APPENDIX 1

SMEC Report

Longshore Sand Transport and Tidal Inlet Stability Study for The Entrance and The Entrance North

For: Wyong Shire Council

Project Name:	Longshore Sand Transport and Tidal Inlet Stability Study for The Entrance and The Entrance North
Project Number:	3001053
Report for:	Wyong Shire Council

PREPARATION, REVIEW AND AUTHORISATION

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1 INTRODUCTION

The Entrance at Tuggerah Lake is a highly dynamic area with complex coastal processes. This report documents a coastal process investigation at The Entrance, to understand in greater detail the dynamics of The Entrance and thus inform Council Policy on management of the entrance and adjoining beaches.

This investigation:

- Documents a review of existing information to estimate potential longshore sediment transport rates and understand coastal processes;
- Presents a conceptual sediment transport model of the entrance area and adjacent North Entrance Beach, in the form of a sediment budget with “best estimates” of average sand transport rates and sediment transport pathways;
- Presents wave transformation modelling using detailed LADS bathymetric data in the entrance area to help understand coastal processes and calculate net average alongshore sediment transport rates; and
- Provides a review of the existing studies and techniques for analysis of the entrance stability.

The wave transformation modelling has been used to calculate order-of-magnitude estimates of net alongshore sediment transport, based on a median swell wave height and wave period. A range of offshore wave directions has been modelled to derive a range of nearshore wave approach angle for use in the longshore sediment transport calculations. Two recognised approaches are used to derive the estimate of longshore transport rates – the CERC formula and the Kamphuis formula. These approaches are based on various assumptions which are described in detail within this report. Based on the above approach, a conceptual sediment budget is derived for The Entrance and surrounding coastline.

The study area covers The Entrance and several kilometres north of the Entrance along the Entrance North Beach, with a tidal inlet connecting Tuggerah Lake to the Tasman Sea. This tidal inlet interrupts the longshore drift and is likely to be associated with fluctuations in the shoreline of the adjacent beach. Sand is deposited on and removed from the tidal inlet under the combined action of waves and flood tide currents. During the flood tide, more sand is transported onto the upstream entrance shoals and generates the heavily shoaled nature of the entrance. The absence of wave stirring inside the entrance means that less sand is transported out of the entrance on the ebb tide then is transported in on the flood tide. This tends to lead to the entrance shoaling over time, with the entrance naturally tending to closure. Floods due to heavy rainfall then scour the entrance, transporting sand out and widening the entrance channel again, whereby the process of entrance shoaling begins again.

Existing studies (Worley Parsons, 2010; PBP, 1994) suggest that a local southerly reversal of littoral drift causes the northern entrance sand spit to grow southwards which would result in the narrowing and finally closure of the entrance followed by flood level increase in the lake (Worley Parsons, 1994).

The tidal inlet is controlled by wave energy, tidal range, tidal prism, sediment supply and direction and rates of sand delivered to the inlet. Longshore sediment transport in the vicinity of tidal inlets is complex, where sand moves under combined action of waves, currents, superimposed on highly variable bathymetry with constantly changing water levels.

The tidal inlet acts both as a sediment source and a sediment sink, as the sand drift that filled the entrance during high littoral transport was released into the beach system during flood events. The imbalance of this sand circulation between the tidal inlet and adjacent beach system would tend to cause the inlet channel to shoal over time.

Much of the NSW coast is subject to prevailing southerly winds and high year-round Southern Ocean swell, resulting in overall northerly sediment transport. It is estimated by Dyson et al. (2001) that the longshore sediment transport in northern New South Wales (NSW) can reach 500,000m^3y^{-1}. However, on the central coast of NSW, sand transport magnitude is much lower and more compartmentalised, with sand tending to stay within the main embayments. NSW Government (1990) estimates sand transport rates for nearby Wamberal Beach of 12,000 m^3y^{-1}, and Soldiers Beach of 5,000 m^3y^{-1} toward the north. This has led to historical sand accumulation in transgressive dunes at the northern ends of the embayments, such as at the northern end of North Entrance/Tuggerah Beach.

During early investigations, the historic condition of the tidal inlet of the Entrance was found to be highly variable and typically open most of the time. However, the inlet channel is relatively shallow – consequently, Wyong Shire Council conducts dredging operations at The Entrance using a mobile dredge. The dredge is moored in the Wyong River when not in use. Dredging of the active tidal delta shoals has been conducted since about 1990, to maintain tidal flushing of the entrance area. The dredging has secondary benefits such as restoring eroded foreshore and improving recreational amenity.

The aim of this investigation is to provide a better understanding of the entrance sedimentary dynamics to enable Council to evaluate its options for beach nourishment using sand from the Entrance, without de-stabilising the entrance channel leading to major morphological changes to the lakes.

Options available for management of the entrance and channel include:

- Dredging of the entrance area and periodic nourishment of the adjacent beach with dredged sand;
- Protection works in and around the entrance, such as entrance training walls and engineered shoreline protection for properties at threat from coastal erosion at Curtis Parade

The impact of the littoral processes on the viability of the potential management options is examined within this report.

2 REVIEW OF EXISTING INFORMATION

SMEC's project team undertook the review of the existing data, reports and documents relevant to the Tuggerah Lake entrance stability analysis. This review is documented below.

2.1 Tuggerah Lakes, Entrance Training Walls: Technical Discussion (PBP, 1994)

This report documents the entrance evolution and the various options available for the development of Tuggerah Lake entrance. It was found that a flood event would largely scour the channel through the entrance sand spit and the entrance shoal upstream. The entrance bar sand moves onshore due to a local southerly reversal of the littoral drift that causes the entrance sand spit to grow southwards. The flood tide deposits sand on the upstream sand shoals while the ebb tide removes sand from the entrance channel and pushes it back on the entrance sandbar. However, there is more sand moving onto the upstream entrance shoals on the flood tide than leaving them on the ebb tide. This generates some build-up of the shoals that narrow the entrance and eventually lead to closure of the entrance.

The tidal range within the lake was found to be relatively small, between 0.2 and 0.3 m MSL (Mean Sea Level) due to a narrow entrance channel and the extended shoals. However, this range can double during a flood event. There is a low storm surge penetration within the entrance. The tidal flow is 100-150m^3/s and tidal velocities are 1-2m/s. Cost estimates of the dredging work and maintenance were provided.

Under average tidal conditions, the throat of the entrance is around 25-35m wide and 2.0-2.5m deep (at mid-tide).

The entrance was advised to be maintained open to avoid flood, water quality and habitat issues. It was recommended to undertake less regular larger dredging work instead of regular small volume removal to better stabilise the throat dimension. The recommended dredge would be capable of moving 60,000m^3 over a dredging period of 12 weeks.

The report also discussed impacts of measures for stabilising the entrance, such as construction of training walls. However, such measures are not considered viable today due to their potential for significant impacts on the lakes, such as impact on the lake levels and tidal range, increased flooding, storm surge and wave climate in the entrance and shrinkage of the upstream entrance shoals.

Navigation of large draft commuter vessels could be enabled by constructing twin entrance walls associated with major dredging. The entrance throat would reach dimensions of 60-80m width and 6-8m depth. This would have similar but exacerbated impacts as without the twin training walls without dredging. The lake level would be around mean sea level and the tidal range would be increased. Some reworking of the entrance channel would occur due to the high tidal flow. The increased depth would also increase the wave climate inside the lake entrance. Larger rocks would also be required for this option.

2.2 Tuggerah Lakes Entrance – Technical Advice on Dredging Related Matters (Worley Parsons, 2008)

This report documents the current dredging strategy undertaken at Tuggerah Lake. This strategy consists of the enhancement of the ebb dominant northern channel by creating a

50m-wide channel to a level of -2m AHD by commencing the dredging at the upstream end near the road bridge and using a mobile dredging system.

The dredging strategy is undertaken in four stages (as shown in Figure 2.1):

- Creation of a sediment trap across the main channel along the road bridge;
- Enhancement of the main channel with sand placed along the eastern shoreline;
- Enhancement of the ebb dominant channel with sand placed along the eastern shoreline between the road bridge and the caravan park; and
- Enhancement of the ebb dominant channel adjacent to the sand spit with sand placed on North Entrance Beach south of a null point.

This null point was determined qualitatively along North Entrance Beach from the observation of historical aerial photographs. It is located in the vicinity of Hargraves Street. North of this point, some northward sediment transport occurs while south of this point, the sand is worked back to the entrance. Hence, the sand dredged from the entrance is to be placed anywhere south of this null point. The location of this null point from 10 different dates of aerial photography is illustrated in Figure 2.2.

It was recommended to undertake pre- and post-dredging hydro-survey. Beach scraping could be undertaken after a storm event.

It was also observed that it was difficult to maintain the beach along the southern embankment of the entrance.

2.3 Tuggerah Lakes Estuary Modelling (DECCW, 2010)

This report describes the results of a hydrodynamic model undertaken to study the water quality parameters within the lake system, including nutrient concentration, suspended sediment, phytoplankton, etc. Some details about the habitats and ecosystems were provided.

2.4 Water Level Trends of Tuggerah Lake (MHL, 2010)

This report analyses the water level within Tuggerah Lake recorded between 1985 and 2010. Data from 1985 to 1995 appeared inconsistent and was not used. The harmonic analysis of tides was inappropriate for this study. Flood events were removed from the measured data as rainfall higher than 15mm was found to have a significant impact on the lake level, and an average water level rise ranging from 3.9 to 6.4mm/year over the period of data collection was calculated within the lake. However, the accuracy of the calculation is not optimal and more detailed works and data collection would be required to obtain accurate water levels.

Outlines of dredge areas are schematic only.
Based on notes supplied by Wyong Shire Council.

Figure 2.1 – Dredging Strategy at Tuggerah Lake Entrance (Worley Parsons, 2008)

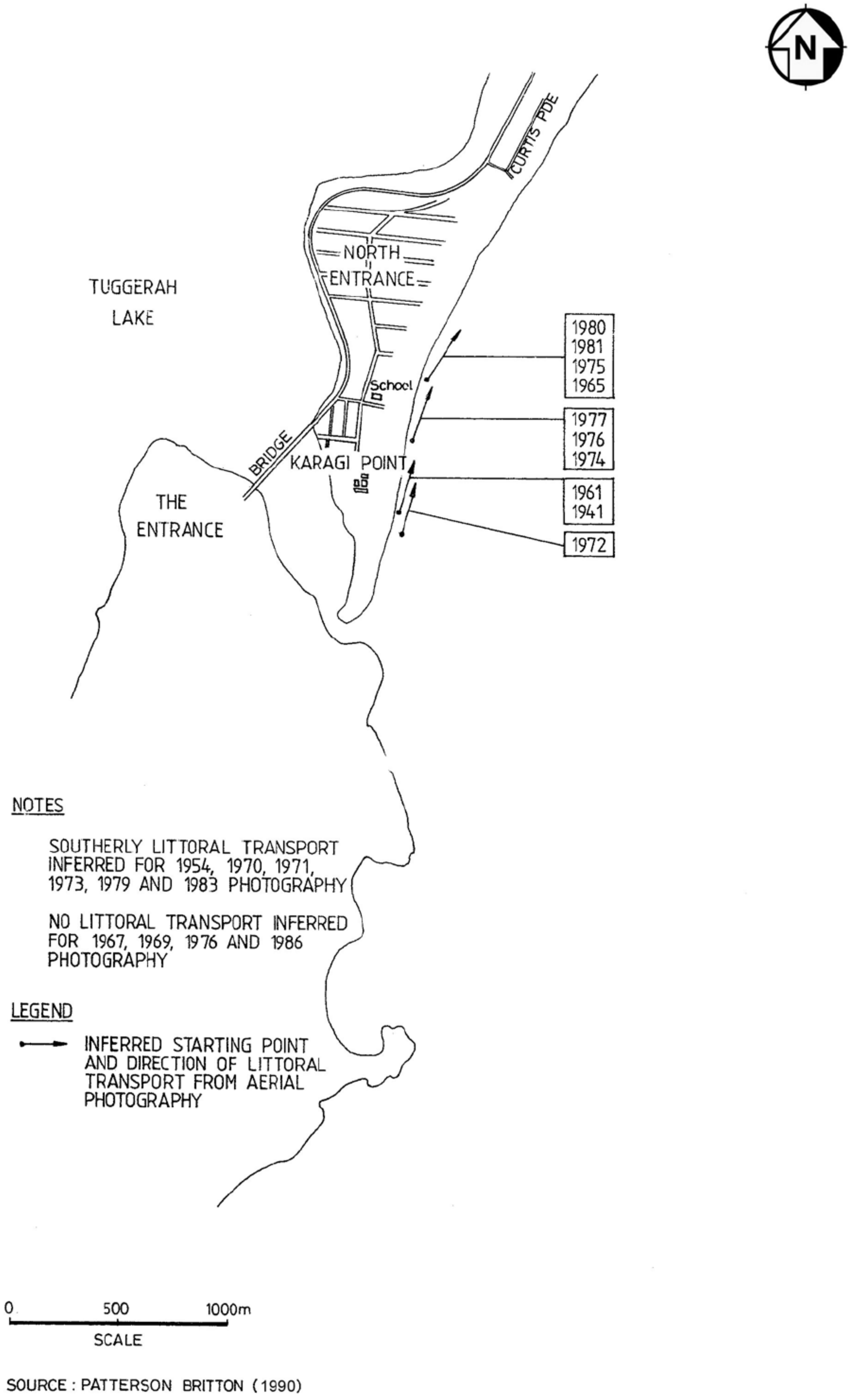


Figure 2.2 – Location of the null point over time (Worley Parsons, 2008)

3 ANALYSIS OF HISTORIC AERIAL PICTURES

Several historic aerial pictures dating from 1941 to 2006 were analysed to determine the evolution of Tuggerah Lake entrance.

November 1941 Tuggerah Lake entrance is closed at this date. There are only a few developments at The Entrance North. A large wind blow-out area is noticeable where Curtis Parade is currently located and most of the beach is subject to wind blow-out. Sand appears to be transported into the lake at this location. The Central Coast Highway has not been built yet. The bridge is located at a different location to present. Terilbah Reserve has not been reclaimed yet. The lake level appears higher due to the closed entrance. Shoals extend over the whole entrance width.

September 1961 There are more developments along The Entrance North. Some patches of vegetation are present on the large blown-out area and the southern end of the beach appears more stable. The channel adjacent to the west of The Entrance North follows the alignment of the existing highway and the main channel at this location appears narrower than the existing channel. The entrance is open on the southern side and has a northwards direction. The main channel of the entrance is split in two with one channel along the southern bank and one along the sand spit. The northern end of the caravan park has been built. A “sand tail” appeared south of Terilbah Island up to the present bridge.

July 1967 Central Coast Highway has been constructed as well as Curtis Parade but there is no dwelling along the latter. The entrance is open with a large entrance channel. The beach appears more stable but some blow-outs are still visible.

May 1970 The entrance is open but is narrower than in 1967 and has a northwards direction. The main channel is located along the southern embankment and there are extended shoals within the entrance. The new bridge has been built and the caravan extended southwards. The southern end of the sand spit stretches landwards.

September 1971 There are some extended shoals all over the entrance and below the northern half of the bridge. The entrance is open in an eastward direction.

