also attempted for other years where it was evident that the landform data would not have changed).

Table 3: Aerial photography examined as part of investigation reported herein

Date	Scale (1 to)	Source	Registration Error (m)		Storminess Indicator[33]	Comments
			Maximum	Average		
9 March 1943	18,900	United	1.9	0.9	1.9	Photogrammetric date
26 April 1956	32,230	Lands	1.4	1.2	0.8	
12 August 1964	46,610	Lands	1.0	0.7	1.1	Photogrammetric date
6 April 1969	58,590	Lands	2.5	0.9	0.4	Photogrammetric date
8 October 1972	18,400	RTA	3.8	1.9	0.8	
15 April 1973	25,000	Lands	0.6	0.1	0.2	Photogrammetric date
9 May 1973	26,460	Lands	2.3	1.0	0.2	Partial coverage
3 April 1974	25,910	United	3.5	1.5	1.5	
23 June 1974	40,250	Lands	5.0	3.3	1.7	
28 November 1980	10,000	RTA	3.1	1.4	0.4	Only covers small part of beach
26 October 1981	16,000	Lands	0.3	0.2	0.1	
as above, S photo			3.1	1.8		
31 August 1983	10,060	Lands	0.8	0.4	0.7	Photogrammetric date
as above, S photo			2.9	1.5		
9 May 1988	10,200	Lands	0.4	0.2	1.7	Photogrammetric date
as above, S photo			6.9	4.1		
17 September 1989	10,000	RTA	4.5	3.2	2.1	Covers most of beach
17 June 1993	10,280	Lands	5.5	3.6	1.4	
as above, S photo			4.0	2.9		
2 April 1996	8,000	RTA	4.5	3.3	0.8	Only covers small part of beach
28 June 1996	10,150	Lands	3.4	1.7	1.0	
as above, S photo			2.3	1.0		
1 June 2000	15,000	Council	0.0	0.0	1.7	
21 August 2000	Unknown	DIPNR	0.0	0.0	1.7	
7 September 2002	25,000	Lands	2.7	1.5	1.4	
18 May 2003	Unknown	GHD	0.0	0.0	1.6	Covers centre of beach
26 September 2003	Unknown	RTA	2.7	2.2	1.1	Only covers small part of beach
29 May 2004	15,000	Council	1.1	0.5	1.2	
as above, S photo			1.1	0.6		
7 August 2004	10,470	Lands	4.7	2.3	1.2	
as above, S photo			6.4	3.3		

Based on the photography, it was evident that the subject property was almost entirely cleared of vegetation from at least 1943, excluding portions in the central south. An unsealed road traversed along virtually the entire length of Sapphire Beach in 1943. This road was about 80m landward of the seaward property boundary at the southern end of the proposed Beachside Tourist Precinct, reducing to about 20m landward at the northern end of the Precinct. Dune vegetation was sparse at a number of locations along Sapphire Beach in 1943, particularly at the southern end, perhaps due to cattle grazing and traffic damage. The central portion of the subject property (northern end of the Beachside Tourist Precinct) had sparse dune vegetation.

Much of the vegetation at the subject property had re-established by 1956, and by 1964, the unsealed road traversing the beach was no longer clearly visible[35]. Also, in 1964, it was evident that dune vegetation was re-establishing in the central portion of the subject property. The dune was still generally densely vegetated in 1969.

By 1972, only a narrow strip of dune vegetation remained, due to sand mining undertaken in 1971 (Section 3.2). The area landward of the seaward subject property boundary was entirely cleared of vegetation for a shore-normal distance of at least 70m (about 110m at the southern end). That is, the entire Beachside Tourist Precinct was cleared. The dune seaward of the subject property had become patchily vegetated, perhaps related to traffic associated with the mining operations. An access road was constructed for the mining along the southern property boundary [36]. Given the apparent damage to the dune, it appears that both Jones (1981) and PWD (1992b) had perhaps understated the effect of the mining operations on the dunal structure of Sapphire Beach. Photography in 1973 and 1974 indicated that extensive lengths of the dune seaward of the subject property still had a virtual absence of tree cover, particularly in the central portion (northern end of the Beachside Tourist Precinct). The mined areas remained cleared over this time.

The dune vegetation cover had significantly improved by 1980, and has generally continued to improve since then[37]. Seaward of the subject property, an extensive coverage of dunal vegetation had established by 1988. Also, the mined areas remained patchily vegetated until 1988, but were not densely vegetated until 2000.

4.2 RE-ANALYSIS OF SAPPHIRE BEACH PHOTOGRAMMETRIC DATA

4.2.1 Overall Recession Trends

Photogrammetric data for Sapphire Beach was obtained from DIPNR, as described in PWD (1992b), and discussed in Section 3.4. This data comprised shore-normal beach profiles, based on aerial photography taken in 1943, 1964, 1969, 1973, 1983 and 1988[38].

Also, additional photogrammetric data was provided by DIPNR in May 2005. It comprised beach profile information at Sapphire Beach for the dates of 28 June 1996 and 7 August 2004. A

[35] Areas with sparse vegetation were in the vicinity of the creek passing through the 7a area at the NE of the subject property, evident in Figure 2 (page 5).
[36] The access road, which linked up with the Pacific Highway, remained clearly visible in aerial photography until 1988, and it was still faintly evident in the 2004 photography. Tracks leading from the southern end of the subject property to the beach, coming off this access road, were still evident in the 2004 photography. The unsealed road is still in existence and is traversable by vehicles.
[37] Die-off of understorey vegetation appeared to have occurred in 2002, perhaps related to drought conditions. However, cover had been restored by 2003.
[38] Note that shifted and original profiles were provided for 1943. However, only elevations had been shifted, and not positions (as noted in Section 3.4, the shifted 1943 profiles were meant to have been translated landward by 8m).

summary of the 8 dates thus independently analysed to determine long term recession rates[39] as part of the investigation reported herein is provided in **Table 4**.

Table 4: Dates of photography analysed at Sapphire Beach

Date	Scale (1 to)	Storminess Indicator	Likely Beach State[40]	RMS Error (m)[41]	
				Plan	Elevation
9 March 1943	18,900	1.9	Eroded	1.5	1.0
12 August 1964	46,610	1.1	Average	0.9	0.3
6 April 1969	58,590	0.4	Accreted	0.7	0.6
15 April 1973	25,000	0.2	Accreted	0.4	0.2
31 August 1983	10,060	0.7	Average-Accreted	0.3	0.2
9 May 1988	10,200	1.7	Eroded	0.3	0.2
28 June 1996	10,150	1.0	Average	0.3	0.3
7 August 2004	10,470	1.2	Average-Eroded	0.3	0.3

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[42]. BMAP also allows the position (chainage) of a particular elevation to be determined. For the study reported herein, the positions of the 3m AHD elevation are reported[43].

For each of the 56 profiles, the rate of change of the volume above 0m AHD, and the rate of change of the position of the 3m AHD elevation, was determined. The rates were calculated for the 1964 to 2004 period, and derived by linear regression, that is by determining the line of best fit (least squares error) in each case[44]. 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 11**. Further analysis of the 1964-1988, 1969-1988 and 1973-1988 periods is given in **Appendix A**.

[39] Given the number of years between each photography date, analysis to determine storm demand was not considered to be warranted (see Section 3.4).
[40] 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 (see Section 5.4.5).
[41] RMS errors for 1996 and 2004 were approximate only, and were obtained from Clout (2005).
[42] The volume above 0m AHD was used as it was defined in about 28% of profiles without necessity for extrapolation (and 50% and 70% of profiles extended below 0.5m AHD and 1m AHD respectively), and particularly because it is the typical datum level used in the method of Nielsen et al (1992). Selecting a higher level would have discarded relevant data.
[43] The position of the 3m AHD elevation was used as it was defined in 97% of profiles (and 92% of profiles for which it was not defined were for the spurious 1943 data), was high enough to minimise unwanted noise, and was reasonably representative of long-term coastal processes.
[44] This does not imply that there were uniform rates of volume or positional change between dates of photography.

For calculation purposes, a landward limit was applied to the profiles. That is, not all data from 0m chainage was used, given that a significant proportion of the profiles would be landward of natural coastal processes. Referring to Figure 10, it is evident that some profiles extended landward of the vegetated dune into cattle grazing and residential areas, for example. The landward limit was defined by determining a continuous line along the beach (in plan) that was 15m landward of the sand/vegetation interface existing in 2000, which would logically represent a landward limit to typical coastal processes[45].

Note that the results for the 1943-2004 period are not shown in Figure 11. As discussed in Sections 3.3 and 3.4, the 1943 data was not considered to be of sufficient accuracy to be reliable, and the attempted shifting of the data did not instil much greater confidence in the results. Given the relative consistency in the beach profiles from 1964 to 2004, and consistency in vegetation lines from 1956 to 2004 (as will be discussed in Section 5.6.3), it is difficult to envisage massive beach changes (as implied by the 1943 data) occurring from 1943 to 1956, unless they were caused by anthropogenic effects. For reference, the rate of change of the volume above 0m AHD, and the rate of change of the position of the 3m AHD elevation, for the 1943 to 1988 period, are shown in **Appendix A**.

It is evident in Figure 11 that the section of Sapphire Beach actively influenced by coastal processes had generally consistently accreted over the period of photogrammetry from 1964 onwards[46]. The volumetric and positional rates of change are both indicative of this accretionary trend.

The highest rates of accretion were between Profiles 25 and 43, which incorporates most of the proposed Beachside Tourist Precinct at the subject property. The average rate of accretion from 1964 to 2004, along the Beachside Tourist Precinct (Profiles 35 to 47), was 2.0m^3/m/year (volumetric) and 0.4m/year (positional). Averaged over the entire beach, the rate of accretion from 1964 to 2004 was 1.2m^3/m/year (volumetric) and 0.3m/year (positional).

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. Also, in a relative sense, accretion rates based on an analysis period from 1964 to 2004 is likely to be reasonable (or perhaps a slight underestimate of accretion) given likely similar beach states for these dates. Overall, it can be realistically concluded that accretion has occurred seaward of the subject property between 1964 and 2004.

The accretion observed at Sapphire Beach was further evidence of the observations made in Section 3.9, that recession rates in the area were generally low. In fact, seven beaches near to Sapphire Beach appeared to be relatively stable, over a period of record of 30 to 50 years, namely Campbells Beach, Emerald Beach, Sandy Beach, Hearns Lake Beach, Woolgoolga Beach, Ocean View Beach and Corindi Beach.

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[45] However, some aeolian processes may still be have been occurring in areas landward of the applied landward limit, particularly prior to the dune having a stabilising cover of vegetation in the 1980's.

[46] Excluding evidence of slight recession at the southern end of the beach, over 800m south of the Beachside Tourist Precinct at the subject property. There is a possibility that the recession evident at Profile 10, which mainly occurred from 1973-1988, was related development of the Caravan Park and public beach access at the end of Split Solitary Road at this time.

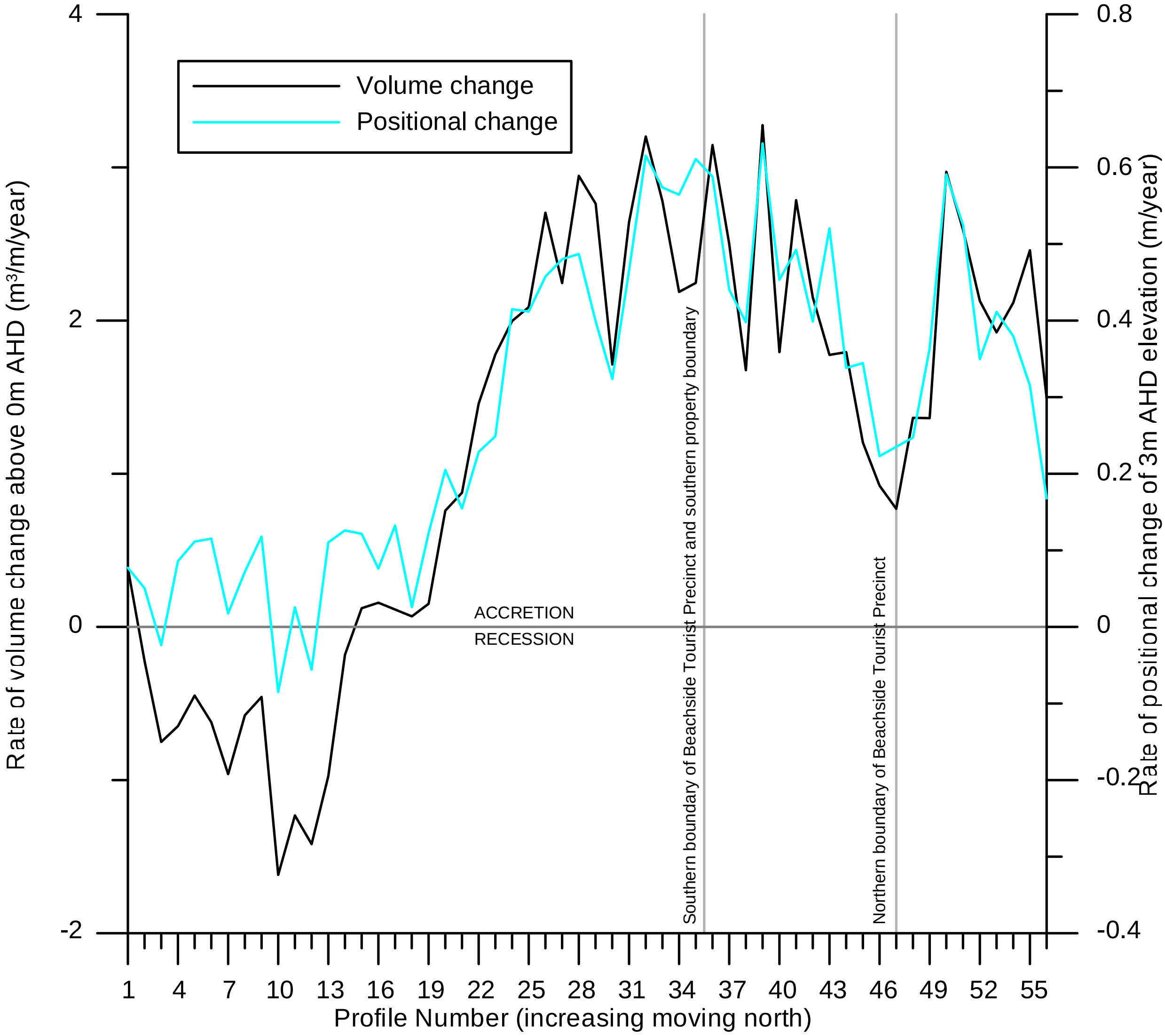

Figure 11: Rate of volume change above 0m AHD, and rate of positional change of 3m AHD elevation, Sapphire Beach, 1964-2004

4.2.2 Temporal and Spatial Variations

The volume in each profile, for each photogrammetric date, is shown in **Figure 12**. The volume changes at each profile between each photogrammetric date (and the net change for the 1964 to 2004 period) are shown in **Figure 13**.

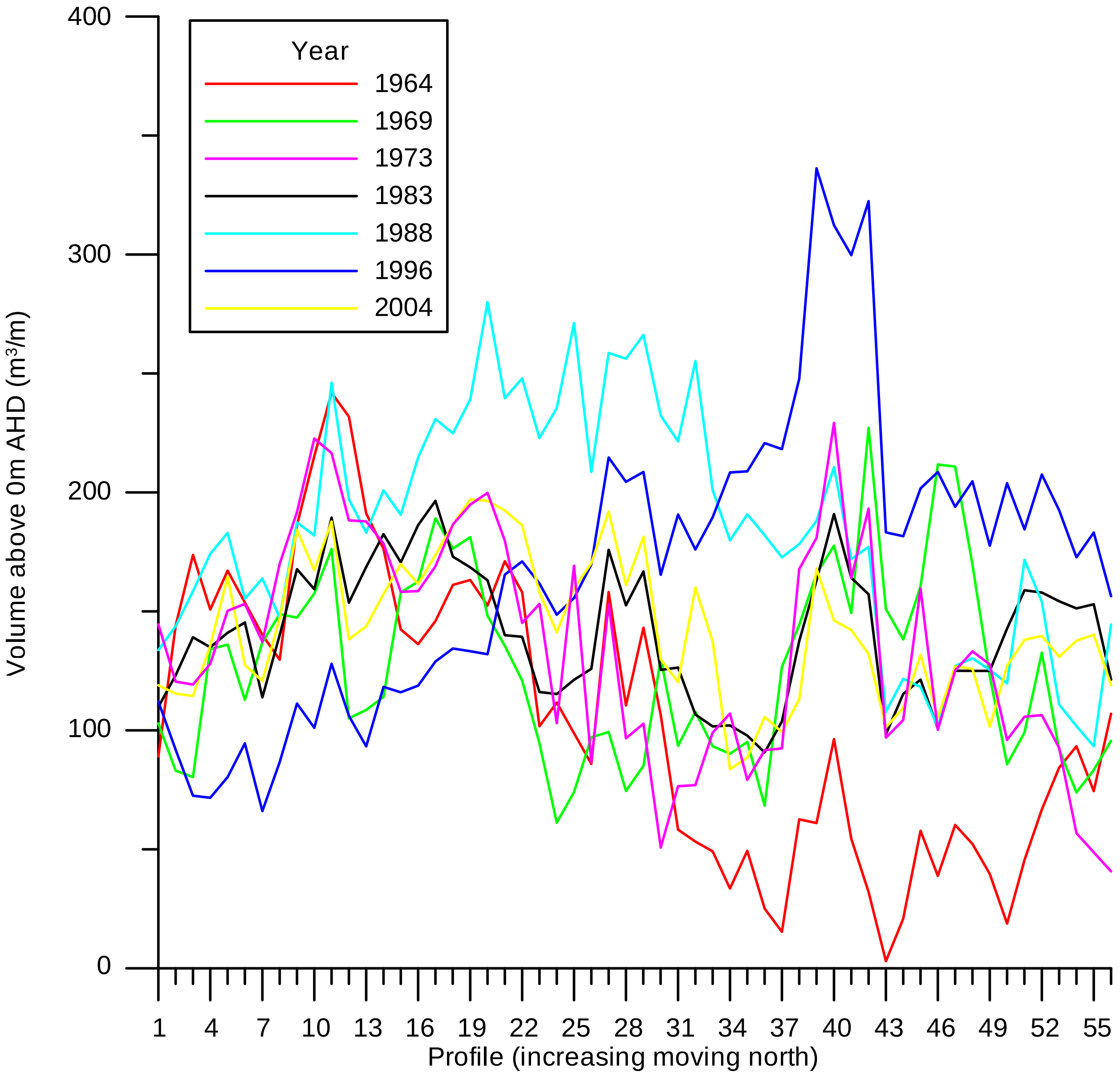

Figure 12: Volume in each profile at Sapphire Beach, for each photogrammetric date

