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 3.6. It was concluded that there was strong evidence for reducing recession rates moving north along beaches in the vicinity of Hearns Lake Beach, as well as relatively low recession rates in the region generally . The photogrammetric data for Sandy Beach was also analysed in Section 4.3. In all, this confirmed that six beaches near to Hearns Lake Beach appeared to be either stable or accreting at their northern ends, over a period of record of 30 to 50 years.

5.6.3 Analysis of Vegetation Lines

In Section 4.2, a listing of aerial photography of Hearns Lake 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, to determine if there were any trends in landward or seaward migration[80]. This was completed for the years of 1943, 1956, 1966, 1972, 1973, 1980, 1986, 1993, 2000 (May and June) and 2002[81]. Also, as part of a survey of the beach seaward of the subject property in August 2004 (Section 4.1), the position of vegetation was noted. The positions of the sand/vegetation interface at Profiles 1 to 3 for this survey were connected by straight lines for this date.

The position of the sand/vegetation interface over the period 1943-1973 is shown in **Figure 24**, over the June 2000 aerial photograph. Similarly, the position of the interface in 1943, 1973 and from 1980-2004 is shown in **Figure 25**. Note that the May and June 2000 vegetation lines were similar, and are not shown in Figure 25 given that the interface is evident in the aerial photography. Furthermore, the 2002 vegetation line was within a few metres of the 2000 line, and is therefore not shown for clarity.

[80] As noted in Section 3.5, movement of vegetation lines can potentially be correlated to long term recession.
[81] The 1969 vegetation line was similar to 1966, and the June and August 1974 vegetation lines were similar to 1973, so these three lines were not digitised.

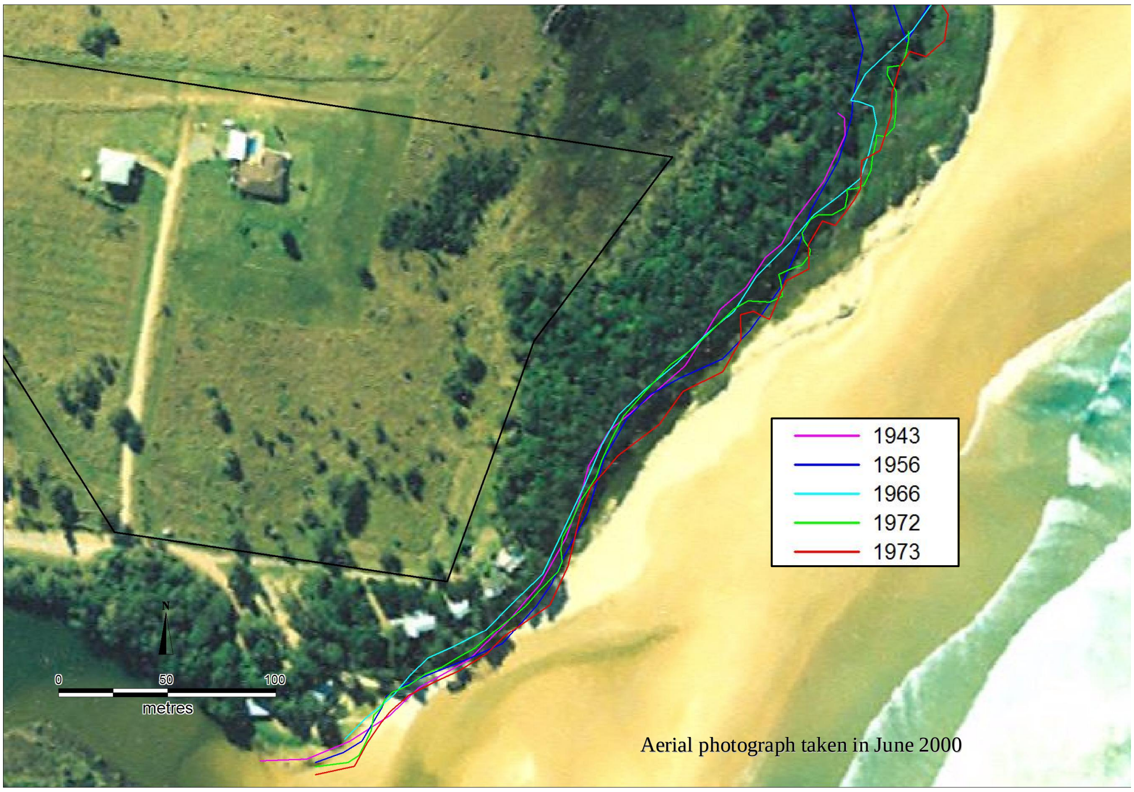

Figure 24: Position of sand/vegetation interface seaward of subject property, 1943-1973

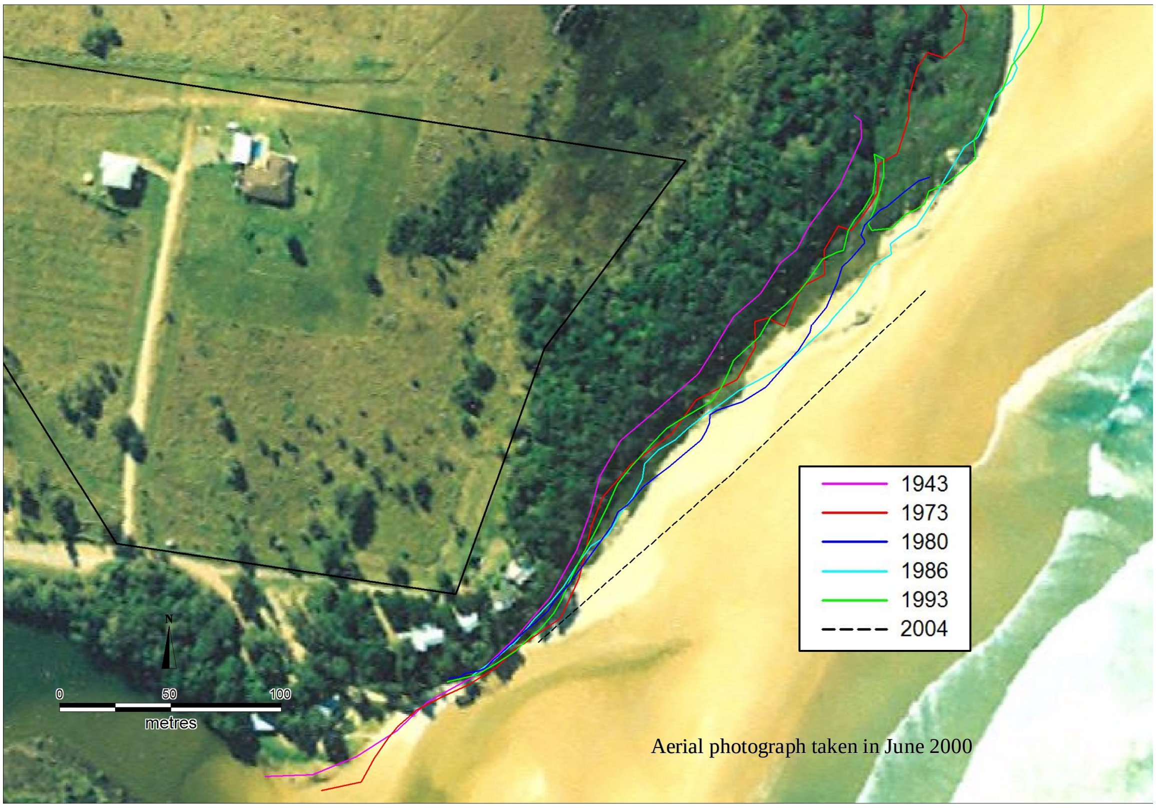

Figure 25: Position of sand/vegetation interface seaward of subject property, 1980-2004 (1943 and 1973 also shown)

It is evident that, seaward of the subject property, the vegetation line migrated seaward between 1943 and 1973, by between about 10m to 15m. South of the subject property, the vegetation line was generally stable[82]. Although there was some fluctuation in the vegetation line position between 1943 and 1973, there was a continuing trend of stability or seaward migration (that is, the 1943 position essentially represented the most landward limit of the vegetation line).

Further seaward migration of the vegetation line was evident between 1973 and 2004. At the year 2000, the vegetation line was typically about 20m seaward of its position in 1943, being about 15m seaward at the southern end of the subject property, and 40m seaward at the northern end. The line moved seaward between 1973 and 1986, moved landward between 1986 and 1993, then moved seaward again between 1993 and 2000. These fluctuations were probably a reflection of the 1977-1984 period being particularly calm, and the relative storminess of 1988-1989 period (Section 5.4.5).

The edge of grasses noted in the August 2004 survey was significantly seaward of the vegetation line positions determined from aerial photography. This is probably a reflection of continuing accretion and landward movement of the vegetation line between 2002 and 2004, as well as capture of different interfaces in each case[83].

5.6.4 Adopted Recession Rate

There is consistent evidence that Hearns Lake Beach, in the vicinity of the subject property, has been accreting over the last 61 years. From a coastal processes perspective, this is most likely to be related to the property being at the northern end of a beach which has net sediment transport to the north, and a low rate of transport further to the north past Flat Top Point.

As noted in Section 5.6.2, six beaches near to Hearns Lake Beach also appeared to be either stable or accreting at their northern ends, over a period of record of 30 to 50 years. Furthermore, as described in Section 5.6.3, the sand/vegetation interface at Hearns Lake Beach has migrated seaward since 1943. This relative stability of Hearns Lake Beach has occurred despite sand extraction occurring at the northern end of the beach in the 1960's and 1970's (Section 3.1).

The relative stability of Hearns Lake 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 0.05m/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 2.5m at 2054, and 5m at 2104.

[82] Note that shadowing in this area made identification of the vegetation line difficult for some dates.
[83] Referring to Figure 1, there are two distinct interfaces in the vegetation. The most seaward interface is the edge of patchy grasses and sand. The next interface moving landward, evident in the centre of Figure 1, is between the patchy grasses and more densely spaced grasses, creepers and shrubs. Despite this, there is strong evidence of beach accretion between 2002 and 2004.

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[84]. 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)[85]. 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:

- 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[86];
- magnitude of the storm surge accompanying the event;
- amount of wave setup and runup on the beach during and immediately following the storm;

[84] 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).
[85] 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 between about 3m AHD and 6m AHD (Section 3.2).
[86] 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.

- 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 Hearns Lake Beach

The available photography at Hearns Lake 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 3.2, 3.3, 3.6 and 4.2)[87]. Therefore, storm demand must be estimated on the basis of published studies or numerical modelling.

It can be noted that, based on discussions with a local resident who has lived in one of the leasehold shacks at the top of the dune at Hearns Lake Beach for 45 years, none of the shacks have been under threat from coastal erosion over this entire period[88]. This is an indication that no storms with a storm demand greater than about 150m^3/m above 0m AHD have occurred over this period.

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 Hearns Lake Beach, it would be reasonable to assume a uniform storm demand for the entire study area[89].

To further attempt to quantify the storm demand at Hearns Lake 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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[87] 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.
[88] The shacks, which have been evident in aerial photography since at least 1956, are visible in Figure 3.
[89] 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 Hearns Lake Beach, the landward sections of the initial (pre–storm) beach profiles were derived from the 2004 land survey (as described in Section 4.1). These profiles were extended seaward by using bathymetric information given by MHL (1986) for the northern end of Woolgoolga Back Beach, which is described in Section 6.4.2.

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[90], such that the peak water level (1.5m AHD) coincided with the peak wave height[91].

The 100 year ARI design wave height, wave period and water level time series used as input to SBEACH for storm cut modelling of Hearns Lake Beach, is shown in **Figure 26**. Note that a grain size of 0.15mm was used in the modelling, which is realistic[92].

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[90] 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).
[91] Note that SBEACH computes wave setup, and therefore the design water level must exclude wave setup.
[92] Sampling by Short (1993) at the nearby Safety Beach and Woolgoolga Beach indicated mean grain sizes in the swash zone of about 0.16mm.

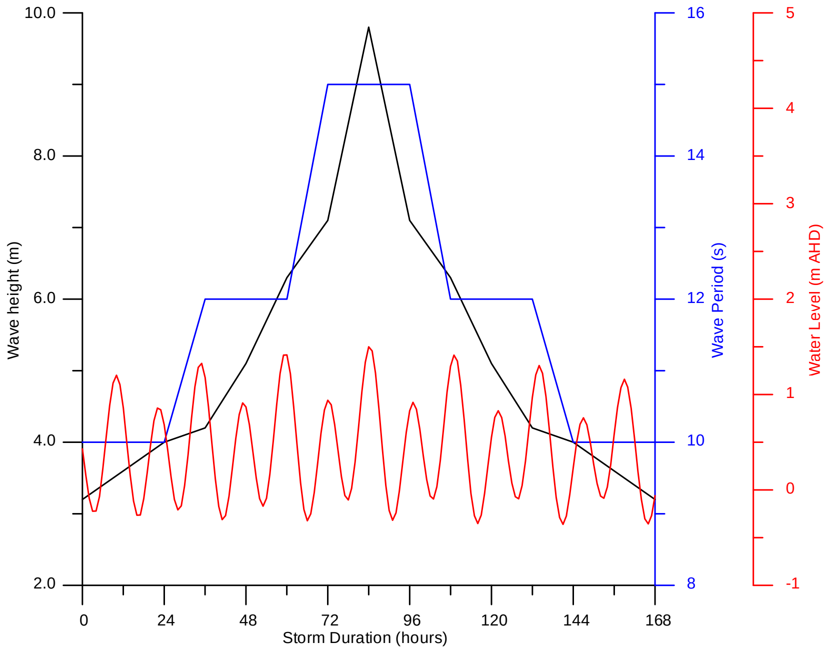

Figure 26: 100 year ARI design wave height, wave period and water level used for SBEACH modelling of Hearns Lake Beach

Using the design input time series as outlined in SBEACH, the resulting erosion volumes above 0m AHD, for each of the four profiles at the subject property, are shown in **Table 8**.