June 1974 The entrance is widely open and the entrance channel is relatively large. Some vegetation is growing on the “sand tail” of Terilbah Island.

August 1975 The entrance is narrow and the channel appears very shallow.

August 1976 The entrance is very similar to the 1974 layout with a large entrance and wide channel. Some additional houses have been constructed along Curtis Parade.

August 1977 The channel along the southern embankment behind the entrance is shallower. However, the entrance itself is still wide. Curtis Parade is more developed.

July 1979 The entrance appears very shallow with large shoals south of the entrance. The entrance channel is narrow. More vegetation is observed on the “sand tail” of Terilbah Island.

April 1986	The entrance is very narrow and has a northward direction. The "sand tail" is fully vegetated. A landward movement of the sand spit is visible. Large shoals split the main channel. A large discontinuity in the natural shape of the beach is observed in front of Curtis Parade.
May 1990	The entrance is widely open to the east.
April 1993	Extended shoals are noted within the entrance and split the main channel in two. The sand spit is very large and some dredging works are in progress. Terilbah Reserve has been reclaimed and the channel along it stabilised. The "sand tail" extended westwards and a small ear is visible west of Terilbah Island. A small island has formed north of the centre of the bridge.
February 2002	The entrance is wide toward the east. Some shoals split the main channel in two.
March 2006	Some dredging works are in progress. The entrance has a north-east direction.
General Comments	At the different dates, some large rips were noticeable along the beach. The southern end of the sand spit appears to have a regular westward movement.

4 WAVE CLIMATE ANALYSIS

4.1 Wave Climate

The central coast of NSW experiences high wave energy. The offshore swell wave climate (wave height, period and direction occurrences) has been recorded by the NSW Government Manly Hydraulics Laboratory with Waverider buoys located offshore from Sydney for many years. The Waverider buoy located at Sydney has measured wave direction also since 1992. An important step in understanding the coastal processes at the site is to develop an understanding of the wave climate.

Wave height and direction are the principal drivers of longshore sediment transport at the site. Long period swell waves, which have the potential to cause sediment transport, would not undergo severe refraction when they approach the Entrance and would be expected to arrive at the beach from a wide range of directions with high wave energy. Several nearshore reefs are present, however, that would modify the nearshore wave height and direction, influencing nearshore sediment transport patterns.

To examine this understanding of the wave climate in sufficient detail for estimation of longshore sediment transport rates and seasonal patterns, a SWAN wave transformation model was set up, with detailed bathymetry provided by a combination of survey data at the site and bathymetric soundings from Admiralty Charts.

4.1.1 SWAN Model

SWAN (acronym for **S**imulating **WA**ves **N**earshore – Cycle III version 40.11) is a numerical wave transformation program developed at the Delft University of Technology (Holthuijsen *et al.*, 2000). SWAN can be used to describe wave transformation in shallow water and to obtain realistic estimates of wave parameters in coastal areas, lakes and estuaries from given wind, bathymetric and current conditions.

SWAN is based on the wave action balance equation (or energy balance in the absence of currents) with sources and sinks. The background to SWAN is provided in Young (1999) and Booij *et al*., (1999).

The following wave propagation processes are represented in SWAN:

- rectilinear propagation through geographic space;
- refraction due to spatial variations in bottom topography and current;
- shoaling due to spatial variations in bottom topography and current;
- blocking and reflections by opposing currents;
- transmission through, blockage by or reflection against obstacles.

The following wave generation and dissipation processes are represented in SWAN:

- generation by wind;
- dissipation by white-capping;
- dissipation by depth-induced wave breaking;
- dissipation by bottom friction;
- wave-wave interactions (quadruplets and triads);
- obstacles.

Wave-induced set-up of the mean sea surface is computed in SWAN. In (geographic) 1D cases the computations are based on exact equations. In 2D cases, the computations are based on approximate equations as the effects of wave-induced currents are ignored (in 1D cases they do not exist).

Diffraction is not modelled in SWAN, so SWAN can not be used in areas where variations in wave height are large within a horizontal scale of a few wavelengths. Because of this, the wave field computed by SWAN will, generally, not be accurate in the immediate vicinity of obstacles and certainly not within harbours.

SWAN does not calculate wave-induced currents. If relevant, such currents can be provided as input to SWAN (*e.g*. from a hydro-dynamic model, which can be driven by waves from SWAN in an iterative procedure).
SWAN has been validated using field data by Nielsen & Adamantidis (2003).

Bathymetric data for the model comprised:

- digitised soundings on a 1 km grid as provided by Geoscience Australia (Petkovic & Buchanan, 2002);
- digitised soundings and contours from the *Admiralty Chart Aus 193*, *Port Jackson to Sugarloaf Point*, scale 1:150 000;
- Photogrammetric data along the beach from 1942 to 2002, and including profiles from 1973 and June 1974(immediately following the May 1974 storm event);
- Surveyed soundings to RL -15m AHD along the entire Wyong Shire coastline; and
- Laser Airborne Depth Sounder (LADS) data at the level of the lake entrance.

Long term wave statistics were derived from a Waverider buoy operated by the Manly Hydraulics Laboratory, DPWS offshore of Sydney as published in Lord and Kulmar (2000).

The domain of the wave transformation model extended from Port Stephens in the north to Port Hacking in the south, extending some 50 km offshore into water depths in excess of 100 m (Figure 4.1). This region was schematised onto a 2 km square grid from data derived from the soundings on the 1 km grid.

A 200 m nested grid, covering all of the Wyong Shire coastline and the surrounding coast out to 100m depth, provided a more detailed schematisation of the study region (Figure 4.1). Data for this grid was derived from the 1 km grid as provided by Geoscience Australia supplemented with detail from the *Aus. 809* Admiralty Chart *Port Jackson to Sugarloaf Point*, as well as the surveyed soundings along the Wyong Shire coastline.

A 40 m nested grid is centred at Curtis Parade (Figure 4.2). Data for this grid was derived from soundings and contours from the *Admiralty Chart Aus 193*, *Port Jackson to Sugarloaf Point* and surveyed soundings along the Wyong Shire coastline.

To obtain detailed wave transformation information around the area of interest, details in the nearshore area of The Entrance and adjacent North Entrance Beach were finally schematised on a 15 m grid based on soundings and contours from the *Aus. 193* Admiralty Chart Port Jackson to Sugarloaf Point, and the surveyed soundings adjacent to The Entrance North and are depicted in Figure 4.2.

Detailed bathymetric data in the nearshore region available for the modelling are shown in Figure 4.3.

4.1.2 Offshore Swell Waves

Summary wave statistics are available from the Manly Hydraulics Laboratory (*e.g*., as published in Lord and Kulmar, 2000). The wave data show that the predominant swell wave direction is south-southeast (SSE, 157.5°TN) with over 70% of swell wave occurrences directed from the SE quadrant. The average deep water *significant* wave height, as measured at Sydney, is around 1.5 m (Figure 4.4) and the average wave period is around 10 s. Analysis of storms recorded at Sydney has provided wave height/duration data for various annual recurrence intervals, which are presented in Figure 4.5. Detailed analysis of the percentage of swell waves from offshore directions in 22.5° increments from SSW to NE is provided in Kulmar et al. (2005). This information has been used to estimate net longshore transport rates at various locations along North Entrance Beach.

The transformation of offshore swell waves with a *significant* wave height of H_s = 1m to the area of The Entrance and adjacent North Entrance Beach was undertaken using the SWAN model, to examine the range of nearshore wave angles and magnitudes that is possible at the site. Nine locations along North Entrance Beach, as shown in Figure 4.6 were examined in detail. It can be seen in Figure 4.7 that, due to the effect of swell wave refraction for swell waves with a period of 10 seconds and for all offshore wave directions between NE and SSW (45°-202.5°TN), the range of wave approach directions possible at North Entrance Beach is between 85° and 118°TN. This compares with a shoreline orientation angle of 97.5° to 119°TN, indicating that swell waves typically approach the shore at an angle of -20.5° to +12°(positive value represents a northward wave approach direction and negative value represents a southward direction), which would induce some southward or northward sediment transport at different sites.

A vector diagram of offshore waves approaching from the SSE with a 10s wave period is given in Figure 4.6. It can be seen that the swell wave vectors mostly approach North Entrance Beach at a positive angle to the shoreline, which would tend to induce northward longshore sediment transport. At the northern spit of the entrance, the wave vectors approach at a negative angle to the shoreline, which would indicate that at this location, the longshore sediment transport would be southward entering the tidal inlet.

Vector diagrams indicating the refracted wave paths and wave transformation coefficients due to wave refraction of average swell waves (H_s offshore = 1m) at The Entrance and North Entrance Beach are provided in Appendix A. It can be seen that wave focusing occurs, particularly from S-SSE (135° to 180°TN) at RP6 – RP9 areas and, in particular, that the offshore wave height can be increased by up to 1.2 times its original value. At the RP1-RP3 areas, offshore swell waves approaching from the ENE to ESE (67.5°-112.5°TN) have a wave refraction coefficient of around 1 while the waves approaching from the S to SSE range between 0.8 and 0.95. The wave transformation modelling has shown that extensive wave energy is refracted towards the nearshore areas along North Entrance Beach, resulting in a higher wave climate. These coefficients can be applied to the offshore wave heights to determine the design *significant* wave height used to calculate sediment transport rates.

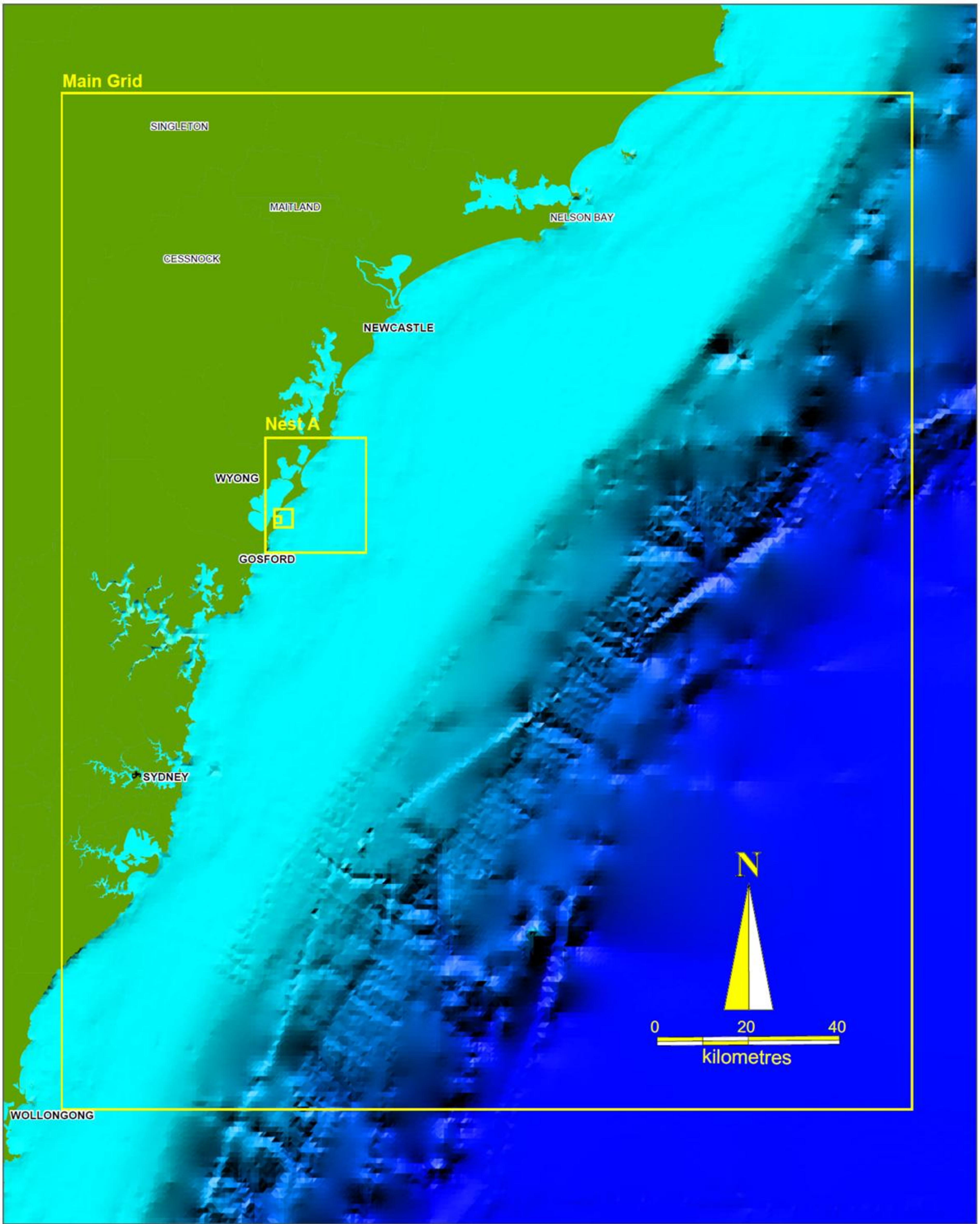
While the average swell wave period for the NSW coast is around 10 seconds, swell wave period can vary between 8s and 18s. The variation in wave period would have an effect on the nearshore wave approach direction, as wave period alters wave refraction. The sensitivity of the nearshore wave angle to variations in swell wave period has been examined in the SWAN model (Figure 4.8). It was found that, for swell waves of 8s wave period, nearshore wave directions can vary from 80° to 138°TN along North Entrance Beach within the study area. For swell waves of 15s period, nearshore wave directions can vary from 88° to 132°TN within the study area. This compares with a shoreline orientation angle of 85° to 130°TN measured at wave breaking depths, indicating that short period swell waves would strike the shore of study area at a range of oblique angles larger than the angles that long period waves generate due to less refraction effect. While the swell waves with long period contain higher wave energy, they undergo more severe refraction from offshore to nearshore to arrive at the beach close to perpendicular to the shore, thus reducing the sediment transport potential when compared with shorter period swell waves.

The above nearshore wave approach angles are used in the estimation of *Potential* longshore sediment transport. The conceptual sediment transport model is set up based on the division of coastal areas into five compartments (as shown in Figure 4.9) within which shoreline angle is relatively uniform. Within these compartments, “best estimates” of average sand transport rates (order of magnitude) and sediment inflow/outflow pathways have been calculated.

4.1.3 Summary Of Wave Climate

From the above analysis of the wave climate for the site, it was found that:

- For the range of swell wave periods experienced on the Central Coast of NSW, nearshore wave angle can vary from -38.5° to 27.5°(positive value represents northward wave approach direction and negative value represents southward direction);
- The *significant* swell wave height can reach H_s = 1.8m at the northern spit of the Entrance due to SSE(157.5°TN) swells and H_s = 1.5m along the northern part of North Entrance Beach due to E(90°TN) swells;
- The direction of approach of wave energy along North Entrance Beach would mostly favour northward longshore sediment transport for the swell waves while a southward sediment transport would be generated at the northern spit of the Entrance.