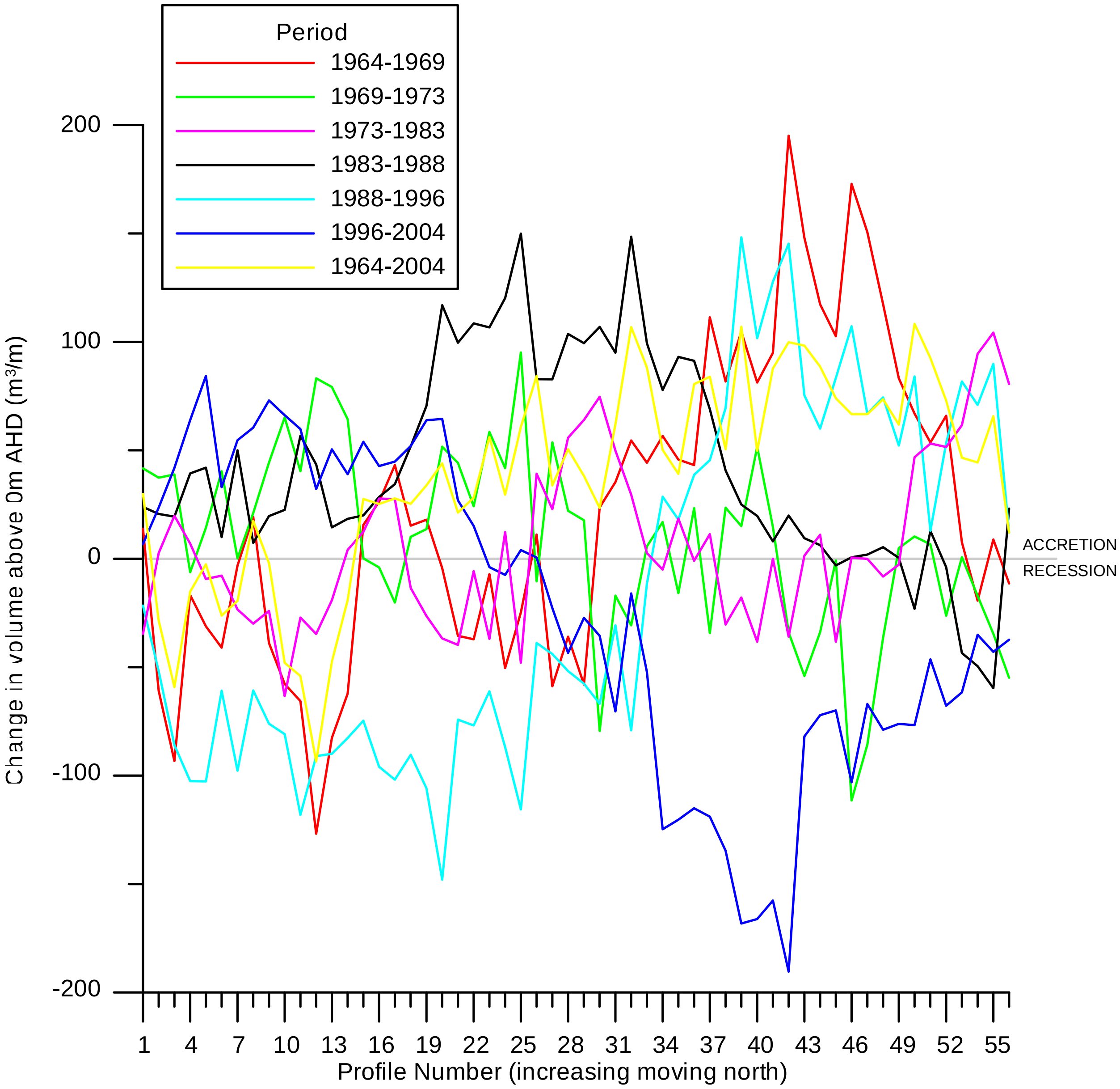

Figure 13: Net volume change at each profile between each photogrammetric date, and for the entire 1964 to 2004 period, at Sapphire Beach

It is evident that there was a significant gain in sand volume at the northern end of Sapphire Beach (Profile 30 and northwards) from 1964 to 1969. From 1969 to 1973, sand volumes generally increased at the southern end of the beach (Profile 29 and southwards). Between 1973 and 1983, sand volumes were relatively steady. There was an increase in sand volume between 1983 and 1988, over virtually the entire beach, and particularly in the centre (Profiles 20 to 36).

From 1988 to 1996, there were significant sand volume losses at the southern end of the beach (Profile 33 and southwards), with corresponding sand volume increases at the northern end of the beach (Profile 34 and northwards). Conversely, from 1996 to 2004, there were sand volume increases at the southern end of the beach (Profile 26 and southwards), with relatively large sand losses at the northern end of the beach (Profile 27 and northwards, and particularly at Profiles 34 to 42).

Overall, the net volume change from 1964 to 2004 (yellow curve in Figure 13) indicated accretion from Profile 15 and northwards. This was a similar result to the linear regression trends shown in Figure 11, with volumetric accretion also occurring from Profile 15 and northwards in the trend analysis.

4.2.3 Southern Oscillation Index Relationships

There have been attempts (Ranasinghe et al, 2004) to explain beach rotation in terms of shifts in the Southern Oscillation Index (SOI)[47]. Specifically, Ranasinghe et al (2004) proposed that beaches rotate clockwise (with the northern end accreting and southern end receding) in El Niño phases (negative SOI). Conversely, it was proposed that beaches rotate anti-clockwise (with the northern end receding and southern end accreting) in La Niña phases (positive SOI)[48]. The variation in SOI over the last 45 years is shown in **Figure 14** (1960 to 1983) and **Figure 15** (1983 to 2004), with dates of photogrammetry at Sapphire Beach also shown.

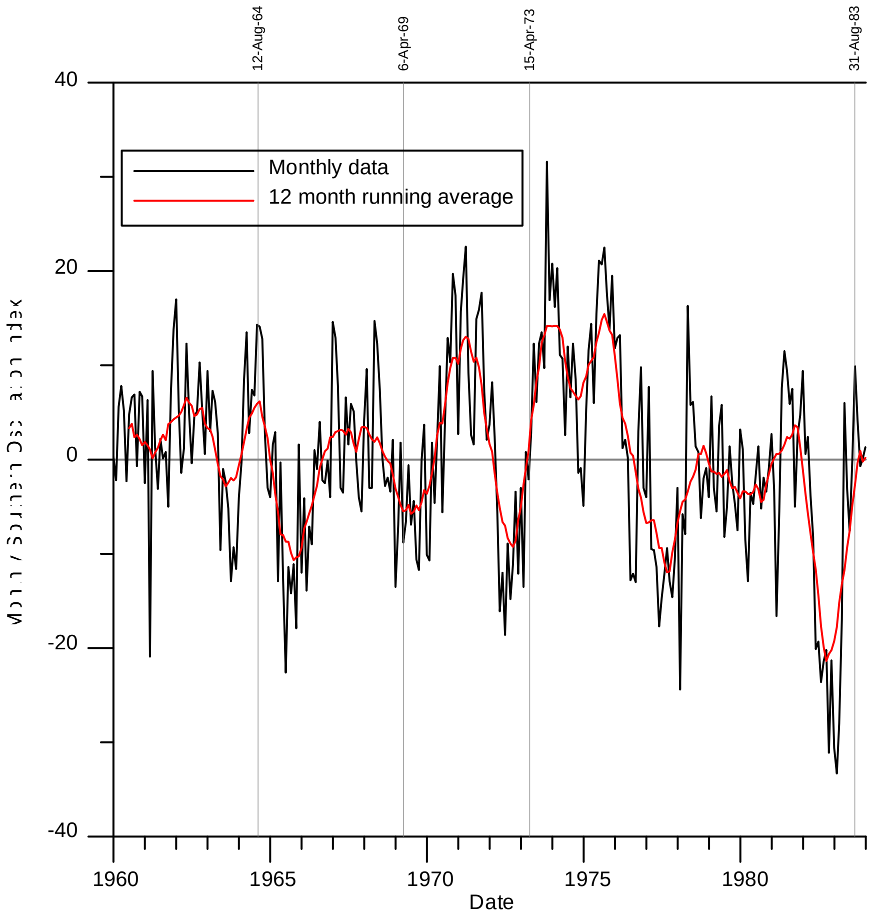

Figure 14: Variation in monthly SOI, 1960 to 1983

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[47] The SOI is calculated from the monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin. The method used by the Australian Bureau of Meteorology is the Troup SOI which is the standardised anomaly of the Mean Sea Level Pressure difference between Tahiti and Darwin (Bureau of Meteorology, 2005a).
[48] It was also found that La Niña phases were associated with more energetic (erosive) conditions.

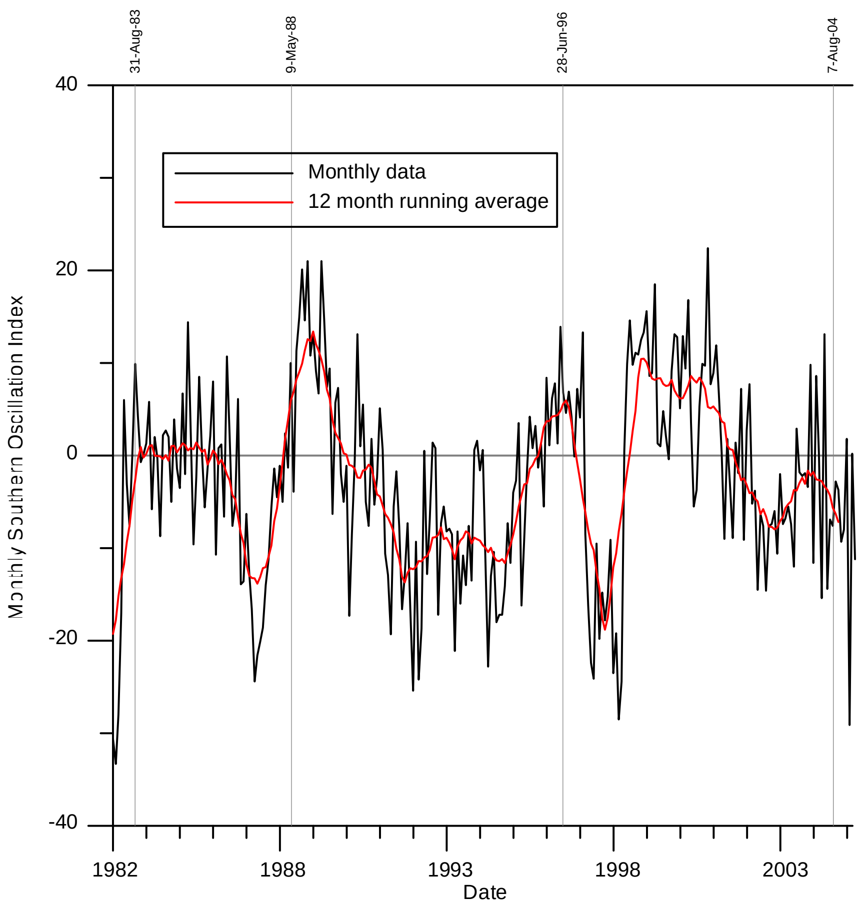

Figure 15: Variation in monthly SOI, 1983 to 2004

The predicted beach rotations (based on Ranasinghe et al, 2004), using the median SOI between photogrammetric dates, are shown in **Table 5**, and compared to the actual beach behaviour (as described in Section 4.2.2)[49].

Table 5: Expected (Ranasinghe et al, 2004) and actual beach rotations at Sapphire Beach

Period	Median SOI[50]	Expected beach rotation	Actual beach rotation
1964 to 1969	–1.9	Clockwise	Clockwise (N end)
1969 to 1973	0.8	Anti-clockwise	Anti-clockwise (S end)
1973 to 1983	0.1	None	None
1983 to 1988	–1.4	Clockwise	None (accretion in centre)
1988 to 1996	–4.0	Clockwise	Clockwise
1996 to 2004	0.3	Slight anti-clockwise	Anti-clockwise

[49] Note that the Ranasinghe et al (2004) model is not necessarily applicable to the North Coast of NSW.
[50] Monthly SOI values were obtained from the Bureau of Meteorology (2005b). The use of the median SOI between photogrammetric dates was not supported in the literature, but was considered to be a reasonable statistical measure with some limitations (eg elevated water levels are not considered), much like the storminess indicator.

It is evident that the median SOI and corresponding expected beach rotation was generally a reasonable predictor of actual beach rotation between photogrammetric dates. It can also be inferred that much of the sediment movement at Sapphire Beach is related to “natural” storm and SOI cycles, and is not a reflection on any permanent loss of sand from the beach.

Note that it has been postulated that, as a result of the greenhouse effect, El Niño conditions will be favoured in the future (Cai and Whetton, 2000; Boer et al, 2004), thus favouring clockwise beach rotation. Being nearer the north of the beach, it is therefore most likely that the Beachside Tourist Precinct would undergo relative accretion under these conditions (ignoring other effects)[51].

[51] El Niño conditions are also associated with reduced frequency of coastal storms (Ranasinghe et al, 2004), so it could potentially be argued that this in itself would favour beach accretion under global warming (with the counteracting long term recession due to sea level rise).

5 COASTAL PROCESSES

In this Section, the coastal processes operating in the vicinity of the subject property at Sapphire 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); and,
- climate change (Section 5.9).

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[52]. 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 Sapphire Beach, Waverider buoys are located offshore of Byron Bay and Coffs Harbour, about 150km north and 20km south respectively from the subject property[53]. 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 16**. It can be seen that H_s values exceeding 4m occur less than 1% of the time[54]. 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, 1997a). The average T_p at

[52] 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.
[53] 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.
[54] 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).

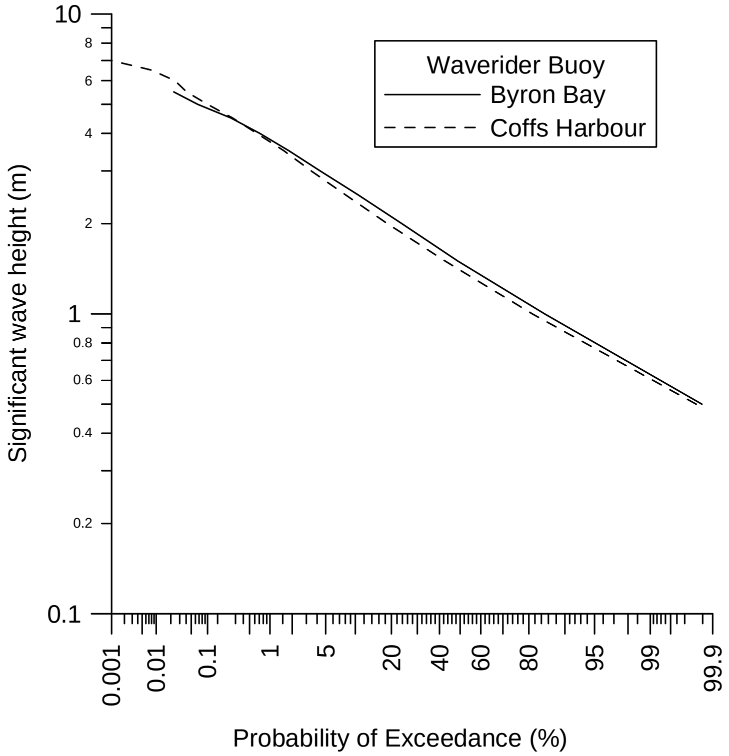

Figure 16: Significant wave height exceedance for Byron Bay and Coffs Harbour, based on data collected from 1976 to 1999 (after Lord and Kulmar, 2001)

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 average recurrence interval (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). It is therefore considered that the 6 hour duration is the most appropriate to use for beach erosion and wave runup considerations, and as such has been adopted for use in the investigation reported herein. The relationship between H_s, duration and ARI, at the Byron Bay Waverider buoy (for all data collected up to 31 December 1999), is shown in **Figure 17**[55].

