Data was previously recorded near Jims Point[38] (Station 200440) from 1886 to 1988, recording similar variables to the current Airport site. This station has been at various locations (Les Lever, Field Office Manager, Bureau of Meteorology, Lord Howe Island, personal communication 8 October 2013), namely near Jims Point from November 1954 until when it was closed in November 1988 (Figure 27), and at various locations prior to 1954 including the first official Bureau site which was located at the Flying Boat base building (near the present Post Office located near the northern end of Lagoon Beach) from 1939 to 1954.

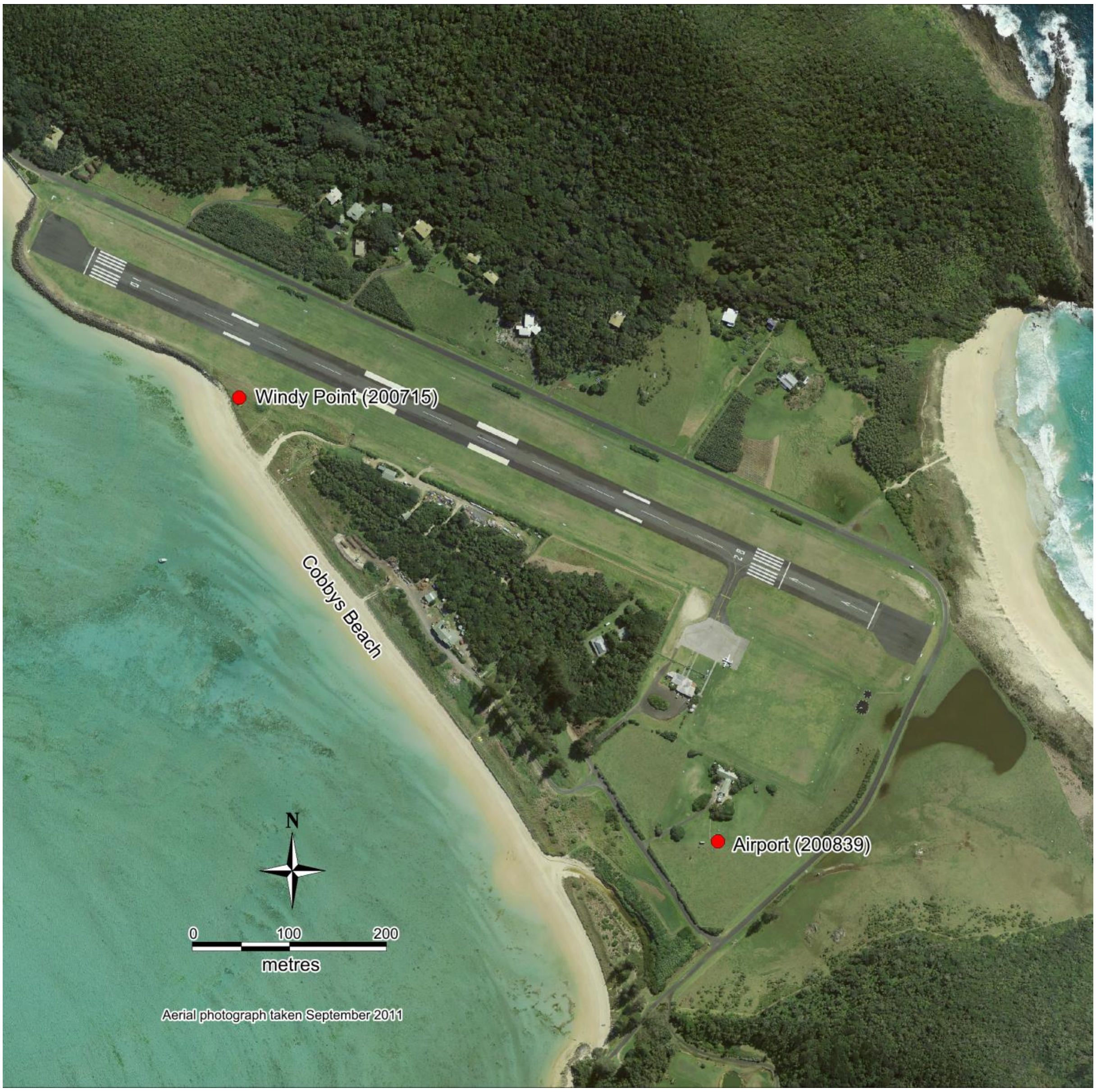

Figure 26: Location of current Bureau of Meteorology stations at Lord Howe Island

[38] Denoted as "Lord Howe Island" by the Bureau of Meteorology, with a station elevation of 46m. The latitude/longitude location of this station given by the Bureau at http://www.bom.gov.au/climate/averages/tables/cw_200440.shtml (accessed 15 April 2014) is not correct.

Figure 27: Location of Jims Point Bureau of Meteorology station (used from 1954 to 1988)

A selection of available relevant Lord Howe Island meteorological data was purchased from the Bureau of Meteorology in January 2014, namely:

- all daily and hourly records from the Airport, Windy Point and Jims Point;
- hourly data for the Airport site from 20 July 1994 to 3 January 2014, with near-continuous recording not commencing until July 2002 (about 59% data capture over the 1994 to 2014 period, and 96% data capture from July 2002 onwards), comprising rainfall, air temperature, wet bulb and dew point temperatures, relative humidity, wind speed, wind direction, speed of maximum wind gust in last 10 minutes, mean sea level pressure, station level and QNH pressure; and

• hourly data for the Windy Point site from 13 September 2004 to 3 January 2014, comprising wind speed, wind direction, and speed of maximum wind gust in last 10 minutes (with about 95% data capture over this period).

Based on analysis of the hourly data, 16 point compass wind roses for the Airport and Windy Point are provided in Figure 28 and Figure 29 respectively. It is evident that:

- most winds come from the E then ENE at both sites, then ESE (Windy Point) or SW (Airport);
- for the stronger winds (speed exceeding 40 km/hr) at the Airport, 31% come from the WSW, 24% from the E, 16% from the ENE and 12% from the W;
- for the stronger winds (speed exceeding 40 km/hr) at Windy Point, 18% come from the E, 18% from the SW, 15% from the WSW and 14% from the SSW.

Note that topographical features would affect wind directions, for example reducing the strength of winds from N to NE directions at Windy Point, and from the S to SE directions at the Airport. The southern mountains at Lord Howe Island are known to modify wind fields, creating a marked orographic effect (Martin et al, 2014).