DATE 25/10/2010	COORDINATE SYSTEM MGA 94 Zone56	Wyong Shire Council
PROJECT NO. 3001053	PROJECT TITLE Longshore Sediment Transport modelling study for the Entrance and Entrance North	
FIG NO. 4.1	FIGURE TITLE Locality Map and SWAN Grids	SMEC
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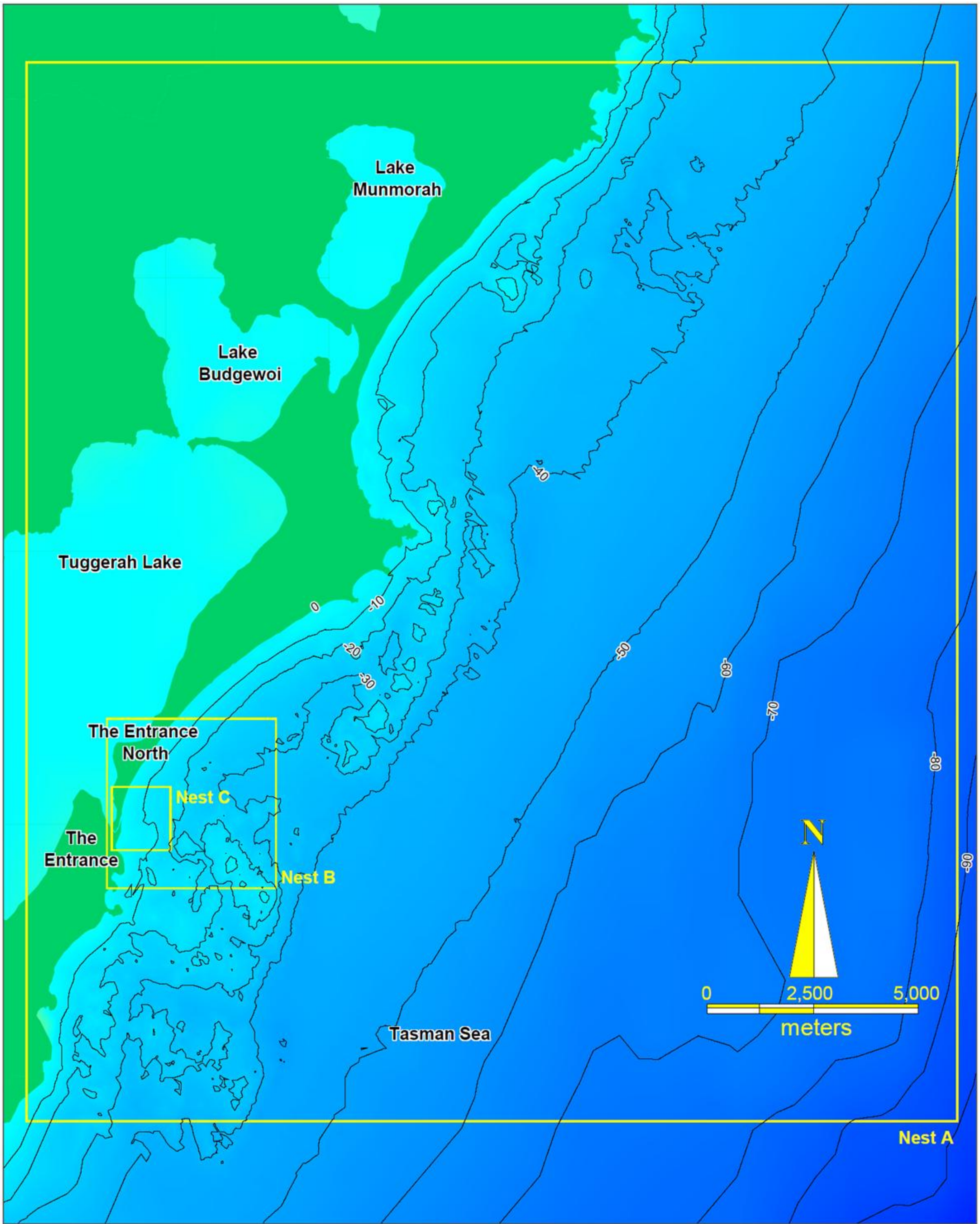

DATE 25/10/2010	COORDINATE SYSTEM MGA 94 Zone56	
PROJECT NO. 3001053	PROJECT TITLE Longshore Sediment Transport modelling study for the Entrance and Entrance North	
FIG NO. 4.2	FIGURE TITLE Locality Map and SWAN Grids (Zoom)	
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Wyong Shire Council

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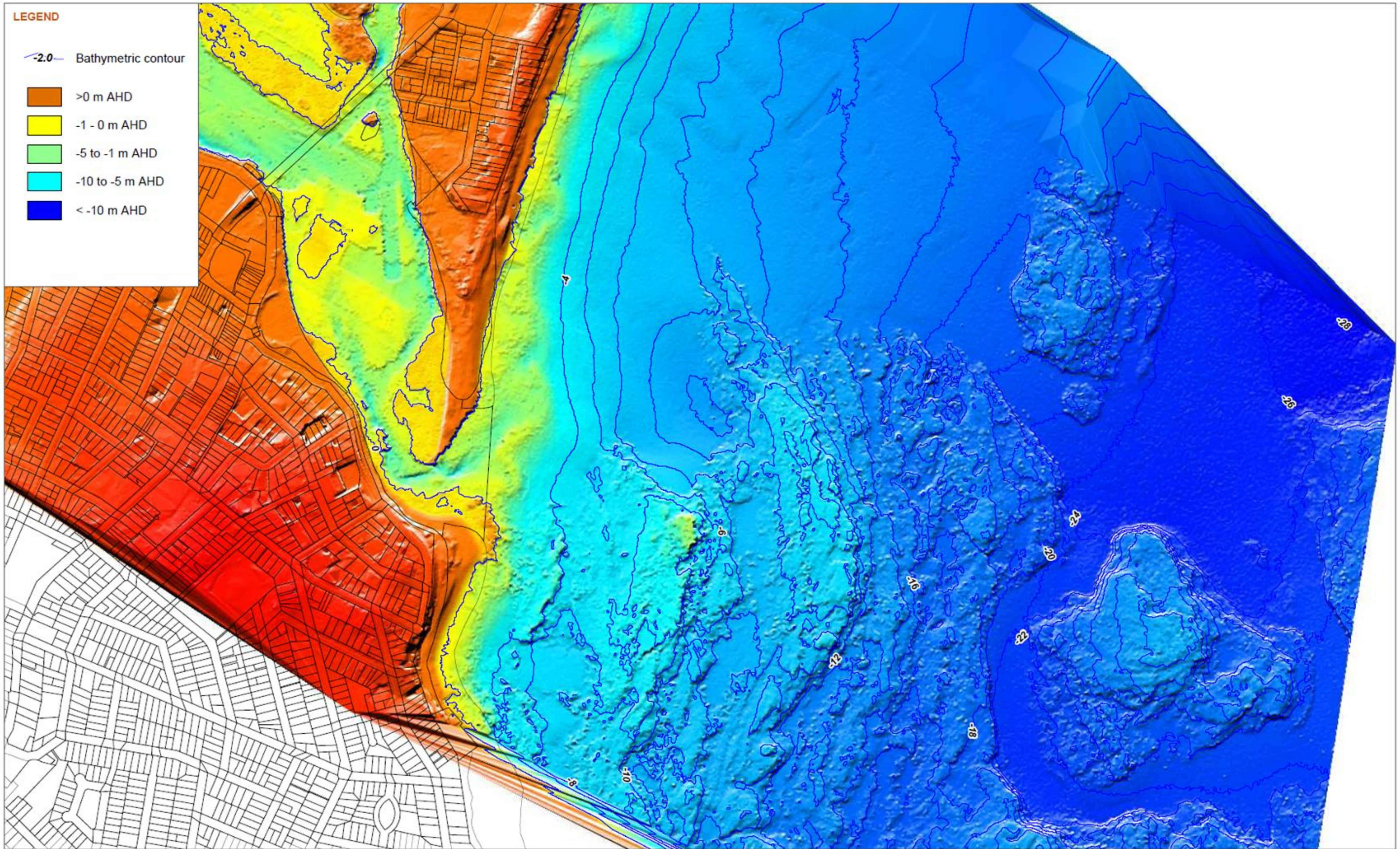


DATE 10/02/2011	COORDINATE SYSTEM MGA 94 Zone 56	FIG NO. 4.3	FIGURE TITLE Detailed LADS bathymetric data
PROJECT NO. 3001053	PROJECT TITLE Longshore Sediment Transport Modelling Study for The Entrance and The Entrance North	CREATED BY C. Adamantidis	LOCATION I:\projects\31461 - Wyong CZMP\2010 Sediment transport and Entrance stability analysis\Data\GIS\The Entrance.WOR

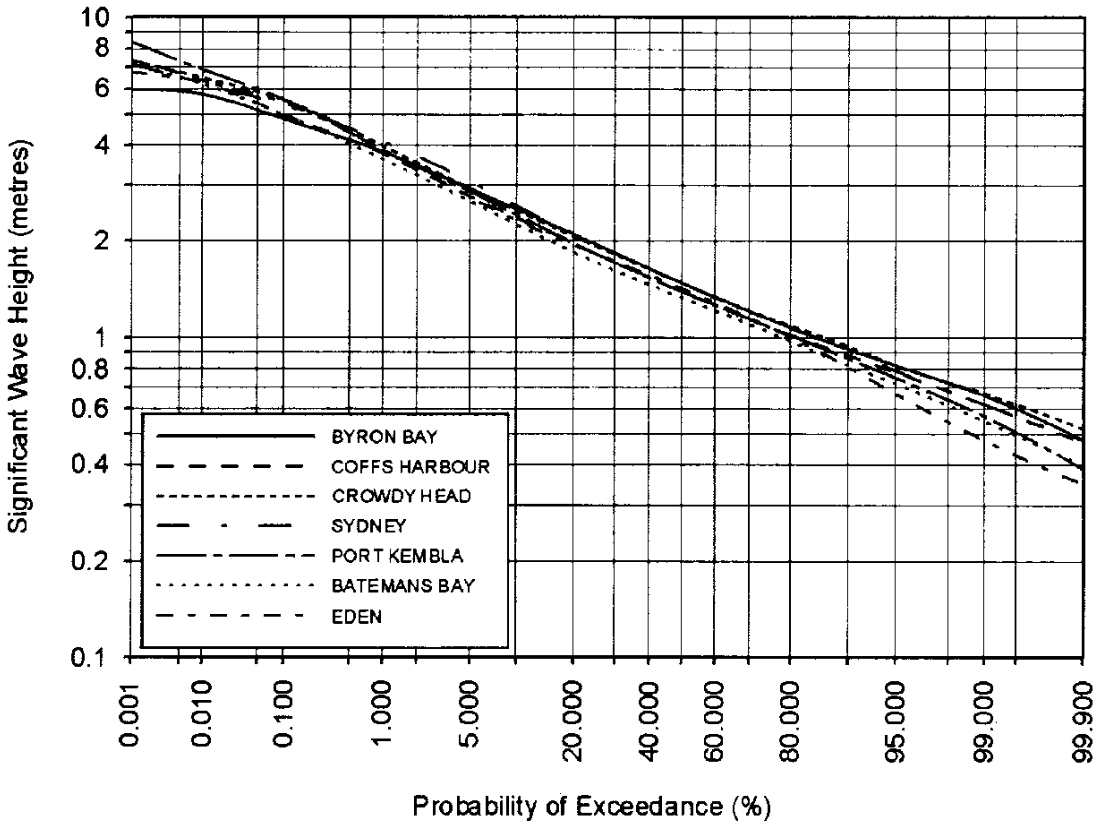


Figure 4.4 – Significant wave height exceedance for NSW coast (Lord & Kulmar, 2000)

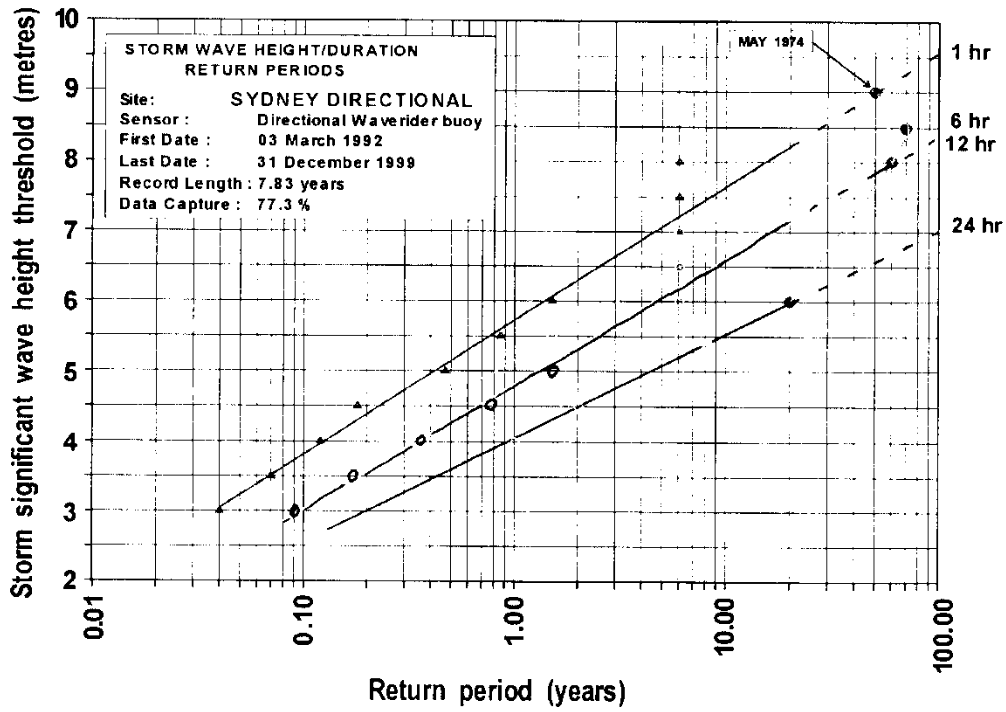
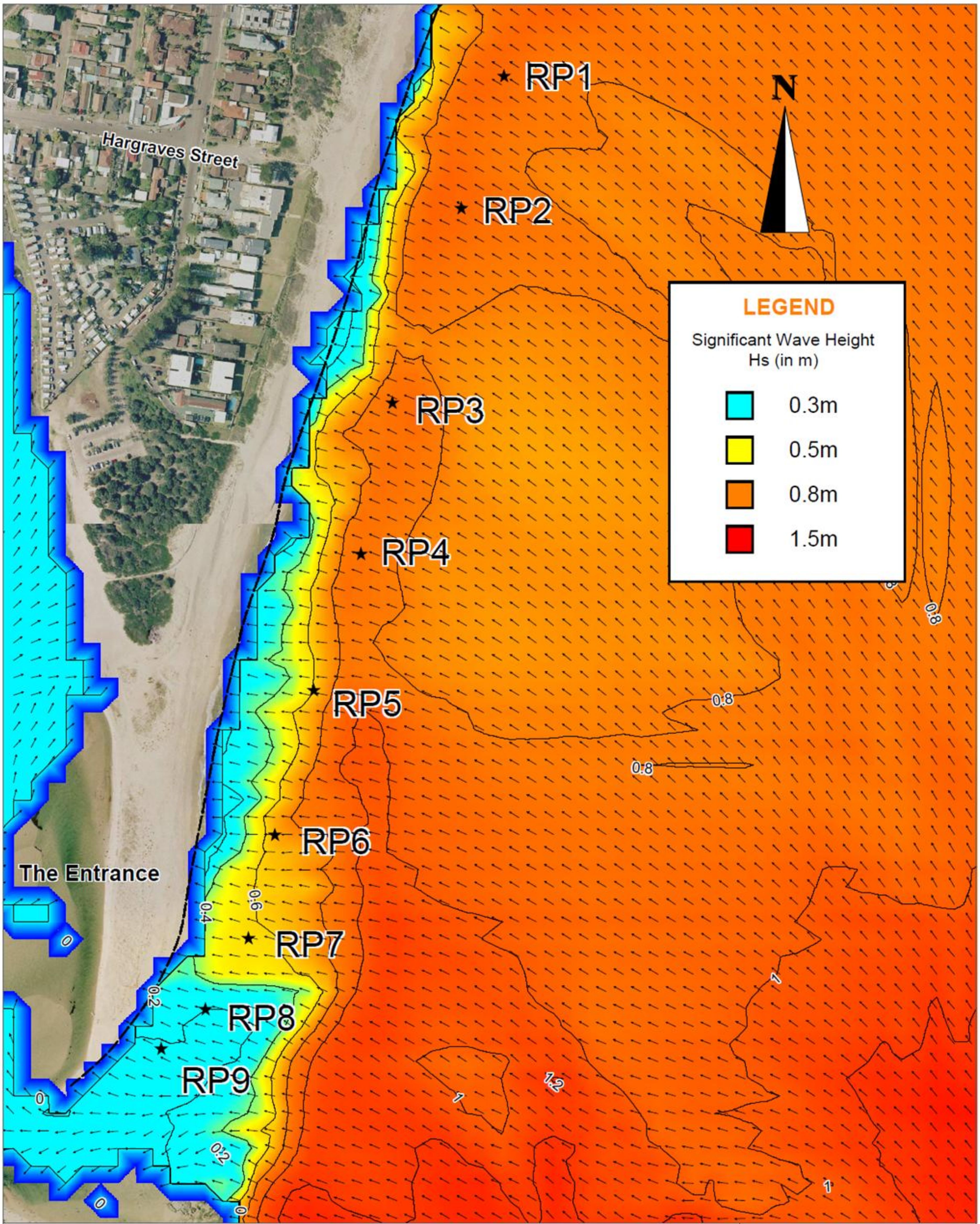


