Appendix D

Physical Processes

The principal coastal processes relating to morphological processes at The Entrance are described below.

- Wave Processes;
- Current Processes
- Water Levels;
- Sediment Transport and Storm Erosion; and
- Climate Change.

D.1 Wave Processes

Waves that propagate to The Entrance and nearby shoreline may have energy in two distinct frequency bands. These are principally related to the generation and propagation of ocean swell and local sea (wind/waves). Large waves generated by a storm are generally categorised as wind waves because wind energy is still in the process of being transferred to the ocean to form the waves. However, offshore waves have been treated as swell for this investigation.

Waves are irregular in height and period and so it is necessary to describe wave conditions using a range of statistical parameters. In this study the following have been used:-

- H_{mo} significant wave height (H_s) based on the zeroth moment of the wave energy spectrum (rather than the time domain $H_{1/3}$ parameter);
- H_{max} maximum wave height in a specified time period;
- T_p wave energy spectral peak period, that is, the wave period related to the highest ordinate in the wave energy spectrum; and
- T_z average zero crossing period based on upward zero crossings of the still water line. An alternative definition is based on the zeroth and second spectral moments.

Wave heights defined by zero up-crossings of the still water line fulfil the Rayleigh Distribution in deep water and thereby provide a basis for estimating other wave height parameters from H_s. In shallow water, i.e. within the near shore areas, significant wave height defined from the wave spectrum, H_{mo}, is normally larger (typically 5% to 8%) than $H_{1/3}$ defined from a time series analysis.

Directional Spreading

Although neither of these characteristics is addressed explicitly in this study, directional spreading was included in the numerical wave modelling work undertaken to describe the design wave climate along the Ettalong Beach shoreline. Directional spreading causes the sea surface to have a more short-crested wave structure in deep water.

Nearshore Processes

Waves also have a dominant direction of wave propagation and directional spread about that direction that can be defined by a Gaussian or generalised cosine ($\cos^n$) distribution (amongst others), and a wave grouping tendency. Directional spread is reduced by refraction as waves propagate into the shallow, near shore regions and the wave crests become more parallel with each other and the seabed contours.

Waves propagating into shallow water may undergo changes caused by refraction, shoaling, bed friction, wave breaking and, to some extent, diffraction.

Wave refraction is caused by differential wave propagation speeds. That part of a shoreward propagating wave that is in the more shallow water has a lower speed than those parts in deeper water. When waves approach a coastline obliquely, these speed differences cause the wave fronts to turn and become more coast parallel. Associated with this directional change there are changes in wave heights. On irregular seabeds, wave refraction of irregular waves becomes a very complex process.

Waves propagating shoreward develop reduced speeds in shallow water. In order to maintain constancy of wave energy flux (ignoring energy dissipation processes) their heights must increase. This phenomenon is termed shoaling and leads to a significant increase in wave height near the shoreline.

A turbulent boundary layer forms at the seabed with associated wave energy losses that are manifested as a continual reduction in wave height in the direction of wave propagation – leaving aside further wind input, refraction, shoaling and wave breaking. The rate of energy dissipation increases with greater wave height.

Wave breaking occurs in shallow water when the wave crest speed becomes greater than the wave phase speed. For irregular waves this breaking occurs in different depths so that there is a breaker zone rather than a breaker line. Seabed slope, wave period and water depth are important parameters affecting the wave breaking phenomenon. As a consequence of this energy dissipation, wave set-up (a rise in still water level caused by wave breaking), develops shoreward from the breaker zone in order to maintain conservation of momentum flux. This rise in water level increases non-linearly in the shoreward direction and allows larger waves to propagate shoreward before breaking. Field measurements have shown that the slope of the water surface is normally concave upward. Wave set-up at the shoreline can be in the order of 15% of the equivalent deep-water significant wave height. Lower set-up occurs in estuarine entrances, but the momentum flux remains the same. Wave set-up is smaller where waves approach a beach obliquely, but then a longshore current can be developed. Wave grouping and the consequent surf beats also cause fluctuations in the still water level.

Wave diffraction will not be particularly important for this study, other than where waves propagate around headland features. It was included in the SWAN wave propagation model applied to this study.