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

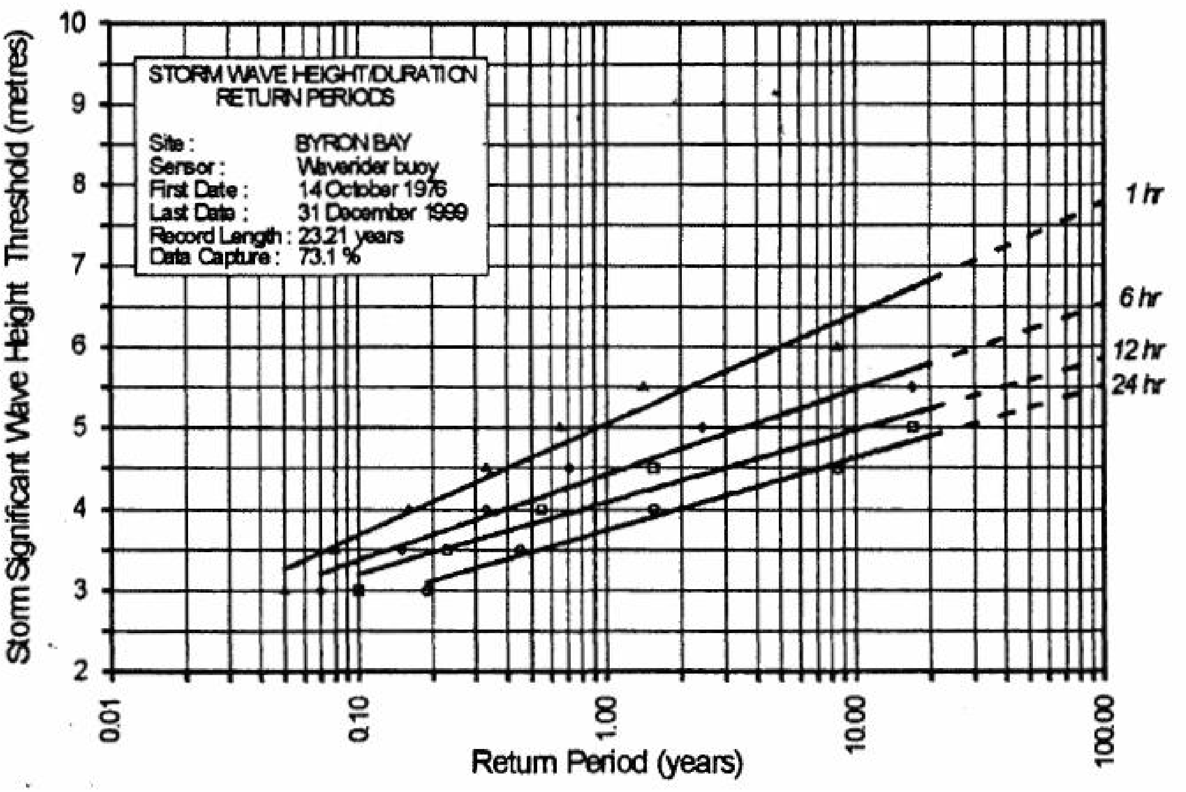

Figure 17: Relationship between significant wave height, duration and ARI for the Byron Bay Waverider buoy, 1976-1999 (from Lord and Kulmar, 2001)

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[56]. Although it is surprising that this value is 15% larger than the corresponding value for Byron Bay[57], 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[58]. Analysis of the Sydney directional data from 1992 to 1999 indicated that 34% of waves came from the SSE, with 17% of

[56] The corresponding 1 hour duration wave height was estimated as 8.4m. Nielsen et al (2001) estimated a similar value of 8.3m.
[57] The 1 hour duration value is only 6% larger at Coffs Harbour compared to Byron Bay.
[58] 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.

waves from the SE and 14% of waves from the S. Furthermore, the SSE direction was dominant for larger waves (Lord and Kulmar, 2001)[59].

5.2 ELEVATED WATER LEVELS

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

- astronomical tide[60];
- storm surge (barometric setup[61] and wind setup[62]); and,
- wave setup (caused by breaking waves[63]).

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 5.9.1.

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[64]. 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[65]. If a severe storm

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[59] Analysis of the same data for a longer period (to the end of 2003), by Treloar (2004), similarly indicated that 30% of waves were from the SSE, 17% from the SE and 16% from the S. For waves larger than 4m, 36%, 34% and 10% of waves were from S, SSE and SE respectively.

[60] 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.

[61] 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.

[62] 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.

[63] 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).

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

[65] 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

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.

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[66]. 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[67]. The highest recorded water level at Fort Denison was 1.48m AHD in May 1974[68]. 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 Sapphire Beach, 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, the 100 year ARI wave setup was determined as 1.1m. Therefore, a 100 year ARI total design still water level (astronomical tide plus storm surge and wave setup) of 2.6m AHD was adopted for the investigation reported herein[69].

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.

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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).

[66] 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.

[67] 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). Haradasa et al (1991) provided similar and slightly higher estimates to MHL (1992), namely 1.50, 1.47 and 1.43m AHD for the 100, 50 and 20 year ARI events.

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

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

Hanslow and Nielsen (1995) provide guidance on calculating wave runup. They found that the runup above the still water level (with the still water level excluding wave setup)[70] was given by:

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

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:

$$L_s = \frac{g T_s^{\,2}}{2\pi} \qquad (2)$$

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

At Sapphire 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[71], 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[72]. 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[73].

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

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[70] It must be emphasised that the water level, to which R is added to determine the runup elevation, *excludes* wave setup. Numerous authors have applied the methodology over-conservatively by including wave setup in the water level component.

[71] Sapphire Beach has generally been slightly flatter than this, with the beach slope in the vicinity of a few metres of mean sea level typically about 1 in 15. That is, the value of 1 in 10 chosen is conservative.

[72] 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 3.5).

[73] Refer to Section 5.9.1 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).

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[74], as shown in **Table 6**.

Table 6: 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[75], 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 Sapphire 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)[76].

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:

[74] 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 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).

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

[76] 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.

- 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 18**.

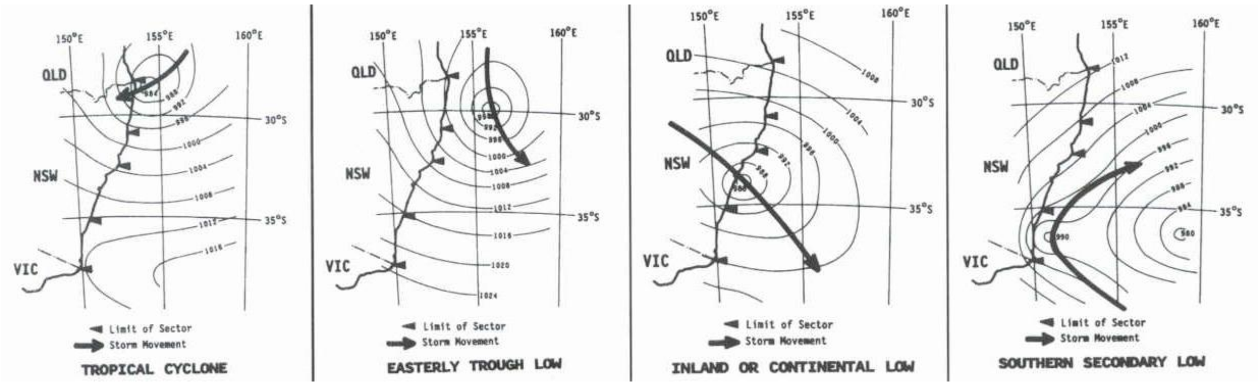

Figure 18: Typical synoptic patterns for tropical cyclones, easterly trough lows, inland trough / continental lows, and southern secondary lows (after NSW Government, 1990)

Based on PWD (1985, 1986b), the spatial variation in occurrence of these six storm types along the NSW coast is shown in **Figure 19**, with monthly variations in storm occurrence on the North Coast shown in **Figure 20**. 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[77], as well as southern secondary lows[78]; 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.

[77] These storm types are predominantly weather systems that come from the north.
[78] Note that the NSW Government (1990) presented the information in Figure 20 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.

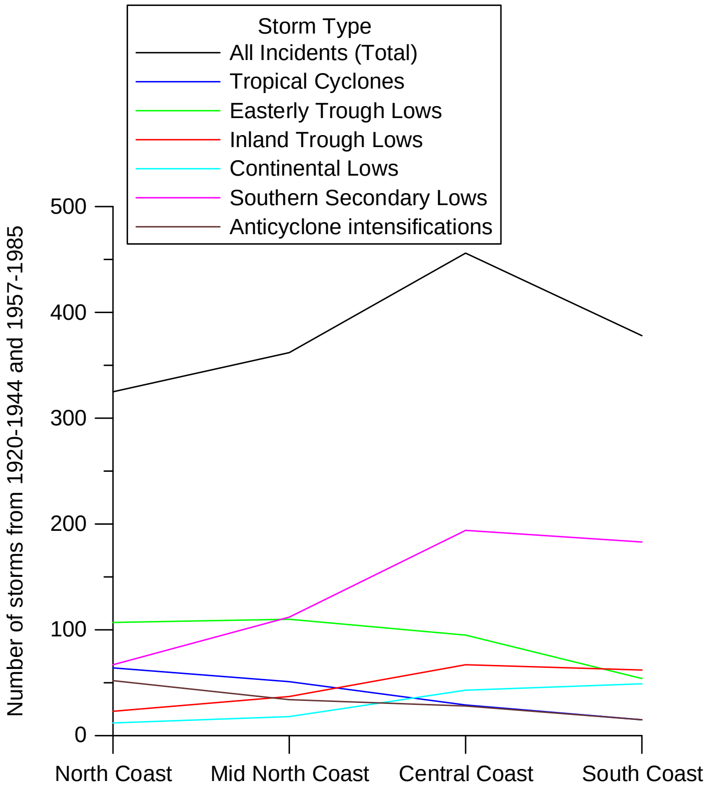

Figure 19: Variation in occurrence of different major storm types (significant wave height exceeding 2.5m) along the NSW coast (based on PWD 1985, 1986b)

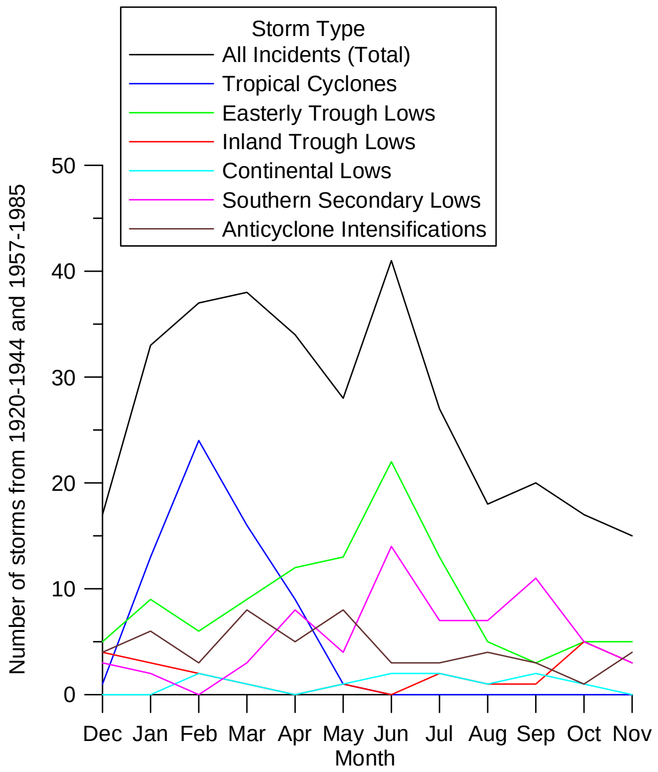

Figure 20: Monthly variation in storm occurrence (significant wave height exceeding 2.5m), North Coast of NSW (based on PWD 1985, 1986b)

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, 2004a, 2004b, 2005). 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, up until the end of 2004. Further information on this data is given in Section 5.1.

Based on the PWD (1985) and MHL (2004a) data, a total of 93 Category A events were hindcast from January 1880 to May 1976, with 41 Category A events recorded at either Coffs Harbour or Byron Bay from June 1976 to December 2004[79], a total of 134 events. This represents an average of 1.1 Category A events per year, in the 125 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 10 Category X events recorded at either Coffs Harbour or Byron Bay from June 1976 to December 2004[80]. This represents an average of 1 Category X event every 4.3 years, in the 124 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 7**, 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 2004 are listed in **Table 8**, with the recorded H_s and T_s values also shown[81].

[79] Of the 41 events, 16 were Category A at Coffs Harbour only, 16 were Category A at Byron Bay only, and 9 were Category A at both locations. There were 4 events exclusively noted by PWD (1985, 1986) that are not included in the 41 events from 1976 to 2004, given that they were not recorded to be Category A at either the Byron Bay or Coffs Harbour Waverider buoys.

[80] There were 8 Category X events recorded at Coffs Harbour only from 1976 to 2004, and 2 Category X events at Byron Bay which were lower Category events at Coffs Harbour.

[81] The Category X storms at Byron Bay that were milder events at Coffs Harbour occurred from 13-16 September 1988 (Category B at Coffs Harbour) and 8-12 May 1997 (Category A at Coffs Harbour).

Table 7: 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
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 8: Category X storms measured at Coffs Harbour from 1976 to 2003

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
24-28 February 2004	6.5	9.6

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[82]. 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[83]. 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[84]. 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 83;
- 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, 2004a).

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

[82] 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).
[83] 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).
[84] In the Coffs Harbour area, Chapman et al (1982) particularly noted that extensive erosion occurred at Woolgoolga (with the Surf Club damaged) and Park Beach (with a car park threatened) in 1974.

coincided with the highest recorded water level along the NSW coast[85]. 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[86]. 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 2004[87].

It is apparent that no photogrammetry (Section 4.2), was captured immediately after the significant storms in February 1954, June 1967, February 1972, February 1974 and May 1997. This further emphasises that storm demand cannot be readily estimated from the available data (also refer to Sections 3.3, 3.5, 3.9 and 5.7.2).

There was some aerial photography available relatively soon after some of these storms (Section 4.1). There was photography taken in October 1972, eight months after the February 1972 storm. However, clearing of vegetation for sand mining operations dominated the landscape at this time, making any erosion difficult to discern. Also, there was photography taken in April and June 1974, two and four months respectively after the February 1974 storm. There was no evidence of significant erosion having occurred.

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[88]. According to Airy theory, the total wave energy in one wavelength per unit crest width is given by (in deep water):

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

[85] 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).
[86] This was the largest anomaly over the predicted tide recorded at Coffs Harbour since records began in 1986.
[87] A number of other storms were examined by MHL (1998), including the Category X storms in August 1986 and June 1989 (Table 8), and a Category A storm in April 1989. In terms of wave energy, these storms were ranked 1st, 2nd, and 4th largest to be measured from 1976 to 2004. 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.
[88] 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).

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:

$$L_o = \frac{gT^2}{2\pi} \tag{4}$$

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 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 21**.

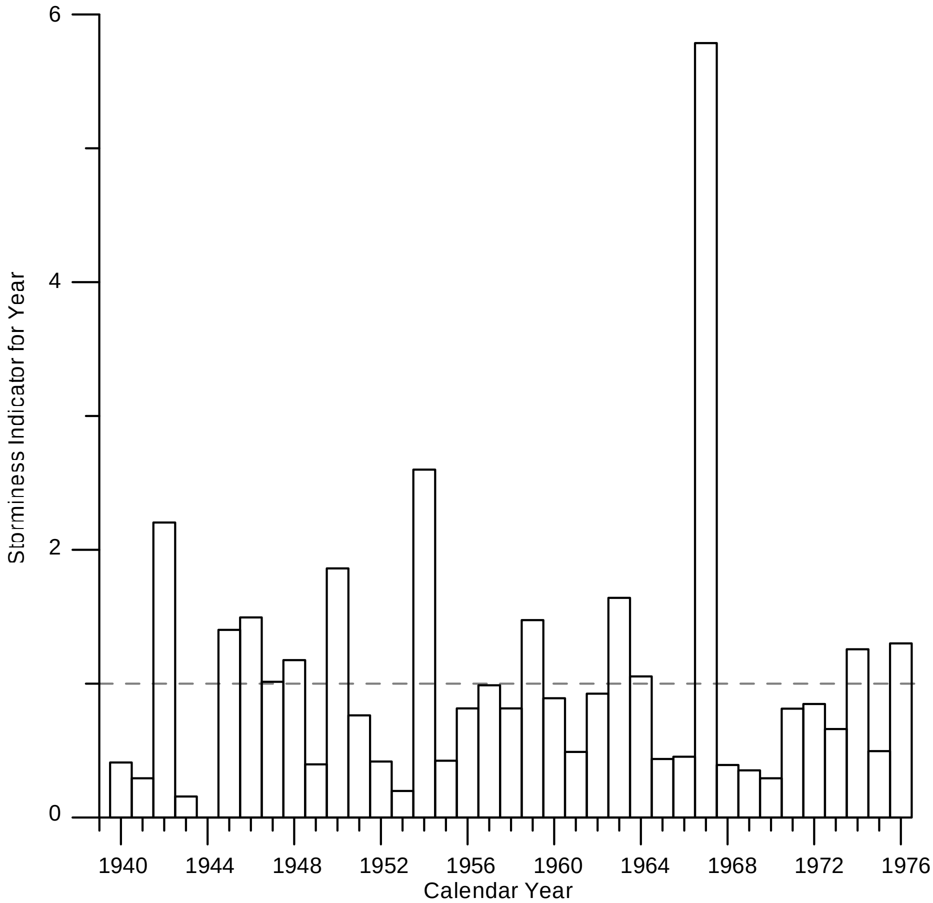

Figure 21: Yearly storminess indicators for 1940-1976

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 a selection of the dates of aerial photography listed in Section 4.1[89] is shown in **Figure 22**. 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.

[89] 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 3.3). The date of 12 December 1967 was included as it was also utilised in the Sawtell Beach photogrammetric analysis.

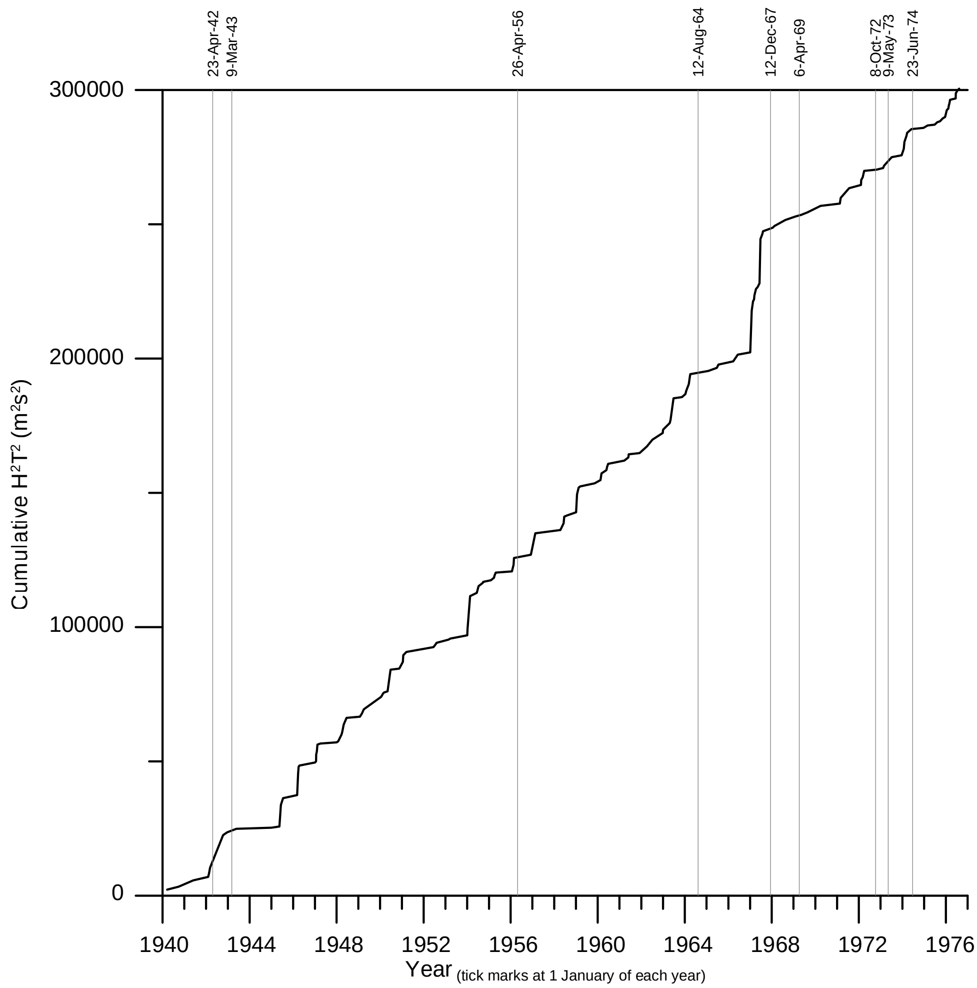

Figure 22: Cumulative sum of squares of H times T for 1940-1976

For the 1977 to 2004 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)[90].