Figure 4.5 – Storm wave height duration recurrence (Lord & Kulmar, 2000)



DATE 16/12/2010

0 50 100 metres

COORDINATE SYSTEM MGA 94 Zone56

PROJECT NO. 3001053

PROJECT TITLE Longshore Sediment Transport Modelling Study for The Entrance and The Entrance North

FIG NO. 4.6

FIGURE TITLE Location of Measurement Reference Point of the predominant wave approach angle for swell waves Hs = 1m; T = 10s; offshore wave direction = SSE

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LOCATION I:\projects\31461 Wyong CZMP\009DATA\data\MapInfo\Workspaces

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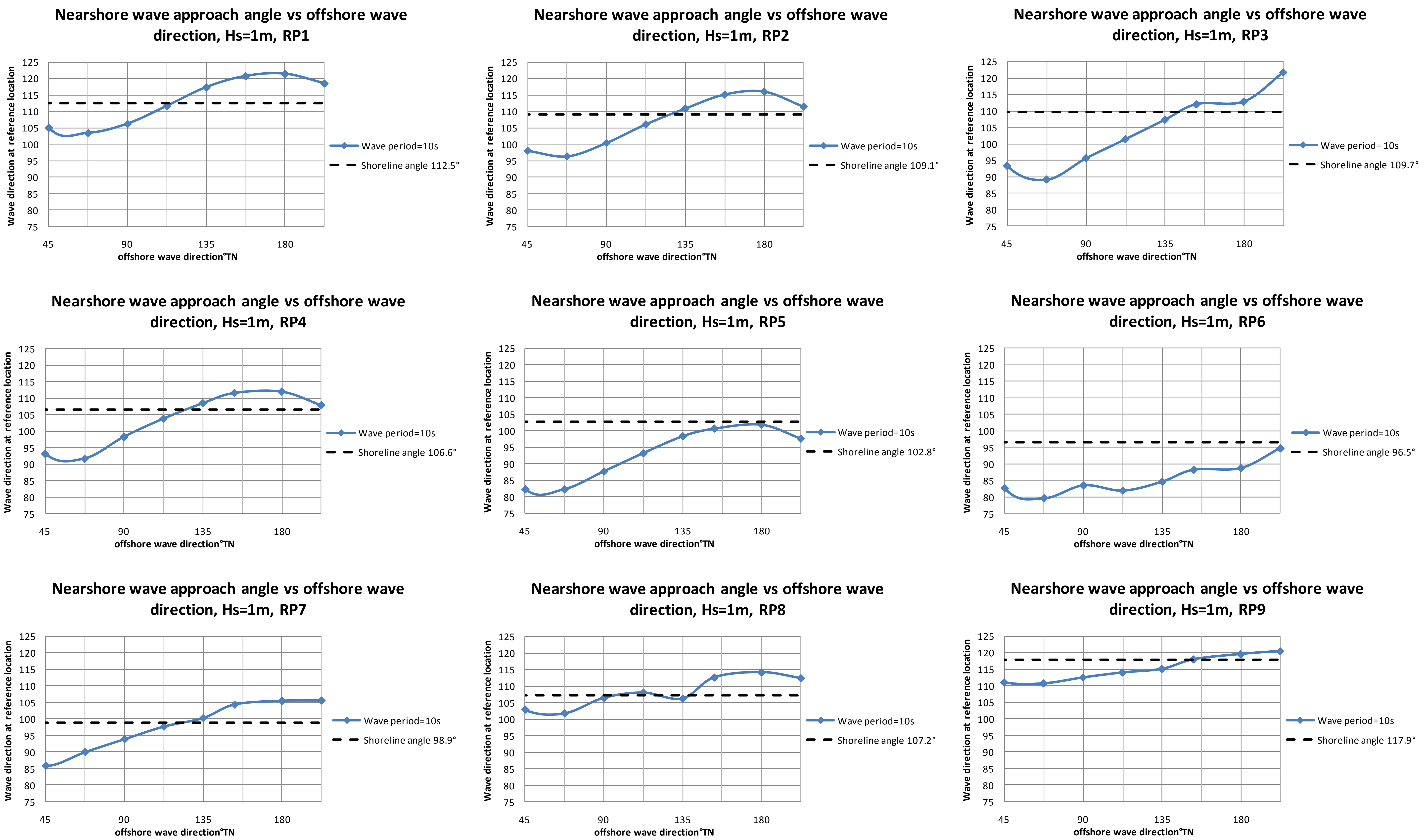


Figure 4.7 – Nearshore swell wave approach angle vs. offshore wave direction, Reference Point 1-9

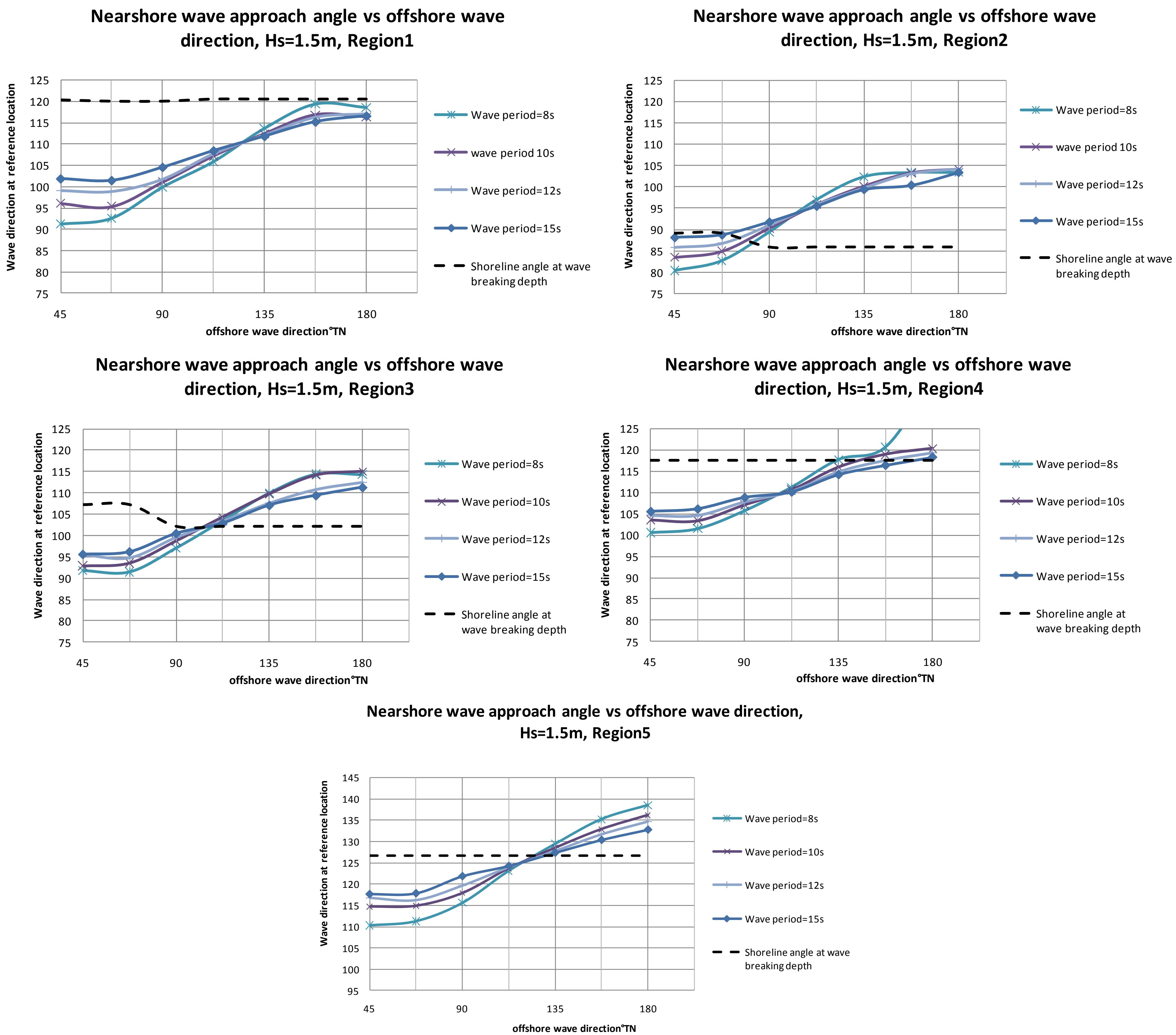
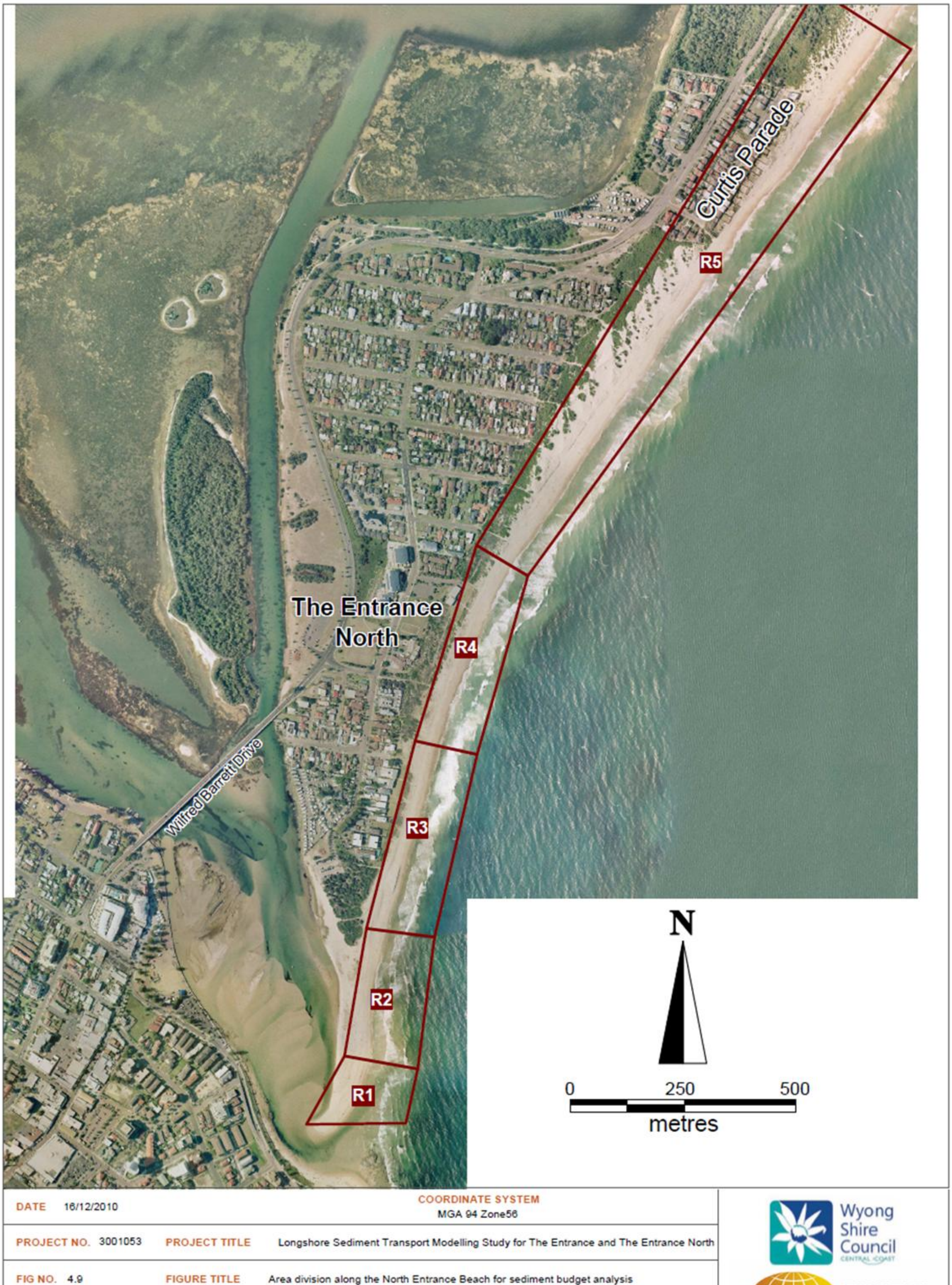


Figure 4.8 – Nearshore swell wave approach angle vs. offshore wave direction, Regions 1 to 5



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PROJECT NO. 3001053	PROJECT TITLE	Longshore Sediment Transport Modelling Study for The Entrance and The Entrance North	
FIG NO. 4.9	FIGURE TITLE	Area division along the North Entrance Beach for sediment budget analysis	
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Wyong Shire Council CENTRAL COAST

SMEC

5 LONGSHORE SEDIMENT TRANSPORT

The sediment pathways and magnitudes play a key role in tidal inlet opening and stabilisation. Wave-induced longshore currents carry sediment from the erosion of the updrift coast to downstream of the tidal inlet, transiting by the tidal channel. Over long time scales, the total amount of sand stored in the tidal inlet would attain a reasonably constant volume if the inlet is in equilibrium. The estimation of longshore sediment transport at the inlet and adjacent beaches can help us to evaluate how an inlet evolves in its natural configuration.