Table 8: Erosion volumes determined using SBEACH

Profile	Erosion volume above 0m AHD (m^3/m)
1	38
2	42
3	34
4	46

It is evident that the erosion volume above 0m AHD for the four profiles was a maximum of about $50m^3/m$[93]. This is much smaller than the $220m^3/m$ above 0m AHD value 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[94].

[93] The maximum erosion volumes for the entire profile, generally found to be above about –5m AHD, were up to about $210m^3/m$. Given the depth at which this is measured, it has no equivalency to a storm demand measured above 0m AHD.

[94] 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.

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 indicated storm demands of about 25% of this value[95].

5.8 GEOTECHNICAL CONDITIONS

A geotechnical investigation of the general area has been undertaken by Holmes & Holmes (2003). This covered the subject property, as well as the nearby Lot 4 DP 612977 and Lot 32 DP 1047234, located to the west (and east of the Pacific Highway).

The substrata was found to typically be a silty clay, firm to stiff, with extremely weathered, very weak and fractured claystone being encountered at 1m to 2m depth.

From a coastal engineering perspective, geotechnical conditions at the seaward edge of the subject property are of most interest. No boreholes were taken in this area, with the closest borehole (BH2) being located about 95m NNW of the SE corner of the subject property.

Of particular interest is the seaward extent of clay and other suitable foundation materials. All calculations of coastline hazards in the investigation reported herein conservatively assume a profile composed entirely of sand. Given the presence of clay elsewhere on the subject property, it is considered possible that subsurface clay materials would be present in the active coastal zone. Also, the steep and high dune seaward of the subject property (which may be unstable if sandy), with some cohesive materials visually inferred in the dune profile during a cursory site inspection, provides further evidence that clay would be present in the active coastal zone[96]. These issues are discussed further in Sections 6.8 and 7.

5.9 HEARNS LAKE ENTRANCE PROCESSES

5.9.1 General

Sediment transport near the Hearns Lake entrance is influenced by wave action, flood flows, and tidal flows, with waves dominating the energy regime. Based on aerial photography, the variable state of the entrance Hearns Lake over the last 61 years could be estimated at discrete intervals. This analysis is presented in Section 5.9.2.

Flood tide deltas are common at the entrances to estuaries along the NSW coast, at which marine sand is transported into the estuary mouth by wave action and flood tide currents. The net landward transport of sand results from the asymmetry of tidal currents; flood tide velocities are higher but of shorter duration than ebb tide velocities, and flood tide currents are reinforced by shoaling waves (Chapman et al, 1982).

[95] 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 2m to 3m), given the relatively high dune.

[96] There were also exposed bedrock outcrops noted along the northern shoreline at the entrance to Hearns Lake.

The position of the landward (upstream) edge of the flood-tide delta at Hearns Lake, denoted as the flood tide dropover, was digitised based on aerial photography. This analysis is presented in Section 5.9.3.

Further discussion on estuary processes is given in Section 8.

5.9.2 History of Entrance Conditions

Based on aerial photography (Section 4.2)[97], the state of the entrance at Hearns Lake Beach could be estimated from 1943 to 2004. Details of this analysis are provided in **Table 9**. To assist in this analysis, daily rainfall data was obtained from the Bureau of Meteorology for the following stations near Hearns Lake Beach:

- Woolgoolga (High Street), Station 59039, January 1887 to February 2004;
- Bucca Lower Forestry, Station 59005, January 1939 to March 1957;
- Lower Bucca, Station 59006, September 1901 to August 2004;
- Woolgoolga State Forest, Station 59051, January 1956 to August 1969;
- Safety Beach[98], Station 59106, December 1972 to June 1986; and,
- Coffs Harbour, Station 59040, February 1943 to October 2004;

Unless stated otherwise, all rainfall data described in Table 9 was derived from Station 59039[99]. The term "entrance", when used to describe a position, applies to the location of the north bank of Hearns Lake where the channel width is narrowest (shown in **Figure 27**).

Table 9: State of Hearns Lake entrance from 1943 to 2004

Date	Storminess Indicator[100]	Rainfall (mm) in previous			Comments
		Day	Week	Month	
9 March 1943	1.6	0	1.5	15	Partly open. Evidence of flow over beach to ocean over 50m width. Lake appeared to be relatively shallow, suggesting it was draining to ocean. Flood tide dropover evident.
11 March 1943	1.6	0	1.5	10	Closed near sand/vegetation interface alignment, channel aligned to S centre and 35m wide. Channel filling with sand along S shoreline for 70% of width, upstream to flood tide dropover.
23 March 1943	1.6	0	40	41	Closed to 120m upstream of sand/vegetation interface alignment. S 70% of shoreline filled with sand to flood tide dropover.
26 April 1956	0.8	22	22	106	Closed near sand/vegetation interface alignment, channel aligned to N for 90m, and 30m wide. Flood tide dropover evident over 70% of width near entrance.
12 August 1964	1.1	0	0	2	Closed about 230m N of entrance, with narrow channel traversing seaward of dunes (also on 19 Aug). Relatively little sediment evident in entrance area upstream of beach berm (flood tide dropover still present).

[97] Also, a field inspection and land survey was undertaken in August 2004 (Section 4.1).
[98] Safety Beach is a suburb located immediately north of Woolgoolga.
[99] Other stations were found to be generally similar to Station 59039. Station 59005 was used for the 1943 dates, and Station 59051 was used in 1956.
[100] See Section 5.4.5.

Date	Storminess Indicator[100]	Rainfall (mm) in previous			Comments
		Day	Week	Month	
7 February 1966	0.3	0	12	40	Possibly partly open. Lake appeared to be filled with water and not draining. Channel at maximum width (50m) upstream of closure. Evidence of wet sand along beach to N seaward of dunes for 220m, caused by possible oceanic intrusion at high tide or freshwater / groundwater flows. Flood tide dropover faintly evident, presumably due to large water depths. Last major rainfall had been in late November and early December 1966 (246mm in 19 days).
6 April 1969	0.4	0	13	56	Closed at 45m upstream of sand/vegetation interface alignment, with deeper channel at N side for about 40% of width, with flood tide dropover to S. Possible sand extraction operations at entrance.
8 October 1972	0.8	0	44	55	Closed at about 70m N of entrance, channel 30m wide. S 60% of shoreline filled with sand to flood tide dropover.
14 April 1973	0.2	0	51	182	Closed at about 100m N of entrance, channel 40m wide.
3 May 1973	0.2	5	26	159	Slightly open. Narrow (10m wide) meandering channel linking with ocean about 150m N of entrance. Channel about 20m wide from entrance to flood tide dropover, aligned against N bank. Lake generally appeared to be shallow, probably draining.
28 March 1974	1.5	0	64	798	Closed. Poor quality photo. Lake appeared to be well scoured to entrance and filled with water, suggesting closure. Possible high tide linkage to N.
23 June 1974	1.7	0	13	200	Closed to at least 10m landward of sand/vegetation interface alignment. Intrusion of sand into entrance at N end for 60m. Generally filled with sand to flood tide dropover, with narrow (10m wide) channel against S bank.
18 August 1974	1.3	0	0	15	Similar to above, but less sand evident between entrance and flood tide dropover.
2 December 1976	1.4	0	0	112	Slightly open. Centrally located, partly meandering, narrow channel linking with ocean. Flood tide dropover evident.
19 March 1980	0.4	0	8	115	Closed to near sand/vegetation interface alignment, with further landward intrusion of sand at S end. Relatively little sediment evident in entrance area upstream of beach berm (no flood tide dropover).
29 January 1983	0.4	0	3	115	Slightly open. Limited photo coverage (only on beach). Very narrow channel meandering to ocean just north of entrance.
31 August 1983	0.8	0	21	85	Slightly open. Limited photo coverage (only on beach). Channel about 15-20m wide, meandering to N, joining with ocean about 150m N of entrance.
22 June 1986	1.3	0	21	48	Closed. Channel about 10-15m wide, traversing seaward of dunes to N of entrance, ending up about 210m N, at back beach erosion escarpment. Flood tide dropover just developing.
9 May 1988	1.7	0	3	176	Closed at about 220m N of entrance, with channel about 40m wide, traversing directly seaward of dunes. Very little sediment evident in entrance area upstream of beach berm (no flood tide dropover).
17 June 1993	1.4	0	0	49	Closed at about 130m N of entrance, with shallow channel about 20m wide, traversing about 20m seaward of dunes. Relatively little sediment evident in entrance area upstream of beach berm (faint flood tide dropover).
28 June 1996	1.0	0	2	101	Slightly open. Narrow (3m wide) channel linking with ocean about 110m N of entrance. Generally filled with sand to flood tide dropover, with 20m wide channel mainly against N bank.
17 May 2000	1.8	0	18	138	Slightly open. Narrow (5m wide) channel linking with ocean about 140m N of entrance. Partly filled with sand to flood tide dropover, with narrow (10m wide) channel against S bank, and significant plug of sand covering N 80% of entrance.
1 June 2000	1.8	0	4	115	Closed at about 140m N of entrance, with narrow (10m wide) channel. Similar to above regarding flood tide dropover.

Date	Storminess Indicator[100]	Rainfall (mm) in previous			Comments
		Day	Week	Month	
7 September 2002	–	0	4	175	Slightly open. Narrow (5m wide) channel linking with ocean about 190m N of entrance. Partly filled with sand to flood tide dropover, with distinct 12m wide meandering channel mainly against N bank.
26-27 August 2004	–	0	0	29	Field inspection and land survey. Closed at about 100m N of entrance, with channel about 20m wide.

It is evident that Hearns Lake is usually closed, only opening when significant rainfall-runoff occurs. After opening, closure tends to progress relatively rapidly. The favoured location of the entrance, when open, is to form a narrow channel moving approximately parallel to the shoreline, to the north.

Note that the vegetated banks of Hearns Lake (near the entrance) have remained relatively stable since 1943. That is, the sandy entrance channel has always been formed within these bounds. Therefore, it is unlikely that the Hearns Lake channel would meander such that the subject property was placed at risk.

5.9.3 Analysis of Flood Tide Dropover Position

Similar to the analysis of vegetation lines presented in Section 5.6.3, the location of the flood tide dropover was digitised, to determine if there were any migratory trends. This was completed for the years of 1943, 1956, 1966, 1969, 1972, 1973, 1974 (June and August), 1980, 1986, 1993, 2000 (May and June) and 2002.

The position of the flood tide dropover position over the period 1943-1973 is shown in **Figure 27**, over the June 2000 aerial photograph. Similarly, the position of the interface from 1973-2002 is shown in **Figure 28**. Note that the 1969 dropover position was similar to 1966, there was no dropover evident in August 1974, and the 1993 dropover position was similar to 1986, so these three lines are not shown in the analysis. Also, the May and June 2000 dropover positions were similar, and are not shown in Figure 28 given that the June 2000 position is evident in the aerial photography.

It is evident that the flood tide dropover migrated upstream between 1943 and 1956, but was relatively stable between 1956 and 1973. Significant rainfall-runoff in 1974 caused the flood tide dropover to be scoured out. In June 1974, the dropover had substantially reduced in size compared to 1973, and by August 1974, had been completely removed. In 1980, the dropover was still virtually absent. However, by 1986, the dropover had grown substantially (but not to the extent of 1973), with the position being similar from 1986 to 2002.

These observations imply that tidal exchange is limited at Hearns Lake, which is usually closed. Furthermore, there is no evidence that there has been any alteration in the general coastal processes at the entrance over the last 60 years. For example, the entrance does not appear to be gradually becoming more choked with sand.