Wave Spectrum

In a random wave field each wave may be considered to have a period different from its predecessors and successors, and the distribution of wave energy is often described by a wave energy spectrum. In fact, the whole wave train structure changes continuously and individual waves appear and disappear until quite shallow water is reached and dispersive processes are reduced. In developed sea states, that is swell, the Bretschneider modified Pierson-Moskowitz spectral form has generally been found to provide a realistic wave energy description. For developing sea states the JONSWAP spectral form (Hasselmann *et. al.*, 1973), which is generally more ‘peaky’, has been found to provide a better spectral description and was applied in this study.

Maximum Wave Height

For structural design in the marine environment it may be necessary to define the H_{max} parameter related to storms having average recurrence intervals (ARI) of R years. However, the expected H_{max}, relative to H_s in statistically stationary wave conditions, increases as storm/sea state duration increases. Based on the Rayleigh Distribution the usual relationship is defined by Equation 1.

Equation 1: Maximum Wave Height Relationship

$$H_{max} = H_s \sqrt{(0.5 \ell nNz)}$$

where Nz is the number of waves occurring during the time period being considered, where individual waves are defined by Tz.

ln is the natural logarithm

This relationship has been found to overestimate H_{max} by about 10% in severe ocean storms. In shallow water the relationship is not fulfilled. In very shallow water, H_{max} is replaced by the breaking wave height, H_b. That is, in shallow water, wave height becomes limited by the depth of water. The breaking wave height can be 'estimated' using the breaking criterion defined by Equation 2 – noting that the constant (0.85) is really a variable.

Equation 2: Breaking Wave Criteria

$$H_b/d_b = 0.85$$

where d_b is the breaking wave depth

Hydrodynamic Effects

Waves propagating through an area affected by a current field are caused to turn in the direction of the current. The extent of this directional change depends on wave celerity (the wave propagation speed), current speed and relative directions. Wave height is also changed. Opposing currents cause wave lengths to shorten and wave heights to increase and may lead to wave breaking. When the current speed is greater than one quarter of the phase speed, the waves are blocked. Conversely, a following current reduces wave heights and extends wave lengths.

D.2 Current Processes

Currents within the Tuggerah lakes and at the shoreline of The Entrance are caused by a range of phenomena, including:-

- Astronomical Tides
- Winds
- Creek Discharges
- Coastal Trapped Waves and Other Tasman Sea Processes
- Nearshore Wave Processes
- Density Flows

The astronomical tides are caused by the relative motions of the Earth, Moon and Sun, see Section D.3. The regular rise and fall of the tide level in the sea causes a periodic inflow (flood tide) and outflow (ebb tide) of oceanic water to the Lakes and mixed oceanic and freshwater from the Lakes to the sea, respectively. A consequence of this process is the generation of tidal currents. The volume of sea water that enters the Lakes or leaves the Lakes on flood and ebb tides, respectively, is termed the tidal prism; which varies due to the inequality between tidal ranges and spring/neap tide ranges. The tidal prism is affected by changes in inter-tidal areas, such as areas of reclamation, but not by dredged areas below low tide.

Wind forcing is applied to the water surface as interfacial shear, the drag coefficient and consequent drag force varying with wind speed. Momentum from the wind is gradually transferred down through the water column by vorticity, the maximum depth of this effect being termed the Ekman depth. At the surface, wind caused currents are in the direction of the wind, but in the southern hemisphere they gradually turn to the left of the wind direction until they flow in the opposite direction at the Ekman depth. The Tuggerah lakes are too shallow for this condition to develop fully and wind driven currents are affected by the lakebed boundary layer and form. Wind driven currents diminish with depth. Because wind forcing is applied at the water surface, the relative effect is greater in shallow water where there is less water column volume per unit plan area. Therefore wind driven currents are greater in more shallow areas. Maximum surface current speed is in the order of 1% to 3% of the wind speed, depending on water depth. Where water is piled up against a coastline by wind forcing, a reverse flow develops near the seabed.

Density currents may be caused by freshwater inflows, for example, when the Wyong River is in flood. The freshwater is more buoyant and tends to spread across the Lake surface until mixing with the ambient saline water occurs. Those flows transport sediment and nutrients into the Lakes and affect their distribution, thereby affecting ecological processes.

Coastal Trapped Waves (CTW) are long period wave phenomena that propagate northward along the continental shelf (Freeland et al, 1986). Their origin is not fully understood, but they are believed to originate from the passage of successive high and low pressure meteorological systems across southern Australia. These systems have inter-arrival times varying from 3 to 7 days, typically, and these are the periods of the observed CTW. These waves are irregular and cause approximate coast parallel currents and variations in water levels. They are trapped on the continental shelf by refraction and the Coriolis force. CTW are known to occur on the continental shelf of NSW and will affect observed water levels in the Lakes. As they propagate through The Entrance they cause inflow and outflow currents that are additional to the tidal currents.