Using the understanding of the coastal processes and the SWAN numerical model from Section 4.1, a ***potential*** net longshore sediment transport rate has been estimated for the site. ***Potential*** net longshore sediment transport refers to the amount of sediment that would be transported along the shoreline by wave action over a given period of time, assuming that there is an infinite supply of sand available on the updrift side, and ignoring the effects of currents, coastal structures, bedrock in the surf zone and onshore-offshore transport processes. The net transport rate refers to the sum of the sediment transport for each possible wave condition and duration, summed over a chosen time period.

5.1 Derivation Of Sediment Transport Rate by *CERC*

The Coastal Engineering Research Center (CERC) suggests various methods of deriving gross longshore sediment transport rates for a site, including using the known transport rate at a nearby site, measured sediment volume changes between two bathymetric surveys of the site, or use of the CERC formula (Shore Protection Manual, 1984) for potential sediment transport. The CERC formula assumes that the longshore sediment transport rate depends on the longshore component of energy flux in the surf zone.

The CERC formula is given by:

$$Q = \frac{K}{(\rho_s - \rho)ga'} P_{ls} \qquad (5.1)$$

where

- Q = Longshore sediment transport rate
- K = dimensionless empirical coefficient, related to sediment grain size
- ρ_s = sediment density
- ρ = water density
- g = acceleration due to gravity
- a = solids fraction of the in-situ sediment deposit (1 – porosity).

and the longshore component of energy flux in the surf zone is given by:

$$P_{ls} = \frac{\rho g}{16} H_{sb}^2 C_{gb} \sin(2\theta_b) \qquad (5.2)$$

where

- H_{sb} = nearshore breaking height of the significant wave
- C_{gb} = wave group speed at breaking, and
- θ_b = angle breaking wave crest makes with the shoreline.

In shallow water,

$$C_{gb} = \sqrt{g d_b} \qquad (5.3)$$

where

d_b = depth of wave breaking, which is assumed to be related to the wave breaking height as $H_b = 0.78 d_b$.

The values for the parameters in the CERC formula are given below:

- K = dimensionless empirical coefficient, related to sediment grain size. Sediment sampling was undertaken at the Entrance North along the spit and the sieve analysis is illustrated in Figure 5.1. The median grain size of sediment (D_{50}) in the surf zone at The Entrance North is 0.35 mm. From Coastal Engineering Manual (2003), an empirically based value for K is around 0.62, based on the median grain size (refer Figure 5.2).
- ρ_s = sediment density = 2650 kg/m^3
- ρ = water density = 1025 kg/m^3 for seawater
- g = acceleration due to gravity = 9.81 m^2/s
- a = solids fraction of the in-situ sediment deposit (1 – porosity). Porosity of a typical beach berm is around 40%, so a = 0.6;
- H_{sb} = nearshore breaking height of the significant wave – from the analysis in Section 4.2.2;
- C_{gb} = wave group speed at breaking, which varies with the wave height in accordance with Equation 5.3;
- θ_b = angle breaking wave crest makes with the shoreline, which is -38.5° to +27.5°(positive value represents northward wave approach direction and negative value represents southward direction).

The CERC formula provides an estimate of the instantaneous (gross) sediment transport, ignoring the effects of currents and onshore-offshore processes. The above parameters were used in conjunction with long-term statistics on swell wave direction to derive longshore sediment transport rates for North Entrance Beach. It should be noted that the longshore sediment transport rates derived using the CERC formulation provide at best an order-of-magnitude estimate of the sediment transport, as there is considerable scatter in reported estimates of the dimensionless K value (refer Figure 5.1), and as the formulation does not take the effect of wave period into account in the calculations.

Table 5.1 shows the annual *potential* net longshore sediment transport induced by offshore swell waves at reference locations along North Entrance Beach under typical conditions (detailed calculations shown in *Appendix A-1*). The estimates are based on analysis of wave statistics for wave direction, significant wave height and period for Sydney provided in Tables 5.2 and 5.3. The swell–generated longshore sediment transport has been weighted for each direction between NE and SSW (45° - 202.5°TN), three significant wave heights (0.5m, 1.5m and 2.5m) and four wave periods (8s, 10s, 12s and 15s) using the wave occurrence statistics shown in Table 5.2 and 5.3. The above conditions are representative of around 95% of all recorded wave directions and periods on the Central Coast of NSW.

The wave height used for sediment transport estimation was 0.5m for the "0.00→0.99" significant wave height, 1.5m for the "1.00→1.99" significant wave height and 2.5m for the "2.00→2.99" significant wave height. The three typical significant wave heights used in the calculation cover 94.8% of wave height occurrences. The frequency of occurrence for wave periods of 8s, 10s, 12s and 15s are 33.5%, 30%, 32.5% and 4% respectively which cover approximately 100% of wave period occurrence in NSW. For example, the sediment transport generated by a SSE swell wave direction with a wave period of 8s and significant wave height of 1.5m was weighted using a coefficient of $\frac{18.20}{94.8} \times 33.5\%$ from Table 5.2 and 5.3. Weighted potential sediment transport rates for all combinations of wave period, direction and height were added to give an estimated potential net annual sediment transport rate at each representative reference location along the beach. Sediment Transport reference locations are shown in Figure 4.9. It should be noted that the estimates are indicative only based on average statistics (as well as uncertainties inherent in the sediment transport formulae) and that net sediment transport rates would vary significantly from year-to-year.

The *potential* longshore sediment transport rates at Region 3 (R3), Region 4 (R4) and Region 5 (R5) are mainly driven by the swell waves from SSE (157.5°TN) and ENE (67.5°TN), resulting in overall northerly sediment transport with a local southerly reversal of littoral drift moving sands along the northern entrance sand spit back to the entrance. The CERC equation predicted northward *potential* longshore sediment transport of up to 4 M m^3/yr for R2, 1.1 M m^3/yr for R3 and 0.4 M m^3/yr for R5, with reduced longshore transport magnitude further north. However, long term beach recession was generally observed to increase northward along the beach, from photogrammetric data analysis in the Wyong Coastal Hazard Study (SMEC, 2010). The increased long term recession further north along the beach may be due to offshore sand transport during storms or aeolian transport into the dune system, as longshore transport rates are relatively low along the northern parts of the beach.

The ***net*** actual sediment transport rate would be a lot smaller than ***potential*** sediment transport, as this estimate does not take into account the availability of sediment for transport, the input of sediment to the system from other sources such as sand from occasional wind-blown sand transport and tidal sand outflow from the channel of the entrance. While the ***net*** sediment transport rate at the site is not known precisely, it is evident that the main potential is for sediment transport from south to north along the northern beach away from the tidal inlet and gradually reverses direction from north to south entering the tidal inlet.

Table 5.1 – Estimated potential longshore sediment transport using CERC (1984) formula in typical conditions

Longshore Sediment Transport ('000 m^3/yr)	T=8s	T=10s	T=12s	T=15s	Total '000 m^3/yr
R1	-425	-580	-689	-76	1770 S
R2	877	1028	1163	110	3178 N
R3	227	358	200	20	805 N
R4	30	-81	-117	-20	188 S
R5	136	57	48	-4	236 N

**Positive value represents northward transport and negative value southward transport.*

Table 5.2 – Sydney wave height occurrence by direction to December 2004 (Kulmar et al., 2005)

Start Date: 03-Mar-1992 **End Date:** 31-Dec-2004 **Record:** 12.84 years **No. Records:** 86,595 **Capture:** 82.7%

Hsig (metres)	Wave Direction (° True North)									TOTAL
	NNE	NE	ENE	EAST	ESE	SE	SSE	SOUTH	SSW	
0.00 → 0.99	0.02	0.43	1.27	1.71	1.87	3.20	5.75	1.96	0.08	16.48
1.00 → 1.99	0.06	2.34	6.44	7.53	6.39	9.74	18.20	9.91	0.41	61.13
2.00 → 2.99		0.35	1.08	1.46	1.52	2.35	5.27	5.03	0.13	17.19
3.00 → 3.99		0.01	0.11	0.29	0.24	0.51	1.29	1.39	0.04	3.89
4.00 → 4.99			0.03	0.08	0.08	0.15	0.31	0.33		0.98
5.00 → 5.99				0.02	0.02	0.05	0.10	0.09		0.27
6.00 → 6.99							0.02	0.01		0.04
7.00 → 7.99							0.01			0.01
TOTAL	0.08	3.13	8.93	11.09	10.12	16.00	30.96	18.73	0.66	100.00

Table 5.3 Wave Period Occurrence for all stations to December 2004 (Kulmar et al., 2005)

TP1 (sec)	Byron Bay	Coffs Harbour	Crowdy Head	Sydney	Port Kembla	Batemans Bay	Eden
2 → 3.99	0.404	0.429	0.301	0.353	0.924	0.401	0.260
4 → 5.99	5.492	5.879	5.201	5.702	6.035	6.955	7.569
6 → 7.99	16.005	15.475	15.289	15.492	17.017	20.330	19.309
8 → 9.99	34.185	33.744	32.731	24.037	31.913	30.271	31.325
10 → 11.99	27.168	28.026	27.833	36.302	25.600	25.785	24.320
12 → 13.99	14.742	14.399	15.853	14.160	15.871	14.733	15.127
14 → 15.99	1.796	1.824	2.382	3.415	2.307	1.341	1.865
16 → 17.99	0.199	0.215	0.387	0.469	0.310	0.176	0.208
18 → 19.99	0.011	0.010	0.023	0.069	0.023	0.007	0.016
Average TP1	9.57	9.57	9.71	9.83	9.57	9.36	9.41
Start Date	14-Oct-1976	26-May-1976	10-Oct-1985	03-Mar-1992	07-Feb-1974	27-May-1986	08-Feb-1978
Record (years)	28.23	28.62	19.24	12.84	30.91	18.61	26.91
No. Records	142,000	164,021	145,059	86,595	171,794	148,537	152,809
Capture (%)	71.5	84.6	86.0	82.7	83.5	91.0	80.6