[90] 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 2004 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 2004 inclusive are shown in **Figure 23**.

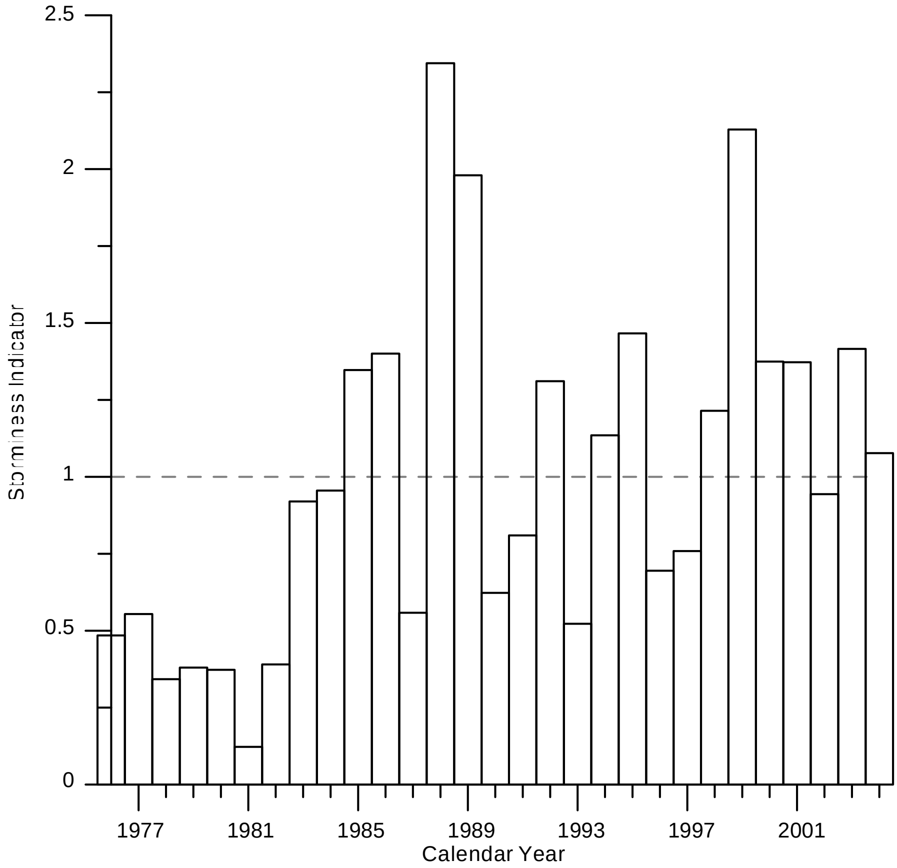

Figure 23: Yearly storminess indicators for 1977-2004

It is evident that 1988, 1999 and 1989 were the most stormy years (from highest to lowest), with the 1998 to 2004 period notably stormy. Conversely, the 1977 to 1984 period was particularly calm.

In February 2004, a Category X storm occurred with a peak H_s of 6.5m. This was the first Category X storm that had been recorded at the Coffs Harbour Waverider buoy since July 1999, and the tenth largest storm (in terms of wave energy) to be recorded over the period of record from 1976. It is likely that Sapphire Beach was still recovering from the beach erosion in this storm, and the relative storminess of the previous 6 years, when the August 2004 photography was taken.

The relationship between the cumulative storm energy per unit wave crest width (E_s) for 1977-2004 (from which the storminess indicator was derived) and a selection of dates of aerial photography listed in Section 4.1[91] is shown in **Figure 24**.

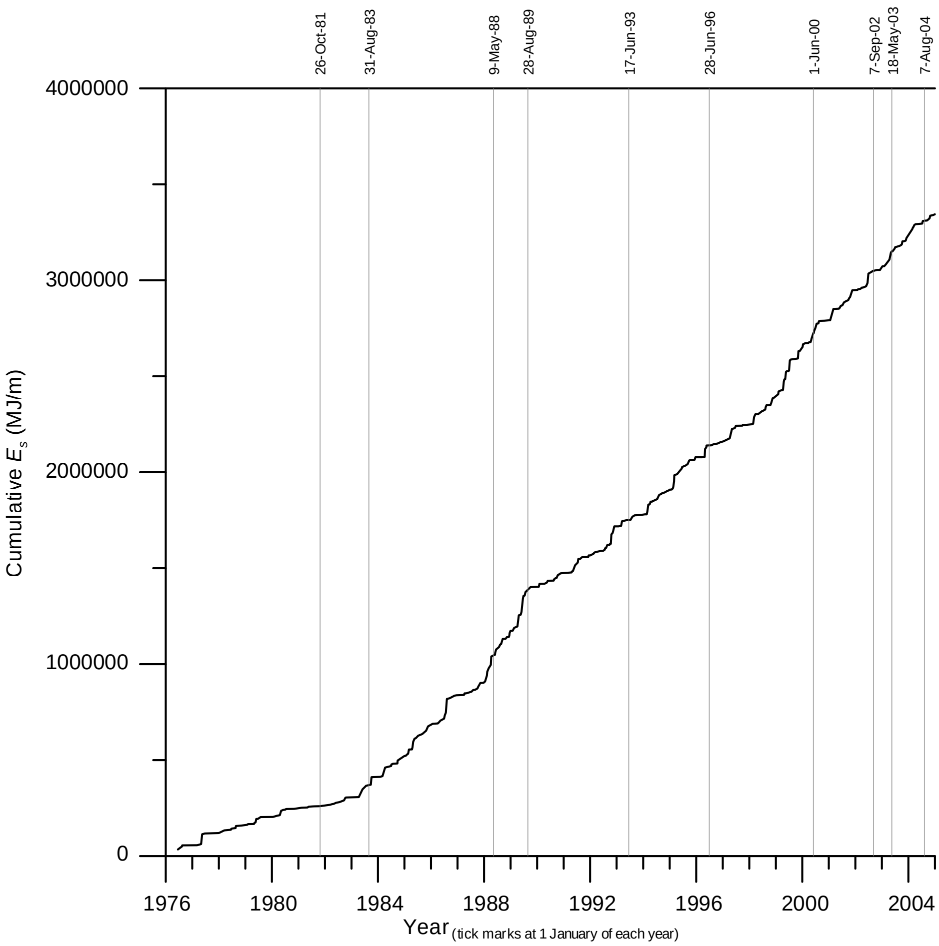

Figure 24: Cumulative storm energy per unit wave crest width for 1977-2004

Note that despite the different methodologies employed from 1940-1976 compared to 1977-2004, 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 1977-2004) to those determined using the H^2T^2 methodology (as applied for 1940-1976), using the 1977-2004 data set. The correlation is shown in **Figure 25**. Given the reasonable correlation, it can be accepted that storminess indicators before and after 1976 are comparable.

[91] The date of 28 August 1989 was included as it was also utilised in the Park and Hills Beach photogrammetric analyses (Section 3.3).

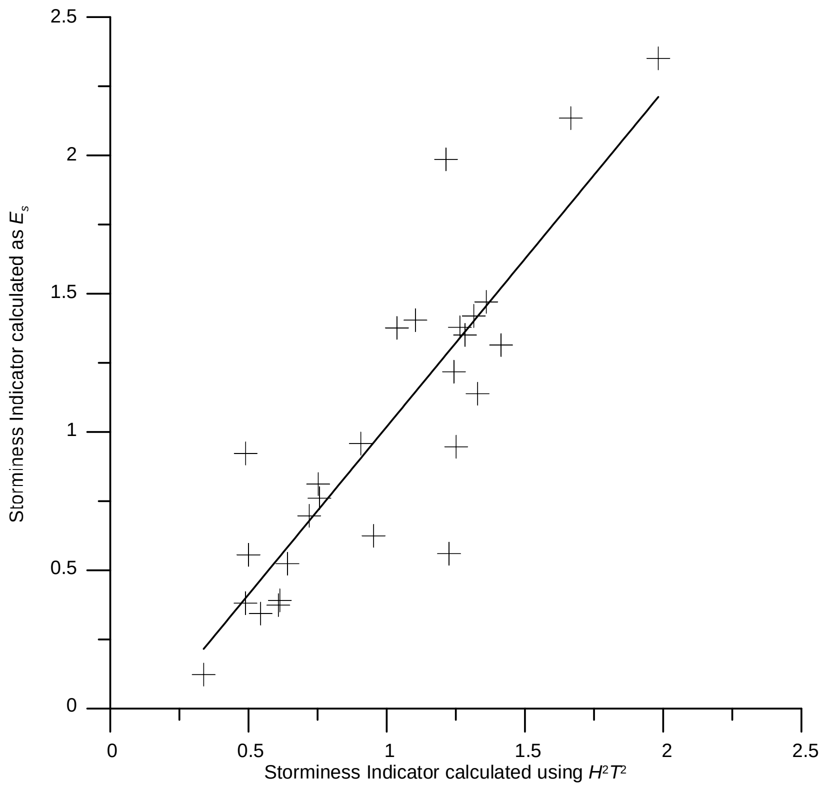

Figure 25: Correlation between storminess indicators calculated for 1977-2004 period, using simple and rigorous methodologies

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[92], 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[93]. 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 85km north of Sapphire Beach)[94]. 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[95].

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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[92] 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).

[93] 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.

[94] 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.

[95] 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[96] between controlling headlands was considered to be the result of this longshore transport process (see **Figure 26** and **Figure 27**).

The coastline in the vicinity of Sapphire Beach does not indicate strong embayment (Figure 1), which may perhaps be due to the likely relatively uninterrupted supply of sediment around White Bluff, as has been evident in aerial photography.

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 Sapphire Beach may be in this process, if at all[97].

It has been postulated that the construction of the eastern breakwater at Coffs Harbour, finalised in 1939 (MHL, 1998)[98], caused a complete 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 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.

[96] 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).

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

[98] 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.

It is uncertain if there has been a reduction in sediment supply to Sapphire Beach from the south, as a result of the construction of the breakwater at Coffs Harbour (which is about 10km south). However, it is possible that there are naturally lower rates of longshore transport bypassing Diggers Head (which is about 4km south of Sapphire Beach), meaning that the influence of the reduced supply of sand from Coffs Harbour has been reduced.

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

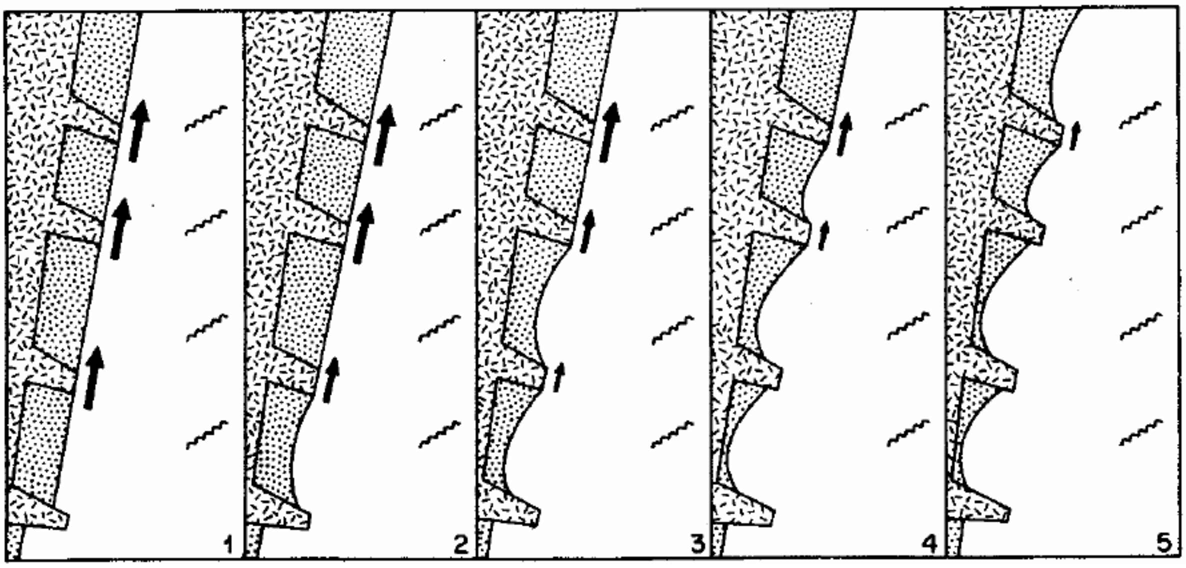
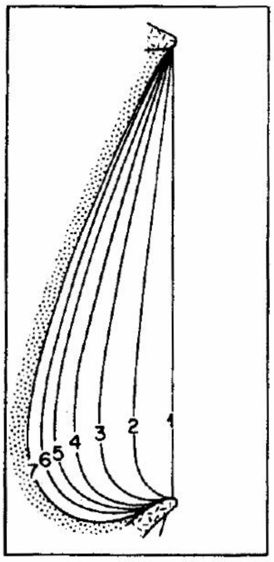


Figure 26: Successive stages in the evolution of coast with net northwards longshore sediment transport and progressive compartmentisation (after Stephens et al, 1981)



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

5.6.2 Interpretation of Local Studies

In Section 3, a number of coastal studies that had been undertaken in the Coffs Harbour area were described, as summarised in Section 3.9. It was concluded that there was strong evidence for relatively low recession rates in the region generally . The photogrammetric data for Sapphire Beach was also analysed in Section 4.2. In all, this confirmed that seven beaches near to Sapphire Beach appeared to be relatively stable, over a period of record of 30 to 50 years, with the Sapphire Beach data itself indicating strong evidence of accretion from 1964 to 2004.

Furthermore, land survey data collected in 2004 revealed that an incipient dune had developed at Sapphire Beach since 1988 (Patterson Britton, 2005). This is a further indication of the relative stability of Sapphire Beach.

5.6.3 Analysis of Vegetation Lines

As noted in Section 3.4, for the six dates photogrammetrically analysed by PWD (1992b) at Sapphire Beach (namely in 1943, 1964, 1969, 1973, 1983 and 1988), various planform features were plotted, including vegetation lines (that is, the interface between sand and dune vegetation)[99].

In Section 4.1, a listing of aerial photography of Sapphire Beach that was analysed was provided. In particular, it was noted that for a number of dates, photography was relatively accurately (generally to within a few metres) registered to real world coordinates. For this registered photography, the interface between sand and dune vegetation was digitised and/or observed, to determine if there were any trends in landward or seaward migration, in conjunction with analysis of the vegetation lines determined photogrammetrically[100].

The position of the sand/vegetation interface over the period 1969-2000 is shown in **Figure 28**, over the June 2000 aerial photograph. For clarity, only the 1969, 1973, 1983, 1988 and 2000 vegetation lines are shown, for which all but the latter were determined photogrammetrically[101]. The 1943 line was not shown due to concerns with accuracy. The 1956 and 1964 lines were similar to 1969. The 1974 and 1981 lines were similar to 1973 and 1983 respectively. The 1993-2004 lines were all generally similar, with slight seaward migration of the line evident by 2004. Therefore, the coverage of Figure 28 is essentially from 1956 to 2004.

It is evident that, seaward the subject property, the vegetation line migrated seaward between 1969 and 2000 (and therefore between 1956 and 2004), typically by about 60m to 90m seaward of the Beachside Tourist Precinct. This was generally a continuing trend over this 48 year period. Most of seaward migration of the vegetation line occurred between 1969 and 1973, and 1973 and 1980, as the dune vegetation became more established and extensive, and dune blowouts were stabilised.

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[99] Note that landform information was not provided for the additional dates analysed since the PWD (1992b) report was completed, namely for 1996 and 2004 (see Section 4.2.1).
[100] As noted in Section 3.7, movement of vegetation lines can potentially be correlated to long term recession.
[101] Note that the 1969 and 1973 lines were determined as the position of “light vegetation”, rather than the position of “incipient vegetation/grass”. In this manner, vegetation lines for all dates corresponded to the same sharp interface evident in photography.