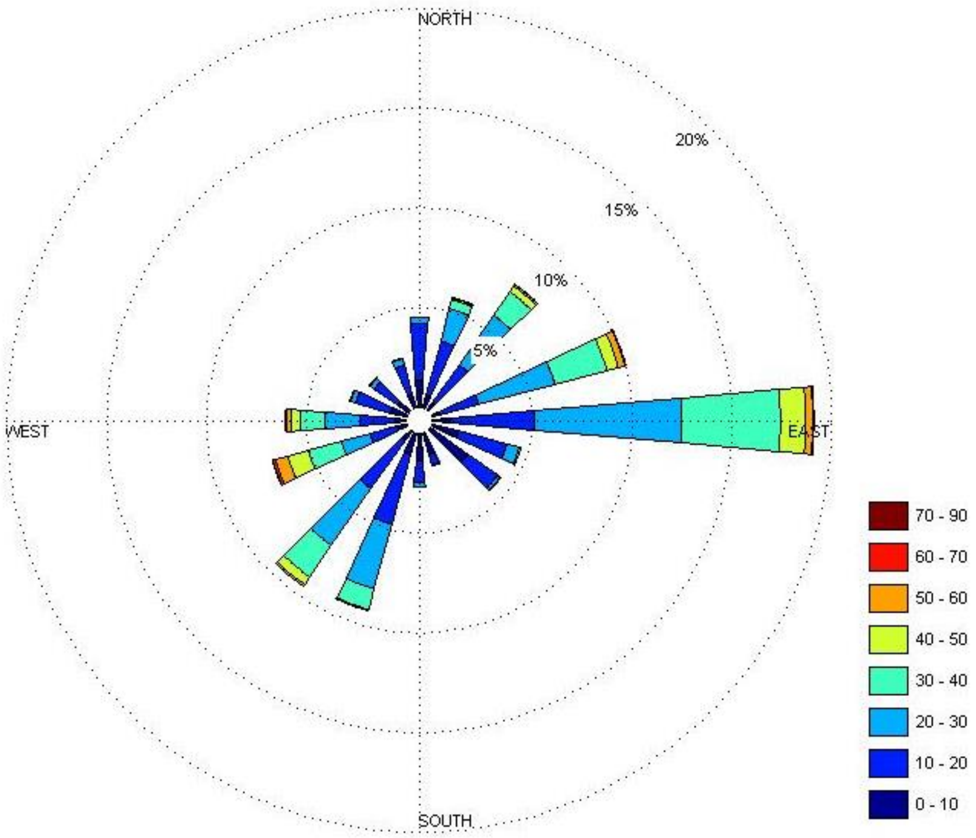

Figure 28: Wind rose for Airport site based on hourly data from 1994 to 2014

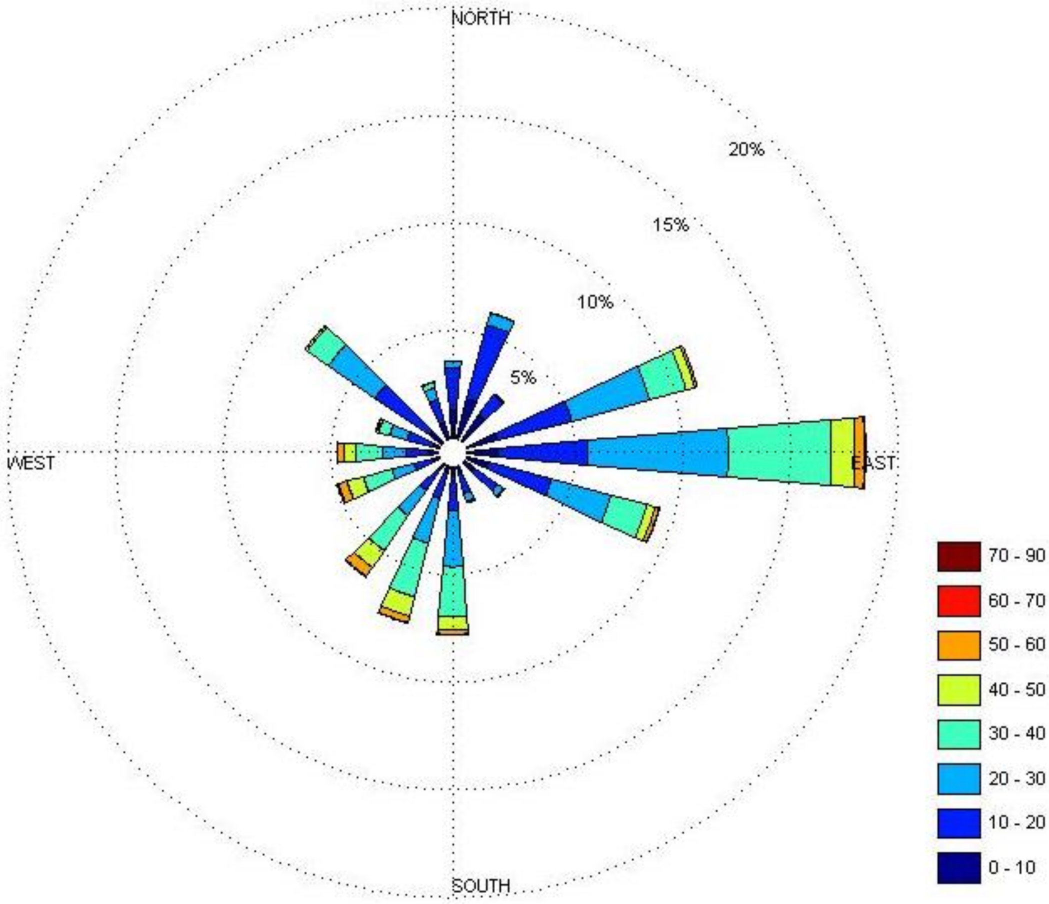

Figure 29: Wind rose for Windy Point site based on hourly data from 2004 to 2014

Analysis of the hourly Windy Point and Airport wind data over the coincident measurement period from 2004 to 2014 indicated that:

- wind speeds were (on average) about 1.2 times larger at Windy Point than the Airport; and
- wind directions were more easterly at Windy Point.

In terms of producing wind waves in the Lagoon impacting on the shoreline, the only wind directions of significance are SE through W to NW. A tabulation of the occurrence of winds from these directions (in all cases based on only the winds from SE through W to NW adding to 100%) and averaging the Windy Point and Airport data is provided in Table 4.

Table 4: Occurrence of onshore wind wave directions at Lagoon Howe Island Lagoon

Direction	Overall occurrence (%)	Occurrence for winds exceeding 40km/hour (%)
NW	11.0	1.2
WNW	6.5	1.5
W	11.7	18.6

Direction	Overall occurrence (%)	Occurrence for winds exceeding 40km/hour (%)
WSW	12.9	38.0
SW	17.3	20.7
SSW	18.2	12.4
S	11.4	7.5
SSE	3.8	0.05
SE	7.1	0.1

It is evident that although the overall winds are reasonably balanced (which would suggest no distinct net wind wave transport direction in the Lagoon), the highest winds are more from the west than south, which may cause a dominance of sediment transport to the south as littoral drift[39].

[39] Note that the Lagoon shoreline faces SW.

7. COASTAL PROCESSES

7.1 Preamble

Coastal processes in the Lagoon area at Lord Howe Island are complex. There is an interaction of waves, coral reef, reef passages, currents and elevated water levels that causes complex sediment transport patterns. There are also numerous structures that have been constructed along Lagoon Beach. These include the runway rock revetment that juts out into the Lagoon, as well as an adjacent Seabee revetment to the north and sand-filled geotextile container (bag) wall further north again. These structures are likely to be having some effect on coastal processes. That stated, erosion was occurring in the vicinity of these structures prior to their construction (including prior to construction of the runway revetment in 1974).

7.2 Water Levels

Analysis of water level data collected in the Lagoon at Lord Howe Island was discussed in Section 6.4.

7.3 Wave Climate

Analysis of wave climate numerical hindcasts representative of Lord Howe Island was discussed in Section 6.5.

Large swell waves at Lord Howe Island, which as noted in Section 6.5 generally come from the S-WSW quadrant, are likely to be generated by the following weather systems:

- Southern Ocean Lows (also known as mid-latitude cyclones, or Southern Tasman Lows when generating waves affecting the NSW mainland coast[40]). These are low pressure systems associated with fronts that move from west to east between about 40° and 60°S[41] (south of the Australian mainland), typically every 3 to 4 days. These systems would generate long period swell at Lord Howe Island, but generally not elevated water levels, due to the distance of the low (thousands of kilometres) from the island.
- East Coast Lows, which are low pressure systems that form between 20° and 40°S and generally move parallel to the NSW coast, often intensifying rapidly (Shand et al, 2011). These can generate both large waves and elevated water levels due to storm surge.
- Southern Secondary Lows, which are storms that form as a cut off low in the wake of a cold front in a mid-latitude westerly circulation (Shand et al, 2011)[42].
- Ex Tropical Cyclones, where the cyclones generally form north of 20°S. These can lead to particularly large waves and elevated water levels at Lord Howe Island if the cyclone tracks close to the Island. Tropical Cyclones typically form in the warmer months (November to April) only.

[40] For example, Shand et al (2011) used the “Southern Tasman Lows” term. Southern Ocean Lows are the dominate source of swell waves that affect Indonesia, Western Australia, South Australia and Victoria. Once Southern Ocean Lows have moved far enough east to generate waves that affect the NSW mainland, the term “Southern Tasman Lows” can be used.
[41] Covering the “roaring forties”, “furious fifties” and “screaming sixties”, a region characterised by westerly gales.
[42] Shand et al (2011) classified East Coast Lows and Southern Secondary Lows as “East Coast Cyclones”, and also included Inland Troughs and Tropical Cyclones in this category.

With reference to PWD (1986) and Callaghan and Helman (2008), the four largest events in the 1979 to 2009 WAVEWATCH III® analysis (Section 6.5) were East Coast Lows (July 1986 and June 2006), and Southern Secondary Lows (July 1982[43] and August 1988). However, note that WAVEWATCH III® does not resolve tropical cyclones well, and there is evidence that more tropical cyclones tracked towards Lord Howe Island in the 1950s to 1970s than in recent decades.

7.4 Ocean Currents

The East Australian Current (EAC) carries warm low salinity Coral Sea water southward into the cooler more saline Tasman Sea. The northern limit of the EAC is usually defined as latitude 18°S whilst its southern boundary, usually at latitude 32°S, is quite variable and can extend as far south as 42°S (NCCOE, 2012).

The EAC is present at all times of the year but is generally strongest between December and April. Its surface speed is usually between 0.5 and 1.0 m/s and its effect can be felt at depth. Seaward of the continental shelf the current speed at a depth of 250m is approximately half that at the surface. The maximum width of the EAC is about 150km (NCCOE, 2012).

The landward edge of the current frequently encroaches onto the shelf with an effect on coastal processes such as the movement of seabed sediment. The southerly flow often separates from the coast between 29°S and 32°S, heading east across the Tasman Sea. At the point of separation the current repeatedly forms loops that break off as large eddies that can sometimes interact with coastal waters similarly to the EAC itself (NCCOE, 2012). With Lord Howe Island at 31.5°S, the warmer EAC waters thus episodically reach the Island.