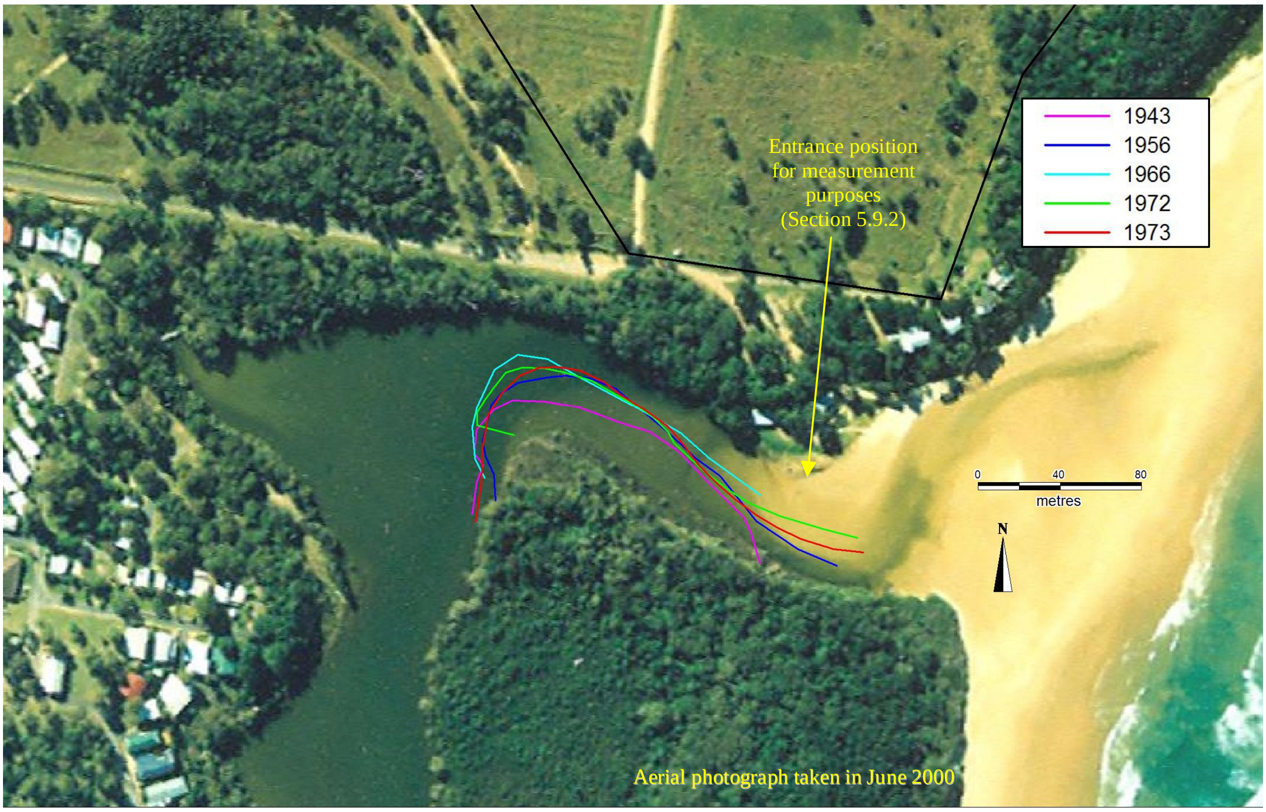

Figure 27: Position of flood tide dropover in Hearns Lake, 1943-1973

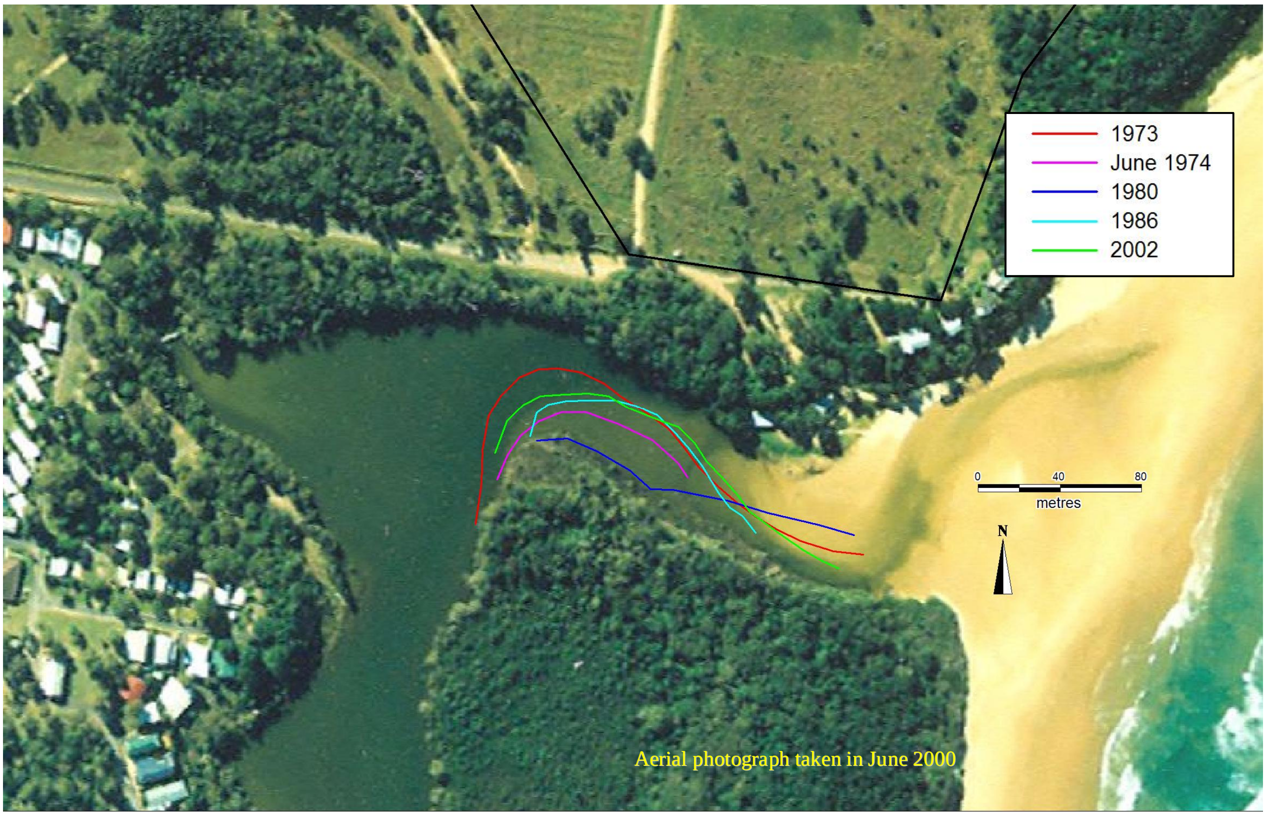

Figure 28: Position of flood tide dropover in Hearns Lake, 1973-2002

5.10 CLIMATE CHANGE

5.10.1 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) 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)[101].

The global average sea level rises predicted by the IPCC between 1990 and 2100 are shown in **Figure 29**. 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.

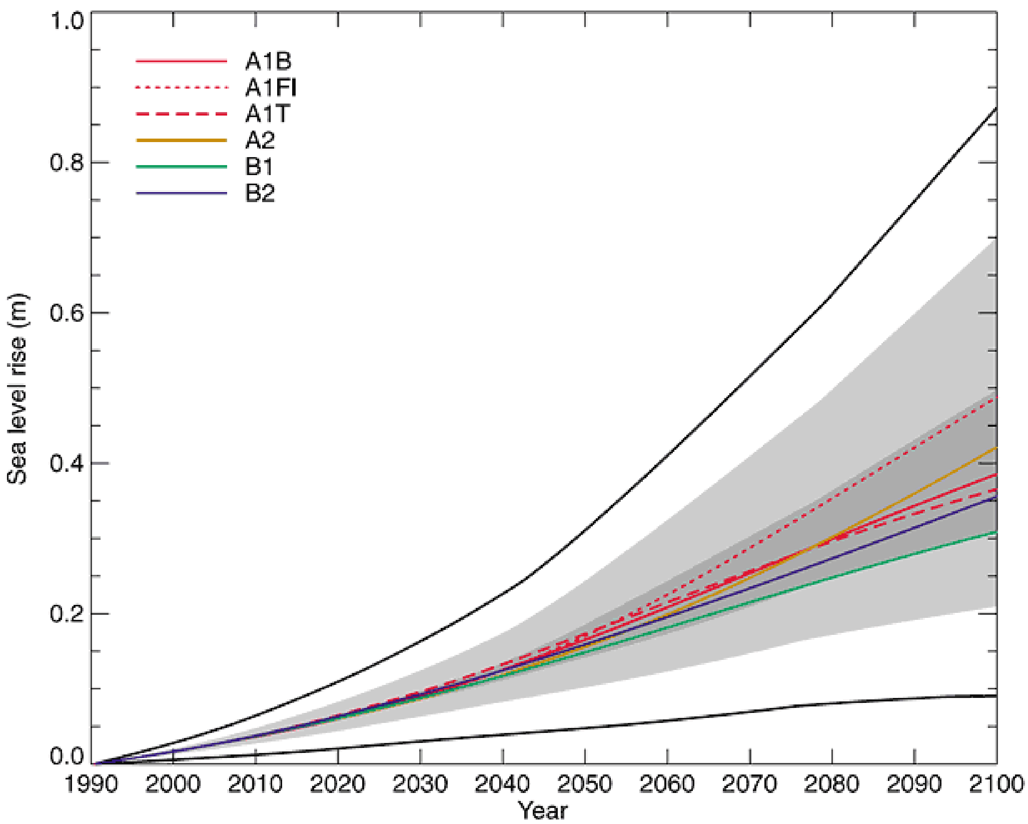

Figure 29: Global average sea level rise predicted due to climate change from 1990 to 2100, based on various emission scenarios (IPCC, 2001b)

[101] 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).

Based on IPCC (2001b), a brief summary of the inherent assumptions governing the six emission scenarios shown in Figure 29 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 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.

In Figure 29, 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 2054, 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 2054 was 0.2m, and the adopted sea level rise at 2104 was 0.5m[102]. 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 29.

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.

5.10.2 Other Climatic Change Considerations

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

102 The IPCC (2001b) estimates extend to 2100. The estimate at 2104 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.

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[103]. 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.

[103] 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 is 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 5.10.1. Also, the possibility of other effects caused by climate change, such as increases in storm intensities, was discussed in Section 5.10.2.

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.

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 1963 to 1983, 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 0.05m/year. This rate would largely 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):

$$R = \frac{S \times B}{h + d_c} \qquad (6)$$

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[104] 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

[104] 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[105].

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

$$d_c = 1.75 H_e \qquad (7)$$

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 Hearns Lake Beach), from Figure 12, H_e is about 4.8m. Therefore, the predicted depth of closure at Hearns Lake 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

[105] 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.

Palimpest 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 (2004) 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. Based on detailed bathymetric data, Patterson Britton & Partners (2004) 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 Hearns Lake Beach is limited. The hydrographic chart AUS 812[106] 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)[107].

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[108]. Bathymetric data collected for Woolgoolga Headland extended south, offshore of Woolgoolga Back Beach, for a distance of about 650m, and relatively close to the subject property. From this, it was evident that the –11m AHD depth of closure was at a distance of about 600m offshore[109]. Assuming that similar bathymetry existed offshore of Hearns Lake Beach, it was determined that the inverse slope of the active beach profile was about 40.

In Section 5.10.1, it was noted that the adopted sea level rise at 2054 and 2104 was 0.2m and 0.5m respectively. Using Equation 6, the long term recession due to sea level rise at 2054 and 2104 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[110]. 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.

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[106] 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.
[107] 1 fathom is equal to 6 feet.
[108] Flat Top Point was also investigated as an outfall site, but no bathymetric data was collected there.
[109] Note that there was evidence of a change of slope at around –11m AHD, providing some further confirmation that the depth of closure chosen was reasonable.
[110] 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 1943 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[111]. 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 1943 to 2004, this represented a sea level rise of 52mm 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 2.1m, 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 1943, which has occurred while the beach at the subject property has appeared to accrete, is an indication that the adopted recession rate of 0.05m/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[112] into the hinddune), and can result in abrasion, burial, blockage and damage to coastal developments (NSW Government, 1990).

[111] 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.

[112] 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).

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 (which has been continuously evident in aerial photography examined, taken since 1943).

However, it is 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 of at Hearns Lake 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.

It is recommended that, if possible, beach access be maintained via the northern shoreline at the entrance to Hearns Lake into the future, rather than attempting access directly through the dunes that are seaward of the subject property.

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 proposed development are above 9m AHD (Figure 8), and generally a few metres higher, 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.

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 Hearns Lake Beach at present. As part of the proposed development, this situation is not expected to be altered. That is, it is recommended that rainfall-runoff from the subject property is directed to Hearns

Lake, or the ephemeral wetland to the north-east of the subject property, to reduce the likelihood of additional coastal erosion.

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 30**.

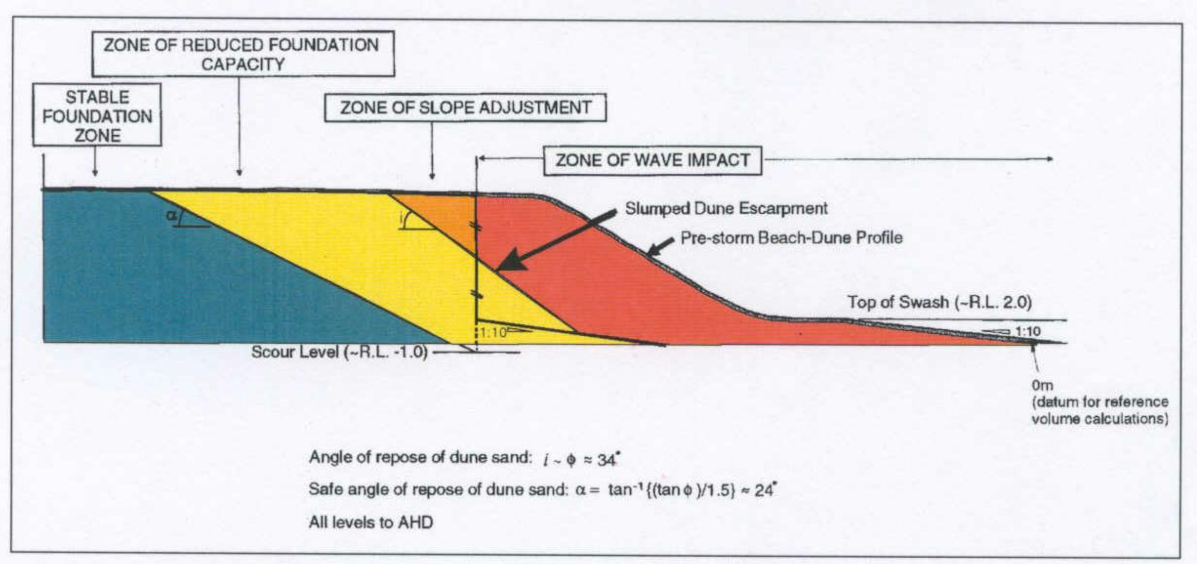

Figure 30: Schematic representation of coastline hazard zones (after Nielsen et al, 1992)

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 7, 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 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)[113]. 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 2004 Hazard Line, 2054 Hazard Line and 2104 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 2004, 2054 and 2104 respectively[114].

In **Table 10**, the components added to derive the final Hazard Lines are listed, with the 2004 Hazard Line determined as a volume removed from the 2004 survey profiles, which was the best estimate of current average beach full conditions within the study area. The volumes were applied as per Nielsen et al (1992), see Figure 30, at each of the survey profiles. Thus, at each profile, a position on the 2004 Hazard Line was determined.

Table 10: Coastline hazard components summed to determine 2004, 2054 and 2104 Hazard Lines

Component	2004	2054	2104
Beach erosion hazard (storm demand), m^3/m	200	200	200
Long term recession due to net sediment loss, m	0	2.5	5.0
Long term recession due to future sea level rise, m	0	8.0	20.0
Discounting due to historical sea level rise, m	0	0	0
TOTAL (m^3/m) *plus* (m)	200	200 10.5	200 25.0

In determining the Hazard Lines for 2054 and 2104, the 2004 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.