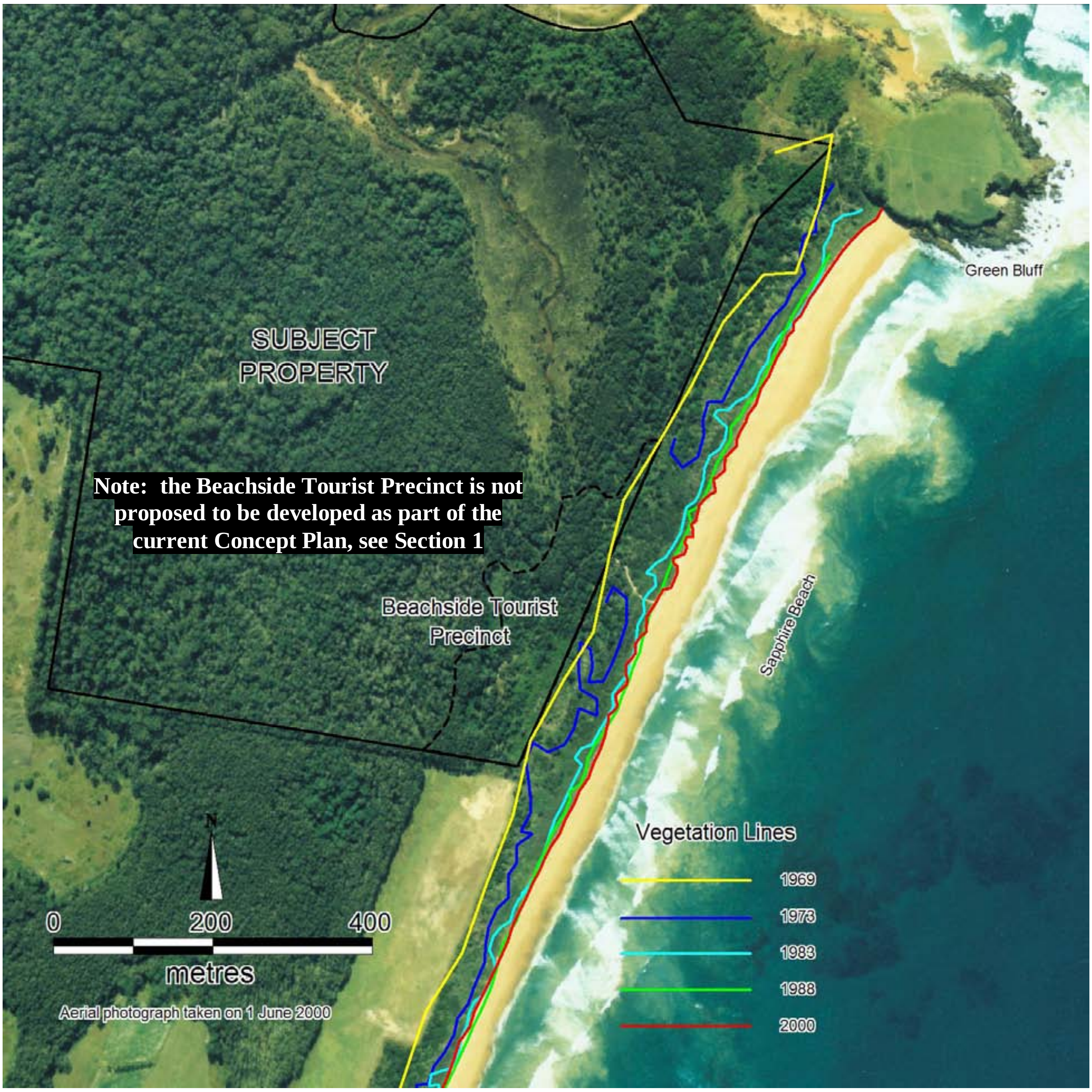

Figure 28: Position of sand/vegetation interface seaward of subject property, 1969-2000

5.6.4 Adopted Recession Rate

There is consistent evidence that Sapphire Beach, in the vicinity of the subject property, has been accreting over the last 48 years. This is considered to be most likely related to the stabilising cover of dunal vegetation becoming more established, after it was damaged by anthropogenic activities prior to 1956 (perhaps cattle grazing and traffic) and in the early 1970's (most likely due to sand mining).

As noted in Section 5.6.2, photogrammetric data has indicated that Sapphire Beach generally accreted between 1964 and 2004. Also, seven beaches near to Sapphire Beach also appear to be relatively stable, over a period of record of 30 to 50 years. Furthermore, as described in Section 5.6.3, the sand/vegetation interface at Sapphire Beach has migrated seaward since 1956.

The relative stability of Sapphire Beach would be expected to continue into the future, and it would not be unreasonable to assume that future recession due to net sediment loss would be negligible. However, a conservative allowance of 0.1m/year recession was adopted as the long term recession due to net sediment loss for the investigation reported herein, to account for uncertainties in future behaviour. This is equivalent to a long term recession due to net sediment loss of 5m at 2055, and 10m at 2105.

5.7 ONSHORE/OFFSHORE SEDIMENT TRANSPORT

5.7.1 General

Onshore/offshore (also known as cross-shore) sand movement is caused by natural variations in wave climate and water level. The offshore movement of sand is usually referred to as storm erosion. This onshore/offshore movement of sand results in short term fluctuations in the width of the beach profile.

During storms, the beach is cut by storm waves with beach sand moving offshore to form bars in the surf zone. This process typically occurs over a period of hours to days. When extended periods of calmer waves occur, the material held in these bars migrates onshore to re-build the beach berm[102]. Depending on the magnitude of the preceding storm, this beach building process can occur over a time scale of days to years.

Onshore /offshore sand movement can also be caused by wind, particularly manifested as landward sand drift of sandy beach areas that are above the swash zone into dune areas (see Section 6.5 for further discussion on aeolian sand movement).

5.7.2 Storm Demand

The amount of sand which can be removed from a beach during a storm event, and transported offshore, is referred to as the "storm demand". This quantity is generally measured above 0m AHD (approximately mean sea level), and is usually expressed as a volume per metre length of beach (m^3/m)[103]. Knowledge of the storm demand for a beach allows estimation of the amount of material required to be held in reserve for a storm in order to protect a given asset. It also allows estimation of the degree to which a beach would be eroded or cut back in a storm for a given pre-storm beach profile.

The reason that the storm demand is generally measured above 0 m AHD is a reflection on the manner in which the data to describe storm demand has been obtained. Storm demand estimates are typically derived from survey or photogrammetric techniques, where only that portion of the beach above mean sea level is either considered or is visible.

At any location, at any point in time, the storm demand is dependent on a number of variables including the:

[102] Long period ocean swell wave action generates a quasi-steady shoreward current at the seabed. Within the nearshore zone, this onshore current transports sediment shorewards in calmer conditions (NSW Government, 1990).
[103] Storm demand can also be measured in terms of the landward movement of a significant beach feature, such as the position of the back beach erosion escarpment, or a particular contour level usually between about 3m AHD and 6m AHD (Section 3.3).

- wave height and period as well as the duration of the storm;
- state of the beach before the storm;
- direction of the storm relative to the orientation of the beach[104];
- magnitude of the storm surge accompanying the event;
- amount of wave setup and runup on the beach during and immediately following the storm;
- tidal range at the time of the storm; and
- state of the tide at the peak of the storm.

Chapman et al (1982) considered that major erosion generally occurred during a phase of erosive conditions, with a final culminating storm.

Because the actual storm demand is a complex function of these variables, it is usual to express the storm demand in terms of an average recurrence interval (ARI), that is the storm demand for a 50 year ARI event, or 100 year ARI event, for example. In the study reported herein, the storm demand is estimated for a storm having an ARI of 100 years.

5.7.3 Estimate of Storm Demand for Sapphire Beach

The available photography at Sapphire Beach, and photogrammetry for nearby beaches, does not generally allow an estimate of storm demand to be made, given that no pre-storm to post-storm sequences were captured (Sections 3.3, 3.4, 3.5, 3.9, 4.1, 4.2, and 5.4.4)[105]. Therefore, storm demand must be estimated on the basis of published studies or numerical modelling.

Gordon (1987) estimated that the storm demand above 0m AHD was about 220m^3/m for the 100 year ARI event, for exposed NSW beaches at rip heads. In practice, in any one storm relatively large erosion would occur at discrete locations corresponding to the location of major rips. However, given that rips would be likely to form anywhere on Sapphire Beach, it would be reasonable to assume a uniform storm demand for the entire study area[106].

To further attempt to quantify the storm demand at Sapphire Beach, storm cut modelling was undertaken using the numerical model SBEACH.

SBEACH is an acronym for Storm–induced Beach Change, a numerical model written by the Coastal Engineering Research Center, U.S. Army Corps of Engineers, as documented in Cialone (1991) and supplements. Comprehensive documentation on the development, testing, and application of SBEACH is contained in Larson and Kraus (1989) and Larson et al. (1990), with "hands on" guidance for implementing SBEACH given in Rosati et al. (1993). A summary of this work is given in Larson et al. (1988).

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[104] Chapman et al (1982) noted that the occurrence of unusual conditions, out of phase with the normal, can cause damaging erosion along the coastline, as well as extreme erosive conditions.
[105] It can be noted that there has been no evidence of significant storm cut over the photographic record commencing in 1943, which is indicative of relatively low storm demand and/or rapid beach recovery following storms.
[106] Rip spacing is approximately four times the surf zone width (Short, 1993), with the surf zone width varying depending on the location of wave breaking, in turn particularly dependent on wave height, water level and beach slope. Therefore, rips can form in different locations for each particular storm (it was evident in the review of aerial photography that rips formed at variable locations for each date). Rip spacings are typically between 100m and 500m on NSW open coast beaches.

SBEACH simulates beach profile change, including the formation and movement of major morphologic features such as longshore bars, troughs, and berms, under varying storm waves and water levels. It is a geomorphic–based model founded on extensive analysis of beach profile changes produced in large wave tanks and in the field. SBEACH is two–dimensional in that longshore wave, current and sediment transport processes are omitted.

Breaking waves and changing water levels are the major driving agents in SBEACH that produce cross–shore (that is onshore/offshore) sediment transport and beach profile change. Water level changes are calculated from the storm surge, tide and wind. The experiments on which SBEACH was based were carried out for sandy beaches with uniform representative grain sizes in the range of 0.20mm to 0.42mm.

In the storm cut modelling undertaken for Sapphire Beach, the landward sections of the initial (pre–storm) beach profiles were derived from the 1988 photogrammetric data (as described in Sections 3.4 and 4.2). These profiles were extended seaward by using bathymetric information given by MHL (1986) for the northern end of Sapphire Beach, which is described in Section 6.4.2. Each of the nine profiles immediately south of the Beachside Tourist Precinct at the subject property (that is, Profiles 27-35) were considered[107].

Carley and Cox (2003) presented a methodology for deriving time-dependent design wave height, wave period and water level information (for a particular storm duration) for input into process-based numerical models such as SBEACH. Considering the NSW East Coast in particular, the time dependent 100 year ARI wave height was derived from an analysis of the exceedance durations of wave heights measured at the Sydney and Port Kembla Waverider buoys (see Section 5.1 for further information). The design wave height time series so derived was used in the investigation reported herein, which is conservative given that the North Coast wave climate is milder than the Central Coast wave climate.

For proper utilisation of a time series in beach erosion models, a representative water level time series was developed by Carley and Cox (2003). This was achieved by taking a typical predicted Spring tidal time series, and by then adding a time series of design tidal anomalies[108], such that the peak water level (1.5m AHD) coincided with the peak wave height[109].

The 100 year ARI design wave height, wave period and water level time series used as input to SBEACH for storm cut modelling of Sapphire Beach, is shown in **Figure 29**. Note that a grain size of 0.15mm was used in the modelling, which is very conservative[110].

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[107] This work was originally undertaken as part of the Patterson Britton (2005) investigation. It was not considered necessary to update to the 2004 profiles at the subject property, as conclusions would most likely be similar as herein using these profiles.

[108] A tidal anomaly is the difference between a measured water level and predicted astronomical tide. For example, for Coffs Harbour, the 100 year ARI tidal anomaly is 0.54m for 1 hour, 0.51m for 24 hours, 0.46m for 3 days, and 0.36m for 7 days (Carley et al, 1998). For deep stillwater stations with negligible wave setup and runup, the tidal anomaly is an effective representation of storm surge (MHL, 1992).

[109] Note that SBEACH computes wave setup, and therefore the design water level must exclude wave setup.

[110] Sampling by Short (1993) at Sapphire Beach indicated mean grain sizes in the swash zone of about 0.33mm. It was found that by using this grain size, very little erosion above 0m AHD could be achieved in the SBEACH simulations.

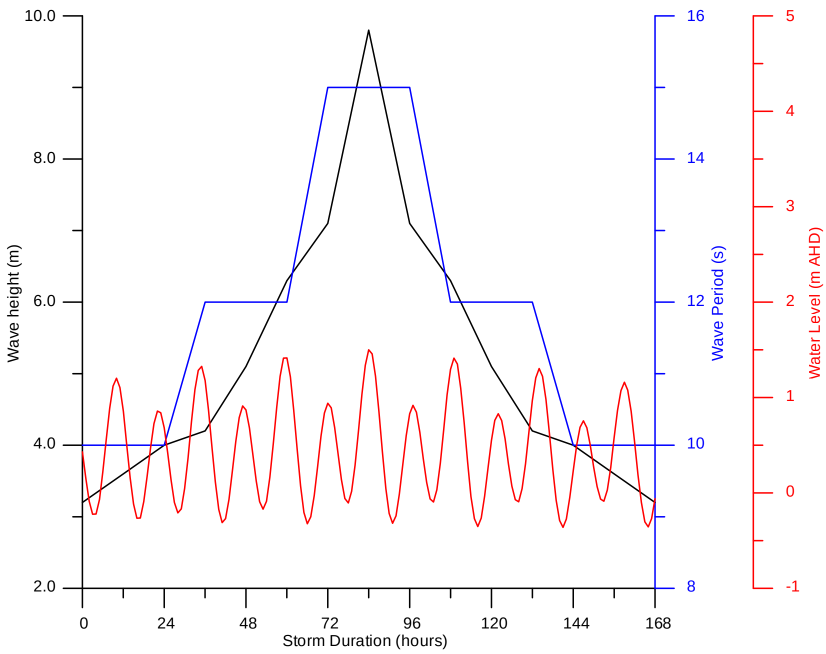

Figure 29: 100 year ARI design wave height, wave period and water level used for SBEACH modelling of Sapphire Beach

Using the design input time series as outlined in SBEACH, the resulting erosion volume above 0m AHD was about 90m^3/m[111]. This is much smaller than the value of 220m^3/m above 0m AHD adopted by Gordon (1987) for the 100 year ARI event.

The SBEACH modelling provided evidence that the storm demand at the subject property is particularly low. This may be because the beach profiles are relatively flat[112].

As noted in Section 5.4.5, wave energy can be expected to correlate with shoreline erosion (storm demand), which for a constant wave period, can be expected to be proportional to the wave height squared. Short (1993) estimated that Sapphire Beach was slightly sheltered by Split Solitary Island, with wave heights about 94% of those at fully exposed beaches in the area[113]. Therefore, the wave energy at Sapphire Beach can be expected to be about 88% of the wave energy at fully exposed beaches. That is, based on Gordon (1987) and assuming a reduction factor of 88%, a storm demand above 0m AHD of 190m^3/m can be estimated at Sapphire Beach for the 100 year ARI event.

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[111] The maximum erosion volumes for the entire profile, generally found to be above about –5m AHD, were up to about 160m^3/m. Given the depth at which this is measured, it has no equivalency to a storm demand measured above 0m AHD.

[112] Simulating exactly the same input conditions for a Narrabeen Beach profile in Sydney gave a storm demand of 160m^3/m above 0m AHD, and a maximum of 310m^3/m over the entire profile.

[113] Examination of bathymetric information (including unpublished detailed offshore surveys undertaken by the PWD in the early 1980's) indicated that there are also extensive shallower bedrock reef areas adjacent to Split Solitary Island, including areas to the west of the island and east of Riecks Point and White Bluff. WP Geomarine (1998) identified that these areas would significantly alter the wave climate approaching the shoreline. It would be expected that these reefs would dissipate some storm wave energy approaching Sapphire Beach from the S to SE directions.

Note that the same wave energy correlation to open coast storm demand (based on the square of the wave height) was used in a Geomarine (1991) study of the sheltered Fishermans Beach at Collaroy. In this Geomarine (1991) report, numerous investigations were cited that had used such a technique, including studies of Pearl Beach, Ocean Beach and Umina Beach in Gosford LGA (during which field measurements had confirmed the relationship); and a study of Boomerang Beach and Blueys Beach in Great Lakes LGA (where the relationship had been derived analytically). This gives confidence in the validity of the correlation of storm demand to wave energy (as wave height squared).

A storm demand value of $200m^3/m$ was adopted for the investigation reported herein. This is only 10% less than the value reported by Gordon (1987), and is considered to be conservative given that SBEACH modelling (with conservative grain sizes) indicated storm demands of about 45% of this value, and because Sapphire Beach would not be expected to be fully exposed to wave energy from the S to SE directions[114].

5.8 GEOTECHNICAL CONDITIONS

A geotechnical investigation of the subject property has been undertaken by Coffey Geosciences Pty Ltd (2004b). This included the excavation of 9 Test Pits (TP1 to TP9), to depths between 1.5m and 3m over the site. TP8 and TP9 were located at the seaward edge of the Beachside Tourist Precinct, and indicated that this area was essentially sandy, with some surface fill.

Coffey Geosciences Pty Ltd (2004a) similarly noted that the eastern portion of property to the south of the subject property was generally underlain by aeolian sandy soils to a depth of at least 1.5m.

The NSW Minerals Department (1975) outlined the results of around 150 boreholes that were drilled along the seaward edge of the subject property, presumably to estimate the heavy minerals content of the subsurface. This included information of the depths to indurated sand, clay and bedrock. It was beyond the scope of the investigation reported herein to analyse this information further.

All calculations of coastline hazards in the investigation reported herein conservatively assume a profile composed entirely of sand, as discussed further in Sections 6.8 and 7.

5.9 CLIMATE CHANGE

5.9.1 Sea Level Rise

The possibility of global climate change accelerated by increasing concentrations of greenhouse gases, the so-called Greenhouse Effect, is now widely accepted by the scientific and engineering communities. This is predicted to cause globally averaged surface air temperatures and sea levels to rise. Water level gauge data indicates that the global average sea level rose between 0.1 and 0.2m during the 20th century. The latest Intergovernmental Panel on Climate Change (IPCC)

[114] Note that WBM (2003) arbitrarily adopted the same value of $200m^3/m$ above 0m AHD for the Ballina Shire Coastline Hazard Definition Study, using a fully accreted pre-storm profile as the base profile. Increasing the value to $220m^3/m$ only represents a small landward translation in the hazard (in the order of a few metres), given the relatively high dune.

estimates of the future globally averaged sea level rise are 0.09 to 0.88m between 1990 and 2100, with a central value of 0.48m. This eustatic sea level rise is primarily due to thermal expansion of the ocean and loss of mass from glaciers and ice caps caused by global warming (IPCC, 2001a)[115].

The global average sea level rises predicted by the IPCC between 1990 and 2100 are shown in **Figure 30**. The different curves displayed represent six illustrative emission scenarios (covering a wide range of the main demographic, economic and technological driving forces of future greenhouse gas and sulphur emissions), assumed in the Atmosphere-Ocean General Circulation Models (AOGCMs) used to develop the sea level estimates. Note that global average temperature and sea level are projected to rise under all emission scenarios.