Further information on the EAC is given by Boland and Church (1981).

7.5 Nearshore Wave Climate in Relation to Reef and Lagoon Features

In Figure 30, the vector average swell wave direction of 228°, that is from the south-west, is depicted at various locations. Surrounding Blackburn Island, there is a gap in the reef about 510m wide. At Location 1 (north of Blackburn Island), there would therefore be relatively higher wave energy entering the Lagoon, although the wave energy reaching Lagoon Beach would be reduced and spread (through diffraction) due to the relatively narrow gap between the reef and island of about 100m[44]. This may be a factor in the area near Location A at Lagoon Beach in Figure 30 not showing significant progradation, unlike surrounding areas[45].

At Location 2 (south of Blackburn Island), there would again be relatively higher wave energy entering the Lagoon. Although diffraction may again reduce wave energy, and the deeper areas in the Lagoon would also transform wave height and direction through refraction, it would be expected that Location B along Lagoon Beach in Figure 30 would be subject to relatively higher wave energy. The extent of this region is due both to:

[43] Initially an Anti-cyclone Intensification.
[44] Gap distance measured perpendicular to the dominant wave direction.
[45] It is understood that a bulldozer occasionally clears the access track from the Aquatic Club to the beach to assist vessel access, which may also have relatively reduced sand volumes in this area.

- the direction windows that would penetrate the gap south of Blackburn Island (SW, WSW, W and WNW waves[46]); and
- the relatively low reef crest levels at Locations 3 and 4 (from 0.3m to 0.7m AHD).x

Location B corresponds to the area receding at the southern end of Lagoon Beach.

At Location 5 in Figure 30 there is also a slight gap in the reef crests and relatively lower reef crest levels, which may be contributing to the recession immediately south of the runway revetment. That stated, there are other factors affecting recession of this area as discussed in Section 7.8.

It is recognised that any opposing current in the reef passages (such as surrounding Blackburn Island) may limit wave energy entering the Lagoon, but the evidence is there that the areas potentially most exposed to wave energy are those that are receding, recognising that there are also other factors affecting recession.

[46] 34% of waves come from the SW, 8% from the WSW, 4% from the W and 3% from the WNW.

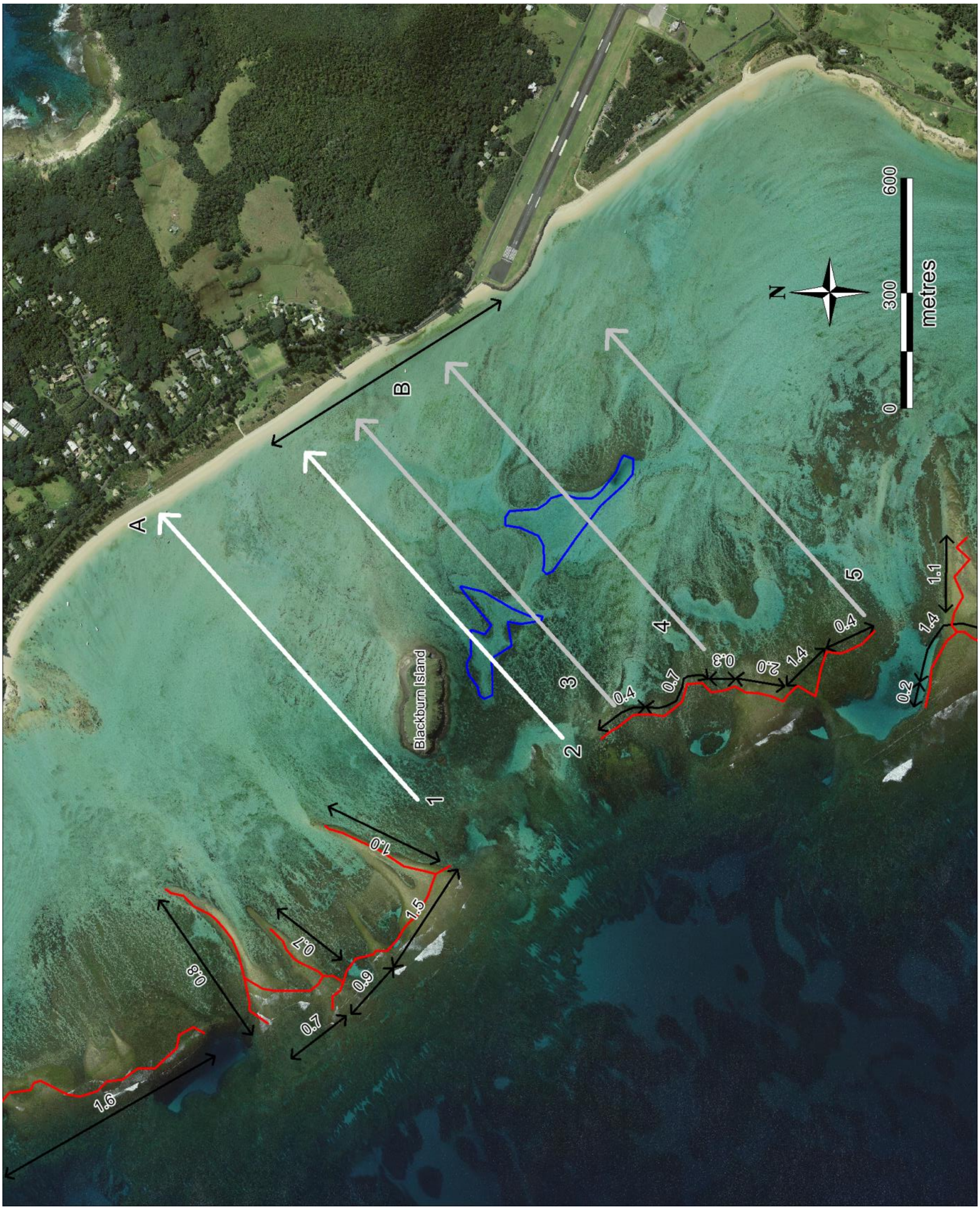

Figure 30: Potential higher wave energy areas (A and B) impacting on Lagoon Beach and Cobbys Beach, with vector average offshore wave direction vectors shown (note that wave transformation in the Lagoon could alter these directions)

7.6 Effects of Structures and Works on Beach

7.6.1 Runway Revetment

If there are significant longshore sediment transport processes along Lagoon Beach and Cobbys Beach, then it would be reasonable to expect that the runway revetment (if it extended a sufficient distance into the Lagoon to interrupt longshore sediment transport) would act like a groyne and cause buildup of sediment on the updrift side and loss of sediment on the downdrift side. There is not conclusive evidence that there has been a significant groyne effect at the runway, and the relatively benign wave conditions along Lagoon Beach for most of the time are consistent with that observation. It is also possible that any modest longshore sediment transport bypasses the runway, as the runway protrusion is relatively insignificant.

It should be noted that literature prepared in relation to managing erosion in the Windy Point area[47] consistently had statements indicating an expectation that the dominant longshore movement of sand along Lagoon Beach was from north to south, and thus that the runway construction had caused accelerated erosion south of the runway. If this was the case, the area north of the runway revetment would (if anything) have benefited from sand accretion due to the runway construction.

That stated, a conceptual model of sediment transport prepared by Patterson Britton & Partners (1991)[48] as presented in Manidis Roberts Consultants (1993) indicated that there was an expectation that the runway was a transition zone for the direction of sediment transport, with sand moving to the north from north of the runway and sand moving to the south from south of the runway.

Manly Hydraulics Laboratory (1968) noted that changes in beach conditions from construction of the airstrip could be studied in a model to minimise any objectionable features. No such studies are known to have been undertaken.

A structure such as the runway located in areas of wave impact and sediment transport would be expected to have some localised "end effects", where there can be additional erosion (beyond what would have occurred if the structure had not been there) adjacent to the structure[49]. Consideration of the magnitude of these end effects (in relation to the adjacent and more substantial Seabee revetment) is made in Section 7.6.2.

There is also the possibility that the runway construction (in combination with the Seabee revetment) could be considered to be a "hard point" or "artificial headland" around which Lagoon Beach is realigning. SMEC (2012) noted this process in relation to "a shoreline evolution model which can predict the crenulated bay response of a shoreline downdrift (in a sediment transport sense) of a fixed headland", although the prediction they developed in Figure 17 of their report (which indicated that the southern end of Lagoon Beach was trending to realign substantially landward, north of the bag wall) was based on limited data. Windy Point may have historically been such a hard point as it jutted out into Lagoon Beach prior to the runway construction.

However, there needs to be care in attributing erosion problems in the Windy Point area to construction of the runway. Erosion of this area was occurring prior to the runway construction based

[47] Including Public Works Department (1989) and Manidis Roberts Consultants (1993).
[48] Reference uncertain. Original document has not been sighted and it was not included in the references of the citation source.
[49] These end effects are sometimes at least partially attributed to the fact that a hard structure "locks up" sand from being available to meet storm demand.

on discussions with long term residents of Lord Howe Island. Manidis Roberts Consultants (1993) also stated that the road at Windy Point had been undermined and rebuilt about six times in the past, prior to the runway construction.