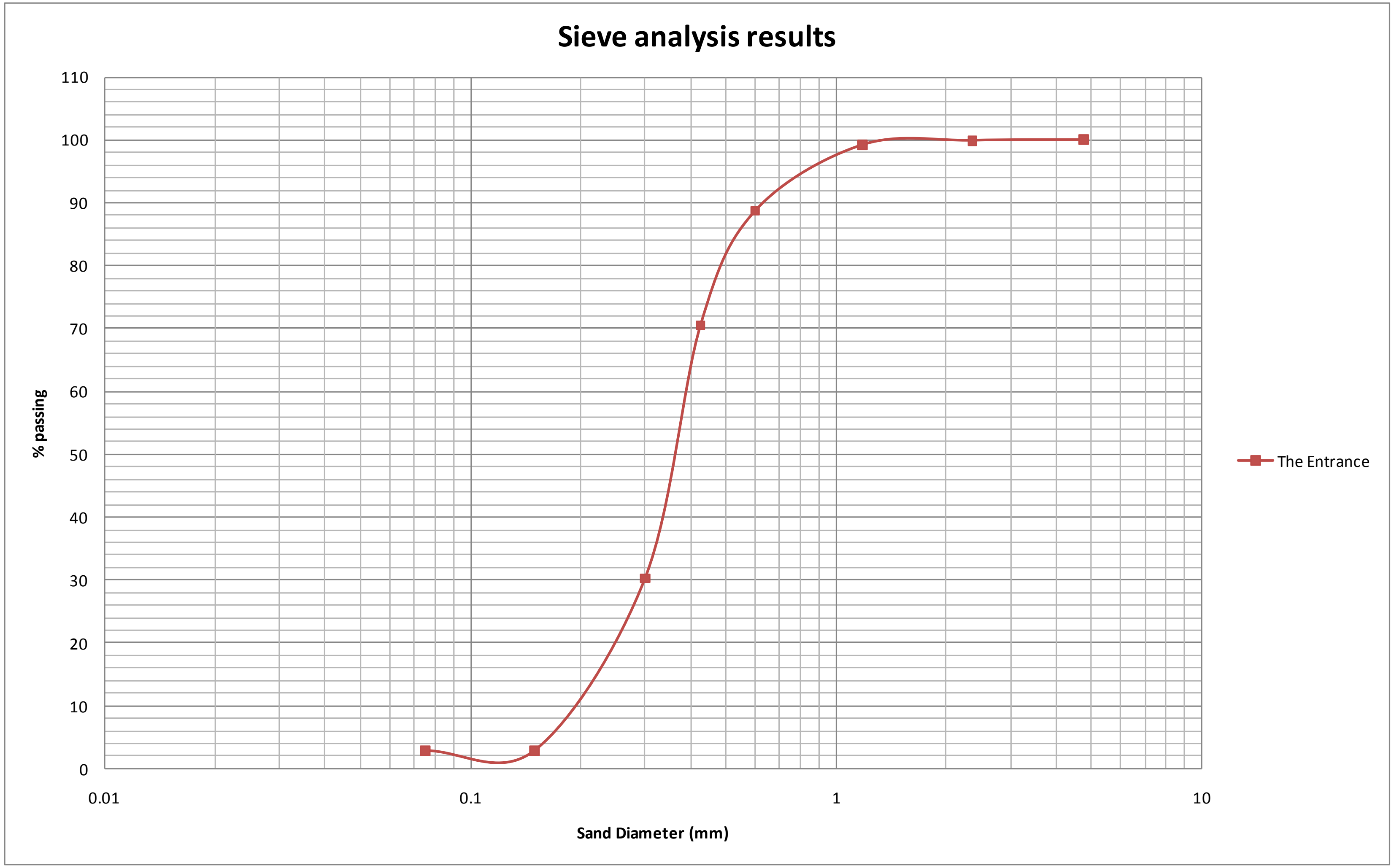


Figure 5.1 – Results of the Sieve Analysis for the Entrance North

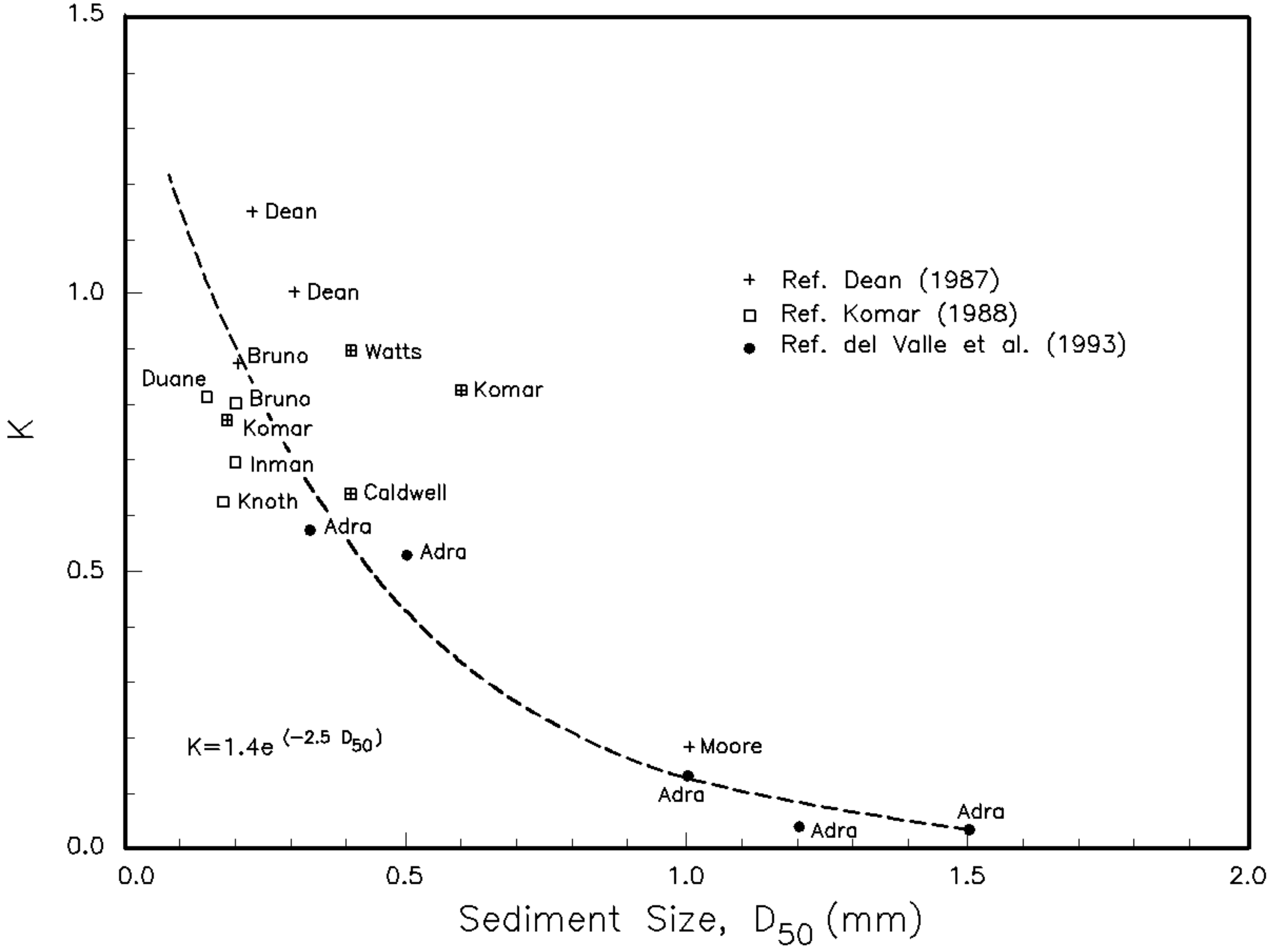


Figure 5.2 – Determination of value of K parameter in CERC sediment transport formula (from Coastal Engineering Manual, 2003)

5.2 Derivation Of Sediment Transport Rate by *Kamphuis*

For comparison purposes, the sediment transport rate was also evaluated using the Kamphuis (1991) expression. This expression is based on an extensive series of hydraulic model tests, and depends on breaking wave height, wave period, grain size, nearshore beach slope and nearshore wave approach angle. The expression is given by:

$$Q_k = (6.4 \times 10^4) H_{sb}^2 T_{op}^{1.5} m_b^{0.75} D^{-0.25} \sin(2\alpha_b)^{0.6}$$

where

Q_k = sediment transport rate, m^3/year

H_{sb} = breaking wave height

T_{op} = wave period (10s for swell waves)

m_b = nearshore beach gradient (i.e. 1:10 as measured in the beach survey)

D = sediment grain size (i.e. 0.25mm according to the sand samples taken along the beach)

α_b = angle breaking wave crest makes with the shoreline, which is ranging from -20.5° to +12°for the different swell wave directions.

Using these parameters, the sediment transport rate as calculated by the Kamphuis expression is provided in Table 5.4 (detailed calculations shown in *Appendix A-2*).

Table 5.4 – Nett Sediment Transport at North Entrance, Kamphuis expression

Longshore Sediment Transport ('000 m³/yr)	T=8s	T=10s	T=12s	T=15s	Total '000 m³/yr
R1	-403	-851	-1311	-206	2771 S
R2	683	1083	1634	229	3631 N
R3	235	460	372	56	1123 N
R4	59	-67	-201	-58	267 S
R5	160	132	160	2	454 N

**Positive value represents northward transport and negative value southward transport.*

The Kamphuis (1991) method gave similar results to the CERC method, with the main potential for sediment transport from south to north along the North Entrance Beach and a reversal of the transport direction from north to south entering the tidal inlet. It is noted that the Kamphuis equation takes into account wave period, a factor that influences wave breaking which is not a parameter used by the CERC equation. The potential sediment transport rates at the Entrance and North Entrance Beach calculated by the Kamphuis equation are a little higher than the values calculated by the CERC equation.

5.3 Conceptual Sediment Transport Model

A conceptual sediment transport model for The Entrance and North Entrance Beach based on the results of the previous calculation is illustrated in Figure 5.3 and Figure 5.4. Along North Entrance Beach, the swell generates a predominantly northward sediment transport, strongly along the coastline in Region 2 between the Entrance northern spit and Karagi Park, but much less further north from Region 3 to Region 5 (refer Figure 4.9 for the locations of the regions). Southward sediment transport entering the inlet is observed at the Entrance and along the Entrance northern spit. A tide-induced sediment circulation between the upstream entrance shoals, entrance sand bar and the entrance spit was identified by earlier studies (PBP 1994). Sand carried out by the ebb tide through the entrance channel deposits on the entrance sand bar area, whereby it becomes available for onshore transport back onto the beach. Flood tide and breaking waves carry the sands from the entrance bar both southward back to the entrance shoals and northward along the coast, with some being brought onshore by wave action. The northward transport in Region 2 may be limited due to limited amount of sand available for transport, but it is likely that some sand is being transported onshore by wave action. The estimated magnitudes and pathways of detailed sediment transport within the five regions along the Entrance North are shown in Figure 5.4.

Cross-shore sediment movement occurs mostly during storm events. Tide-induced sediment transport involves the entrance bar, entrance sand spit and the upstream sand shoals. The action of breaking waves and flood tide currents carries sand onshore, towards the entrance channel, and deposits it on the upstream sand shoals. During ebb tide, sand is removed from the entrance channel and northern and southern channels, transported back through the entrance throat and deposited on the entrance sand bar. In this sand circulation, more sand is transported onto the upstream entrance shoals and gradually builds up the upstream sand shoals.

5.4 Potential impact of training wall at the Entrance

A potential option for management of the entrance area is to construct a training wall at the northern side of the entrance channel. The impacts of such a training wall on the entrance dynamics and sediment transport are discussed below, with reference to the conceptual coastal process model of the area.

5.4.1 Entrance Bar

A training wall at the northern side of the entrance could result in the widening and deepening of the entrance channel and significant scour of the existing entrance bar. The sand circulation between the entrance sand bar, upstream shoals and the entrance channel shown in Figure 5.4 would be cut off by the training wall, as southerly sediment transport into the entrance channel would be blocked, and the ebb tide would continue to scour upstream shoals through the substantial opening entrance throat. The creation of a strong ebb tide jet would build up a new entrance sand bar further offshore. Wave action would be unable to move this offshore sand back onto the beach as readily as it does under existing conditions, and the nearshore wave climate at the southern section of North Entrance Beach would be altered due to changes in nearshore bathymetry, which could cause changes in sediment transport patterns and possible erosion of the entrance spit.

5.4.2 Shoaling

The existing entrance sand shoals would erode due to a permanent loss of sand from littoral drift along northern entrance spit back to the entrance obstructed by the northern training wall. Sand moving onshore by flooding tide and breaking waves would tend to be trapped by the training wall and the ebb tide would continue to scour the upstream sand shoals, transporting sand through the entrance throat onto the new sand bars. Hence the sand deposited onto the upstream shoals would be greatly reduced. However, increased tidal currents would tend to bring sediment further into the estuary and extend the flood tide delta upstream.

5.4.3 Erosion and Sedimentation

The construction of northern training wall perpendicular to the beach would interrupt the local southerly reversal of littoral drift back onto the entrance upstream shoals. The sand captured against this wall would accumulate so as to form a fillet of sand. If the training wall were to be constructed for the purpose of keeping the entrance channel open, the northern training wall would need to be of a sufficient length such that the naturally occurring equilibrium plan alignment of the beach in this fillet results in no sand being able to be swept by waves around its end (and into the mouth of the entrance) during periods of southerly sand transport. This sand is no longer available to be moved onshore from the entrance sand bar due to the scour of the entrance sand bar. This would exacerbate the North Entrance beach erosion due to lack of sand supply to feed northward longshore sediment transport. There would be massive sand relocation from the upstream shoals to the margins of adjacent beaches.

5.4.4 Tuggerah Lake

Continued scour of the entrance channel would result in an increasing trend in the tidal range and tidal prism of the Tuggerah Lake. The entrance channel would evolve toward an equilibrium following entrance training, and allow ocean swell to propagate through the entrance. Scour in the entrance channel as a result of increasing tidal flow could threaten the foundations of the road bridge resulting in expensive remedial works to the bridge abutments. The Wilfred Barrett Drive would be exposed to sediment scour of the bridge piers by swift tidal currents. The ecological environment within Tuggerah Lake would be influenced greatly by the rate at which water in the lake is exchanged with oceanic waters through the entrance, as well as changes to the natural tidal regime, changing the natural assemblages of vegetation communities in the area.

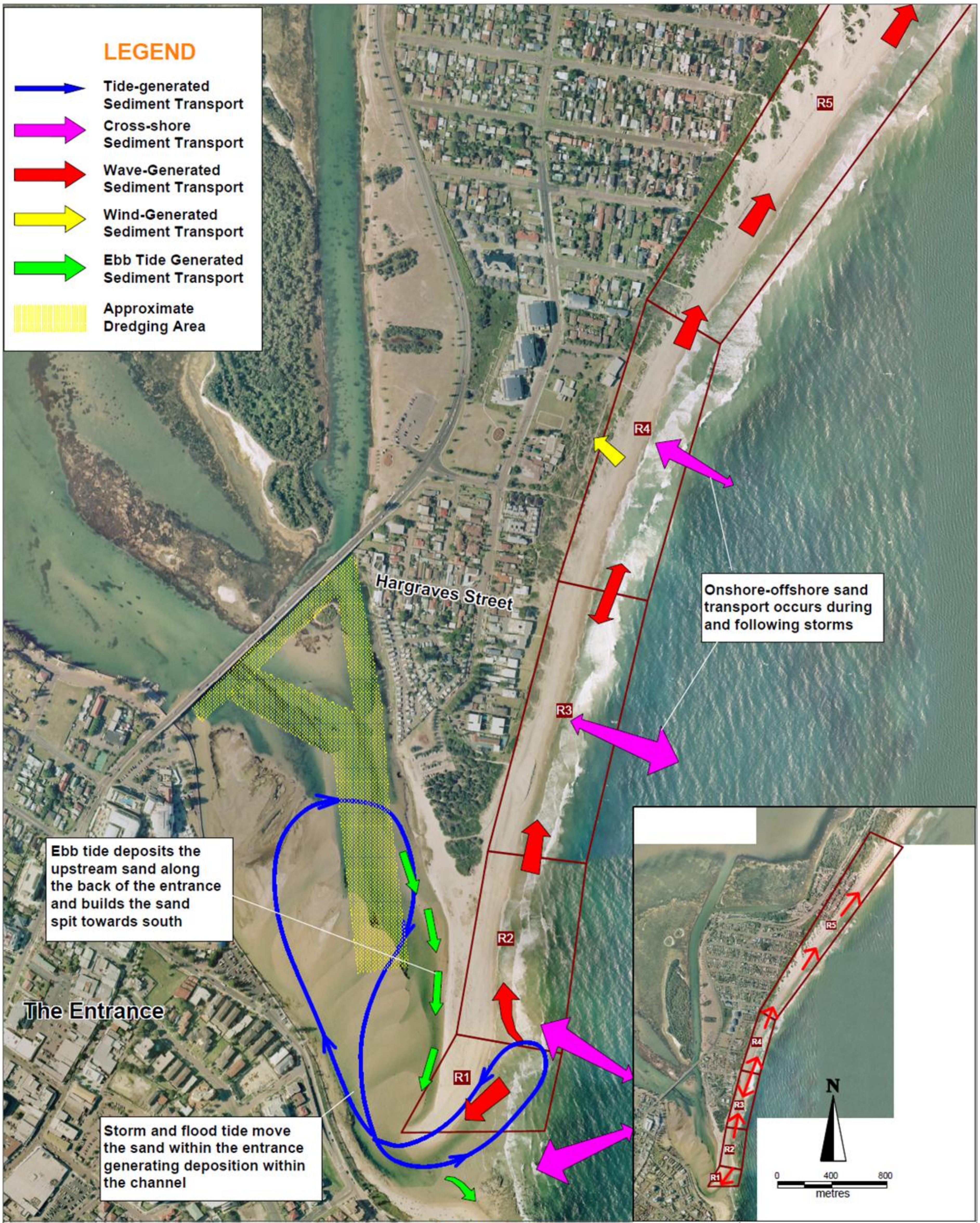
5.4.5 Flooding

The gradually removal of upstream shoals would have an adverse effect on entrance stability. An extreme flood event could split the main channel of the entrance into two with one channel along the southern bank and one along the sand spit. A training wall in front of the northern entrance spit would therefore need to extend upstream along the entrance channel toward the bridge so as to prevent breakthrough of the entrance spit in a large flood event.

5.5 Historic Sediment Transport

The existing wave climate was compared to the shoreline angle observed from the historic aerial photographs to determine a general trend in the sediment transport and observed the location of the null point over time. A similar pattern to the existing circulation was noted with a southward sediment transport at the entrance and a northward sediment movement further north. The difference in the pattern occurs in 1941 when the sand spit was closed and some northward sediment movement was observed at the southern end of the entrance.

The null point was found to migrate between Hargraves Street and the northern end of the unvegetated sand spit. This range of migration was similar to that reported in Worley Parsons (2010) and illustrated in Figure 5.5.