[113] The Zone of Wave Impact was also defined as part of the calculations, but is not depicted here.
[114] That is, the Hazard Lines do not represent future predicted shorelines, but future predicted erosion escarpments after a 100 year ARI coastal storm.

Landward of the 2004, 2054 and 2104 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 with the ZRFC would be considered to have an inadequate factor of safety. The 2004, 2054 and 2104 ZRFC Lines represent the predicted landward limit of this Zone in 2004, 2054 and 2104 respectively. The position of the ZRFC was determined as outlined in Section 6.8 in each case. The ZRFC was approximately 11m to 23m landward of the corresponding Hazard Line (17m in 2104), 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. Geotechnical engineering advice is recommended if foundations within the ZRFC are proposed.

The 2004 Hazard Line and ZRFC Line within the study area is shown in **Figure 31**, the 2054 Hazard Line and ZRFC Line is shown in **Figure 32**, and the 2104 Hazard Line and ZRFC Line is shown in **Figure 33**. These Figures include the proposed subdivision layout (as per the Reg Walters & Partners Drawing 03274-01, "Proposed Subdivision:- Lot 21 DP 714858, Hearnes (sic) Lake Road, Woolgoolga", 8 December 2003), with Lot numbers shown.

It is evident that the 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.

In 2104, a ZRFC extends over the southern eastern corner of the subject property (Lot 1). This is not considered to preclude development in this area, given that engineering solutions can mitigate the relatively small associated risks, and given the long planning period. Rather, it is recommended that for any development seaward of the ZRFC, detailed consideration of foundation conditions is made.

It is recommended that for any development seaward of the ZRFC, consideration be given to placement of structures on piers (spread footings or piles) extending into the Stable Foundation Zone as defined by Nielsen et al (1992), unless geotechnical conditions enable reduced foundation depths[115]. A geotechnical investigation in this localised area may be warranted, as it is considered possible that the extent of the ZRFC could be reduced by the presence of subsurface clay materials, which are present elsewhere on the subject property (Section 5.8). Reassessment of the ZRFC position could be undertaken after review of the results of any geotechnical investigation, if required.

[115] It is not considered necessary to stipulate that piers are essential. Given the relatively long 100 year planning period, it is recommended that the relative risks are weighed against the increased construction costs and nature of the development, in conjunction with DIPNR and Council.

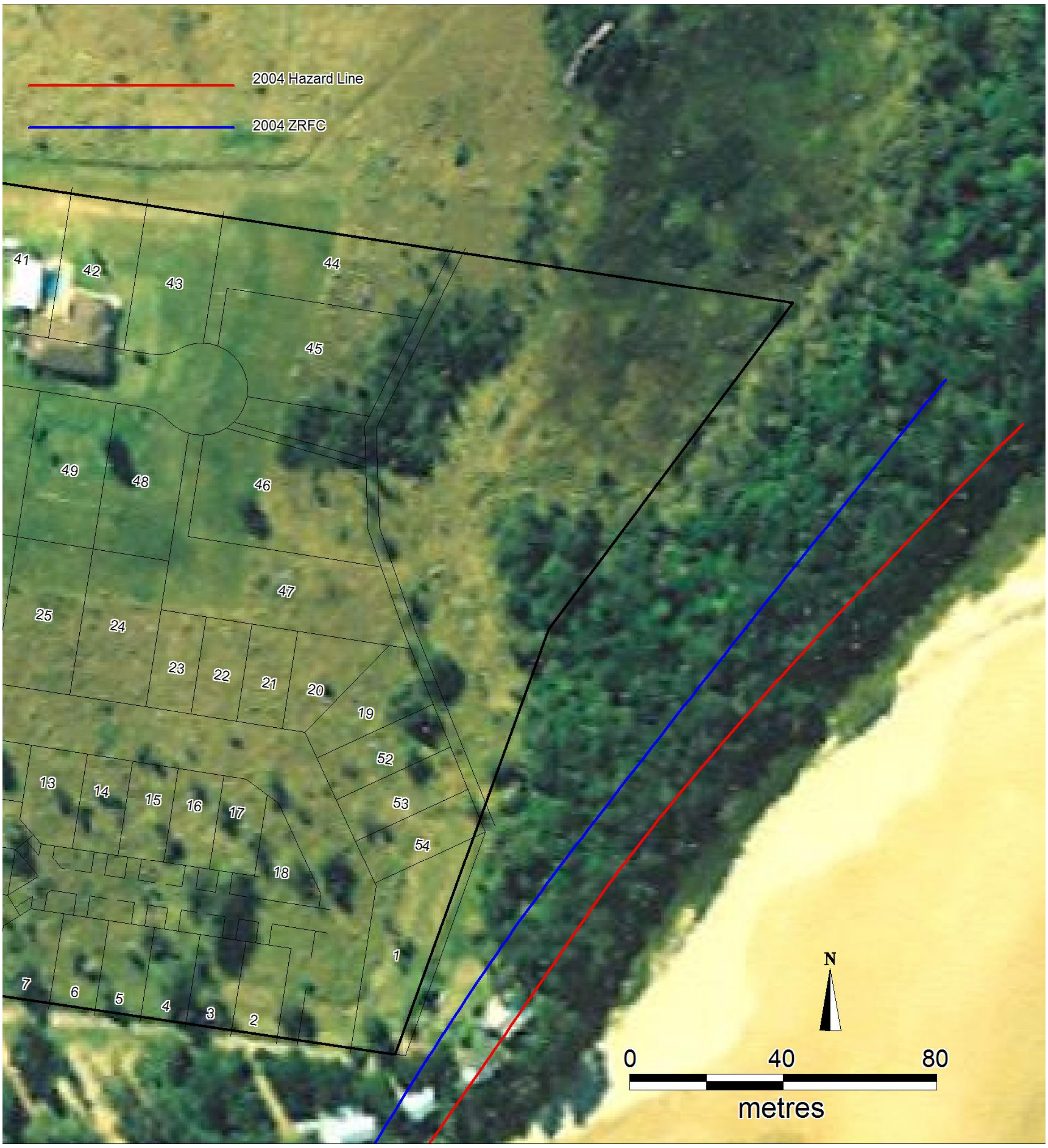

Figure 31: 2004 Hazard Line and Zone of Reduced Foundation Capacity (ZRFC) for subject property

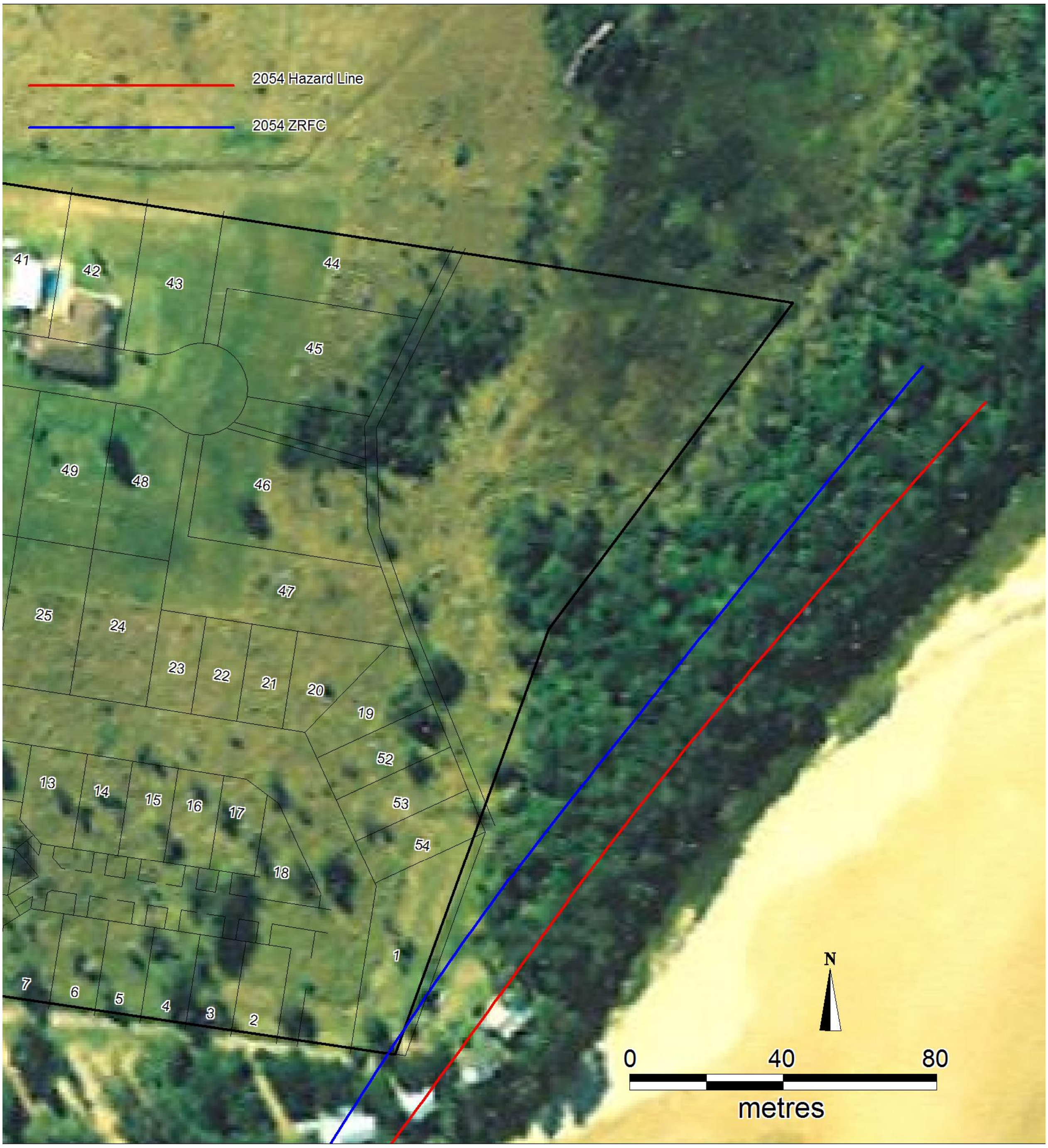

Figure 32: 2054 Hazard Line and Zone of Reduced Foundation Capacity (ZRFC) for subject property

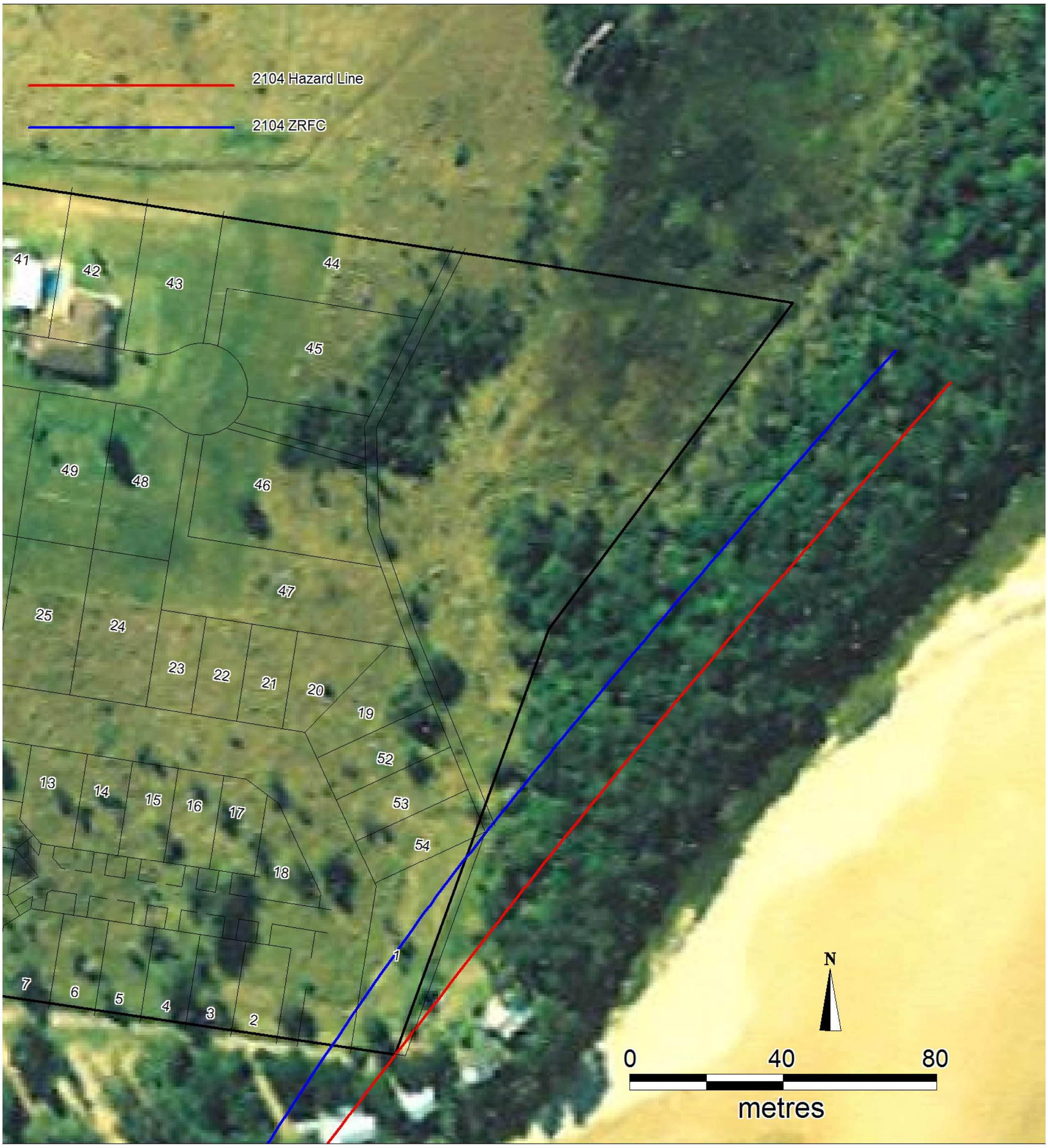

Figure 33: 2104 Hazard Line and Zone of Reduced Foundation Capacity (ZRFC) for subject property

8 ESTUARY CLASSIFICATION AND PROCESSES

8.1 NATIONAL LAND AND WATER RESOURCES AUDIT

As part of the National Land and Water Resources Audit [NLWRA] (2002), the condition of 979 estuaries and coastal waterways (including coastal lakes) around Australia were assessed. It was found that 50% were in near-pristine condition, 22% in largely unmodified condition, 19% in modified condition, and 9% in extensively modified condition.