7.6.2 Seabee Revetment

Public Works Department (1989) noted that construction of a sloping revetment (of which a Seabee revetment is an example) would create flanking problems, that is accelerating recession of adjacent unprotected sections of beach. However, they considered that a 280m length of protective works north of the runway revetment (similar in length to the Seabee revetment that was constructed) would not be likely to result in increased erosion hazard to existing backbeach development at the ends of the works that was present at that time[50].

Department of Environment, Climate Change and Water [DECCW] (2010a) has released “Draft Guidelines for Assessing the Impacts of Seawalls”. For a structure such as the Seabee revetment, which can be considered to be located between the intertidal zone and the 1 year ARI wave runup level, it was suggested that the alongshore extent of additional erosion adjacent to the wall was the lesser of 70% of the length of the wall or 500m. For the 300m long Seabee revetment, using this methodology, the additional erosion extent would be predicted to be 210m.

Note that the DECCW (2010a) methodology is simplistic and does not take into account the direction and magnitude of longshore sediment transport, or magnitude of storm erosion demand, for example. Furthermore, beach profile changes over time would indicate that the area south of the Seabee revetment and runway revetment has been accreting from beyond 80m from these structures.

7.6.3 Beach Scraping

It is understood that it has been an historical practice to push sand up to the eroding dune from around the low tide area as a form of beach scraping at the southern end of Lagoon Beach, and at Windy Point prior to the construction of the Seabee revetment.

The Board had a NSW Marine Parks Permit for “beach scraping to protect the foredune, beach access and the Pinetrees Boatshed from further coastal erosion” (covering the area approximately 40m to either side of the Boatshed) that was applied for in April 2011, but has now lapsed.

More recently (in the last year or so), it is understood that the methodology for beach scraping may have changed to sourcing sand from about 50m to 200m north of Pinetrees boatshed (again at the low tide level) and transporting the sand alongshore (south) along the beach before pushing the sand upwards and forming a mound adjacent to the erosion escarpment. An example of a mound of sand formed seaward of Pinetrees boatshed and caused by beach scraping carried out in this manner is depicted in Figure 31. Such works were undertaken three times in 2012.

[50] Which would have included Lagoon Road (although note that Pinetrees boatshed was not present at this time).

Figure 31: Sand from beach scraping pushed against erosion escarpment at Pinetrees boatshed, 28 August 2012

Carley (2010) has defined beach scraping as “the movement of sand from the intertidal zone to the dune or upper beach by mechanical means”. The term “cross-shore beach scraping” has been used herein to describe the mechanical cross-shore transport of sand from the lower to the upper profile. To distinguish between this, and alongshore mechanical sand transport prior to cross-shore scraping, the latter has been denoted as “longshore and cross-shore beach scraping” herein (see Figure 32 for illustration of concepts). However, note that it is uncertain how much “cross-shore beach scraping” versus “longshore and cross-shore beach scraping” has been undertaken, as the final results of the works appear similar.

Given the relatively sheltered nature of Lagoon Beach with low height waves for most of the time, the process of beach recovery after storms could be relatively slow, reducing the effectiveness of cross-shore beach scraping. Indeed, Carley (2010) noted that where beach scraping rates exceed natural recovery rates, this may cause over-steepening of beaches and additional erosion. There could be this concern for cross-shore beach scraping at Lagoon Beach. It is thus recommended that cross-shore beach scraping is discontinued at Lagoon Beach.

The same concerns could be raised with regard to “longshore and cross-shore beach scraping”, although depending on the direction of longshore sand transport these works may be beneficial in reducing erosion in the Pinetrees boatshed area[51].

It is recommended that the practice of mounding sand in a localised bulge immediately adjacent to the erosion escarpment is discontinued, as it is likely to contribute to losses of this material from the sandy beach into dunal areas from wind action. It is likely to be more effective to spread the material over a wider cross-shore area.

It is also recommended that the sand source for longshore scraping is moved further north (north of the access track opposite the Board’s Administration office), and that excess sand removed from the slipway area at the northern end of Lagoon Beach is also utilised as a sand source. Based on historical accretion rates at the northern end of the beach, it is likely that at least 500m^3/year of sand could be sourced from the northern end of the beach and placed at the southern end, without any long term impact on coastal processes.

[51] If longshore transport is to the north, then removing sand from north of the boatshed and transporting it and placing it back near the boatshed is likely to reduce erosion in its vicinity. Conversely, if longshore transport is to the south, this operation would create a hole (sink) for sand north of the boatshed that would need to fill, thus causing downdrift erosion to the south due to reduced longshore supply of sand (until the filling of the hole occurred and longshore transport rates were fully re-established). Given that the first scenario is considered to be most likely, removing sand from north of Pinetrees boatshed and transporting it and placing it back near the boatshed is likely to reduce coastline hazards at the boatshed.

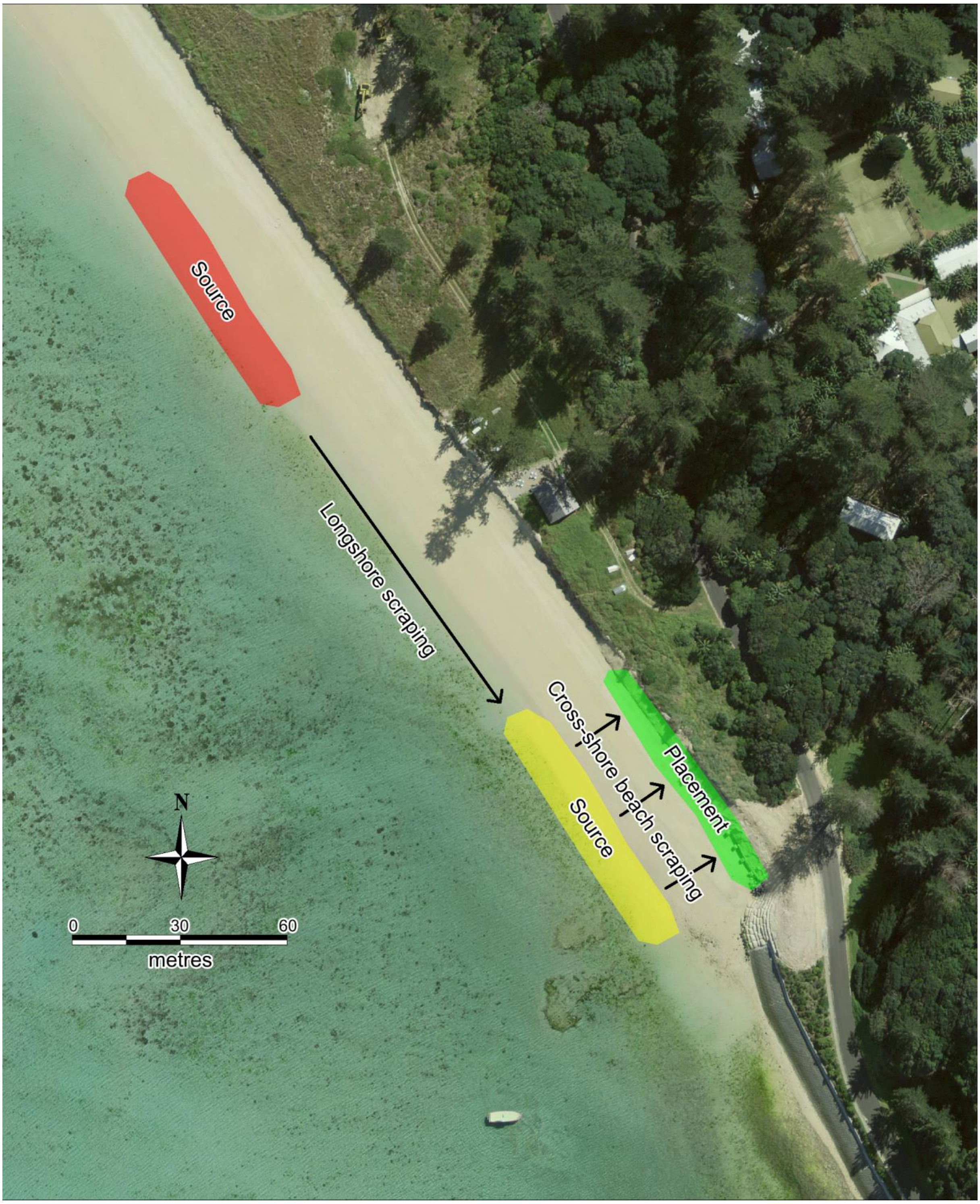

Figure 32: Difference between "cross-shore beach scraping" and "longshore scraping" as illustrated in the vicinity of Pinetrees boatshed (if longshore scraping was undertaken it would provide source for cross-shore beach scraping)

7.7 Sediment Transport

7.7.1 Onshore/Offshore Sediment Transport

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 volume and width of the beach profile.