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PROJECT NO. 3001053 — PROJECT TITLE Longshore Sediment Transport Modelling Study for The Entrance and The Entrance North

FIG NO. 5.3 — FIGURE TITLE Conceptual Sediment Transport Model for North Entrance Beach

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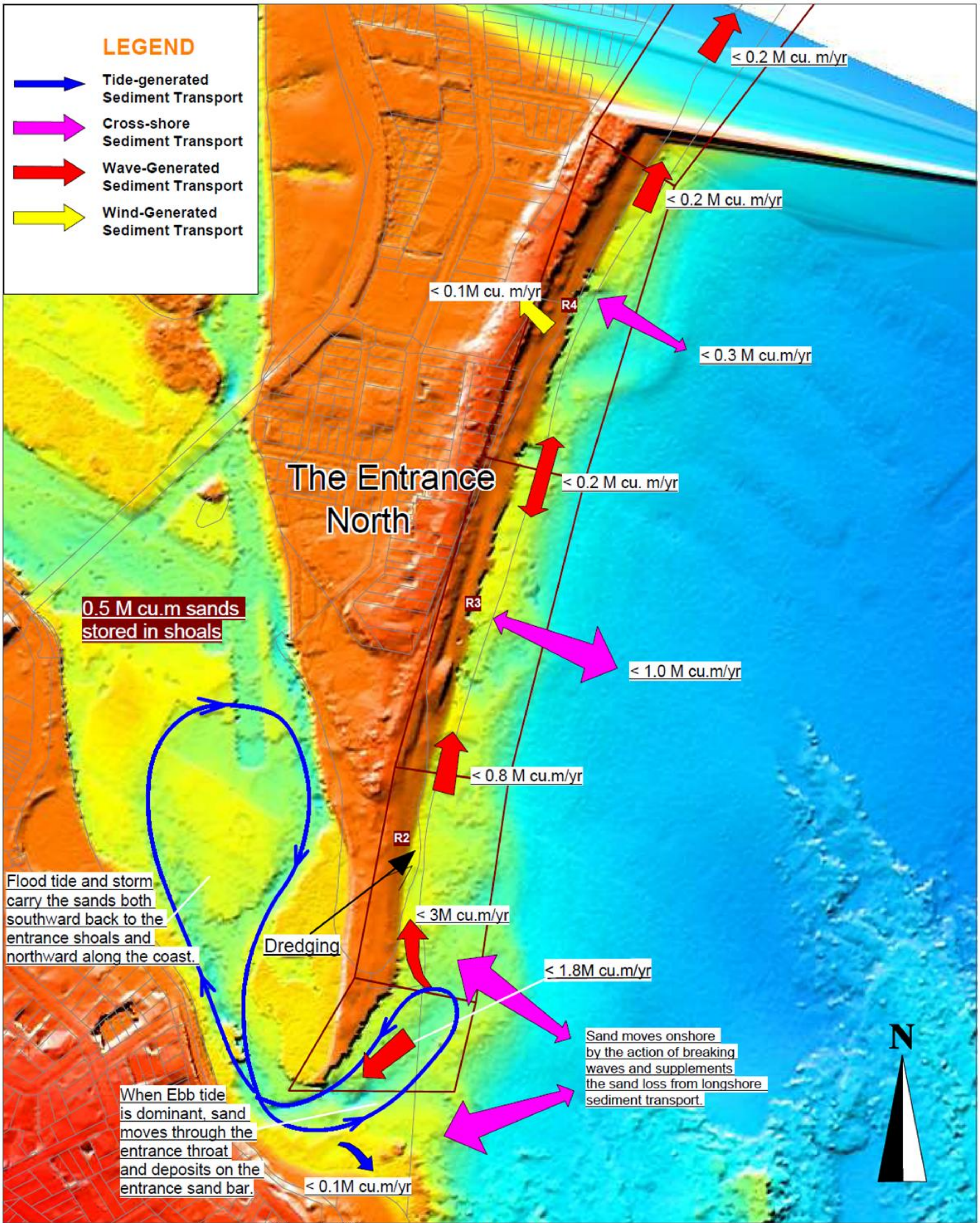

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PROJECT NO. 3001053

PROJECT TITLE Longshore Sediment Transport modelling study for the Entrance and Entrance North

FIG NO. 5.4

FIGURE TITLE Longshore/offshore sediment transport along the Entrance North Beach and tide-induced sand circulation between the entrance sand bar and upstream sand shoals

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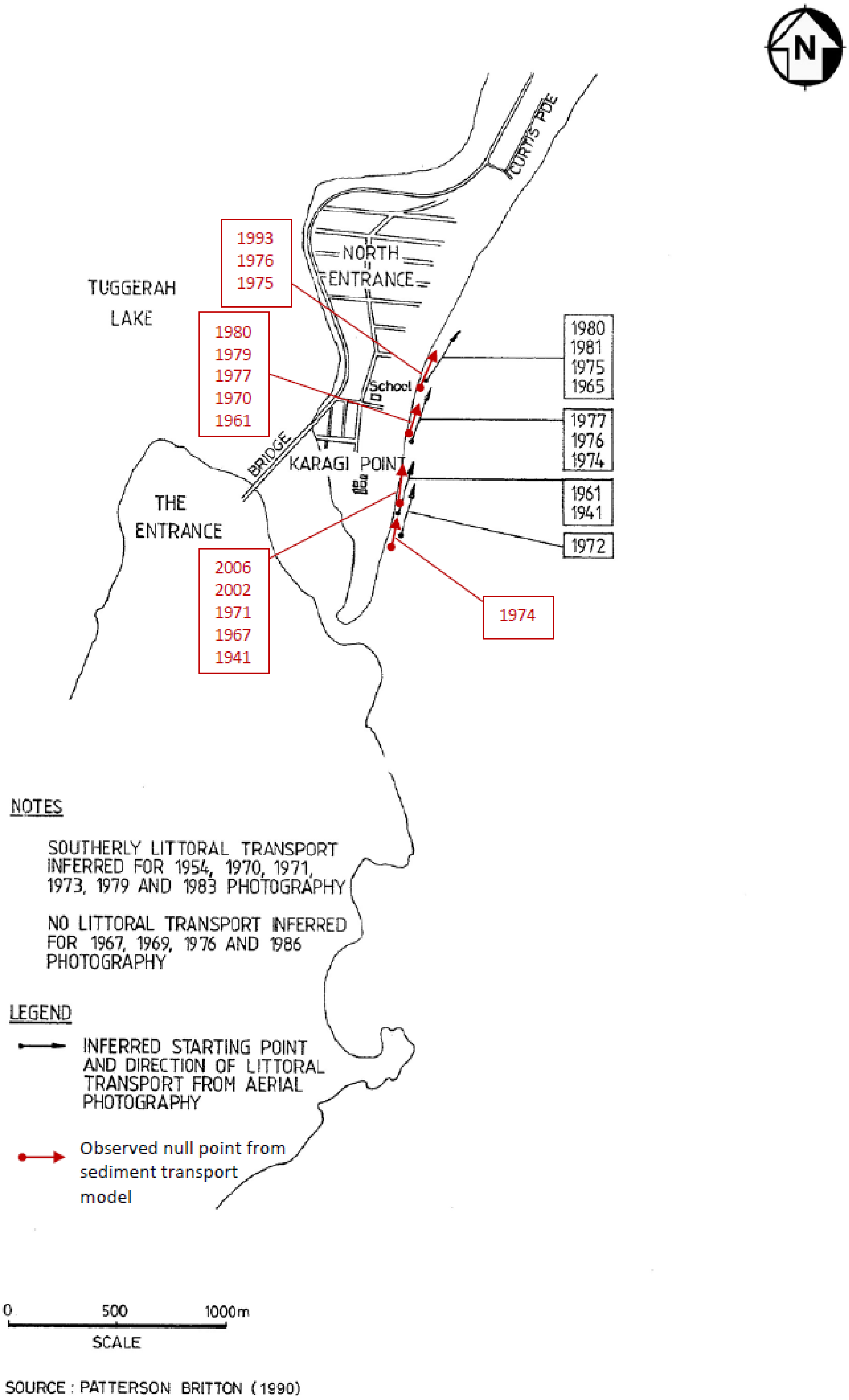

Figure 5.5 Locations of null point observed from sediment transport model compared with Worley Parsons (2008).

6 ENTRANCE STABILITY ANALYSIS

The cross-sectional stability of a tidal inlet has been first analysed by Escoffier in 1940. Escoffier's theory analysed the permanency of the stability of the entrance depending on its size and the maximum current speed at the entrance. The relationship between cross-sectional area and maximum velocity is illustrated in Figure 6.1. When the maximum velocity is equal to the equilibrium velocity, the cross-sectional area is in equilibrium and the entrance is stable. When the maximum velocity is lower than the equilibrium velocity, the current is not strong enough to move the sediments carried into the inlet by littoral drift and the sediments will deposited into the entrance reducing the cross-sectional area. When the maximum velocity is higher than the equilibrium velocity, the sediment transport capacity of the inlet currents will be larger than the volume of sediment carried into the inlet entrance by littoral drift and the entrance will therefore erode and the cross-sectional area will increase. From this and Figure 6.1, it can be observed that:

- if the cross-sectional area A is lower than A1 (A<A1), the sediments will deposit into the entrance and the entrance will tend to close over time;
- if A1 < A < Ae, the entrance will erode until A = Ae;
- if A > Ae, the sediments will be deposited into the inlet entrance and the entrance cross-sectional area will reduce until A = Ae;
- if A = A1, the equilibrium is unstable. If there is any storm depositing or removing some sediment from the entrance, the entrance would either close or widen to reach the equilibrium area Ae; and
- if A = Ae, the equilibrium is stable. If a storm deposits or removes some sediments from the entrance it will recover to reach A = Ae.

Hence, the entrance is stable for A > A1.

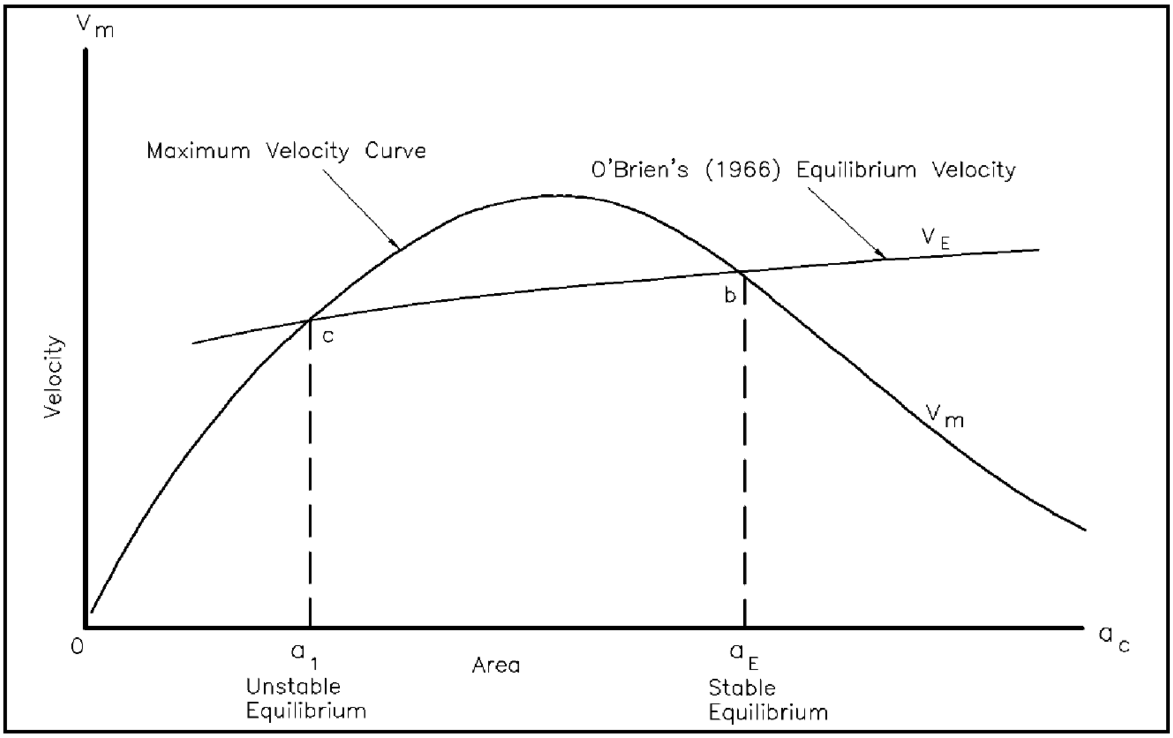

Figure 6.1 – Escoffier (1940) curve, maximum and equilibrium velocities versus inlet cross-sectional area (C.E.M., Chap. II-6)

However, the equilibrium cross-sectional area may be subject to long term changes. O'Briens (1966) determined a relationship between cross-sectional area and tidal prism. Assuming a maximum velocity $u_i = \hat{u}_i \sin(wt)$ with w the angular frequency of the tide and t the time, it follows:

$$\Omega_i = \frac{A_i \hat{u}_i T}{\pi}$$

with Ω_i = Tidal Prism of the estuary

A_i = Cross-sectional area of the inlet entrance

T = Tidal period

This formula is usually presented as:

$$A = C\Omega^n$$

with C and n free parameters. These parameters can be obtained by analysing the correlation between the tidal prism and the cross-sectional area of several estuaries located within the same region. This correlation has been undertaken along Australia's East Coast by BMT WBM (2008) as shown on the graph in Figure 6.2.

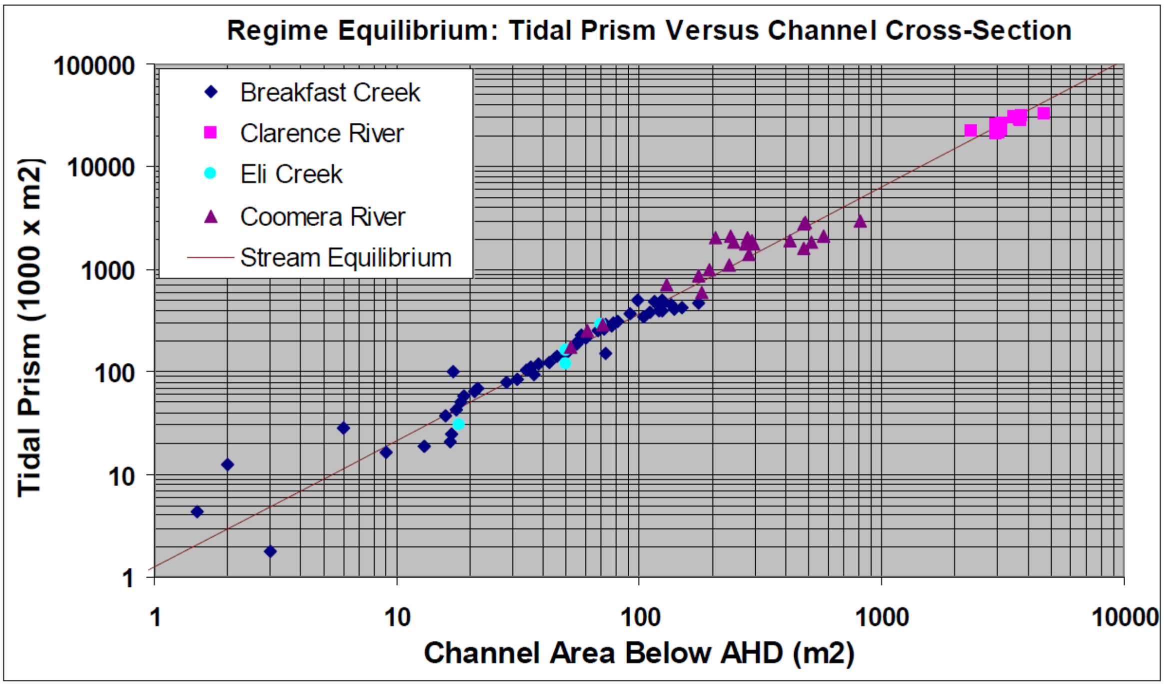

Figure 6.2 – Regime equilibrium relationship for tidal estuaries along Australia's East Coast (BMT WBM, 2008)

From this graph, the relationship derived was identified as:

$$A = 3.1 \text{ x } 10^{-3}\Omega^{0.81}$$

This cross-sectional area-tidal prism relationship has been used for Tuggerah Lake at The Entrance.

The dimensions of the lake entrance were observed using the historic aerial photographs and available bathymetric soundings. It was found that the channel entrance width was varying between around 20 and 100m, its length ranges between 90 and 450m and its depth was assumed to range between 0 and 2m.