The propagation of waves (swell and sea) into the near shore region leads to wave breaking and energy dissipation. Where waves propagate obliquely to the shoreline this process leads to the generation of a longshore current in the surf zone, and to some extent seaward of that line. These currents are of some importance to shoreline processes in The Entrance area, where ocean waves propagate to the shoreline.

D.3 Water Levels

Water level variations within the Lakes may be influenced by one or more of the following natural causes:-

- Eustatic and tectonic changes;
- Tides;
- Wind set-up and the inverse barometer effect;
- Wave set-up;
- Wave run-up;
- Fresh water flow;
- Climate change; and
- Global variations in meteorological conditions.

Eustatic and Tectonic Changes

Eustatic sea level changes are long term world-wide changes in sea level relative to the land mass and are generally caused by isothermic expansion and melting of polar ice caps. No rapid changes are believed to be occurring at present, although predictions of future climate change indicate a potential for such an outcome to occur. Projected climate change is further addressed below.

Nevertheless, a typical sea level rise of 1.7mm per annum is now generally accepted for this region. Tectonic changes are caused by movement of the Earth's crust; they may be vertical and/or horizontal and cause local sea level changes that can propagate shoreward and cause very large run-up heights in some parts of the world.

Tides

Tides are caused by the relative motions of the Earth, Moon and Sun and their gravitational attractions. While the vertical tidal fluctuations are generated as a result of these forces, the distribution of land masses, bathymetric variation and the Coriolis force (the deflection of currents due to the rotation of the Earth) determine the local tidal characteristics.

The tidal range within the Lakes is attenuated significantly by the constriction and frictional characteristics of The Entrance and then the surface area of the lakes in comparison with the tidal influx.

Wind Set-up and the Inverse Barometer Effect

Wind set-up and the inverse barometer effect are caused by regional meteorological conditions. When the wind blows over an open body of water, drag forces develop between the air and the water surface. These drag forces are proportional to the square of the wind speed. The result is that a wind drift current is generated. This current may transport water towards the coast, against which the water piles up causing wind set-up. Wind set-up is inversely proportional to depth.

In addition, the drop in atmospheric pressure, which accompanies severe meteorological events, causes water to flow from high pressure areas on the periphery of the meteorological formation to the low pressure area. This is called the 'inverse barometer effect' and results in water level increases up to 1cm for each hecta-Pascal (hPa) drop in central pressure below the average sea level atmospheric pressure in the area for the particular time of year, typically about 1,010 hPa. The actual increase depends on the speed of the meteorological system and 1cm is only achieved if it is moving slowly. The phenomenon causes daily variations from predicted tide levels up to 0.05m. The combined result of wind set-up and the inverse barometer effect is called storm surge. When the meteorological event tracks over water at a speed equal to the long wave celerity resonance may occur and the inverse barometer effect can be bigger than the inverse barometer effect.

Wave Set-Up

Wave set-up is described in Section D.1.

Wave Run-up

Wave run-up is the vertical distance between the maximum height that a wave runs up the beach or a coastal structure and the still water level, comprising tide and storm surge. Wave set-up is included implicitly in wave run-up calculations. Additionally, run-up level varies with surf-beat, which arises from the variation in mean water level as a result wave grouping effects.

Global Variations in Meteorological Conditions

Global meteorological and oceanographic variations, such as the El Nino Southern Oscillation (ENSO) phenomenon in the eastern Southern Pacific Ocean and continental shelf waves, cause medium term (inter-annual) variations in mean sea level. ENSO conditions may persist for a year or more. The causes are not properly understood, but analyses of long term data from Australian tide gauges indicate that annual mean sea level may vary up to 0.1m from the long term trend, whilst mean sea level may vary by more than 0.2m over the time scale of weeks as a result of coastal trapped wave activity (a continental shelf process), for example.

Long period variations are also caused by the Interdecadal Pacific Oscillation.

In addition to the astronomical tides, water levels are also influenced by daily, seasonal and inter-annual oceanographic processes. As discussed above, these processes can cause variations to the predicted tide (astronomical) of up to +/- 0.2m.