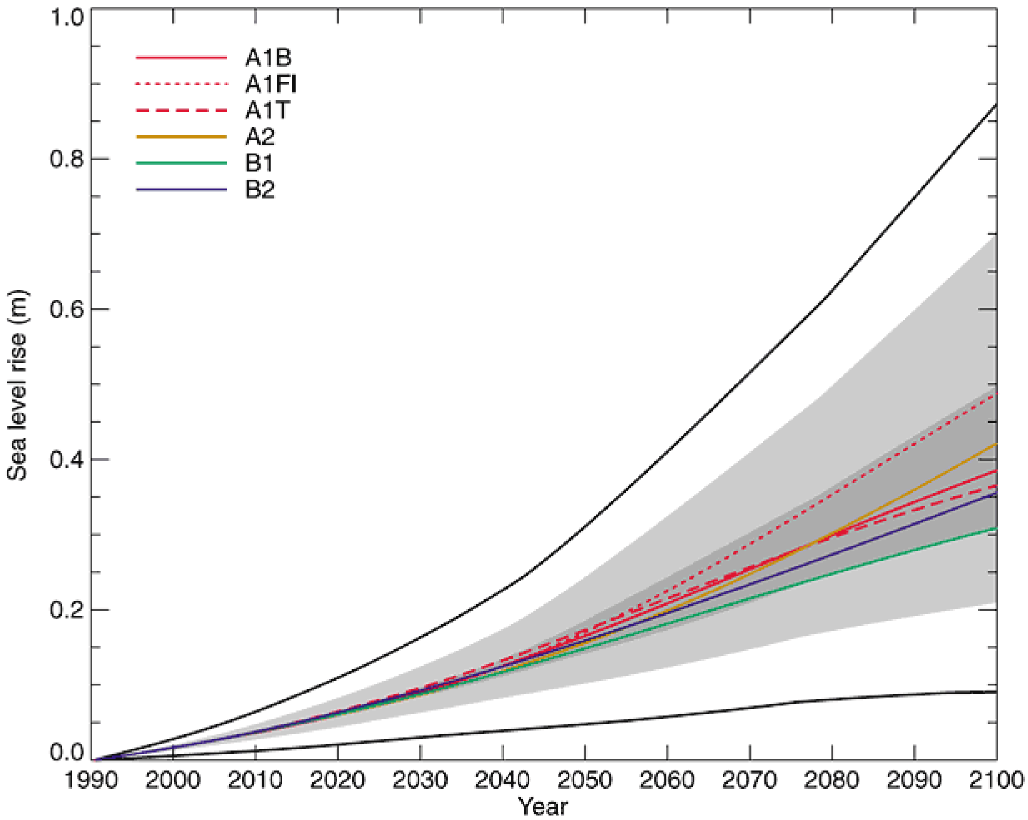

Figure 30: Global average sea level rise predicted due to climate change from 1990 to 2100, based on various emission scenarios (IPCC, 2001b)

Based on IPCC (2001b), a brief summary of the inherent assumptions governing the six emission scenarios shown in Figure 30 is given below:

- A1B – very rapid economic growth, global population that peaks in mid-century and declines thereafter, the rapid introduction of new and more efficient technologies, with substantial

[115] The term "eustatic" implies a change in sea level due to alteration to the volume of the world ocean. Relative sea level change can also be caused by vertical land movements. Relative sea level rise occurs where there is a net increase in the level of the ocean relative to local land movements. Climate modellers largely concentrate on estimating eustatic sea-level change. Impact researchers focus on relative sea-level change (IPCC, 2001c).

reduction in regional differences in per capita income, with a *balance* of fossil intensive and non-fossil energy sources; it produced the 3rd highest sea level rises at 2100.

- A1F1 – as above, but with an emphasis on *fossil intensive* energy sources; it produced the highest sea level rises at 2100.
- A1T – as above, but with an emphasis on *non-fossil* energy sources; it produced the 4th highest sea level rises at 2100.
- A2 – very heterogeneous world, continuously increasing population, regionally oriented economic development, and per capita economic growth and technological change more fragmented and slower than other scenarios; it produced the 2nd highest sea level rises at 2100.
- B1 – same population patterns as the A1 scenarios, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies; it produced the lowest sea level rises at 2100.
- B2 – a world with continuously increasing global population (at a rate lower than A2), intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 storylines. The scenario is also oriented towards environmental protection and social equity, especially focussing on local and regional levels; it produced the 2nd lowest sea level rises at 2100.

In Figure 30, the region in dark and light shading shows the range of the average and range respectively of AOGCMs for all 35 emission scenarios tested. The region delimited by the outermost lines shows the range of all AOGCMs and scenarios including uncertainty in land-ice changes, permafrost changes and sediment deposition. Note that this range does not allow for uncertainty relating to ice-dynamical changes in the West Antarctic ice sheet (IPCC, 2001b).

For the mid-range A1B scenario, the predicted sea level rise after 50 years, at the year 2055, is about 0.18m. For this scenario, the predicted sea level rise after nearly100 years, at the year 2100, is about 0.38m. However, there is significant variability in these estimates, particularly at 2100, depending on the emission scenario selected. For example, the predicted sea level rise at 2100 for the A1F1 and A2 scenarios are about 0.49m and 0.42m respectively (these are the highest predictions of the six illustrative emission scenarios).

For this study, the adopted sea level rise at 2055 was 0.2m, and the adopted sea level rise at 2105 was 0.5m[116]. These values are consistent with the IPCC (2001b) predictions for the upper limit of the average of all 35 emission scenarios tested. However, it should be noted that there is considerable uncertainty regarding these predictions, and future sea level rise could be much smaller or larger than predicted, as indicated by the light shaded region in Figure 30.

As discussed in Section 6.4.2, it is generally expected that recession of the open coast will occur under conditions of accelerated sea level rise.

5.9.2 Other Climatic Change Considerations

Another potential outcome of the Greenhouse Effect is an increase in the frequency and intensity of storm events.

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[116] The IPCC (2001b) estimates extend to 2100. The estimate at 2105 provided was an extrapolation.

Modest to moderate increases in average and maximum cyclone intensities are expected in the Australian region in a warmer world. However, cyclone frequency and intensity are strongly associated with the El Niño/Southern Oscillation (ENSO) phenomenon. How this phenomenon will vary in a warmer world is currently unknown (CSIRO, 2001; CSIRO Marine Research, 2001).

Mid latitude storms have been predicted to increase in intensity but decrease in frequency with global warming (CSIRO, 2002), due to a reduction in equator to pole temperature gradients. However as with tropical cyclones, climate modelling at present lacks the resolution to accurately predict changes associated with global warming.

If overall weather patterns change as a result of global warming, there is potential for changes in the angle of approach of the predominant wave climate (Moratti and Lord, 2000). For some beaches this may cause realignment of the shoreline, with resulting recession and accretion.

As discussed in Section 4.2.3, there have been attempts to explain beach rotation in terms of shifts in the Southern Oscillation Index (SOI). Ranasinghe et al (2004) proposed that beaches rotate clockwise (with the northern end accreting and southern end receding) in El Niño phases (negative SOI). Conversely, it was proposed that beaches rotate anti-clockwise (with the northern end receding and southern end accreting) in La Niña phases (positive SOI)[117].

It has been postulated that, as a result of the greenhouse effect, El Niño conditions will be favoured in the future (Cai and Whetton, 2000; Boer et al, 2004), thus favouring clockwise beach rotation. At the subject property, which is located at the northern end of Sapphire Beach, this would most likely reduce the risk of coastline hazards being realised in the future.

Given the above uncertainty and difficulty in quantitative prediction, no specific account was taken of any potential changes to storm frequency and intensity, or changes in wave directions[118]. However, this uncertainty should be taken into consideration when assessing the risk and consequences of recession occurring in the future. The potential for climate change related recession needs to be continually reviewed as more information develops in the scientific community.

[117] It was also found that La Niña phases were associated with more energetic (erosive) conditions.
[118] A generally conservative approach was used in the estimation of other coastline hazards.

6 COASTLINE HAZARDS

6.1 INTRODUCTION

The coastline hazards examined in this study are those set out in the *Coastline Management Manual* (NSW Government, 1990), namely:

- climate change
- beach erosion;
- shoreline recession;
- sand drift;
- coastal inundation;
- stormwater erosion; and,
- slope instability.

Each of the above hazards are discussed in turn in Section 6.2 to Section 6.8.

6.2 THE HAZARDS OF CLIMATE CHANGE

A discussion on sea level rise associated with climate change was provided in Section 5.9.1. Also, the possibility of other effects caused by climate change, such as increases in storm intensities, was discussed in Section 5.9.2.

Under the future predicted conditions of accelerated sea level rise, it is expected that shoreline recession will occur. This issue is discussed in Section 6.4.2, as part of the discussion on shoreline recession hazards.

6.3 BEACH EROSION HAZARD

During storms, large waves, elevated water levels and strong winds can cause severe erosion to sandy beaches. The hazard of beach erosion relates to the limit of erosion that could be expected due to a severe storm or from a series of closely spaced storms (NSW Government, 1990).

The beach erosion hazard is analogous to the "storm demand" discussed in Section 5.7.2, where it was concluded that a storm demand or beach erosion hazard value of $200m^3/m$ above 0m AHD was conservative for the study area, for a 100 year ARI storm.

6.4 SHORELINE RECESSION HAZARD

The hazard of shoreline recession is the progressive landward shift in the average long term position of the coastline (NSW Government, 1990). Two potential causes of shoreline recession are net sediment loss, and an increase in sea level, as outlined in Sections 6.4.1 and 6.4.2 respectively. It is also appropriate to discount the historical recession due to net sediment loss, due to actual sea level rise that occurred during the measurement period from 1964 to 2004, as discussed in Section 6.4.3.

6.4.1 Long Term Recession Due to Net Sediment Loss

Long term recession due to net sediment loss is a long duration (period of decades), and continuing net loss of sand from the beach system. According to the sediment budget concept, this occurs when more sand is leaving than entering the beach compartment. This recession tends to occur when:

- the outgoing longshore transport from a beach compartment is greater than the incoming longshore transport;
- offshore transport processes move sand to offshore "sinks", from which it does not return to the beach; and/or,
- there is a landward loss of sediment by windborne transport (NSW Government, 1990).

Shoreline recession due to net sediment loss should not be confused with beach erosion, which results in a short term exchange of sand between the subaerial and subaqueous portions of the beach, not a net loss from the active beach system. Shoreline recession is therefore a long term process which is overlaid by short term fluctuations due to storm activity.

The long term recession rate for the study area adopted in Section 5.6.4 as 0.1m/year. This rate would largely be considered to be due to net sediment loss, and also historical sea level rise as discussed in Section 6.4.3.

6.4.2 Long Term Recession Due to Sea Level Rise

A progressive rise in sea level may result in shoreline recession through two mechanisms: first, by drowning low lying coastal land, and second, by shoreline readjustment to the new coastal water levels. The second mechanism is probably the more important since deeper offshore waters expose the coast to attack by larger waves, the nearshore refraction and diffraction behaviour of waves may change, and a significant volume of sediment may move offshore as the beach seeks a new equilibrium profile (NSW Government, 1990).

Bruun (1962) proposed a methodology to estimate shoreline recession due to sea level rise, the so-called Bruun Rule. The Bruun Rule is based on the concept that sea level rise will lead to erosion of the upper shoreface, followed by re-establishment of the original equilibrium profile. This profile is re-established by shifting it landward. The concept is shown graphically in Bruun (1983), and can be described by the equation (Morang and Parson, 2002):

$$R = \frac{S \times B}{h + d_c} \tag{6}$$

where R is the recession (m), S is the long term sea level rise (m), h is the dune height above the initial mean sea level (m), d_c is the depth of closure[119] of the profile relative to the initial mean sea level (m), and B is the cross-shore width of the active beach profile, that is the cross-shore

[119] The depth of closure is the water depth beyond which repetitive profile surveys (collected over several years) do not detect vertical sea bed changes, generally considered to be the seaward limit of littoral transport. The depth can be determined from repeated cross-shore profile surveys or estimated using formulas based on wave statistics. Note that this does not imply the lack of sediment motion beyond this depth (Szuwalski and Morang, 2001).

distance from the initial dune height to the depth of closure (m). This equation is a mathematical expression that the recession due to sea level rise is equal to the sea level rise multiplied by the average inverse slope of the active beach profile.

PWD (1995a) assumed that the inverse slope of the active beach profile was 50, in their investigation of beaches in the Coffs Harbour LGA. To check the validity of this estimate, it was first necessary to estimate the depth of closure.

Nielsen (1994) found that, based on a synthesis of field and laboratory data and analytical studies (particularly offshore of SE Australia), there were consistent limits of subaqueous beach fluctuations, namely water depths (relative to AHD) of:

- 12m ± 4m being the limit of significant wave breaking and beach fluctuations;
- 22m ± 4m being the absolute limit of sand transport under cyclonic or extreme storm events; and,
- 30m ± 5m being the limit of reworking and onshore transport of beach sized sand under wave action.

The 12m ± 4m depth can be considered to be analogous to the depth of closure for use in the Bruun Rule, given that it is the limit of significant beach fluctuations, and consistent with formulae for its prediction[120].

Rijkswaterstaat (1987), approximating the work of Hallermeier (1978, 1981, 1983), found the following simplified estimate for the effective depth of closure, d_c, namely:

$$d_c = 1.75H_e \tag{7}$$

where H_e is the effective significant wave height exceeded for 12 hours per year (that is, the significant wave height with a probability of exceedance of 0.137%). For the Coffs Harbour and Byron Bay Waverider buoys (representative of offshore wave conditions at Sapphire Beach), from Figure 16, H_e is about 4.8m. Therefore, the predicted depth of closure at Sapphire Beach from Equation 7, using this value, is 8.4m.

Bruun (1988) suggested a depth of closure of $2H_b$, where H_b is actual breaker height of the highest waves within a certain time period, namely 50 to 100 years according to Dubois (1992). Arbitrarily using H_e (as defined above) for H_b, the predicted depth of closure is 9.6m using this methodology.

Sedimentological data consistently shows distinct changes in the characteristics of sediments with water depth. These changes include variations in grain size, sorting, carbonate content and colour. The boundary between Inner and Outer Nearshore Sand is typically found at about 11-15m depth (relative to AHD), while the boundary to Inner Shelf Sand (also known as Shelf Plain Relict or

[120] The 12m ± 4m depth has been used in almost all known investigations that have utilised the Bruun Rule to determine recession due to sea level rise in eastern Australia, where the depth of closure has been related to the limit of significant long term profile changes, and where rock reef has not been present. A rare exception would be Gordon (1991), who estimated a depth of closure of 37m relative to AHD for the coastline in the vicinity of Belmont Ocean Outfall near Newcastle.

Palimpsest Sand) is usually at 18-26m depth. The boundary between Nearshore (Inner and Outer) Sands and Inner Shelf Sands correspond to those parts of the seabed considered to be active and relict (Nielsen, 1994).

The boundary between Inner and Outer Nearshore Sand in the vicinity of Coffs Harbour, analogous to the depth of closure, is typically at a depth of approximately 11m relative to AHD (Stephens, 2004). Nielsen (1994) reported that three studies had identified the boundary between Inner and Outer Nearshore Sand at approximately 10m depth (relative to AHD) in the Byron Bay area. Patterson Britton & Partners (2004a) found that the boundary between Inner and Outer Nearshore Sand was approximately at 11m depth (relative to AHD) in the Lennox Head area, based on detailed mapping undertaken in 1982 and 1983. Using detailed bathymetric data, Patterson Britton & Partners (2004a) found that a depth of closure of 11m (relative to AHD) was appropriate for the Evans Head area, since there was a change in slope at this depth, and profile variation at shallower depths. Given the available evidence from nearby sites, a depth of closure of 11m (relative to AHD) was selected for use in the investigation reported herein.

Available bathymetric information offshore of Sapphire Beach is limited. The hydrographic chart AUS 812[121] covers the region, but is of coarse accuracy, being 1:150,000 scale, and with depth contours in the vicinity of the depth of closure only at 5 and 10 fathoms relative to ISLW (10m and 20m respectively relative to AHD)[122].

As part of work associated with determining ocean outfall options for the Coffs Harbour area in the late 1980's, MHL (1986) captured bathymetric information in the vicinity of a number headlands in the region. This included Woolgoolga Headland, Bare Bluff, Look at Me Now Headland, and Green Bluff[123]. Bathymetric data collected for Green Bluff (north of the subject property) extended south, offshore of Sapphire Beach, for a distance of about 200m. From this, it was evident that the –11m AHD depth of closure was at a distance of about 550m offshore. Assuming that similar bathymetry existed offshore of the Beachside Tourist Precinct, it was determined that the inverse slope of the active beach profile was about 40.

In Section 5.9.1, it was noted that the adopted sea level rise at 2055 and 2105 was 0.2m and 0.5m respectively. Using Equation 6, the long term recession due to sea level rise at 2055 and 2105 is 8m and 20m respectively. These values were adopted for the investigation reported herein.

It should be noted that the Bruun Rule only applies to equilibrium profiles. An equilibrium profile is the long term average cross-shore beach profile, assuming that the profile is composed of sand and therefore not constrained by rock or other controls[124]. In this, the idealised profile and sediment grain size distribution are in equilibrium with the long term incident wave climate and existing average water level. It is also assumed that the profile is two dimensional.

[121] AUS 813, "Australia – East Coast, New South Wales, Smoky Cape to Clarence River", published by the Hydrographic Service, Royal Australia Navy, 30 March 1961, New Edition 27 January 1994.
[122] 1 fathom is equal to 6 feet.
[123] Flat Top Point (north of Hearns Lake) was also investigated as an outfall site, but no bathymetric data was collected there.
[124] Bruun (1988) defined an equilibrium beach as "a statistical average profile which maintains its form apart from small fluctuations including seasonal fluctuations".

6.4.3 Discounting of Historical Recession Rates

Shoreline recession rates determined from historical data may be influenced by any sea level rise which occurred in the period of the historical record, in this case from 1964 to 2004 (the period over which the long term recession rate was determined). If this contribution is significant, the historical recession rates should be adjusted (discounted) to represent recession due to sediment loss only. This is because, in the prediction of the future position of the coastline, shoreline recession due to net sediment loss and shoreline recession due to sea level rise are calculated separately.