On the NSW mainland coast, beach sand typically moves offshore to form bars during storms (when relatively large and steep waves occur). This process typically occurs over a period of hours to days. When extended periods of calmer wave conditions occur (characterised by relatively long period and low height swell, that is less steep waves), the material held in these bars migrates onshore to rebuild the beach. Depending on the magnitude of the preceding storm, this beach building process can occur over a time scale of days to years.

Along Lagoon Beach and Cobbys Beach at Lord Howe Island, there is less certainty as to the mechanisms of onshore/offshore sediment transport. Storm erosion certainly occurs at Lord Howe Island, but it is uncertain if significant offshore bars form, or sand is smeared more widely over the Lagoon, given the relatively flat Lagoon bed. Also, there is uncertainty as to the effectiveness of long period and low height swell in rebuilding these beaches after storms. This is because wave heights within the Lagoon are relatively low during calmer conditions (due to the offshore reef), and may not have sufficient energy to mobile sediment. Indeed, it is possible that it is the large and steep storm waves (rather than calmer conditions) that mobilise sediment off the reef and Lagoon bed and move it onshore (with such storms leading to upper beach erosion but onshore sediment transport over the wider Lagoon bed).

The amount of sand which can be removed from a beach during a storm event (or series of closely spaced storms) and transported offshore is referred to as the “storm demand”. On the NSW mainland, this quantity is generally measured above 0m AHD (approximately mean sea level on the NSW mainland, but 1.2m below mean sea level in the Lagoon at Lord Howe Island), and is usually expressed as a volume per metre length of beach (m^3/m). 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 landward of the beach. 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.

7.7.2 Adopted Long Term Recession Rate Due to Net Sediment Loss

Based on review of photogrammetric data (**Appendix B**), the long term recession due to net sediment loss rates listed in Table 5 were adopted:

Table 5: Adopted long term recession due to net sediment loss rates

Profiles	Rate (m/year)
1-17	Nil
18-21	0.1
22-34	0.4
35-37	0.5

Profiles	Rate (m/year)
38-52	Nil

7.8 Conceptual Model of Sediment Transport Mechanisms

The rates of beach change outlined in Section 6.1 do not definitively reveal where the gains and losses in each compartment have come from (that is from offshore or alongshore). However, there appears to be a general pattern of progradation at these beaches, which is considered to be most likely from an ongoing onshore transport of sediment from the relatively shallow Lagoon at the northern end of Lagoon Beach and from offshore of Cobbys Beach[52]. There may also be some swell wave driven alongshore transport of sand near the waterline, expected to be to the north along Lagoon Beach on average[53].

However, given that 8,000m^3 of sand (sourced from Blinky Beach) was placed along the position of the current Seabee revetment in 1991, the rates of change measured in Section 6.1 may be an overestimate of the natural rates of progradation (in the order of 20%)[54]. That is, the prograding areas of Lagoon Beach and Cobbys Beach are still likely to be naturally prograding, but the measured progradation is likely to have been influenced by the previous nourishment in 1991.

Superimposed on this general progradation are isolated losses adjacent to the runway revetment and Seabee revetment, which may be considered as related to :

- the higher wave energy impinging on this area (Section 7.5) causing relatively higher offshore sand transport in storms;
- "end effects" and additional seaward erosion associated with structures interfering with natural coastal processes;
- the deeper areas in the vicinity of Comets Hole (Section 7.5) acting as a sink for sediment (reducing onshore supply of sediment and generally capturing sand transport in this area); and
- general circulation patterns in the Lagoon.

Although erosion did occur at the southern end of Lagoon Beach prior to the structures being built (erosion is a natural process, that is a natural response to large waves and elevated water levels), it appears that the structures may have enhanced the loss of sediment from these areas in storms, and/or inhibited the recovery of sediment volumes after storms (perhaps by additional turbulence etc causing sediment to be moved further offshore in storms). Structure effects are recognised in the coastal engineering literature due to turbulence and oblique wave reflection. That stated, additional analysis (such as sediment tracing) would be required to more definitively ascertain the relative contribution of natural and anthropogenic processes causing erosion in the vicinity of these structures.

Lord Howe Island residents (such as Clive Wilson and Anthony Riddle) have noted that water circulation patterns in the Lagoon are towards the south in the vicinity of Cobbys Beach. Anthony Riddle has also noted that there is a northwards flow offshore of Lagoon Beach. From a coastal

[52] It is considered to be unlikely that there is much transport of sand around the Signal Point area at the northern end of Lagoon Beach. There may be some infeed of sand from the south at Cobbys Beach, but this is uncertain given the reported water circulation patterns to the south in this area (see further discussion below).
[53] Local wind waves may also drive alongshore sediment transport, but these have not yet been considered.
[54] The observed gains in volume at the northern end of Lagoon Beach and southern end of Cobbys Beach between 1984 and 2001 were about 19,700m^3 and 21,500m^3 respectively. Thus 8,000m^3 of nourishment sand could have contributed up to about 20% of this volume gain.

processes perspective, such flows are plausible as waves pump up lagoon water levels, which leads to strong flows out of the reef passages. The Seabee revetment location represents the midpoint between North Passage and Erscotts Passage and may be the point where circulations shift in direction from northerly to southerly. Note however that it is uncertain if these circulation currents are fast enough to transport sand-sized sediment, particularly near the shoreline[55].

A preliminary conceptual model of sediment transport processes that is an attempt to document the observed beach changes and is consistent with observed circulation patterns is depicted in Figure 33. The size of arrows indicates the magnitude of sediment transport in the direction shown. Although offshore transport (due to erosion in storms) can occur along the entire length of Lagoon Beach and Cobbys Beach as shown, it is considered that the areas near the Seabee revetment and runway revetment may have additional offshore erosion which combined with reduced offshore supply of sediment may be causing the net recession in this area (in combination with some longshore transport of sediment).

It is also likely that beach recovery after storms is relatively slow at Lagoon Beach, and the natural rebuilding of eroded areas after storms may take months or years, or possibly not ever be completely achieved (particularly if onshore sediment supply is diminished), leading to long term recession.

A sediment tracing study (Section 12.2.7) would provide valuable insight into a more refined conceptual model of sediment transport mechanisms.

[55] As noted above, it would also be possible to get alongshore movement of sand due to wave effects, where waves break at an angle to the shoreline.