The central-coast regions of the NSW coastline are subject to storm surge during intense storm systems. These storms can form from strong frontal systems passing through the southern Tasman Sea or from remnant tropical weather systems. The most intense ECL in the last 50 years for the central-coast region of NSW was the May 1974 event. This intense storm produced a storm surge in the order of 0.5m along the central-NSW coast caused by wind setup and inverse barometer effects and wave set-up. An estimated storm tide of 1.2m AHD occurred within the Lakes in May 1974 with very little rainfall. The astronomical tide component would have been in the order of only 0.2m.

D.4 Coastal Inundation

Coastal inundation is the flooding of coastal lands by ocean waters. The types of low lying coastal areas that are subject to coastal inundation include wetlands, the fringing areas of coastal lagoons and estuaries, and the areas behind beach and low dune systems and swale areas. Inundation of these areas can be caused by storm wave run-up and overtopping and elevated water levels associated with severe storm events. Severe coastal inundation occurs infrequently and over a very short period of time (usually several hours) (NSW Government, 1990). However, it can cause a significant amount of damage to public and private property, including clean-up costs.

Coastal inundation occurs due to the combination of elevated water levels (storm surge) and wave action. Wave processes can cause inundation through two related mechanisms, namely:-

- Wave set-up; and
- Wave run-up and overtopping.

Wave run-up and wave set-up are normally not included in the same design specification. That is, both processes can be estimated relative to the still water level and the inundation level is determined from either the run-up level (which implicitly includes wave set-up) or wave set-up height combined with storm tide (astronomical tide plus storm surge); depending upon the design/shoreline circumstances. Note, however, that high water levels can also occur at times when there is no local storm (e.g. during a King tide or passing coastal trapped wave).

D.5 Tsunamis

Tsunamis are caused by sudden movements of the Earth's crust and are commonly, but incorrectly, called 'tidal waves'. They are infrequent and unlikely to occur during a storm. They are known to occur on the eastern coast of Australia, but their impacts in terms of loss of life and damage to property have not been significant. Their incidence and effects are being investigated at selected sites by Cardno for the NSW Government and are not a focus of this study.

D.6 Sand Drift

Sand drift describes the movement of sediment by aeolian processes and can cause significant hazard within the coastal zone. Resulting hazards may include the abrasion of motor vehicles, buildings, vegetation and park and garden fittings; the burial of roadways, rail lines, agricultural land and coastal ecosystems; the blockage of street gutters and stormwater drains; and structural damage to buildings caused by forces imposed by the sand.

D.7 Climate Change

Research into the implications of climate change for Australia has been conducted by a broad spectrum of individuals and organisations that includes universities, research institutes, consultancies, government bodies and community groups.

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has been a major contributor in providing ongoing research and knowledge concerning the status, risk exposure and opportunities from climate change in Australia. The CSIRO has published numerous reports examining the potential impact of climate change on a national, regional and local scale which have guided the private and public spheres on how to respond to climate change.

For the purposes of this study, the regional coastal projections of climate change are discussed under the following subheadings:

- Sea level rise (SLR);
- Rainfall;
- Wind;
- Frequency of extreme events.

D.7.1 Sea Level Rise

At the regional scale, sea levels can be influenced by variations in ocean currents and in the atmosphere due to different wind regimes (McInnes *et al.,* 1998). Coastal responses to SLR can be highly variable and often unpredictable, and are greatly influenced by the local geomorphology. Temporary flooding/inundation associated with storm systems is generally of short duration, due to the infrequent and large-magnitude nature of these events, as well as the dependence of these processes on tide level, which varies from high to low water over about 6 hours.

On the other hand, the cumulative erosion and inundation, of presently affected sites, that would be associated with global SLR or land subsidence processes would be of longer duration, and may be associated with what are presently low-magnitude events that have no effect. Although the magnitude of future SLR may be relatively small in isolation, where severe storms coincide with elevated sea levels, wave attack and storm surge will result in significant impacts on presently and newly vulnerable coastal areas.

Research into the long term SLR estimates for Australia indicates that the rate of SLR is slightly less than the global average. Church *et al.* (2006) analysed two of Australia's longest tide gauge records: Fort Denison, Sydney, and Fremantle, in Western Australia. That study determined that the local SLR from 1950 to 2000 was 1.3 (± 0.5) mm/year, compared with a global average of 1.8mm/year. The difference is primarily thought to be due to the more frequent and intense El Niño events that have occurred since the mid-1970's, which caused lower sea-levels around Australia (Holper *et al*., 2005).