Based on analysis of average annual water levels at Fort Denison in Sydney Harbour from 1887 to 1987, the NSW Government (1990) estimated that the mean sea level rise over these 101 years of record was 0.5mm/year. More recent estimates of Church et al (2001) indicated that for the two water level recording stations with the longest records in Australia (both in excess of 80 years), at Sydney and Fremantle, the observed rates of relative sea level rise were 0.86 ± 0.12 mm/year (from 1915 to 1998) and 1.38 ± 0.18 mm/year (from 1897 to 1998) respectively[125]. The Department of Defence (1999), cited in Nielsen et al (2001), estimated that the rate of relative sea level rise at Newcastle (on the NSW Central Coast), from 1967 to 1999, was 1.18mm/year. Averaged around Australia, the relative sea level rise from 1920 to 2000 was about 1.2mm/year (CSIRO Marine Research, 2004).

Adopting a rate of relative sea level rise of 0.86mm/year from 1964 to 2004, this represented a sea level rise of 40mm over this period. Using the adopted inverse slope of the active beach profile of 40 (Section 6.4.2), this was equivalent to a reduction in shoreline recession of about 1.6m, that can be accounted for (that is, subtracted from the calculated total recession, or added to the calculated total accretion). The postulated recession due to historical sea level since 1964, which has occurred while the beach at the subject property has appeared to accrete, is an indication that the adopted recession rate of 0.1m/year is conservative.

6.5 SAND DRIFT HAZARD

Aeolian sand transport can occur at beaches when dry sand is entrained by aeolian (wind) processes, particularly if the dunes are not densely covered by vegetation.

Sand drift is a result of this aeolian movement of beach sediment, and as such can be controlled to a large extent by the presence of a well vegetated foredune. Sand drift leads to a number of hazards depending on the volume of sand involved. For low sand volumes, sand drift is only of nuisance value. However, for high sand volumes it can represent a permanent loss of sand from the active beach system, thereby causing shoreline recession (if the sand moves landward beyond the foredune[126] into the hinddune), and can result in abrasion, burial, blockage and damage to coastal developments (NSW Government, 1990).

[125] Corrected for land movement, the absolute rates of sea level rise at Sydney and Fremantle were about 1.2 and 1.6 mm/year respectively.

[126] The foredune is the larger and more mature dune lying between the incipient dune (generally characterised by grass vegetation coverage) and hinddune area (generally). Foredune vegetation is characterised by grasses and shrubs. Foredunes provide an essential reserve of sand to meet erosion demand during storm conditions. During storm events, the foredune can be eroded back to produce a pronounced dune scarp (NSW Government, 1990).

The importance of the stabilisation provided by dune vegetation cannot be understated. The stability of Sapphire Beach is considered to be predominantly due to the improving coverage of vegetation since the 1970's (Section 5.6.4). At present, the hazard posed by drifting sand is generally not significant at the subject property, due to the presence of a well vegetated foredune.

It is also important to recognise that dune vegetation is necessary to stabilise dune systems and protect them from wind erosion into the future. Should human and vehicular traffic, or fire (for example) impact on the dunes at Sapphire Beach in the future, there is the potential for landward sand drift to occur, with resulting shoreline recession. As noted by the NSW Government (1990), the likely direction of sand drift (where it occurs) on the NSW North Coast is to the NW.

The layout of proposed access points to the beach seaward of the subject property are not yet known. However, it will be necessary to ensure that these access points are fenced and maintained to ensure that degradation of adjacent dune vegetation does not occur.

It is also important that removal of dune vegetation is discouraged in an attempt to create views from the subject property. It is essential that the dune vegetation seaward of the subject property is protected and maintained, including the prevention of informal access points.

Further discussion on dune management is provided in Section 7.

6.6 COASTAL INUNDATION HAZARD

Coastal inundation is the flooding of coastal lands by ocean waters, which is generally caused by large waves and elevated water levels associated with severe storms. Severe inundation is an infrequent event and is normally of short duration, but it can result in significant damage to both public and private property (NSW Government, 1990).

The components which give rise to elevated still water levels at times of storms have been referred to in Section 5.2, namely wind setup, barometric setup, and wave setup. Individual waves cause further temporary water level increases above the still water level due to the process of wave runup or uprush (Section 5.3).

The wave runup value adopted for the investigation reported herein was given in Section 5.3, namely 5.8m AHD.

At the subject property, existing dune levels seaward of the Beachside Tourist Precinct are above 7.7m AHD, and generally a few metres higher[127], and would be expected to be so in the future. Therefore, the coastal inundation hazard at the subject property is considered to be negligible for a 100 year ARI storm event occurring over a conservative planning period of 100 years. This being the case, there are no minimum habitable floor level requirements for the proposed development from a coastal engineering perspective.

[127] The average dune crest level based on the 2004 photogrammetric data, for Profiles 35-47 (seaward of the Beachside Tourist Precinct), was 9.8m

6.7 STORMWATER EROSION HAZARD

During major stormwater runoff events, stormwater collected from back beach areas and discharging into coastal waters can cause significant erosion to the beach berm. This in turn can allow larger waves to attack the beach and can cause migration of the stormwater discharge entrance (NSW Government, 1990). Flow from stormwater pipes and outlets on beaches can also potentially scour the surrounding sand, creating erosion zones.

There are no significant stormwater outlets known to be discharging directly on Sapphire Beach at present. As part of the proposed development, this situation is not expected to be altered. That is, it is expected that rainfall-runoff from the subject property is to be directed landward, which will reduce the likelihood of additional coastal erosion. This would need to be confirmed as the stormwater management design is progressed.

There are no significant river /estuary entrances at Sapphire Beach.

6.8 SLOPE AND CLIFF INSTABILITY HAZARD

Slope and cliff instability hazards relate to the possible structural incompetence of these features, and associated potential problems with the foundations of buildings, seawalls and other coastal works (NSW Government, 1990).

The subject property was assumed to be composed entirely of sand within the active coastal zone. Therefore, the slope hazard for this investigation only relates to sandy beach and dune areas. For such areas, based on Nielsen et al (1992), a number of coastline hazard zones can be delineated as shown in **Figure 31**.

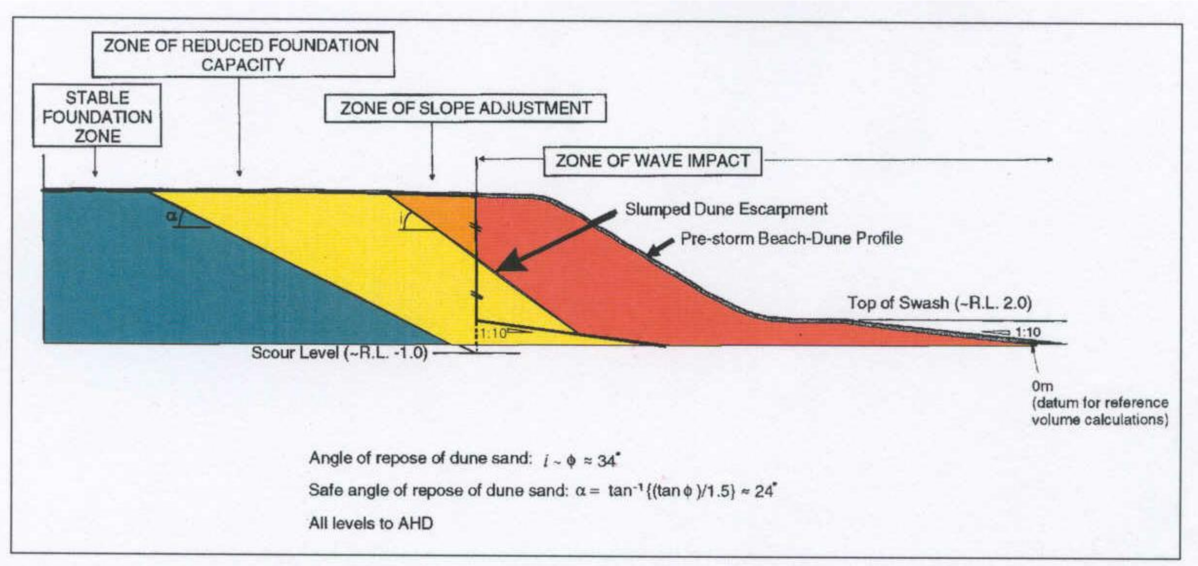

Figure 31: Schematic representation of coastline hazard zones (after Nielsen et al, 1992)

The *Zone of Wave Impact* delineates an area where any structure or its foundations would suffer direct wave attack during a severe coastal storm. It is that part of the beach which is seaward of the beach erosion escarpment (as defined by the beach erosion hazard, Section 6.3).

A *Zone of Slope Adjustment* is delineated to encompass that portion of the seaward face of the beach that would slump to the natural angle of repose of the beach sand following removal by wave erosion of the design storm demand. It represents the steepest stable beach profile under the conditions specified.

A *Zone of Reduced Foundation Capacity* for building foundations is delineated to take account of the reduced bearing capacity of the sand adjacent to the storm erosion escarpment. Nielsen et al (1992) recommended that structural loads should only be transmitted to soil foundations outside of this zone (ie landward or below), as the factor of safety within the zone is less than 1.5 during extreme scour conditions at the face of the escarpment.

In general (without the protection of a terminal structure such as a seawall), dwellings/structures not piled and located with the Zone of Reduced Foundation Capacity would be considered to have an inadequate factor of safety.

The coastline hazard zones for the study area are determined in Section 8, with the position of the Zone of Slope Adjustment and Zone of Reduced Foundation Capacity defined for immediate, 50 year and 100 year planning periods.

7 DUNE MANAGEMENT

In essence, management of a stable dune system involves the control of access, the maintenance of natural levels of vegetation cover, and, if necessary, the re-establishment of sand volumes and crest levels. In the case of the subject property, sand volumes and crest levels are already well established, so key dune management issues would relate to control of access and maintenance of natural levels of vegetation cover.

In *Coastal Dune Management* (DLWC, 2001), guidance on dune management and rehabilitation is provided. In this, it is emphasised that dunes not only provide a reserve supply of sand to meet coastal storm demand, but they also support valuable communities of plants and animals. That is, dunes are recognised as integral parts of beach systems with intrinsic biodiversity values.

As part of the proposed development, it will be necessary to maintain and protect the dune seaward of the subject property. Vegetation cover is a crucial element in the evolution of dune landscapes. Wind velocity is generally reduced by plant cover, encouraging deposition and trapping of wind blown sand.

Control of wind erosion on coastal dunes relies primarily on maintaining a uniform protective cover of suitable vegetation. Mulch, synthetic aggregates or access control structures such as board-and-chain walkways can also limit wind erosion (DLWC, 2001).

Weakening or destruction of dune vegetation can be induced by natural events such as drought, fires (which can also be human-induced) and storm waves, and by disturbance due to a variety of human activities such as trampling and introduction of weeds (such as Bitou Bush).

DLWC (2001) provided guidance on weed control techniques in dune areas, as well as revegetation methodologies and species.

To minimise human trampling of dunal areas, it is recommended that the landward edge of the dune vegetation is fenced to prevent ad-hoc access, seaward of the proposed development. Guidance on protective fencing for dune areas was provided in DLWC (2001). This included information on positioning, fence types and construction, and maintenance.

Furthermore, defined accessways to the beach should be provided. Given the scale of the proposed development, around four accessways would most likely be considered to be sufficient for seaward of the Beachside Tourist Precinct[128]. DLWC (2001) included information on beach accessways (design, position, alignment, gradients, surfaces, fencing, maintenance, and signage), and discussion on structures such as steps and stairways, elevated walkways, and viewing platforms.

[128] However, as noted in Section 1, the Beachside Tourist Precinct is not proposed to be developed as part of the current Concept Plan.

There are no specific requirements for such structures at the proposed development. DLWC (2001) considered that beach access stairways should be avoided if possible, as they were not generally favoured by users, and could become expensive to construct and maintain. They also considered that elevated walkways were relatively expensive structures that were usually only justified in highly trafficked areas and/or where access was to be provided across particularly sensitive environments. Viewing platforms were considered to provide opportunities for people to appreciate the surrounding environment, while discouraging random and uncontrolled exploitation of vantage points.

For accessways, as a general rule, flexible and permeable surfaces were recommended by DLWC (2001) for use in dune areas, to minimise the volume of runoff that could lead to localised erosion. It was also recommended that accessways were fenced to prevent movement off paths.

8 DEFINITION OF COASTLINE HAZARD ZONES

In this Section, coastline hazard zones are defined at the subject property based on the cumulative impacts of the coastline hazards outlined in Section 6, relating to erosion and recession.

Two coastline hazard zones are defined, namely the Zone of Slope Adjustment and the Zone of Reduced Foundation Capacity (Section 6.8)[129]. These are defined for immediate (that is, present post storm), 50 year and 100 year planning timeframes.

For simplicity, the landward limit of the Zone of Slope Adjustment for each of the planning timeframes has been denoted as the "Hazard Line". The position of the 2005 Hazard Line, 2055 Hazard Line and 2105 Hazard Line is thus the predicted position of the back beach erosion escarpment after a 100 year ARI coastal storm, including subsequent slumping to a stable angle of repose, that would exist in 2005, 2055 and 2105 respectively[130].

In **Table 9**, the components added to derive the final Hazard Lines are listed, with the 2005 Hazard Line determined as a volume removed from the most recent 2004 photogrammetric profiles[131]. The volumes were applied as per Nielsen et al (1992), see Figure 31, at each of the survey profiles. Thus, at each profile, a position on the 2005 Hazard Line was determined.

Table 9: Coastline hazard components summed to determine 2005, 2055 and 2105 Hazard Lines

Component	2005	2055	2105
Beach erosion hazard (storm demand), m^3/m	200	200	200
Long term recession due to net sediment loss, m	0	5	10
Long term recession due to future sea level rise, m	0	8	20
Discounting due to historical sea level rise, m	0	0	0
TOTAL (m^3/m) *plus* (m)	200	200 13	200 30

In determining the Hazard Lines for 2055 and 2105, the 2005 Zone of Wave Impact positions were simply translated landward, then the positions of the Zone of Slope Adjustment and Zone of Reduced Foundation Capacity were recalculated. Note that some smoothing of the Hazard Lines was undertaken to avoid significant localised fluctuations in the erosion escarpment position, that would be unlikely to be sustained in practice.

[129] The Zone of Wave Impact was also defined as part of the calculations, but is not depicted here.
[130] That is, the Hazard Lines do not represent future predicted shorelines, but future predicted erosion escarpments after a 100 year ARI coastal storm, plus post-storm slumping of the sand to a stable angle of repose.
[131] It is actually conservative to use the 2004 profiles as the baseline survey, given that the 2004 profiles were captured after a relatively erosive period over 6 years. It is most appropriate to use an average beach full condition as the baseline survey.

Landward of the 2005, 2055 and 2105 Hazard Lines, there would exist a Zone of Reduced Foundation Capacity (ZRFC), which takes account of the reduced bearing capacity of the sand adjacent to the storm erosion escarpment. In general, structures not piled and located within the ZRFC would be considered to have an inadequate factor of safety. For example, the 2105 ZRFC Line represents the predicted landward limit of this Zone in 2105. The position of the ZRFC was determined as outlined in Section 6.8. The ZRFC was on average about 16m landward of the corresponding Hazard Line, with the distance mainly depending on the height of the dune.

Note that the ZRFC was derived assuming a beach profile composed entirely of sand. If there were layers of less erodible or inerodible material, such as stiff clays and/or rock within the ZRFC, then the extent of the Zone could potentially be reduced accordingly[132]. Geotechnical engineering advice is recommended if foundations within the ZRFC are proposed.

The 2005, 2055 and 2105 Coastline Hazard Lines within the study area are shown in **Figure 32**. The 2105 ZRFC is shown in **Figure 33**[133].

It is evident that the Coastline Hazard Line is seaward of the subject property for all planning periods. Therefore, from a coastal engineering perspective, the location of the proposed development is considered to be reasonable[134].

The ZRFC is at the seaward subject property boundary in 2105. Therefore, there are no particular foundation requirements for the proposed development from a coastal engineering perspective.

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[132] However, Coffey Geosciences Pty Ltd (2004b), in a geotechnical investigation of the subject property, noted that the eastern portion of the subject property was generally underlain by sandy soils.
[133] For clarity, it was not considered necessary to show the 2005 or 2055 ZRFC lines.
[134] However, as noted in Section 1, no development is proposed immediately landward of the seaward property boundary as part of the current Concept Plan.

Figure 32: 2005, 2055 and 2105 Coastline Hazard Lines at subject property

Figure 33: 2105 Zone of Reduced Foundation Capacity (ZRFC) at subject property

9 RESPONSE TO DIRECTOR GENERAL'S REQUIREMENTS

The Director General's Requirements were provided as Attachment 1 in a letter dated 20 October 2006 from the Department of Planning to Hillview Heights Estates Pty Ltd. Key coastal-related requirements relevant to the investigation reported herein were as follows:

- Key Issue 4: Coastal zone, access and impacts
  - (4.1) demonstrate the management of the coastal zone will be in accordance with the principles of ecologically sustainable development;
  - (4.2) protect existing public access to and along the beach and coastal foreshore and provide, where appropriate, new opportunities for controlled public access; and,
  - (4.3) address impacts of access to and any development of the coastal foreshore; and identify measures to mitigate and control those impacts including uncontrolled access and clearing of vegetation.
- Key Issue 6: Hazard management and mitigation
  - (6.5) address coastal hazards and the provisions of the *Coastline Management Manual*.

The proposed development is not expected to be impacted by or impact upon coastline hazards in the foreseeable future, applying the precautionary principle. That is, from a coastal perspective, the proposed development can be considered to be ecologically sustainable.

The proposed development is over 400m from the seaward property boundary. As such, issues relating to access and development of the coastal foreshore do not generally apply. The proposed development would not restrict any existing public access to the foreshore. Recommendations regarding dune management and access provisions have been provided in Section 7 (including measures to mitigate the impacts of uncontrolled access and clearing of vegetation), although these issues are less applicable at the subject property given that development within the Beachside Tourist Precinct is not proposed as part of the current Concept Plan (see Section 1).

That is, Key Issue 4 has been addressed herein.

Based on the hazards outlined in the *Coastline Management Manual* (as described in Section 6), coastline hazard zones have been defined seaward of the subject property (see Section 8). That is, Key Issue 6 has been specifically addressed.

Attachment 3 of the Director General's Requirements included a list of technical and policy guidelines. Where relevant, these guidelines have been invaluable reference documents in the completion of the investigation reported herein.