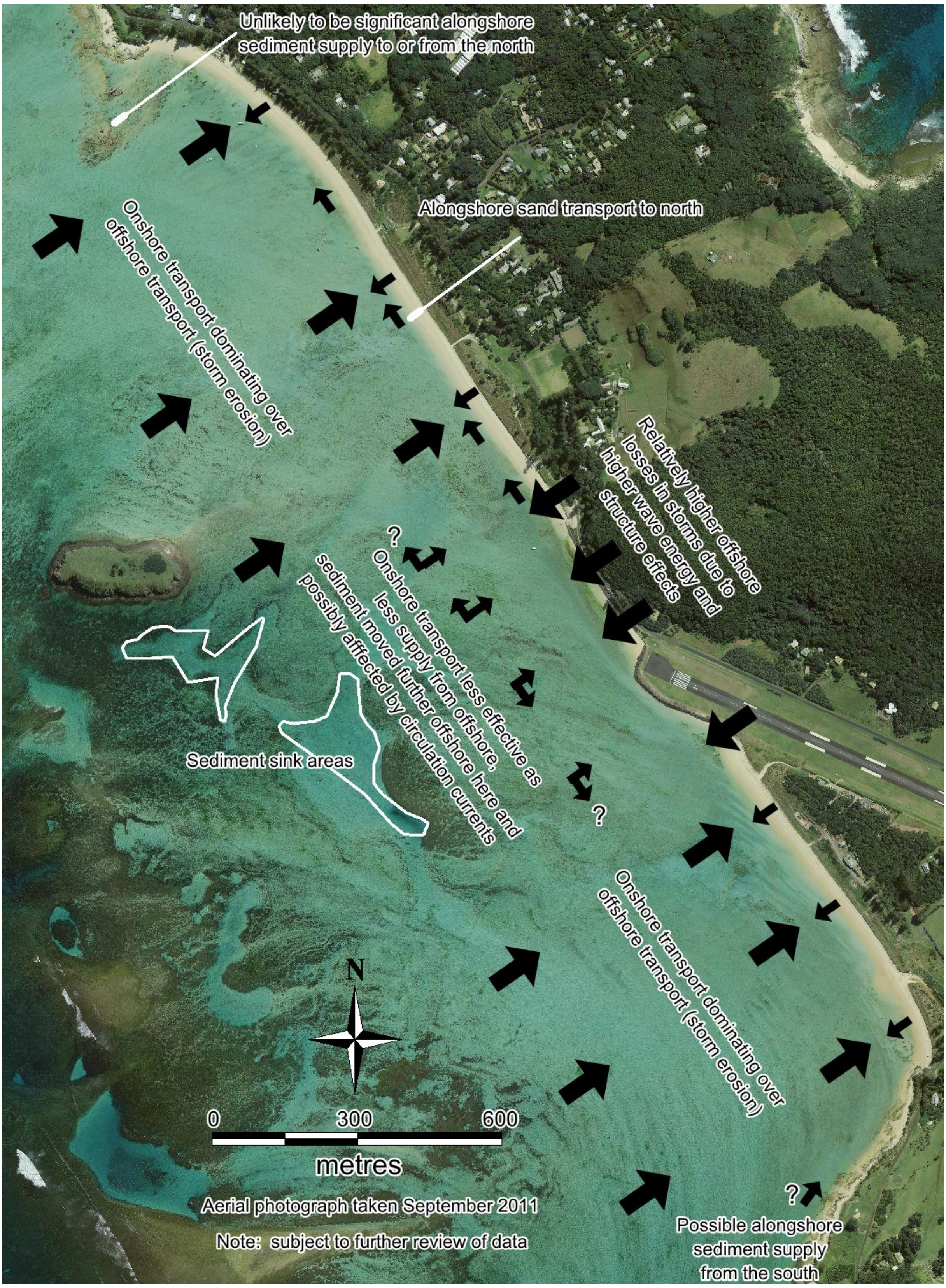

Figure 33: Preliminary conceptual model of sediment transport processes in Lagoon and at Lagoon Beach and Cobbys Beach

7.9 Climate Change

7.9.1 Sea Level Rise

The possibility of global climate change accelerated by increasing concentrations of greenhouse gases, the so-called Greenhouse Effect, is widely accepted by the scientific and engineering communities. This is projected to cause globally averaged surface air temperatures and sea levels to rise.

The Board directed that the sea level rise benchmarks in the former *NSW Sea Level Rise Policy Statement* (DECCW, 2009a, b), which is no longer NSW Government policy, be used to assess future coastline hazards herein. These benchmarks are an increase in mean sea level (relative to 1990) of 0.4m at 2050 and 0.9m at 2100.

The latest (Fifth Assessment) Intergovernmental Panel on Climate Change (IPCC) projections of future sea level rise were released in 2013 (IPCC, 2013a, b). It is recommended that there is consideration of applying these IPCC projections in a probabilistic risk framework, rather than relying on the former *NSW Sea Level Rise Policy Statement* benchmarks, to estimate future coastline hazards. That stated, these former benchmarks provide reasonable conservative allowances for planning purposes.

The actual sea level rise that would occur in the future is uncertain due to approximations in the modelling used to develop the projections, plus the fact that the modelling results are dependent on the greenhouse gas emission scenario adopted (which varies depending on a variety of economic and political influences that cannot be precisely foretold). That stated, it is likely that the sea level rise benchmarks adopted here would be towards the upper end of sea level rise that would be realised.

As discussed in Section 8.3.3, it is generally expected that recession of the open coast will occur under conditions of accelerated sea level rise.

7.9.2 Other Climatic Change Considerations

There are a number of other climate change effects (besides sea level rise) that could potentially impact on Lord Howe Island, namely:

- changes to community composition and structure of coral reef systems driven by increasing sea surface temperatures and ocean acidification[56];
- increased frequency and intensity of extreme rainfall[56] leading to increases in terrestrial runoff and nutrient and sediment loads being input into the Lagoon, impacting on reef health;
- an increase in the frequency and intensity of coastal storm (extreme wave) events, that could lead to increased erosion of beaches;
- changes in the angle of approach of the predominant wave climate, that could cause realignment of the shoreline and resulting recession in some areas and progradation in others;
- alterations to oceanographic circulation patterns, that could lead to localised variations in mean sea level over periods of months, which influences the wave energy that can penetrate into the Lagoon; and
- the reef crest level not keeping up with sea level rise, leading to increasing wave energy penetrating into the Lagoon.

[56] Identified as a key regional risk to Australasia in the IPCC Fifth Assessment (Reisinger and Kitching, 2013).

Ocean acidification is associated with increased carbon dioxide (CO_2) emissions. Coral reefs are particularly vulnerable because the increased CO_2 concentration in seawater, which combines with water to form carbonic acid, can make it hard for corals to grow. Models, observations and laboratory studies consistently indicate that as the ocean becomes more acidic, coral cover and diversity will decrease (Wendel, 2014).

The increased CO_2 concentration in seawater causing a lowering of pH (acidification) is not the only impact on reefs, it is also the reducing concentration of carbonate ions (CO_3^{2-}) that calcifying organisms need to build and cement coral reef (Howard et al, 2012; Shamberger et al, 2014). This reducing concentration of carbonate ions is also referred to as lowering the saturation state of carbonate mineral, and calcium carbonate precipitation at a decreased saturation state requires higher energetic demands from shell-making organisms (Howard et al, 2012).

Anthony and Marshall (2012) also noted that the increased CO_2 concentration in seawater may lead to increased fragility of coral skeletons and accelerated rates of reef bioerosion, increasing the susceptibility of reefs to storm damage. They considered that ocean acidification would reduce reef calcification, driving a shift from net reef accretion to net erosion of reef structure.

At Lord Howe Island, Anderson et al (2012) noted that growth rates of corals may currently be limited by relative cooler winter ocean temperatures, leading to negligible coral growth in winter months. Therefore, increasing ocean temperatures due to climate change may extend the growing period, enhancing overall growth rates. Ridgway (2007) and Ridgway and Hill (2012) identified that the East Australian Current had penetrated about 350km further south over the last 60 years, contributing to ocean warming in more southerly waters.

However, Anderson et al (2012) noted that the positive effects of increasing ocean temperature may be offset by declines in carbonate (aragonite) saturation. They stated that aragonite saturation declines with increasing latitude and climate-induced ocean acidification may further reduce the capacity for growth of calcifying organisms at the latitudinal limits of reef growth at Lord Howe Island[57].

It is unclear how the amplitude or frequency of the El Niño/Southern Oscillation (ENSO) phenomenon may change over the next 100 or so years (Holbrook et al, 2012). This is of interest as it drives changes in sea level, ocean temperature, the East Australian Current, rainfall and tropical cyclones (for example).

It is recommended that research is undertaken, supported, reviewed and tapped into by the Board to investigate the likely effects of climate change on ENSO, ocean currents, sea surface temperature, reef calcification and growth, wave storminess, wave direction and rainfall intensity at Lord Howe Island (and hence impacts of climate change on coral reefs and shoreline alignment, for example). Furthermore, it is recommended that the reef at Lord Howe Island is managed to promote resilience under multiple potential climate change stressors (refer to Section 13.4.1).

Anthony and Marshall (2012) noted that because climate change is likely to amplify the disturbance regime for coral reefs, the fate of these ecosystems will increasingly be determined by their potential for recovery and long-term maintenance of structure, function and goods and services, that is their resilience. Resilience-based management requires that management goals for marine ecosystems

[57] However, there are examples of coral reefs that do thrive in highly acidified environments (Shamberger et al, 2014).

such as coral reefs be expanded to focus on process (eg recruitment success, algal removal rates), as well as state (eg coral abundance, density of fish).

As stated by Anthony and Marshall (2012), to preserve Australia's coral reefs for future generations, it is critical that management efforts are invested into understanding the factors that influence the resilience of ecosystems, and prioritise management efforts toward restoring and maintaining ecosystem resilience. Adaptive resilience-based management is likely to offer the best hope for marine ecosystems, such as the coral reef at Lord Howe Island, in the face of climate change.

8. EROSION/RECESSION COASTLINE HAZARDS

8.1 Preamble

Potential coastline hazards that could impact on the study area are defined in subsequent sections, namely:

- beach erosion (Section 8.2);
- shoreline recession (Section 8.3);
- stormwater erosion (Section 8.4); and
- slope instability in terms of various coastal hazard zones (Section 8.5).

Hazard lines are delineated in Section 8.6, with discussion on risk to assets in Section 8.7.

8.2 Beach Erosion (Storm Demand)

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 7.7.1. On the NSW mainland, various methodologies consistently result in fully exposed open coast areas having an estimated 100 year ARI storm demand of 200m^3/m to 250m^3/m above mean sea level. At Lord Howe Island there are no known measurements of storm cut volumes, and storm cut numerical modelling was beyond the scope of the investigation reported herein, making it difficult to reliably estimate the 100 year ARI storm demand.