The water level response of Tuggerah Lake was calculated using a difference method from the predicted ocean tide level calculated by the software WXTide 32 over a year. An example of the results of the calculation for the entrance channel characteristics as measured using the LADS data (i.e. width=40m, depth=0.85m and length=250m) are provided in Figure 6.3. These results were validated by checking against the real-time tidal data recorded at Toukley by MHL available on their website at the time of writing this report showing a lake level of around 0.2 and a negligible tidal range.

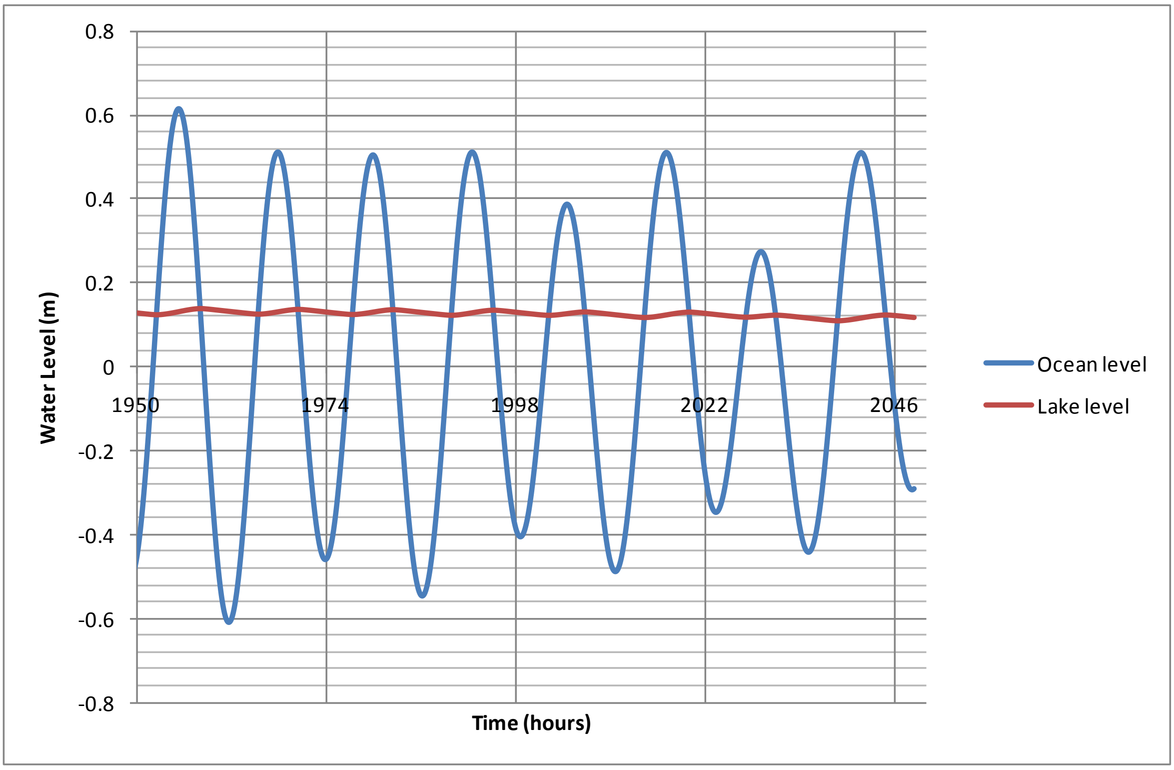

Figure 6.3 – Results of the water level response of Tuggerah Lake using a difference method

A sensitivity analysis was undertaken using the various channel dimension measured from the aerial photographs. The average lake level increases when the entrance is shallower and the tidal range increases when the entrance is wider. The length of the channel slightly reduces the tidal range and increases the water level. The water level in the lake does not exceed 0.15m and the tidal range is around 0.20m. However, these values assume the tidal impact only and do not take into account the rainfall and fluctuations in atmospheric pressure that may increase or decrease them. This is of the same order as the results of MHL (2010) illustrated in Figure 6.4 and confirm the 0.2-0.3m tidal range found by Worley Parsons (2010).

Given the very low tidal range within the lake and therefore the low tidal prism, as well as the various dimensions of the channel entrance, the current velocities will be low and this would result in sand deposition within the entrance over time. Therefore the lake entrance tends to reduce and would eventually close if the dredging is stopped. Flood events may increase the flow at the entrance and generate erosion that would widen the entrance temporarily.

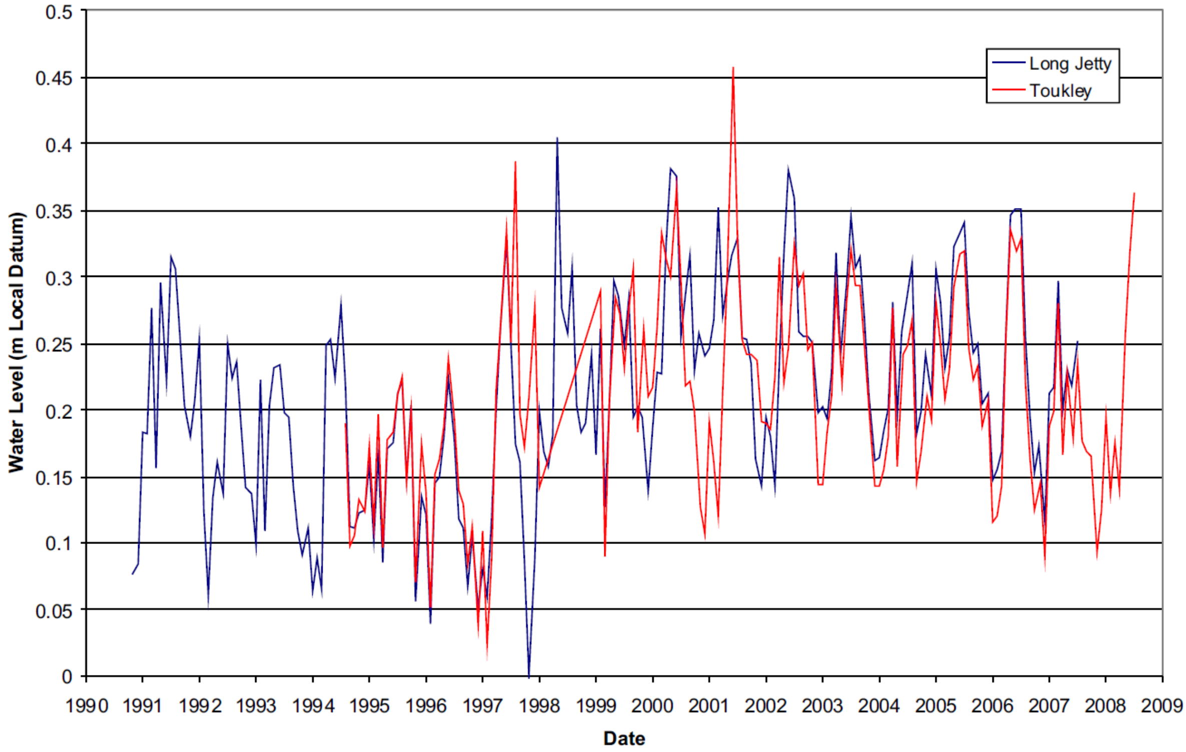

Figure 6.4 – Monthly averaged water level at Toukley and Long Jetty, Tuggerah Lake

7 CONCLUSION

Existing information, documents and data regarding Tuggerah Lake entrance were analysed to create a SWAN model and determine the local wave climate.

Resulting longshore sediment transport rates were calculated. It was found that a main southward movement is observed at the entrance of the lake and a northward movement starts further north from the entrance. The null point where there is a change in direction of sediment transport may vary over time and was observed to be located near the southern end of the vegetated area directly north of the sand spit. If sand dredged from the entrance is placed south of this location, it will make its way back into the entrance; conversely, if the sand is placed north of this location, it would move northward along North Entrance Beach but may subsequently be lost to the littoral system due to offshore transport during storms. . A conceptual sediment transport model of the entrance area and adjacent North Entrance Beach was compiled.

Inlet stability calculations were carried out based on bathymetric data and observation of historical aerial photography. The entrance was found to be unstable due to the narrow entrance width reducing the tidal range and prism. Therefore, it would tend to accrete and close without regular dredging. Only a flood would erode and widen the entrance.

This investigation largely confirms the observations made by Worley Parsons and PBP in earlier investigations. Further information that could confirm the basic coastal process understanding developed in this report could include:

- Calibration of the tidal model against long-term measured water level time series, velocities and channel bathymetry;
- Physical measurement of sediment movement through tracer studies and field data collection at the entrance to confirm the inferred tidal circulation model; and
- Development of a coupled 3D hydrodynamic and sediment transport model to test various management scenarios.

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APPENDICES

A-1 Estimated potential longshore sediment transport using CERC (1984) formula in typical conditions

Longshore Sediment Transport ('000 m³/yr m³/yr)	**R1**			
	T=8s (Occurrence of 34%)	**T=10s** (Occurrence of 30%)	**T=12s** (Occurrence of 32%)	**T=15s** (Occurrence of 4%)
Hs=0.5m (Occurrence of 17%)	-14	-21	-17	-17
Hs=1.5m (Occurrence of 61%)	-807	-1111	-1289	-1127
Hs=2.5m (Occurrence of 17%)	-445	-789	-829	-781
94.8% occurrence of Hs	-1267	-1921	-2134	-1926
100% occurrence of Ts	-425	-580	-689	-76
			Sum	1770 S

Longshore Sediment Transport ('000 m³/yr m³/yr)	**R2**			
	T=8s (Occurrence of 34%)	**T=10s** (Occurrence of 30%)	**T=12s** (Occurrence of 32%)	**T=15s** (Occurrence of 4%)
Hs=0.5m (Occurrence of 17%)	-8	-16	-12	-13
Hs=1.5m (Occurrence of 61%)	902	1317	1493	1127
Hs=2.5m (Occurrence of 17%)	1720	2105	2119	1658
94.8% occurrence of Hs	2613	3406	3600	2773
100% occurrence of Ts	877	1028	1163	110
			sum	3178 N

Longshore Sediment Transport ('000 m³/yr m³/yr)	**R3**			
	T=8s (Occurrence of 34%)	**T=10s** (Occurrence of 30%)	**T=12s** (Occurrence of 32%)	**T=15s** (Occurrence of 4%)
Hs=0.5m (Occurrence of 17%)	-3	-7	-5	-6
Hs=1.5m	64	417	-13	74

Longshore Sediment Transport	R3			
(Occurrence of 61%)				
Hs=2.5m (Occurrence of 17%)	615	778	636	433
94.8% occurrence of Hs	677	1188	618	501
100% occurrence of Ts	227	358	200	20
			sum	805 N

Longshore Sediment Transport ('000 m^3/yr m^3/yr)	R4			
	T=8s (Occurrence of 34%)	T=10s (Occurrence of 30%)	T=12s (Occurrence of 32%)	T=15s (Occurrence of 4%)
Hs=0.5m (Occurrence of 17%)	-1	-3	-5	-6
Hs=1.5m (Occurrence of 61%)	-79	-210	-295	-334
Hs=2.5m (Occurrence of 17%)	168	-54	-62	-174
94.8% occurrence of Hs	88	-267	-361	-514
100% occurrence of Ts	30	-81	-117	-20
			sum	188 S

Longshore Sediment Transport ('000 m^3/yr m^3/yr)	R5			
	T=8s (Occurrence of 34%)	T=10s (Occurrence of 30%)	T=12s (Occurrence of 32%)	T=15s (Occurrence of 4%)
Hs=0.5m (Occurrence of 17%)	3	2	1	-0.5
Hs=1.5m (Occurrence of 61%)	98	32	-0.5	-54
Hs=2.5m (Occurrence of 17%)	304	155	147	-47
94.8% occurrence of Hs	405	188	147	102
100% occurrence of Ts	136	57	48	-4
			sum	236 N

**Positive value represents northward transport and negative value southward transport.*

A-2 *Estimated potential longshore sediment transport using Kamphuis expression in typical conditions*

Longshore Sediment Transport ('000 m³/yr m³/yr)	**R1**			
	T=8s (Occurrence of 34%)	**T=10s** (Occurrence of 30%)	**T=12s** (Occurrence of 32%)	**T=15s** (Occurrence of 4%)
Hs=0.5m (Occurrence of 17%)	-29	-55	-61	-88
Hs=1.5m (Occurrence of 61%)	-915	-1731	-2556	-3235
Hs=2.5m (Occurrence of 17%)	-257	-1035	-1441	-1884
94.8% occurrence of Hs	-1200	-2822	-4058	-5207
100% occurrence of Ts	-403	-851	-1311	-206
			sum	2771 S

Longshore Sediment Transport ('000 m³/yr m³/yr)	**R2**			
	T=8s (Occurrence of 34%)	**T=10s** (Occurrence of 30%)	**T=12s** (Occurrence of 32%)	**T=15s** (Occurrence of 4%)
Hs=0.5m (Occurrence of 17%)	-19	-44	-46	-68
Hs=1.5m (Occurrence of 61%)	923	1729	2543	2874
Hs=2.5m (Occurrence of 17%)	1129	1904	2573	2984
94.8% occurrence of Hs	2033	3588	5065	5790
100% occurrence of Ts	682	1083	1637	229
			sum	3631 N

Longshore Sediment Transport ('000 m³/yr m³/yr)	**R3**			
	T=8s (Occurrence of 34%)	**T=10s** (Occurrence of 30%)	**T=12s** (Occurrence of 32%)	**T=15s** (Occurrence of 4%)
Hs=0.5m (Occurrence of 17%)	-4	-17	-22	-36
Hs=1.5m (Occurrence of 61%)	189	670	172	431
Hs=2.5m	516	871	1000	1027

Longshore Sediment Transport	R3			
(Occurrence of 17%)				
94.8% occurrence of Hs	700	1524	1150	1423
100% occurrence of Ts	235	460	372	56
			sum	1123 N

Longshore Sediment Transport ('000 m³/yr m³/yr)	R4			
	T=8s (Occurrence of 34%)	T=10s (Occurrence of 30%)	T=12s (Occurrence of 32%)	T=15s (Occurrence of 4%)
Hs=0.5m (Occurrence of 17%)	-0.5	--8	-19	-35
Hs=1.5m (Occurrence of 61%)	-54	-296	-654	-1160
Hs=2.5m (Occurrence of 17%)	229	81	51	-261
94.8% occurrence of Hs	174	-223	-622	-1455
100% occurrence of Ts	59	-67	-201	-58
			sum	267 S

Longshore Sediment Transport ('000 m³/yr m³/yr)	R5			
	T=8s (Occurrence of 34%)	T=10s (Occurrence of 30%)	T=12s (Occurrence of 32%)	T=15s (Occurrence of 4%)
Hs=0.5m (Occurrence of 17%)	7	7	8	3
Hs=1.5m (Occurrence of 61%)	164	143	125	-23
Hs=2.5m (Occurrence of 17%)	305	287	363	69
94.8% occurrence of Hs	476	437	496	50
100% occurrence of Ts	160	132	160	2
			sum	454 N

**Positive value represents northward transport and negative value southward transport.*

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