NLWRA (2002), continuing the work of Heap et al (2001), also classified Australian estuaries and coastal waterways into 7 categories, based on the wave, tide and river energies that shaped them, and according to their overall geomorphology (linked to these main energy processes). It was found that:

- 35% were tidal creeks and flats;
- 17% were wave-dominated estuaries;
- 12% were tide-dominated estuaries;
- 10% were wave-dominated deltas;
- 9% were tide-dominated deltas;
- 5% were strandplains[116]; and,
- 12% were "other" types (drowned river valleys, embayments, and very small coastal lakes, lagoons and creeks[117]).

The condition and geomorphic classifications noted above, and other information, was incorporated into a national geoscience database, Ozestuaries (http://www.ozestuaries.org/). Within this framework, Hearns Lake (Estuary 794) was classified as having a "largely unmodified" condition, with estuary modifiers being noted as urban land use, and clearing of 65% of the catchment natural cover. It was also classified as being "wave dominated", in the "other" category. This latter classification was presumably because as a small coastal lake or lagoon, Hearns Lake has low to negligible river input[117], and is therefore usually closed, with limited tidal exchange (compared to a typical wave dominated estuary).

Heap and Harris (2002) considered that the geomorphic classifications could assist in determining the susceptibility of different types of coastal waterways to environmental issues such as sediment trapping, turbidity, poor water quality and circulation, and habitat loss and change due to sedimentation. For a Lagoon such as Hearns Lake, it was considered that it had high sediment trapping efficiency (with sediment generally trapped in the central basin), naturally low turbidity, negative/well-mixed circulation (due to negligible river inputs), a high risk of habitat change due

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[116] A strandplain is a series of dunes, typically associated with and parallel to a beach, and sometimes containing one or more small creeks or lakes (Ryan et al, 2003).
[117] Wave-dominated estuaries are also colloquially known as "coastal lakes" or "lagoons". However, Heap et al (2001) considered the latter to be forms of wave-dominated estuaries which were characterised by low to negligible river input.

to sedimentation, and high susceptibility to contaminants (due to the sediment trapping efficiency and relatively low dispersion and dilution).

8.2 RYAN ET AL (2003)

Ryan et al (2003) built on the work completed for the NLWRA (Section 8.1), presenting conceptual models of the biophysical processes that operated in a wide range of estuaries and coastal waterways found around Australia. They used a similar (7 category) geomorphic classification as per NLWRA (2002), but removed the "other" classification, grouping coastal lagoons with strandplains, and having a separate category for embayments / drowned river valleys.

Hearns Lake was classified as a coastal lagoon / strandplain. Compared to wave dominated estuaries, coastal lagoons were considered to have a relatively greater proportion of wave energy versus river energy[118]. Characteristics of coastal lagoon / strandplains that were noted included:

- very little freshwater and river-sediment input;
- no fluvial delta;
- dominant low energy central basin, which was an efficient trap for terrigenous sediment and pollutants (susceptible to wind-wave resuspension in shallow basins);
- intermittent entrance, often closed, with tides attenuated / excluded for long periods;
- entrance characterised by barrier and tidal delta deposits;
- naturally low turbidity;
- slow infilling, dominated by marine-derived sediment when the entrance is open; and,
- supported habitats limited by chemical conditions induced by poor exchange with the marine environment, and highly variable salinity.

In order to account for seasonality and climatic variation in the estuarine conceptual models, Ryan et al (2002) classified estuaries as either positive (freshwater-dominated) or negative (evaporation-dominated). Hearns Lake was classified as annual positive (that is, freshwater-dominated without strong seasonality).

With regard to the nutrient nitrogen, Ryan et al (2003) emphasised that catchment-derived sources of nitrogen were generally less important in coastal lagoons, with significant input typically only occurring during extreme rainfall events. Groundwater inputs, and input of particulate nitrogen from atmospheric sources such as smoke and ash was considered to be significant. Long residence time was considered to encourage trapping and processing (such as denitrification) of terrigenous nutrient loads, however the system was seen to be potentially susceptible to overloading due to its small size.

8.3 HEALTHY RIVERS COMMISSION

The Healthy Rivers Commission [HRC] (2002) developed a number of principles for managing coastal lakes, including that:

- each coastal lake and its catchment be managed as a whole system; and,

[118] Coastal lagoons / strandplains are essentially wave dominated estuaries with negligible fluvial input.

- management actions addressed the unique characteristics and interrelationships of ecosystems and human activities for each lake, taking into account the degree of existing modification and the conditions sought.

HRC (2002) classified Hearns Lake as having a high natural sensitivity[119], severely modified catchment condition[120], moderately affected lake condition[121], moderate recognised conservation value[122], and healthy modified conditions[123]. Based on the latter classification, different management frameworks were developed.

For the "healthy modified conditions" management orientation, as applied to Hearns Lake, it was recommended that opportunities were determined to harness new development to offset the impacts of existing development, as indeed is proposed for the subject development (see below). Recommended management actions included:

- applying and enforcing controls for new development, to keep their impacts on lake/catchment health within limits that are determined to be sustainable for each lake (as discussed in Section 9, this is indeed proposed for Hearns Lake);
- requiring any new assets that are prone to water damage, significant inconvenience, or which may exacerbate public health problems when lake water levels are high, to be designed in ways that do not necessitate opening a lake entrance artificially (with some exceptions)[124];
- progressively implementing an integrated, cost effective program to mitigate the impacts of all existing sources of wastewater; and,
- encouraging the use of best farming and forestry practices commensurate with the risks to lake/catchment health.

Consistent with the above, as noted in Section 9.1, it has been proposed to connect the nearby Caravan Park, which has a septic system that discharges directly into Hearns Lake, with the sewerage system. This goes beyond the indicative action for "healthy modified conditions"; in fact, removal of sewage discharges and overflows from existing sewerage and on-site systems was only recommended for the "comprehensive protection" management orientation[125]. Furthermore,

[119] This related to the sensitivity to human activities, such as potential pollutant inflows and flushing capacity. The descriptors used were "high", "very high" and "extreme".
[120] This related to the extent of land clearing, and land use types. The descriptors used were "near pristine", "largely unmodified", "modified", and "severely modified".
[121] This related to the existing condition of the waterbody, in particular with regard to water quality problems and fish kills. The descriptors used were "unknown", "pristine", "slightly affected", "moderately affected" and "severely affected".
[122] This descriptor related to presence of threatened species, uniqueness, commercial values and reserves. The descriptors used were "low", "moderate" and "high".
[123] Each coastal lake was classified into one of four management orientation classes, namely "comprehensive protection", "significant protection", "healthy modified conditions" and targeted repair".
[124] The proposed development would not be expected to be impacted by high lake water levels, such that there would be pressure to open the entrance artificially.
[125] The HRC (2002) noted that "Areas around coastal lakes are highly sought after places to live, work and play. New development provides some opportunity to drive remedial actions, by providing additional revenue for funding works such as reticulated sewerage to existing urban areas and/or raising the level of buildings in flood prone areas".

it has been proposed to seal Hearns Lake Road, which is an indicative action for the "significant protection" management orientation[126].

For the four possible management orientations suggested by HRC (2002), it was considered that managers' discretion in determining outcomes and actions for specific lakes was greatest for those lakes classified as "healthy modified conditions" (as applies at Hearns Lake), given the "potential capability of many such systems to sustain some further development, and often, the presence of human factors that entrench their status".

With regard to entrance opening, HRC (2002) expected that for coastal lakes classified as "healthy modified conditions" (as applies at Hearns Lake), "present land use and economic implications typically removed the possibility of returning to a natural entrance regime". As noted in Section 9, the proposed development, and proposed development at 1 Hearns Lake Road, has been designed to provide no increase in pollutant loads compared to existing conditions. Therefore, it would not be expected that pressure for manual lake opening would exist as a result of the proposed development. This goes beyond the expectation of HRC (2002), where it was noted above that natural entrance regimes were less likely for lakes in this condition.

Overall, HRC (2002) suggested that water quality problems were better contained at the source, as opposed to artificially entrance opening, which is agreed with.

8.4 ROY ET AL (2001)

Roy et al (2001) classified eastern Australian coastal water bodies into 5 groups, with various types in each group. The 5 groups were:

I. Bays (with Type 1 – ocean embayments);
II. Tide-dominated estuaries (with Type 2 – funnel-shaped macrotidal estuaries, Type 3 – drowned valley estuaries, and Type 4 – tidal basins);
III. Wave-dominated estuaries (with Type 5 – barrier estuaries, Type 6 – barrier lagoons, and Type 7 – interbarrier estuaries);
IV. Intermittent estuaries (with Type 8 – saline coastal lagoons, Type 9 – small coastal creeks, and Type 10 – evaporative lagoons); and,
V. Freshwater bodies (with Type 11 – brackish barrier lake, Type 12 –perched dune lake, and Type 13 – backswamp).

Roy et al (2001) classified Hearns Lake as being Type IV/8, that is an intermittently closed estuary (saline coastal lagoon[127]), having intermittent entrance conditions (closed and open), and being at an intermediate evolution stage (Stage B)[128].

Roy et al (2001) also recognised four zones in each estuary, namely the marine flood-tidal delta, central mud basin, fluvial delta and riverine channel/alluvial plain. These zones were considered to correspond to mappable sedimentary environments in all estuaries, and to have characteristic water quality, nutrient cycling and primary productivity signatures and ecosystems. The ecology

[126] The indicative action was to "mitigate sediment runoff from high risk sections of unsealed roads (such as sealing those sections with erodible, nutrient rich and acidic soils, particularly adjacent to water courses) and other sources.
[127] Glover (2004) noted that the salinity of Hearns Lake was, on average, about 24ppt.
[128] Evolution stages were categorised as A (youthful), B (intermediate), C (semi-mature) and D (mature).

of a zone was found to be modified by estuary type (which determines the salinity regime), stage of sediment filling (or evolutionary maturity, which controls the spatial distribution/size of the zones), and impacts of various forms of development.

8.5 ICOLL CONSIDERATIONS

Hearns Lake is an Intermittently Closed and Open Lake or Lagoon (ICOLL). There are two classes of estuaries based on their entrance characteristics, namely those that are permanently open, and those that are ephemeral or intermittent in their opening state. For intermittently open estuaries, there are two further groupings, namely ICOLL's, or Seasonally Open Tidal Inlets (SOTI's). ICOLL's and SOTI's are also known as coastal lagoons, that is shallow coastal water bodies separated from the ocean by a barrier, connected at least intermittently to the ocean by one or more restricted inlets, and usually oriented shore-parallel (Pattiaratchi, 2001).

Pattiaratchi (2001) noted that ICOLL's occur in microtidal, wave dominated coastal environments where strong seasonal changes of littoral transport and/or rainfall are experienced. They were closed to the ocean due to the formation of a sand bar at the inlet entrance when the streamflows were low and/or longshore transport was high. The sand bar was eroded when the river discharges were high and the inlet thus opened to the ocean.

Pattiaratchi (2001) considered that the closure of the entrance reduced the flushing of the lake/lagoon which could lead to poor water quality. With increased anthropogenic impacts, primarily through increased nutrient inputs arising from land, there was concern that many of these water bodies would become eutrophic and possibly affected by other land-borne contaminants.

Circulation and mixing characteristics of ICOLL's are different to those of permanently open estuaries because of their location where tidal range and energetics are small. Usually the estuary is connected to the ocean via a narrow (less than 200m wide) and shallow (less than 5m deep) inlet channel. Hence, there is severe attenuation of the tide (by up to 90%) as it propagates into the estuary, mainly due to frictional energy losses. This causes the tidal velocities in the estuary to be small when the inlet is open. In general, tidal velocities in ICOLL's may be expected to be significantly less than those in a permanently open estuary and this influences vertical mixing (Pattiaratchi, 2001).

Roy (1984) classified estuaries into three categories based on their entrance conditions, namely as drowned river valley estuaries, barrier estuaries, and saline coastal lakes. Saline coastal lakes fall into the ICOLL category, and were described as small features located in coastal valleys, with:

- shallow mud basins and muddy fluvial deposits being the dominant sedimentary environments;
- very small fluvial input;
- saline to brackish (but non tidal) lake waters under most conditions;
- winds causing mixing and some transport in the larger lakes;
- normal freshwater inputs accommodated by evaporation and percolation through the porous sand barrier; and,

- fresh water conditions accompanying heavy rains causing inlet breaching by super-elevated lake waters and storm waves, the lake then becoming saline and tidal for weeks to months until open ocean processes reformed the beach berm across the inlet[129].

Ryan et al (2003) considered that both wave dominated estuaries and coastal lagoons / strandplains (Section 8.2) were also ICOLL's. Scanes et al (2002) considered that, in terms of geomorphology, ICOLL's were wave dominated barrier estuaries (presumably Type III/5 of Roy et al, 2001), which were characterised by being shallow, having limited riverine input, and closing readily as a result. This classification was somewhat inconsistent with Hearns Lake being specified as Type IV/8 by Roy et al (2001).

Scanes et al (2002) also noted that since ICOLL's retain much of the catchment/riverine inputs they receive, they were susceptible to ecological disturbance due to pollution.

[129] The rate of infill of entrances after floods is dependent on wave conditions, typically taking from days to months. Therefore, after floods, an entrance can be a sink for sediment.