In Manidis Roberts Consultants (1993), a storm demand volume of 50m^3/m (ARI not stated) above LHITD (presently 0.144m AHD, that is close to 0m AHD) was adopted for Lagoon Beach and Cobbys Beach. This is considered to be a reasonable 100 year ARI value based on correlating storm demand to relative wave energy as explained below:

- Patterson Britton & Partners (1997) estimated a design wave height of 2.4m for design of protective works along Lagoon Beach, say 100 year ARI;
- 100 year ARI breaking wave heights along the NSW mainland that could cause erosion magnitudes of 250m^3/m are in the order of 6m (based on WorleyParsons, 2009);
- various authors have suggested that storm demand is proportional to wave energy, with wave energy being proportional to wave height squared;
- therefore, squaring the Lord Howe Island and NSW mainland wave height ratio, that is $(2.4/6)^2 = 0.16$ and multiplying this by the storm demand of 250m^3/m gives 40m^3/m above mean sea level as the storm demand estimate for Lagoon Beach and Cobbys Beach;
- for an approximate beach slope of 1:10 (vertical:horizontal), as typically occurs along these beaches, the additional volume of sand between mean sea level (1.2m AHD) and 0m AHD is about 12m^3/m;
- hence storm demand for these beaches can be estimated as 52m^3/m above 0m AHD, consistent with 50m^3/m above 0.1m AHD estimated by Manidis Roberts Consultants (1993).

To provide some conservatism, a present day 100 year ARI storm demand of 50m^3/m above 1m AHD was adopted herein.

To determine the position of the Immediate Coastline Hazard Line, the most recent 2011 photogrammetric profiles were used to define the pre-storm beach profile shape. To define the Immediate Hazard Line, the 50m^3/m (above 1m AHD) storm demand volume was applied to each photogrammetric beach profile to estimate the landward storm cut distance into the dune.

8.3 Shoreline Recession Hazard

8.3.1 Preamble

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 8.3.2 and 8.3.3 respectively. It is also appropriate to discount (in the assessment of recession due to net sediment loss) any potential recession due to actual sea level rise that may have occurred over the measurement period of the photogrammetric data[58], as discussed in Section 8.3.4.

8.3.2 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 a 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”, such as gutters within reef systems, 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, with the latter resulting 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 (erosion and accretion) due to storm activity.

The adopted long term recession rates due to net sediment loss were given in Section 7.7.2. For example, a 0.4m/year rate was adopted at the southern end of Lagoon Beach, which is equivalent to 15.6m at 2050 and 35.6m at 2100[59].

8.3.3 Long Term Recession due to Sea Level Rise

In general, 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 a significant volume of sediment may move offshore as the beach seeks a new equilibrium profile (NSW Government, 1990).

[58] The photogrammetric data measurement period was from 1965 to 2011 at Lord Howe Island.
[59] The rates were applied relative to 2011 base profiles, and from 2011 it is 39 years to 2050 and 89 years to 2100.

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

$$R = \frac{S \times B}{h + d_c} \tag{1}$$

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[60] 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 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, with the variables as illustrated in Figure 34.

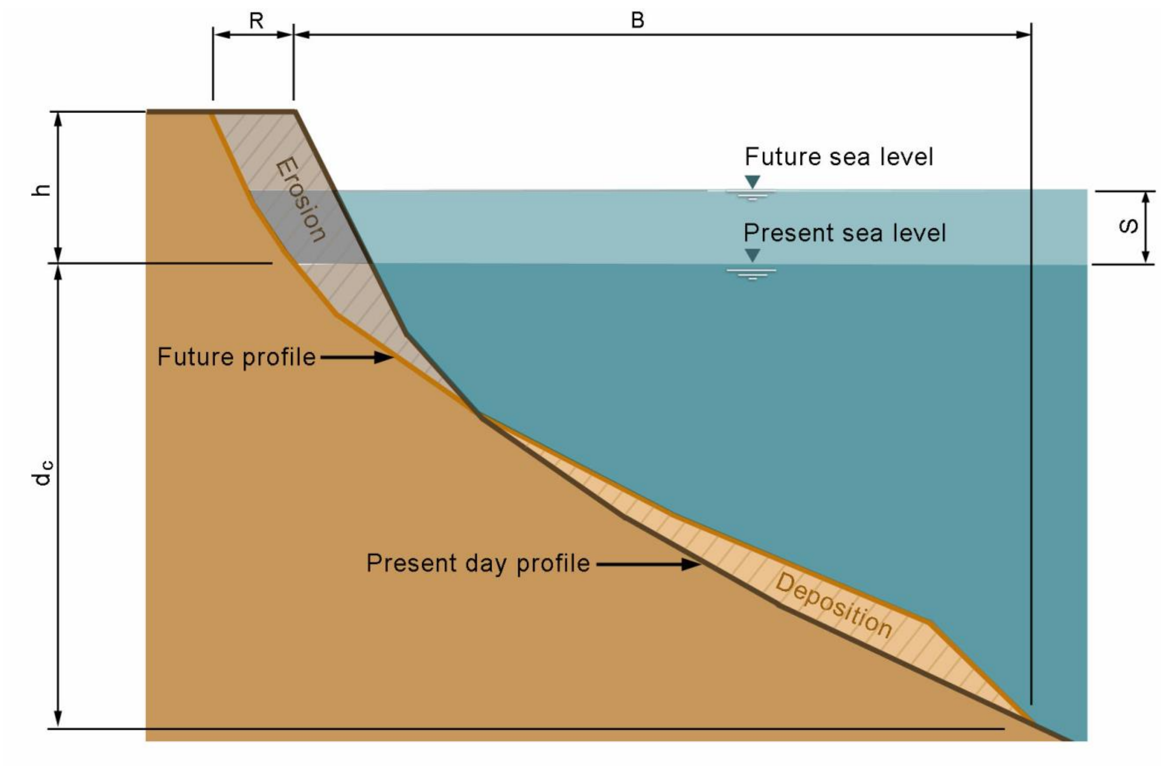

Figure 34: Illustration of variables in the Bruun Rule

Given the flat and shallow Lagoon offshore of Lagoon Beach and Cobbys Beach, with an excess of sand compared to an equilibrium profile, it is considered that only the subaerial beach face would

[60] 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).

potentially adjust due to sea level rise. The inverse slope of the active beach profile (as used in the Bruun Rule) is about 10 for the beach face.

To apply this inverse slope to estimate long term recession due to sea level rise, it is necessary to discount sea level rise that has occurred from 1990 to present. This is because the adopted sea level rises of 0.4m at 2050 and 0.9m at 2100 are defined to be relative to 1990 (see Section 7.9.1).

As described by DECCW (2010b), there was approximately 3mm/year of global sea level rise since 1990. For 2011 base profiles (21 years since 1990), there was thus 63mm of sea level rise to discount (that is, about 0.06m) Therefore, the actual sea level rise to apply at 2050 in using the Bruun Rule is 0.4 minus 0.06, that is 0.34m. Similarly, the sea level rise to apply at 2100 is 0.84m.

Therefore, the projected “Bruun Rule” long term recession due to sea level rise at 2050 and 2100 is about 3.4m (10 multiplied by 0.34) and 8.4m (10 multiplied by 0.84) respectively.

At Lagoon Beach and Cobbys Beach at Lord Howe Island, there is the additional complexity of the coral reef acting to reduce wave heights entering the Lagoon. The amount of wave energy that can enter the Lagoon is dependent on the water level above the crest of the reef, as wave heights are limited by the depth of water over the reef crest.

Assuming that the coral reef does not keep up with sea level rise (that is, does not grow upward at the same rate as sea level rise), then it would be expected that the wave energy entering the Lagoon would increase over time, and in particular the 100 ARI wave height at the shoreline would increase by approximately the same magnitude as the increase in mean sea level relative to the reef crest elevation.

If the reef remains at the same elevation as present, it would be reasonable to assume that the 100 year ARI wave height at Lagoon Beach and Cobbys Beach would increase from 2.4m at present to 2.7m at 2050 and 3.2m at 2100. Assuming that storm demand is proportional to wave height squared, as discussed in Section 8.2, this is an increase in storm demand of about 10m^3/m at 2050 and 30m^3/m at 2100.

8.3.4 Consideration 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 (from 1965 to 2011 at Lord Howe Island). That is, although any long term recession that has occurred over the historical record would mainly be expected to have been caused by net sediment loss, given that there has also been some sea level rise over the historical record it can be argued that any historical long term recession has been partially caused by sea level rise.

Averaged around Australia, the relative sea level rise from 1920 to 2000 was about 1.2mm/year (CSIRO Marine Research, 2004), which is equivalent to a shoreline recession of about 0.01m/year at Lord Howe Island (considering Bruun Rule related recession only and assuming that the reef has maintained grown at least at the rate of sea level rise) . This rate is relatively low and can be ignored for practical purposes. It is not considered warranted to adjust (reduce) the long term recession due to net sediment loss estimates noted in Section 8.3.2.

8.4 Stormwater Erosion Hazard

During major stormwater runoff events, stormwater that is collected from back beach areas and discharges into coastal waters can cause significant localised 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 if not structurally contained (NSW Government, 1990). Flow from stormwater pipes and outlets on beaches can also potentially scour the surrounding sand, creating erosion zones.