10 CONCLUSIONS

Coastline hazards were determined based on the cumulative effects of the 100 year ARI coastal storm erosion, long term recession due to net sediment loss, and long term recession due to sea level rise (over immediate, 50 year, and 100 year planning periods).

From a coastal engineering perspective, the proposed development would not be expected to adversely affect, or be adversely affected by, coastal processes. This is because the Coastline Hazard Line, representing the landward limit of the Zone of Slope Adjustment, is seaward of the subject property for all planning periods up to 100 years, that is at 2105 (refer to Figure 32).

In 2105, a Zone of Reduced Foundation Capacity (ZRFC) was predicted to extend to the seaward subject property boundary. Therefore, there are no particular foundation requirements for the proposed development from a coastal engineering perspective.

There are no minimum habitable floor level requirements for the proposed development from a coastal engineering perspective, given that the coastal inundation hazard was expected to be negligible for the 100 year ARI coastal storm occurring over the next 100 years.

However, it is important that dune vegetation coverage and dune crest levels are maintained seaward of the subject property into the future, between formalised access areas.

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APPENDIX A:
PHOTOGRAMMETRIC ANALYSIS INCLUDING 1943 DATA, AND ADDITIONAL PRE-1988 ANALYSIS

As noted in Section 4.2, the 1943 photogrammetric data was not considered to be reliable enough to be the basis for long term recession estimates. For reference, the results for the 1943-1988 period are shown below[135]. The rate of change of the volume above 0m AHD, and the rate of change of the position of the 3m AHD elevation, including the 1943 to 1988 period, are shown in **Figure 34** and **Figure 35** respectively.

Note that the accretion indicated from north of Profile 28 is a numerical artefact, and not realistic. It was caused by the profiles only being defined above 3m AHD at the seaward end, and therefore the 1943 position of the 3m AHD elevation was first defined (moving landward) in the back beach area.

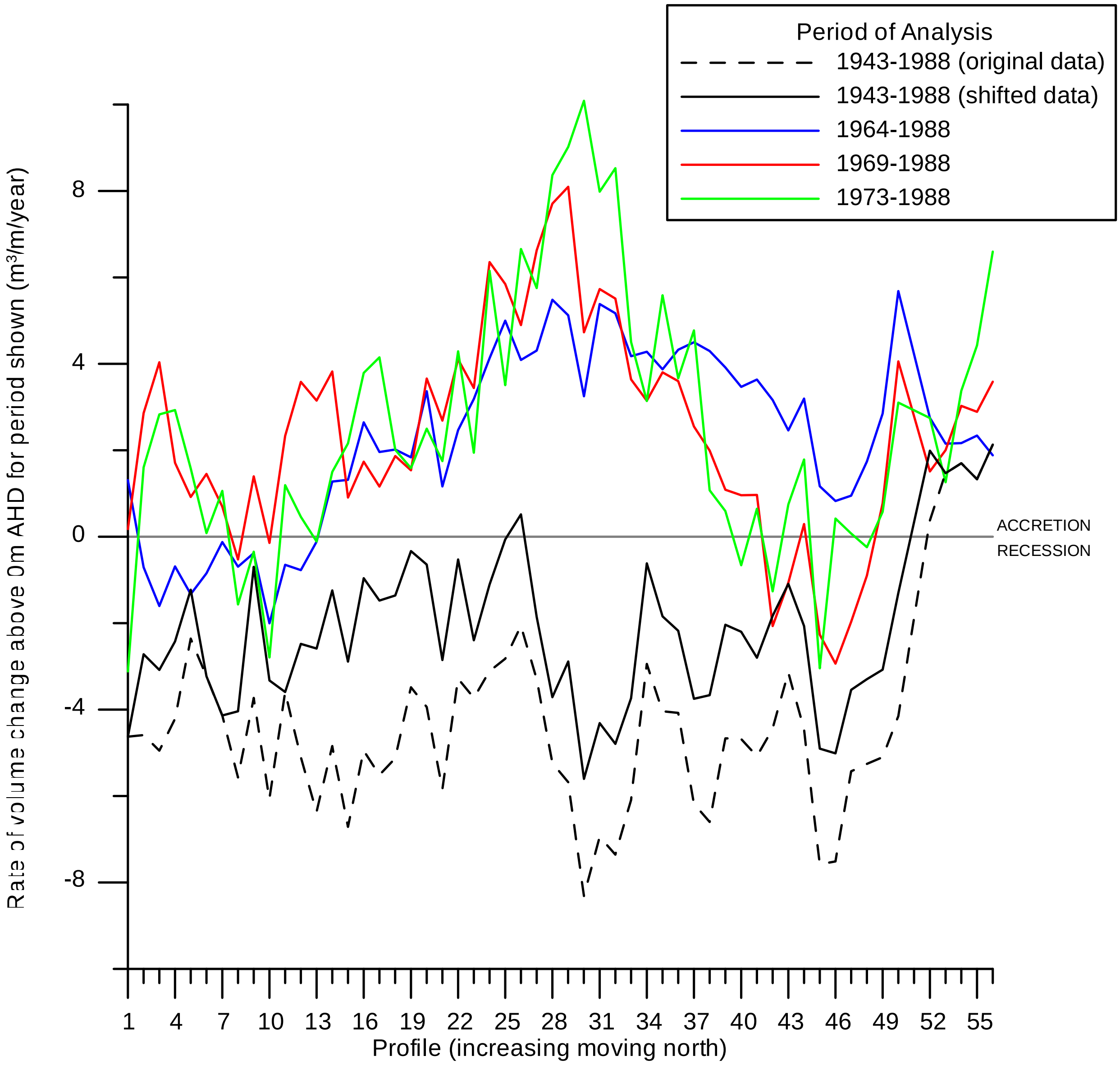

Figure 34: Rate of change of volume above 0m AHD at Sapphire Beach, including 1943 data

[135] The 1996 and 2004 photogrammetric data was obtained after this analysis was completed. It was not considered necessary to re-analyse the data including these dates.

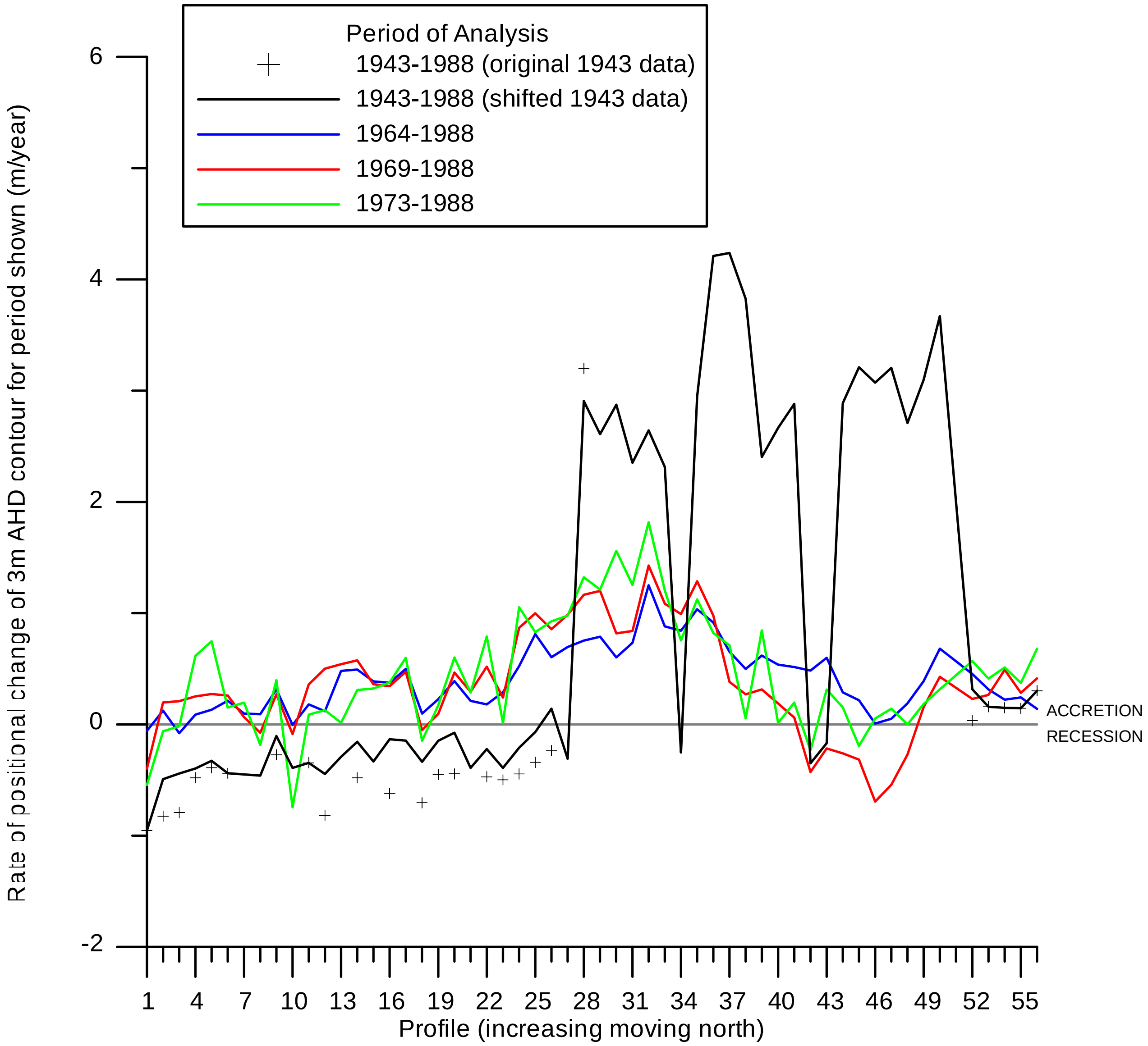

Figure 35: Rate of positional change of 3m AHD elevation at Sapphire Beach, including 1943 data

As part of the Patterson Britton (2005) investigation, additional analysis of the 1964-1988, 1969-1988 and 1973-1988 periods was undertaken. The rate of change of the volume above 0m AHD, and the rate of change of the position of the 3m AHD elevation, was determined as shown in **Figure 36** and **Figure 37** respectively.

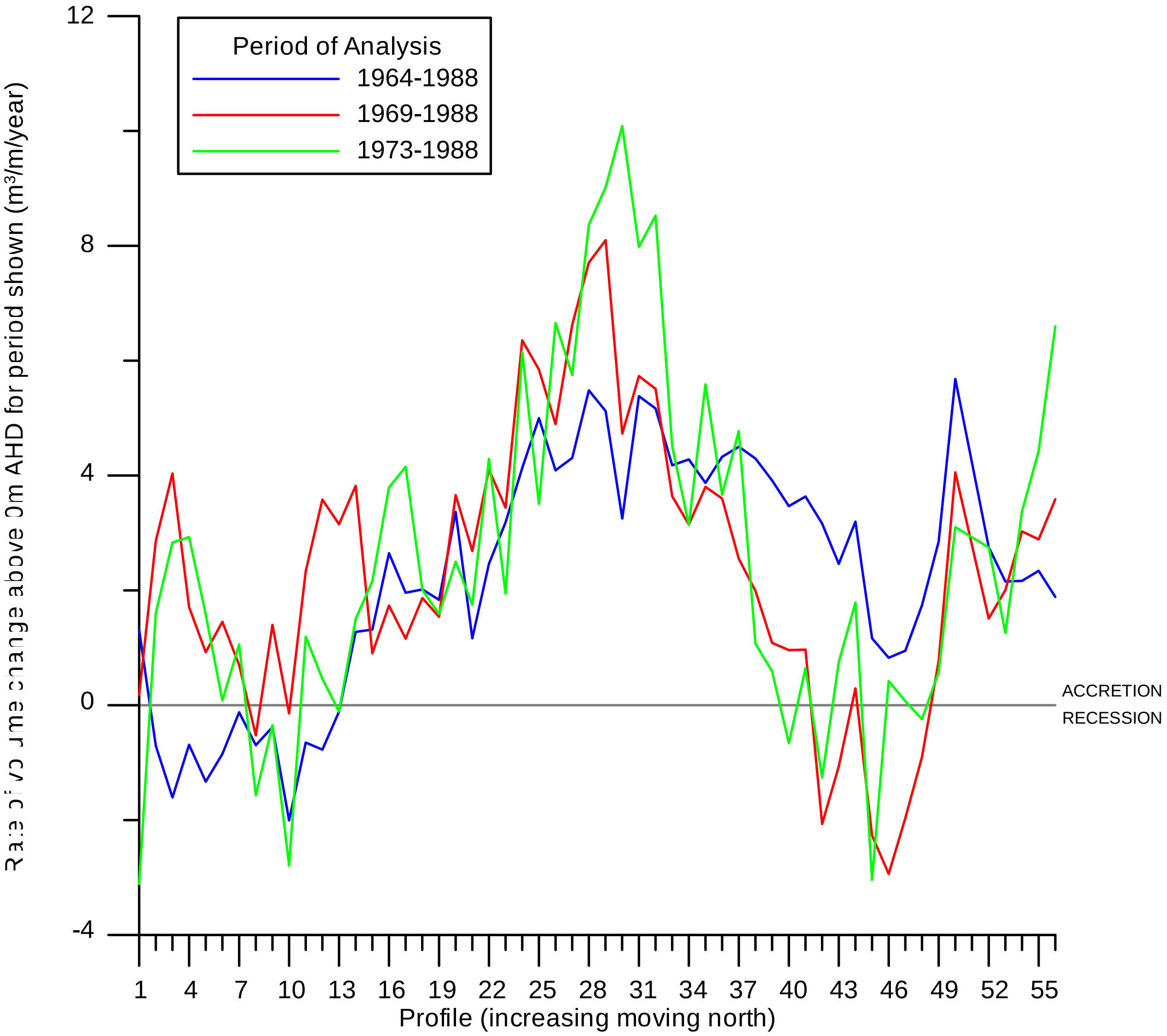

Figure 36: Rate of change of volume above 0m AHD at Sapphire Beach for 1964-1988, 1969-1988 and 1973-1988 periods

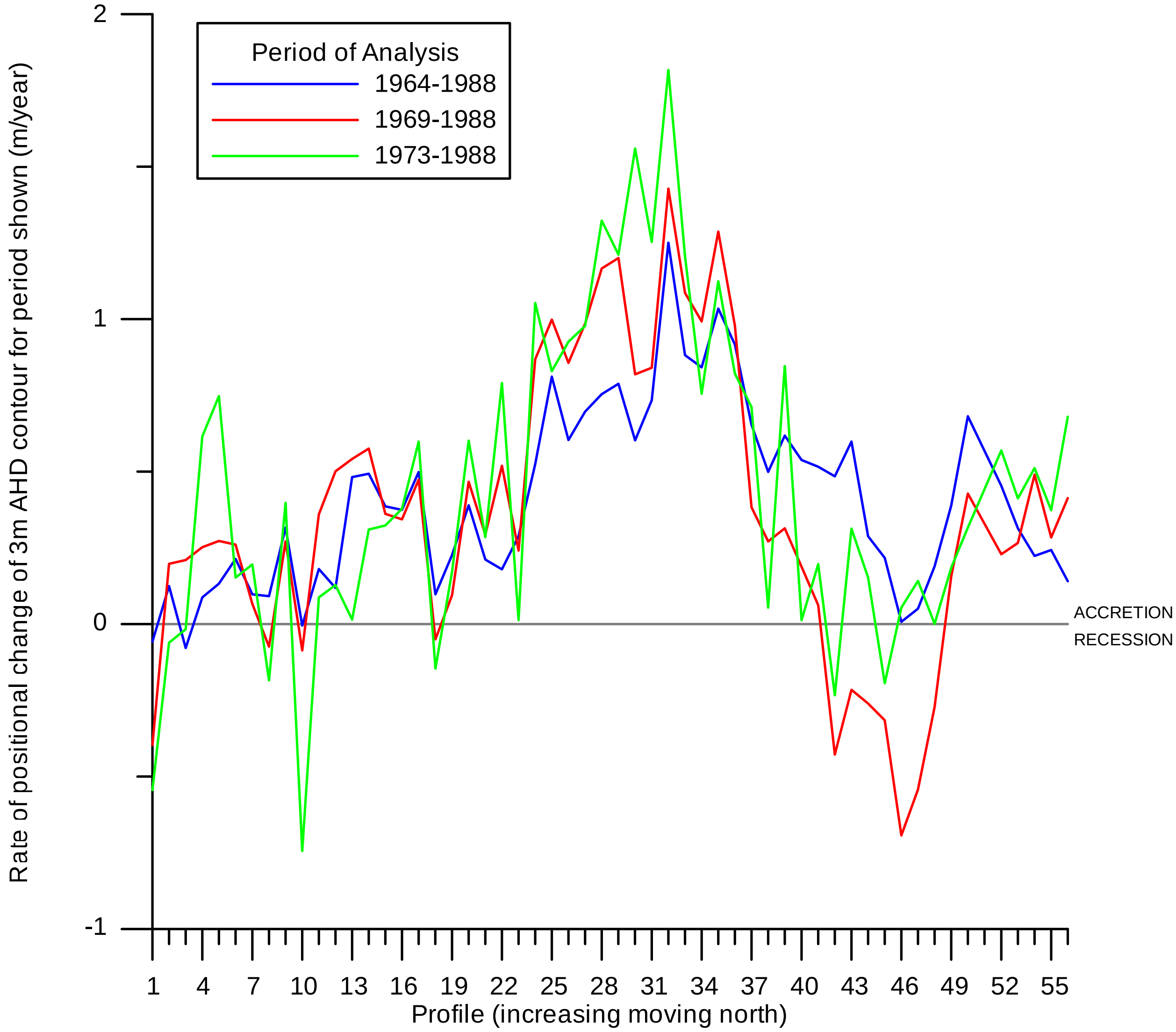

Figure 37: Rate of positional change of 3m AHD elevation at Sapphire Beach for 1964-1988, 1969-1988 and 1973-1988 periods

As noted in Section 4.2, 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 1988, commencing in 1964, 1969 and 1973, were more likely to be slight underestimates (1964), and more significant underestimates (1969 and 1973) respectively. This observation matches the variation in rates, with the 1964 accretion estimate lower than for the other two dates. Overall, it can be realistically concluded that accretion occurred seaward of the subject property between 1964 and 1988.