9 WATER QUALITY AND RELATED ENTRANCE ISSUES

9.1 DIPNR CONCERNS

Concerns have been raised by DIPNR relating to the impact of the proposed development, and proposed development at 1 Hearns Lake Road, on the water quality in the receiving waterbody of Hearns Lake. One particular concern noted was the potential pressure from residents to manually open Hearns Lake in the future, due to odours and/or poor water quality in the lake[130].

Hearns Lake functions as an Intermittently Closed and Open Lake or Lagoon (ICOLL). It is the nature of ICOLL's to remain closed for prolonged periods, during which flushing is therefore restricted and nutrients may build up in the waterbody. It is understood that this may introduce the potential for algal blooms and eutrophication (Section 9.2), which would have a negative impact on both the ecology and amenity of the waterbody. Amenity could also be affected by odours as discussed in Section 9.3.

Therefore, for this development, the key water quality issue relates to pollutant loads exported from the subject site to Hearns Lake. A thorough investigation of pollutant exports associated with the proposed development was undertaken by Gilbert and Sutherland (2003) as discussed in Section 9.4. For 1 Hearns Lake Road, a similar investigation was undertaken by Gilbert and Sutherland (2004).

Gilbert and Sutherland (2003, 2004) concluded that under developed conditions, with treatment measures in place, there would be no increase in pollutant loads exported from the subject site, or 1 Hearns Lake Road, compared to existing conditions. Therefore, if these sites were developed according to the modelling assumptions, the long term water quality impact of developing the sites would be negligible.

This being the case, it is recommended that DIPNR and Council work with the developer to ensure that the proposed water quality management strategies achieve the proposed objectives, so that Hearns Lake water quality is not adversely affected.

In fact, from a development point of view, human activities, such as tourism, would depend on Hearns Lake being healthy. That is, it would be a disadvantage for the developer if the water quality of Hearns Lake deteriorated.

There are other issues in the Hearns Lake catchment that require attention from a water quality perspective. For example, the Caravan Park adjacent to the lake is not connected to the sewerage

[130] Specific written comments were sought from DIPNR on numerous occasions over a period of about 2 months, but had not been provided at the time of finalising the investigation reported herein. Water quality data collected at Hearns Lake was also requested on numerous occasions, along with the results of entrance analyses that had been undertaken, but was also not provided.

system, utilising septic tanks for wastewater treatment. The septic system is known to directly overflow into Hearns Lake. It has been proposed to connect the Caravan Park to the sewerage system in conjunction with the proposed development. Again, it is recommended that DIPNR and Council work with the developer (and Caravan Park management) to ensure that this significant water quality benefit is achieved[131].

Pressure to manually open Hearns Lake may also come due to flooding concerns. This would not be expected to be related to the proposed development, or development at 1 Hearns Lake Road, which are both located well above the 100 year ARI flood level. However, no new assets should be located along the foreshore of Hearns Lake that, due to risks of flooding, would lead to pressure for manual entrance opening.

9.2 EUTROPHICATION

Surface waters cannot support aquatic life if excess nutrients are present. Eutrophication associated with human activities, primarily caused by nitrogen and phosphorus, can lead to algal blooms, low dissolved oxygen, fish kills, cloudy murky water, and depletion of desirable flora and fauna. Scanes et al (2002) found that input control of nutrients was the most important factor in controlling algal populations.

Wilson et al (2002) noted that flooding was the overriding consideration in the decision to artificially open most coastal lagoons in NSW. However, they presented a case study that indicated that an artificial entrance opening at Cockrone Lagoon on the NSW Central Coast caused a sudden decline in water quality and a fish kill. This was related to the lake being eutrophic at the time of opening[132].

That is, even if pressure to artificially open Hearns Lake to improve water quality was mounted (eutrophication being a possible cause) , it can be postulated that water quality may indeed not be improved, also related to the likelihood that the entrance would close relatively quickly.

9.3 CAUSES OF ODOURS

Odours in coastal lakes such as Hearns Lake can be caused by:

- vegetation as it dries and decays; and,
- release of hydrogen sulfide (H_2S), known as “rotten egg gas”, to the atmosphere, generated within lake sediments.

Odours problems related to H_2S have been noted at Lake Wollumboola on the NSW South Coast (WBM, 2002). H_2S is naturally produced by sulfate reducing bacteria within the anoxic zones of

[131] It was also noted in Section 8.3 that there may be a benefit in the proposed sealing of Hearns Lake Road.

[132] The fish kill was caused by anoxia associated with the decomposition of large quantities of filamentous algae that resulted from excess nutrients. Wilson et al (2002) noted that anoxic conditions could also be caused by: opening entrances when the lake was stratified and the deeper layers were deoxygenated, leaving only deoxygenated water after draining; and, opening lakes when dissolved oxygen levels in surrounding wetland areas were low. These anoxic conditions were considered to be more likely when exchange with the ocean, dilution with freshwater inflows and/or wind mixing was not sufficient to replenish the oxygen in the entire water body.

all marine sediments[133]. This H_2S usually combines rapidly with dissolved oxygen in the water to form odourless and harmless sulfate compounds. However, if there is more H_2S than available oxygen, the remaining H_2S escapes to the atmosphere.

At Lake Wollumboola, it was considered that H_2S was constantly being generated within the lake sediments, but was usually contained with the bottom waters of the lake due to stratification. When the lake became destratified, H_2S that had built up within the bottom waters of the lake mixed throughout the water column, generating a massive oxygen demand as it oxidised back to sulfate, and with the depletion of dissolved oxygen, generating H_2S to the atmosphere[134].

WBM (2002) noted examples of conditions under which different estuaries released H_2S to the atmosphere, including nutrient enrichment from sewage discharges and catchment runoff. H_2S can also be directly released to the atmosphere when lakes dry out, and sulfate reducing sediments are exposed.

Based on an understanding of these processes, it would not be sensible to manually open Hearns Lake if an H_2S release occurred, as conditions allowing the formation of the gas would most likely be exacerbated[135]. The best control over odour risks would be catchment management to limit the inflow of sediment and nutrients into the lake, and education of local residents.

Therefore, ensuring that the proposed developments do not increase pollutant loads in themselves, as well as promoting catchment improvements by (for example) connecting the nearby Caravan Park to the sewerage system, would be the logical way forward.

9.4 REVIEW OF GILBERT AND SUTHERLAND (2003) FOR SUBJECT PROPERTY

9.4.1 General

To minimise impacts associated with development, a water management strategy is generally developed. For Masterplan purposes, Gilbert and Sutherland (2003) prepared such a strategy for the subject property. Both stormwater detention (quantity management) and water quality control were considered, as discussed in Sections 9.4.2 and 9.4.3 respectively.

9.4.2 Stormwater Quantity Management

No measures were specifically proposed by Gilbert and Sutherland (2003) to maintain stormwater flows generated at the subject property. Whether on-site detention is required for the site would be a matter for determination by Coffs Harbour City Council.

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133 In the absence of dissolved oxygen (anoxia), organic matter decomposes via the process of sulphate reduction. This process produces H_2S and consumes SO_4^{2-} (Murray et al, 2002). In coastal and estuarine waters, the majority of organic matter feeding this sulfate reduction is derived from micro and macro algae.

134 Low dissolved oxygen conditions were found to be most likely when lake levels were low and/or macroalgae was abundant.

135 This is not only because of direct exposure of sediments, but also because shallow lakes are more likely to be destratified due to wind-driven mixing. At Lake Wollumboola, WBM (2002) also considered that destratification could be caused by density inversion, that is, evaporation of surface waters leading to increased surface salinity and therefore density, which sinks through the water column, causing bottom waters to rise.

In many coastal areas, detention for infrequent storm events is undesirable, given the location close to the outlet of a major watercourse. It is generally preferable to promote flow from such sites to discharge undetained, so that the volume of water generated has been conveyed away before the peak flow of the major watercourse reaches the outlet.

However, given that most of the runoff from the subject property will be eventually discharged into Hearns Lake, some consideration of detention may be reasonable. This is because it would be undesirable to alter the hydrology of Hearns Lake such that entrance breakouts occurred more frequently (which may have further implications for aquatic ecology).

Hydrological investigations were not undertaken for the subject property, however it is reasonable to assume that some detention would be available in the water quality treatment measures proposed (rainwater tanks, bioretention swales and artificial wetland, discussed further in Section 9.4.3).

9.4.3 Water Quality Management

The water quality management strategy proposed by Gilbert and Sutherland (2003) for the subject property was to maintain pollutant export levels at current rates. This was to be achieved through implementation of the following water quality treatment measures:

- capture and re-use of roof runoff in rainwater tanks;
- at source treatment of road runoff in bioretention swales;
- a gross pollutant trap (GPT) prior to discharge from the pipe drainage system to an artificial wetland; and,
- an end of line artificial wetland for treatment prior to discharge to Hearns Lake[136].

The recommended rainwater tank size was 4,000L per household. Analyses have shown that increasing the tank size above 4,000 L does not generally lead to significant improvements in water saving and water quality, particularly when weighed against capital costs (Coombes, 2004). Increasing the rainwater tank size above 4,000 L would only be beneficial for water quality purposes if significant reuse of rainwater was instigated.

The proposed bioretention swales comprised about 3% of the site area and the wetland comprised about 0.5% of the total site area. These proportions were consistent with expected treatment requirements. The design parameters for the bioretention swales and wetlands generally conformed to industry best practice.

Water quality modelling (using AQUALM-XP) was undertaken by Gilbert and Sutherland (2003) to assess the effectiveness of the treatment measures. Suspended solids, total nitrogen and total phosphorus were simulated, using historical daily rainfall data for dry, median and wet years. Three cases were considered, namely:

- undeveloped state (existing conditions);
- developed state without treatment; and,

[136] Given that soils at the site are generally clayey (Section 5.8), infiltration measures would not be recommended without further investigations into soil hydraulic properties.

- developed state with treatment (post-development conditions)[137].

The reduction in pollution associated with the proposed treatment measures (for a median year, compared to the developed case without treatment) was 82% for suspended solids, 43% for total nitrogen, and 48% for total phosphorus. These rates are consistent with typical pollutant removal efficiencies found in available literature on water quality treatment measures.

Compared to existing conditions, the reduction in pollution associated with the development (including the proposed treatment measures, for a median year) was 19% for suspended solids, 10% for total nitrogen, and 6% for total phosphorus.

9.4.4 Suggestions for Later Design Stages

It is considered that the water quality modelling presented by Gilbert and Sutherland (2003) provided sufficient accuracy at this stage. In this Section, suggestions for later design stages are given.

Consistency of the final design with the modelling assumptions would be of critical importance to the success of the water quality control measures in reducing pollutant loads to existing levels. In particular, it is noted that the pollutant removal efficiencies for the GPT were relatively high. While these efficiency rates are not unrealistic, it is important that the actual GPT chosen meets the design criteria modelled. Also, the pollutant removal efficiencies for bioretention were not detailed, and could be provided in subsequent design stages.

In the water quality modelling, hydrologic and pollutant concentration parameters used were adopted based on Brisbane City Council data, which is considered an acceptable initial approach for the subject site, given that detailed data for the region was not available. However, justification for use of this data was not given by Gilbert and Sutherland (2003), and further details could be provided in later design stages. In particular, available geotechnical data could be related to the hydrologic parameters. Accuracy of the modelling could also be improved by using 6 minute pluviograph data, which is available for Coffs Harbour.

The volumetric runoff coefficient, C_v, is a measure of the volume of rainfall over a catchment area which is converted to runoff, typically for an average year. It is given by the annual volume of runoff divided by the volume of rainfall. Catchments with high perviousness, such as forests, tend to have relatively low C_v values, while highly impervious catchments with hard surfaces have relatively high C_v values. There are no specific targets for C_v (as there are for water quality or quantity), rather it is a indicator of the accuracy of other calibration parameters[138].

For a median year, C_v for existing conditions was about 0.27. Under developed conditions without treatment, C_v was approximately 0.31, which is considered to be relatively low[139]. For post development conditions, C_v was again 0.31, with a negligible reduction through the

[137] Assumptions and inclusions for the "developed state without treatment" model, and how it differed from the "developed state with treatment" model, were not stated by Gilbert and Sutherland (2003).
[138] If C_v is outside an expected range, hydrologic parameters require revision.
[139] It would be expected that introduction of significant impervious areas across the site would increase C_v by a greater amount.

introduction of treatment measures[140]. This is unusual, and could be examined in future design stages[141].

Water balance analysis was carried out to estimate the reduction in runoff generated through the installation of rainwater tanks and rainwater reuse. Average rainwater reuse demand for external uses (sprinklers, hand held hoses and car washing) was estimated as 345 L/household/day. This value was adopted from Brisbane City Council water usage data, but may be an overestimation of water demand for this site given the intermittent nature of occupancy of tourist accommodation[142].

Additional options for rainwater reuse, such as toilet flushing and automated irrigation systems, could be investigated for inclusion in the water management strategy. NSW Department of Health guidelines should be complied with when determining possible reuse options. If sufficient rainwater is not reused, the rainwater tanks would remain full and not be available to capture additional water. This would mean a reduction in the pollution reduction rates.

A reduction factor of 65% was applied to runoff from roofs in the water quality model. The basis for this is uncertain given that it was stated elsewhere that rainwater tanks would reduce runoff by only 28%, not the 35% required to give the applied factor of 65%. Furthermore, rainwater tank behaviour could be more accurately modelled by simulating actual tank volumes and daily reuse data, rather than a factor approach.

There is alternative water quality modelling software that could be used (if required) to model the annual variation in rainwater reuse demand and actual rainwater tank storage volumes available. One such model is the Model for Urban Stormwater Improvement Conceptualisation (*MUSIC*) produced by The Cooperative Research Centre for Catchment Hydrology.

9.4.5 Overall Assessment

Although it was not possible to confirm the accuracy of the modelling in detail, the overall water management strategy appeared to be in accordance with industry best practice.

In general, the treatment train approach developed is commended, and the approximate sizes of treatment measures proposed appeared reasonable. It is anticipated that revision to proposed treatment measures as a result of any more detailed investigations would be minor, and could be accommodated within the site layout[143].