In the study area there are no stormwater outlets of significance discharging onto beaches (there are outlets in the runway revetment), with stormwater related scour only occurring at the entrances to watercourses such as Old Settlement Creek, Cobbys Creek and Soldiers Creek (with only Cobbys Creek in the area covered by photogrammetric data). Within the limitation of the spacing of photogrammetric profiles for hazard definition, natural long-term lowering of beach berms surrounding Cobbys Creek is explicitly accounted for in the volumetric analysis defining hazard line positions. That stated, it should be recognised that migration of the entrance of Cobbys Creek is possible.

8.5 Coastline Hazard Zones

For sandy areas, based on Nielsen et al (1992), a number of coastline hazard zones can be delineated as shown in Figure 35.

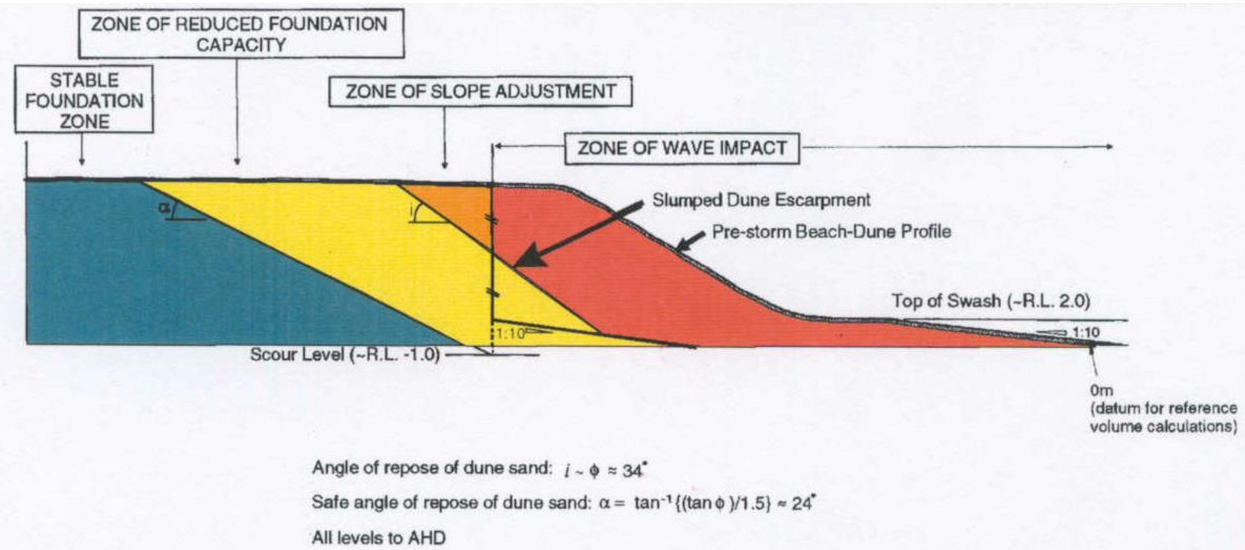

Figure 35: Schematic representation of coastline hazard zones (after Nielsen et al, 1992)

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. It is that part of the beach which is seaward of the beach erosion escarpment[61] (as defined by the beach erosion hazard, see Section 8.2).

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

[61] The beach erosion escarpment is the steep (usually shore-normal) slope that is formed on a sandy beach when there is beach erosion, forming the link between the eroded and uneroded sections.

of the design storm demand. It represents the steepest stable beach profile under the conditions specified.

A *Zone of Reduced Foundation Capacity* (ZRFC) 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 located with the ZRFC and not founded on deep piles would be considered to have an inadequate factor of safety.

8.6 Delineation of Hazard Lines

Immediate (as of 2011), 2050 and 2100 Hazard Lines (defined at the landward edge of the Zone of Slope Adjustment) are depicted in Figure 36 (for Lagoon Beach as far south as the Seabee revetment) and Figure 37 (for the Seabee revetment section of Lagoon Beach, airport revetment area, and Cobbys Beach).

In deriving the hazard lines, an entirely sandy subsurface was assumed, that is existing protective works were ignored. While the Seabee revetment and airport revetment remain in place, the hazard lines would not be realised in these areas[62]. However, the extent of erosion/recession in these areas if the protective works were not in place (as per the derived hazard lines[63]) indicates the importance of maintaining these works to avoid damage to Lagoon Road and the airport runway.

The location of an asset landward of the Immediate Hazard Line does not mean it could not be affected by coastal erosion at present, rather that there is a low probability (in the order of 1% each year) of erosion extending landward of the Line at present (as of 2011).

[62] It is recognised that there are rocky areas landward of Lagoon Road where it extends along the Seabee revetment, that would limit the realisation of long term hazard lines in this area if the seawall failed.
[63] In practice, if the airport revetment failed and was not rebuilt there would be some smoothing of the lines depicted in in the vicinity of the airport in Figure 37.

Figure 36: Immediate, 2050 and 2100 Hazard Lines (at landward edge of ZSA) at Lagoon Beach (north of Seabee revetment)

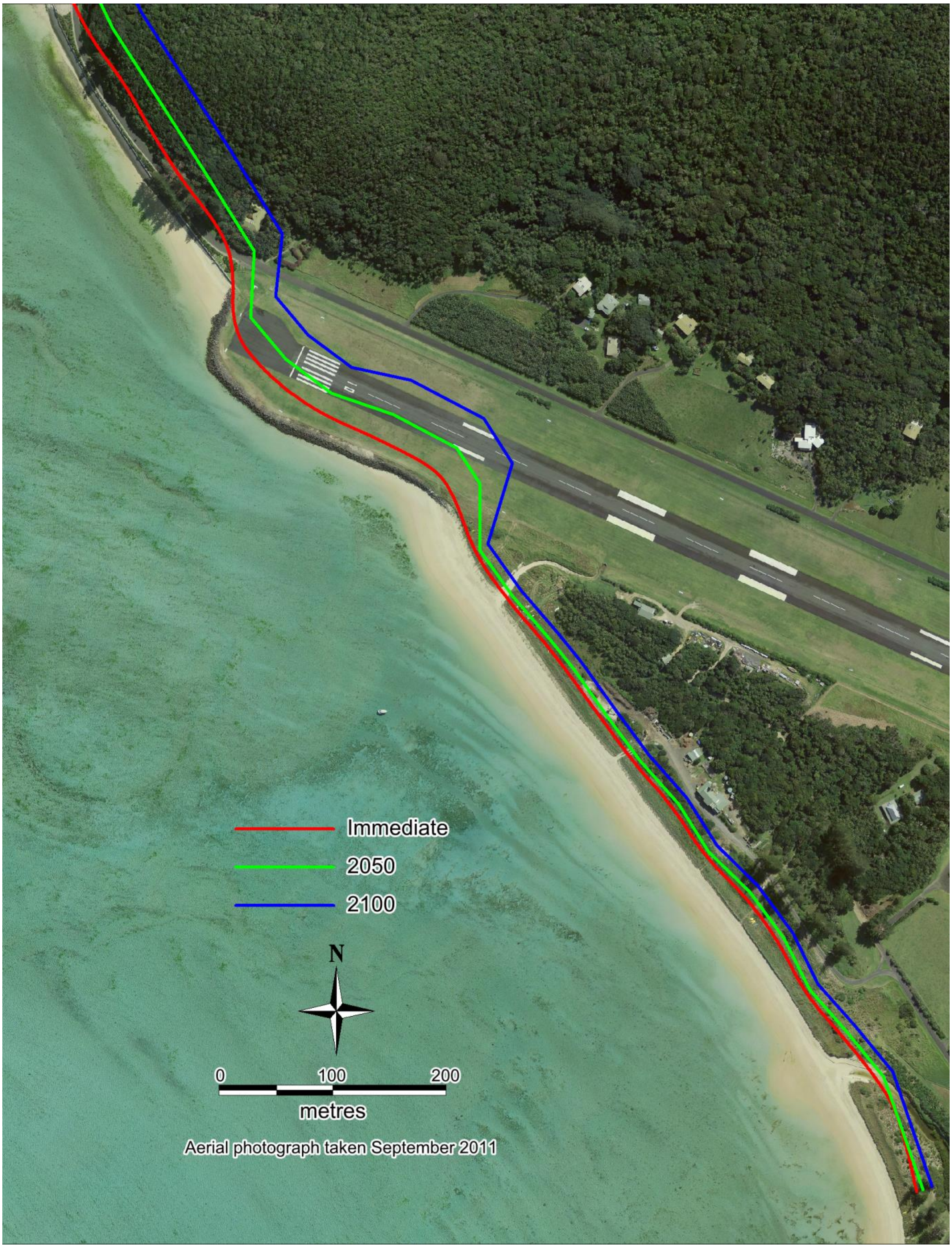

Figure 37: Immediate, 2050 and 2100 Hazard Lines (at landward edge of ZSA) at Seabee revetment, airport revetment and Cobbys Beach