If found to be necessary, possible changes to the water management strategy would be to:

- increase the area (length and/or width) of bioretention swales alongside roads; and/or,
- introduce bioretention basins within lots or communal landscaped areas.

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[140] C_v decreased from 0.314 to 0.309 through the introduction of treatment measures.
[141] It is suggested that hydrologic parameters may require revision to achieve a higher "developed state without treatment" C_v. If this C_v is underestimated, treatment measures may be less than required in practice.
[142] The value may need to be revised to take into account the high annual variation in water consumption found in coastal tourist areas.
[143] Note that the subdivision layout adopted by Gilbert and Sutherland (2003) was different to the layout proposed in the Masterplan. Therefore, some future refinements may be required for this reason alone.

Also, as noted in Section 9.4.2, some on-site detention may be desirable to minimise the impact on the hydrology of Hearns Lake.

9.5 REVIEW OF GILBERT AND SUTHERLAND (2004) FOR NEARBY 1 HEARNS LAKE ROAD

As noted in Section 1, BBK engaged Patterson Britton & Partners to consider water quality issues in relation to a development at 1 Hearns Lake Road, in conjunction with examination of these issues for the subject property at 45 Hearns Lake Road. Similar to the subject property, a water management strategy was also developed for 1 Hearns Lake Road (Gilbert and Sutherland, 2004), and:

- No specific measures were proposed to maintain stormwater flows generated at the subject property. Given that most of the runoff from the subject property will eventually be discharged into Hearns Lake, some consideration of detention may be reasonable (refer Section 9.4.2).

- Proposed water quality treatment measures comprised a GPT, prior to utilising an existing low lying wetland. It was noted that the lot layout was not conducive to the use of "at source" stormwater quality treatment measures, hence the use of end of line controls.

- It is reasonable to assume that a limited quantity of detention may be available in the wetland.

- Rainfall, evaporation and temperature data were obtained from records kept for Coffs Harbour, rather than Ballina as used for 45 Hearns Lake Road, which could be considered to be more representative.

- The existing wetland (within the 1 Hearns Lake Rd property) comprised about 1.1% of the total site area. This proportion is less than expected would be required to meet treatment requirements. However, the wetland extends via a weir into the adjacent property to the east, which would provide additional treatment that was not accounted for.

- The reduction in pollution associated with the proposed treatment measures (for a median year, compared to the developed case without treatment) was 79% for suspended solids, 39% for total nitrogen, and 46% for total phosphorus. These rates are consistent with typical pollutant removal efficiencies found in available literature on water quality treatment measures.

- Compared to existing conditions, the reduction in pollution associated with the development (including the proposed treatment measures, for a median year) was 18% for suspended solids, 8% for total nitrogen, and 6% for total phosphorus.

- For a median year, C_v for existing conditions was about 0.32. Under developed conditions without treatment, C_v was approximately 0.36, which is considered to be relatively low. For post development conditions with treatment, C_v was 0.37. The increase in C_v with the introduction of treatment measures is considered to be unusual.

- It was concluded that the proposed treatment measures have the capacity to significantly reduce the suspended sediment and nutrient loads to a level comparable or below those from the current land use, hence achieving a “no worsening” criteria.

- Consistency of the final design with the modelling assumptions would be of critical importance to the success of the water quality control measures in reducing pollutant loads to existing levels. In particular, it is noted that the pollutant removal efficiencies for the GPT were relatively high. While these efficiency rates are not unrealistic, it is important that the actual GPT chosen meets the design criteria modelled[144].

- For later design stages, accuracy of the modelling could also be improved by using 6 minute pluviograph data, which is available for Coffs Harbour.

- In the main Masterplan report (Smyth Maher & Associates Pty Ltd, 2004), reference was made to runoff from the west of 1 Hearns Lake Road being collected via bio-absorption trenches, and rainwater tanks being installed to all residences. These aspects were not discussed in Gilbert and Sutherland (2004).

- Capturing runoff along the western boundary of 1 Hearns Lake Road in bioretention swales, as is intended, would lead to treatment of runoff not generated from the development site.

- In general, the approximate sizes of treatment measures appeared to be relatively low, ignoring the contribution of the additional wetland area to the east. Revision to proposed treatment measures as a result of any more detailed investigations may be required, such as increasing the wetland volume (depending on its overall capacity when the wetland area outside of the 1 Hearns Lake Road site is considered), installation of additional bioretention swales along roads, and introduction of bioretention basins within lots or communal landscaped areas. Rainwater tanks may also be considered.

[144] Smyth Maher & Associates Pty Ltd (2004) stated that the GPT would reduce the quantity / volume of stormwater runoff. This is not the case, with GPT’s only reducing pollutant loads, not overall volumes.

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 was because the coastline Hazard Line, representing the landward limit of the Zone of Slope Adjustment, was seaward of the subject property for all planning periods up to 100 years, that is at 2104 (refer to Figure 33).

In 2104, a Zone of Reduced Foundation Capacity (ZRFC) was predicted to extend over the southern eastern corner of the subject property. This was not considered to preclude development in this area, given that engineering solutions could mitigate the relatively small associated risks, and given the long planning period. Rather, it was recommended that for any development seaward of the ZRFC, consideration be given to placement of structures on piers (spread footings or piles) extending into the Stable Foundation Zone, unless geotechnical conditions enabled reduced foundation depths. A geotechnical investigation in this localised area may be warranted, as it was considered possible that the extent of the ZRFC could be reduced by the presence of subsurface clay materials, which are present elsewhere on the subject property.

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

As part of water management strategies, Gilbert and Sutherland (2003, 2004) concluded that under developed conditions, with treatment measures in place, there would be no increase in pollutant loads exported from the subject site, and the nearby 1 Hearns Lake Road site, compared to existing conditions. Therefore, if these sites were developed according to the modelling assumptions, the long term water quality impact of developing the sites would be negligible.

This being the case, it is recommended that DIPNR and Council work with the developer to ensure that the proposed water quality management strategies achieve the proposed objectives, so that Hearns Lake water quality is not adversely affected.

11 REFERENCES

Australian Water and Coastal Studies [AWACS] (1989), "Macauleys and Charlesworth Bay Beaches Photogrammetric Analysis", *AWACS Report 88/42*, May, produced by PWD Coast and Rivers Branch

BBK Coastal Development Group (2003), *Masterplan, Solitary Beach, Lot 21 DP 714858, Woolgoolga NSW*, October

Bruun, Per (1962), "Sea Level Rise as a Cause of Shore Erosion", *Journal of the Waterways and Harbors Division, Proceedings of the American Society of Civil Engineers*, Vol. 88, No. WW1, February, pp. 117-130

Bruun, Per (1983), "Review of Conditions for Uses of the Bruun Rule of Erosion", *Coastal Engineering*, Vol. 7, Elsevier, pp. 77-89

Bruun, Per (1988), "The Bruun Rule of Erosion by Sea-Level Rise: A Discussion on Large-Scale Two- and Three-Dimensional Usages", *Journal of Coastal Research*, Volume 4 No. 4, pp. 627-648

Carley, James T and Ronald J Cox (2003), "A Methodology for Utilising Time-Dependent Beach Erosion Models for Design Events", *Pacific Coasts and Ports '03, Proceedings of the 16th Australasian Coastal and Ocean Engineering Conference and the 9th Australasian Port and Harbour Conference*, Auckland, New Zealand, September

Carley, JT, Couriel, ED and DR Cox (1998), "Numerical Modelling Sand Nourishment Profiles/Quantities and Beach Erosion due to Storms and Sea Level Rise", *WRL Technical Report 98/04*, Water Research Laboratory, University of New South Wales

Chapman, DM; Geary, M; Roy, PS and BG Thom (1982), *Coastal Erosion and Coastal Evolution in New South Wales*, Coastal Council of New South Wales, ISBN 0 7240 6582 2

Church JA; Gregory, JM; Huybrechts, P; Kuhn, M; Lambeck, K; Nhuan, MT; Qin, D and PL Woodworth (2001), "Changes in Sea Level", Chapter 11 in *Climate Change 2001: The Scientific Basis, Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by JT Houghton, Y Ding, DJ Griggs, M Noguer, P van der Linden, X Dai, K Maskell and CI Johnson, Cambridge University Press, pp. 639-694

Cialone, Mary A. (1991). "Coastal Modeling System (CMS) User's Manual", *Instruction Report* CERC–91–1, Department of the Army, U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, Mississippi, September; Supplement 1, August 1992, by Mary A. Cialone, David J. Mark, Lucia W. Chou, David A. Leenknecht, Jack E. Davis, Linda S. Lillycrop and Robert E. Jensen; Supplement 2, September 1993, by Mary A. Cialone, David J. Mark, Lucia W. Chou, David A. Leenknecht, Jack E. Davis, Linda S. Lillycrop, Robert E. Jensen, Edward F. Thompson, Mark B. Gravens, Julie D. Rosati, Randall A. Wise, Nicholas C.

Kraus and P. Magnus Larson; Supplement 3, August 1994, by Mary A. Cialone, David J. Mark, Lucia W. Chou, David A. Leenknecht, Jack E. Davis, Linda S. Lillycrop, Robert E. Jensen, Edward F. Thompson, Mark B. Gravens, Julie D. Rosati, Randall A. Wise, Nicholas C. Kraus, P. Magnus Larson and Jane M. Smith

Coastal Engineering Research Center (1984), *Shore Protection Manual*, Volumes 1 and 2, Fourth Edition, Department of the Army, Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi

Coombes, Peter (2004), *Analysis of Water Savings from Rainwater Tanks and Demand Management Methods*

CSIRO (2001), *Climate Change Projections for Australia*, Climate Impact Group, CSIRO Atmospheric Research, Melbourne, 8 pp

CSIRO (2002), *Climate Change and Australia's Coastal Communities*, CSIRO Atmospheric Research, Melbourne, 8 pp

CSIRO Marine Research (2001), "Global Sea-Level Rise", *Fact Sheet No. 45*, November

CSIRO Marine Research (2004), "More storms, surges with warmer conditions", Media Release, 20 April

Department of Defence (1999), *Permanent Committee on Tides and Mean Sea Level*, Defence Publishing Service, Wollongong, May

Department of Land and Water Conservation [DLWC] (1995), "Ocean View Beach Photogrammetric Analysis", *Publication No. HO/37/95*, Coast and Flood Policy Branch, June, ISBN 0731071425

Department of Land and Water Conservation [DLWC] (1996), *Park Beach Photogrammetric Analysis, 1994 Update*, Coastal and Riverine Management Directorate, January

Department of Land and Water Conservation [DLWC] (1997a), *Park Beach Photogrammetric Analysis*

Department of Land and Water Conservation [DLWC] (1997b), *Fiddamans Beach Dune Blowout Detail*, Coastal, Floodplain, and Riverine Resources Directorate, January

Dubois, Roger N (1992), "A Re-Evaluation of Bruun's Rule and Supporting Evidence", *Journal of Coastal Research*, Volume 8, No. 3, Summer, pp. 618-628

Geomarine (1991), "Narrabeen-Collaroy, Fishermans Beach, Criteria for the Siting and Design of Foundations for Residential Development", *Geomarine Report No. 69021R02*, in association with Coffey Partners International, for Warringah Shire Council, February

Gilbert and Sutherland (2003), *Stormwater Management Plan for Proposed Solitary Beach Residential Development, Coffs Harbour*, prepared for BBK Coastal Development Group, October

Gilbert and Sutherland (2004), *Stormwater Management Plan for Proposed Hearns Lake Road Development, Coffs Harbour*, prepared for BBK Coastal Development Group, March

Glover, Russell (2004), Department of Infrastructure, Planning and Natural Resources, Coffs Harbour, personal communication

Gordon, AD (1987), "Beach Fluctuations and Shoreline Change – NSW", *Preprints of Papers, 8th Australasian Conference on Coastal and Ocean Engineering*, Launceston, 30 November to 4 December, Institution of Engineers Australia National Conference Publication No 87/17, pp. 103-167

Gordon, AD (1991), "Belmont Offshore Ocean Outfall Investigation, Coastline and Seabed Movements Study", *Australian Water and Coastal Studies Report 90/26*, May, also published as Hunter Sewerage Project Report No. HSP9103-7

Hallermeier, RJ (1978), "Uses for a Calculated Limit Depth to Beach Erosion", *Proceedings of the 16th International Conference on Coastal Engineering*, Hamburg, American Society of Civil Engineers, , pp 1493-1512

Hallermeier, RJ (1981). "A Profile Zonation for Seasonal Sand Beaches from Wave Climate". *Coastal Engineering*, Volume 4, pp. 253-277

Hallermeier, RJ. (1983). "Sand Transport Limits in Coastal Structure Design", *Proceedings, Coastal Structures '83*, American Society of Civil Engineers, pp. 703-716

Hanslow, DJ and P Nielsen (1995), "Field Measurement of Runup on Natural Beaches", *12th Australian Coastal and Ocean Engineering Conference*, Melbourne

Harcourt Academic Press (2001), "Dictionary of Science and Technology", http://www.harcourt.com/dictionary/

Healthy Rivers Commission [HRC] (2002), *Independent Public Inquiry into Coastal Lakes*, Final Report, April, ISBN 0 9577 268 6 4

Heap, Andrew D and Peter T Harris (2002), "Geomorphology as an Indicator of the Susceptibility of Australia's Coastal Waterways to Contaminants", *Coast to Coast 2002*, pp. 157-160

Heap, A; Bryce, S; Ryan, D; Radke, L; Smith, C; Smith, R; Harris, P and D Heggie (2001) "Australian Estuaries & Coastal Waterways: A Geoscience Perspective for Improved and Integrated Resource Management, A Report to the National Land & Water Resources Audit, Theme 7: Ecosystem Health", *Australian Geological Survey Organisation, Record 2001/07*, Version 1, March, ISSN 1039-0073, ISBN 0 642 39885 2

Holmes & Holmes (2003), *Geotechnical Assessment for Proposed Residential Development at Hearns Lake – Woolgoolga*, 28 August

Intergovernmental Panel on Climate Change [IPCC] (2001a), *Summary for Policymakers, A Report of Working Group I of the Intergovernmental Panel on Climate Change*

Intergovernmental Panel on Climate Change [IPCC] (2001b), *Technical Summary, A report accepted by Working Group I of the IPCC but not approved in detail*, Co-ordinating Lead Authors DL Albritton (USA) and LG Meira Filho (Brazil)

Intergovernmental Panel on Climate Change [IPCC] (2001c), *Climate Change 2001: Synthesis Report*, edited by Robert T Watson and the Core Writing Team, Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, ISBN 0 521 80770 0

Jones, C (1981), "Coffs Harbour Coastal Planning Study, Working Paper 10: Coastal Geomorphology", *NSW Department of Environment and Planning, Report 80/08*, Grafton, July

Larson, M. and N.C. Kraus (1989). "SBEACH: Numerical Model for Simulating Storm–Induced Beach Change, Report 1, Empirical Foundation and Model Development", *Technical Report CERC-89-9*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

Larson, M., Kraus, N.C. and T. Sunamura (1988). "Beach Profile Change: Morphology, Transport Rate, and Numerical Simulation", *Proceedings of 21st Coastal Engineering Conference*, American Society of Civil Engineers, pp. 1295–1309

Larson, M., Kraus, N.C. and M.R. Byrnes (1990). "SBEACH: Numerical Model for Simulating Storm–Induced Beach Change, Report 2, Numerical Formulation and Model Tests", *Technical Report CERC-89-9*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

Lawson, NV and PH Youll (1977), "Storm Duration and Return Interval for Waves off the Central NSW Coast", *Third Australian Conference on Coastal and Ocean Engineering, The Coast, The Ocean and Man*, Melbourne, 18-21 April, Institution of Engineers Australia NCP 77/2

Lord, Douglas and Mark Kulmar (2001), "The 1974 Storms Revisited: 25 Years Experience in Ocean Wave Measurement Along the South-East Australian Coast", *Coastal Engineering 2000, Proceedings of the 27th International Conference on Coastal and Ocean Engineering,* Sydney, 16-21 July 2000, Volume One, pp. 559-572

Lord, DB and A van Kerkvoort (1981a), "A Coastal Process Investigation, Coffs Harbour New South Wales", *Fifth Australian Conference on Coastal and Ocean Engineering*, Perth, November, Institution of Engineers Australia

Lord, DB and A van Kerkvoort (1981b), "The Effects of a Major Harbour Construction on Longshore Sediment Movements – Coffs Harbour New South Wales", *Proceedings of the Conference on Environmental Ocean Engineering 81*, Townsville, Institution of Engineers Australia

Manly Hydraulics Laboratory [MHL] (1986), "Coffs Harbour Northern Areas Outfall Investigation – Stage 1 Report", *Report No. 462*, Public Works Department NSW, PWD Report No. 86039, August, ISBN 724028129

Manly Hydraulics Laboratory [MHL] (1992), "Mid New South Wales Coastal Region Tide-Storm Surge Analysis", *MHL Report No. 621*, Public Works Department, PWD Report No. 92028, 2 October, ISBN 0 7305 9420 3

Manly Hydraulics Laboratory [MHL] (1997), "Evans Head Preliminary Coastal Processes Study", *Report MHL790*, Department of Public Works and Services, June, for the Department of Land and Water Conservation

Manly Hydraulics Laboratory [MHL] (1998), "Coffs Harbour Eastern Breakwater Historical Storm Analysis", *Report MHL914*, Department of Public Works and Services, DPWS Report No. 98020, July, for the Department of Land and Water Conservation, ISBN 0 7313 0727 5

Manly Hydraulics Laboratory [MHL] (2003), Byron Bay and Coffs Harbour Storm History, updated to 31 December 2001, provided by Mark Kulmar

Morang, Andrew and L Parson (2002), "Coastal Morphodynamics", Chapter IV-3 in the *Coastal Engineering Manual*, Part IV, "Coastal Geology", edited by Andrew Morang, Engineer Manual 1110-2-1100, US Army Corps of Engineers, Washington, DC, 30 April

Moratti, Mark and Douglas Lord (2000), "Woody Bay and Shark Bay – A Receding Coastal Compartment", *10th Annual NSW Coastal Conference, Conference Proceedings*, held at Yamba

Murray, Emma; Heggie, David and Brendan Brooke (2002), "Determining the Environmental Status of Coastal Lakes: Science for Estuary Management", *Coast to Coast 2002*, pp. 315-317

National Land and Water Resources Audit [NLWRA] (2002), *Australian Catchment, River and Estuary Assessment 2002*, Volume 1, March, Commonwealth of Australia, ISBN 0 642 37125 3

New South Wales [NSW] Government (1990), *Coastline Management Manual*, September, ISBN 0730575063

Nielsen, AF (1994), "Subaqueous Beach Fluctuations on the Australian South-Eastern Seaboard", *Australian Civil Engineering Transactions*, Volume CE36, No. 1, December, Institution of Engineers Australia, ISSN 0819-0259, pp. 57-67

Nielsen, AF; Lord, DB and HG Poulos (1992), "Dune Stability Considerations for Building Foundations", *Australian Civil Engineering Transactions*, Institution of Engineers Australia, Volume CE34, No. 2, June, pp. 167-173

Nielsen, AF; Carley, JT and RJ Cox (2001), "Brooms Head Beach Coastal Study", *Water Research Laboratory Technical Report 99/43*, University of New South Wales, Manly Vale, Final Draft Revision 2, for Maclean Shire Council, including Appendix A (Community Consultation) by EA Bragg and PA Cuming, and Appendices B, C, D & E

Patterson Britton & Partners (1995a), *Effects of Marine Traffic on the Shoreline of the Parramatta River, Gladesville to Parramatta*, Job 1850, Report 1069, for the NSW Department of Transport, July

Patterson Britton & Partners (1995b), *Proposed Development of Lot 2 DP840016, Pacific Highway, Emerald Beach, Identification of Coastal Hazards and Appropriate Buffer Zone*, for Clark Consulting Services Pty Ltd, Job 2170, Report 1270, November

Patterson Britton & Partners (2001), *Bate Bay Coastline Study, Stage 1 – Coastline Hazard Definition Report*, Issue No .1, November, Job 3828

Patterson Britton & Partners (2004), *Evans Head Coastal Reserves Plan of Management, Coastline Hazard Definition Study*, Issue No. 1, Draft, May, for GHD

Pattiaratchi, Charitha (2001), "Hydrodynamics of Intermittently Closing and Opening Lakes and Lagoons", Centre for Water Research, University of Western Australia

Public Works Department [PWD] (1984), "Assessment of Coastal Processes Affecting Park Beach, Coffs Harbour", *PWD Report No. 84348-950*, Working Draft, Coastal Branch, September

Public Works Department [PWD] (1985), "Elevated Ocean Levels, Storms Affecting NSW Coast 1880-1980", *PWD Report No. 85041*, Coastal Branch, prepared by Blain Bremner and Williams Pty Ltd, in conjunction with Weatherex Meteorological Services Pty Ltd, December

Public Works Department [PWD] (1986a), "Elevated Ocean Levels, Coffs Harbour", *PWD Report No. 86005*, Coastal Branch, prepared by Blain Bremner and Williams Pty Ltd, in conjunction with Weatherex Meteorological Services Pty Ltd

Public Works Department [PWD] (1986b), "Elevated Ocean Levels, Storms Affecting NSW Coast 1980-1985", *PWD Report No. 86026*, Coastal Branch, prepared by Lawson and Treloar Pty Ltd, in conjunction with Weatherex Meteorological Services Pty Ltd, August

Public Works Department [PWD] (1990), "Woolgoolga Beach Photogrammetric Analysis", Coast and Rivers Branch, North Coast Section, February

Public Works Department [PWD] (1992a), "Hills Beach Photogrammetric Analysis", *PWD Report No. 92041*, Coast and Rivers Branch, March, ISBN 0730594300

Public Works Department [PWD] (1992b), "Green Bluff – White Bluff Photogrammetric Analysis", *PWD Report No. 92063*, Coast and Rivers Branch, September, ISBN 0731009533

Public Works Department [PWD] (1993a), "Park Beach Photogrammetric Analysis", Coast and Estuaries Branch, May

Public Works Department [PWD] (1993b), "Campbells Beach Photogrammetric Analysis", Coast and Estuaries Branch, May

Public Works Department [PWD] (1995a), "Coffs Harbour City Coastal Assessment Report", *PWD Report No. 94066*, Coast and Flood Policy Branch, Water Services Policy, March, ISBN 0731027899X

Public Works Department [PWD] (1995b), "Sawtell Beach Photogrammetric Analysis", *PWD Report No. 95046*, Coast and Flood Policy Branch, Water Services Policy, March, ISBN 0731040384

Public Works Department [PWD] (1995c), "Corindi Beach Photogrammetric Analysis", *PWD Report No. 95067,* Coast and Flood Policy Branch, Water Services Policy, March, ISBN 073104097X

Resource Design and Management [RDM] (1998a), *Park Beach Coastline Hazard Definition and Management Study,* for Coffs Harbour City Council and the Department of Land and Water Conservation, December

Resource Design and Management [RDM] (1998b), *Park Beach Coastline Hazard Management Plan*, for Coffs Harbour City Council and the Department of Land and Water Conservation, December

Rijkswaterstaat (1987), *Manual on Artificial Beach Nourishment*, document prepared by the Netherlands Department of Public Works (Rijkswaterstaat), August, ISBN 9021260786

Rosati, JD; Wise, RA; Kraus, NC and M Larson (1993). "SBEACH: Numerical Model for Simulating Storm–Induced Beach Change, Report 3, User's Manual", *Instruction Report CERC-93-2*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

Rosati, JD; Walton, Todd and Kevin Bodge (2002), "Longshore Sediment Transport", Chapter III-2 in the *Coastal Engineering Manual*, Part III, Coastal Sediment Processes, edited by Dr Todd Walton, Engineer Manual 1110-2-1100, US Army Corps of Engineers, Washington, DC, 30 April

Roy, PS (1984), "New South Wales estuaries – their origin and evolution", *Developments in Coastal Geomorphology in Australia*, BG Thom (editor), Academic Press, New York, pp. 99–121.

Roy, PS; Williams, RJ; Jones, AR; Yassinid, I; Gibbs, PJ; Coates, B; West, RJ; Scanes, PR; Hudson, JP and S Nichol (2001), "Structure and Function of South-east Australian Estuaries", *Estuarine, Coastal and Shelf Science*, Volume 53, pp. 351–384, Academic Press

Ryan, David A; Heap, Andrew D; Radke, Lynda and David T Heggie (2003), "Conceptual Models of Australia's Estuaries and Coastal Waterways, Applications For Coastal Resource Management", *Geoscience Australia Record 2003/09*, Commonwealth of Australia, ISSN 10390073, ISBN 0642467668

Scanes, Peter; Coade, Geoff and Jaimie Potts (2002), "Load 'em up? Linking Loads of Nutrients from Catchments to Ecological Outcomes in Coastal Lakes", *Coast to Coast 2002*, pp. 420-423

Short, Andrew D (1993), *Beaches of the New South Wales Coast*, Australian Beach Safety and Management Program, ISBN 0 646 15055 3, reprinted 2000

Smyth Maher & Associates Pty Ltd (2004), *Masterplan, No. 1 Hearns Lake Road, Lot 4 DP 612977, Woolgoolga NSW,* May

Sommerfeld, Barry G; Mason, John M; Kraus, Nicholas C; and Magnus Larson (1994), "BFM: Beach Fill Module, Report 1, Beach Morphology Analysis Package (BMAP) – User's Guide", *Coastal Engineering Research Center Instruction Report CERC 94-1*, March, Waterways Experiment Station, Vicksburg, Mississippi, prepared for Headquarters, US Army Corps of Engineers, Washington DC

Stephens, Andy (2004), Manager, Mineral and Extractive Planning, Bureau of Mining and Petroleum, Department of Natural Resources Mines and Energy, Queensland, personal communication

Stephens, AW; Roy, PS and MR Jones (1981), "Model of Erosion on a Littoral Drift Coast", *Fifth Australasian Conference on Coastal and Ocean Engineering*, Perth, 25-27 November, pp. 125-126

Szuwalski, Andre and Andrew Morang (2001), "Glossary of Coastal Terminology", Appendix A in the *Coastal Engineering Manual*, edited by Andrew Morang, Engineer Manual 1110-2-1100, US Army Corps of Engineers, Washington, DC, October

van Kerkvoort, Anka (1985), "Sediment Bypassing of a Headland – A Sand Tracing Experiment", *Master of Engineering Science Thesis, University of New South Wales*

Watson, Phil (2004), Senior Specialist, Coastal Unit, Coastal Management Branch, Department of Infrastructure, Planning & Natural Resources, personal communication

WBM Oceanics Australia [WBM] (2002), *Lake Wollumboola Odour Processes Study*, Final, Revision No. 3, 30 June, for Shoalhaven City Council

WBM Oceanics Australia [WBM] (2003), *Ballina Shire Coastline Hazard Definition Study*, Final Report, Revision Number 2, 16 December, for Ballina Shire Council

Wilson, Joanne; Evans, Peter and Neil Kelleher (2002), "Fish Kills in Cockrone Lagoon – Implications for Entrance Opening of Coastal Lakes", *to Coast 2002*, pp. 507-510

WP Geomarine (1998), *Campbells Beach Coastline Management Study, Stage One, Coastal Processes and Hazard Definition Study*, Final Report, December, for Coffs Harbour City Council

WP Geomarine (1999a), *Coastal Engineering Advice, Lot 4 DP 774491, Coachmans Close, Sapphire*, May, for Newnham Karl and Partners

WP Geomarine (1999b), *Campbells Beach Draft Coastline Management Plan, Stage Three*, Draft, October, for Coffs Harbour City Council