DECCW (now OEH), in planning for climate change, have produced a Sea Level Rise Policy Statement that sets SLR planning benchmarks of 40cm by 2050 and 90cm by 2100 (relative to 1990 mean sea levels), Table D.1. These benchmarks are derived from both IPCC projections and CSIRO research. The SLR component is derived from the IPCC SRES A1F1 climate change scenario due to the fact that, in the last decade, the observed global average of sea level from satellite data is tracking along the upper bound of the IPCC projections.

Table D.1: Water Level Components of SLR Planning Benchmarks (after DECCW, 2009a and b)

Component	2050	2100
SLR	30 cm	59 cm
Accelerated ice melt	(included above)	20 cm
Regional SLR variation	10 cm	14 cm
Rounding*	-	-3 cm
Total	*40 cm*	*90 cm*

DECCW's SLR Policy has been given statutory effect through SEPP71 – Coastal Protection and through a Ministerial Direction to local councils under Section 117 of the *Environmental Planning and Assessment Act 1979*. The *Sea Level Rise Policy Statement* (DECCW, 2009a) supersedes the 1988 NSW Coastline Hazard Policy. Most objectives from that policy have been included in the NSW Coastal Policy 1997, which remains current. Other objectives from the 1988 NSW Coastline Hazard Policy are updated by the Sea Level Rise Policy Statement.

Should projected sea level rises occur, there will significant changes in water levels within the Lakes that will affect the morphology and functioning of The Entrance.

D.7.2 Rainfall

DECC (2008) quotes CSIRO research that predicts that the Sydney region will experience substantial increase in summer rainfall. However, overall, it is predicted that there will not be a significant net change in average annual runoff. It surmises that there will be some redistribution of runoff across the seasons, with likely increases in summer and autumn and decreases in winter and spring.

Seasonal changes in average runoff are likely to be:-

- Summer: -1% to +22%;
- Autumn: -6% to +14%;
- Winter: -12% to +3%; and
- Spring: -19% to +1%.

Rainfall is not considered in this study.

D.7.3 Wind

CSIRO (2007) undertook a climate change study for NSW and concluded that predictions relating to wind changes for the state contained large uncertainty in most seasons. In general, mean wind-speed projections showed a tendency for increases across much of the state in summer, with decreases in wind from the north-east.

In autumn, there was a tendency towards weaker winds from the south and east, and stronger winds from the north-west. In winter, increases in winds were from the north-west and south, with wind speeds decreasing elsewhere. Lastly, there was a general tendency for stronger winds to occur in spring across the state.

Extreme winds have similar patterns to mean wind speed changes in summer and autumn, although the magnitudes of the changes are larger; particularly over the continent due to frictional effects. In winter, the ocean in the south of NSW showed a tendency for increasing extreme winds with only the north-east of NSW indicating decreasing winds (Hennessy *et al.,* 2004).

This information is not sufficiently detailed to be applied to this entrance morphological study.

D.7.4 Frequency of Extreme Events

There is no current consensus on the impact of climate change on coastal storms in the Central Coast region of NSW. While IPCC (2007) warns of a potential increase in the frequency and intensity of coastal storms and cyclonic events, recent studies (for example CSIRO, 2007, and McInnes *et al.,* 2007) present climate change predictions that indicate both increased and decreased wind speeds along the NSW coast, depending on the model and/or climate change scenario applied.

The Tuggerah lakes are not located in an active tropical cyclone region and even studies that predict the largest increase in the southern extent of the east Australia cyclone region due to climate change processes do not predict cyclones off the Central Coast region within the next 50 to 100 years (CSIRO, 2007).

No change in storm frequency could be included in this study.

D.8 Sediment Transport

Sand is moved by waterborne sediment transport, which occurs due to the action of waves and currents. Sediment is transported onshore, offshore and alongshore, causing the shoreline to undergo a series of erosion and accretion cycles covering periods of time ranging from weeks to decades. This process has implications for the management of coastal areas. Structures may be put at risk by erosion, and while accretion may be beneficial, it can also have negative impacts, such as blocking of storm-water outlets.

The shoreline region of The Entrance is formed from marine sands, but has been significantly modified by dredging and shoreline structures.

The movement and re-suspension of sediment particles commences when the fluid force on a particle is just larger than the resisting force related to the submerged particle weight and friction coefficient. In the case of fine silts that may settle near the mouths of creek entrances, cohesive forces are also important. Thus settled mud particles remain in a stable state on the seabed until they are disturbed by forces that exceed those needed to initiate sediment motion. These forces are caused by tidal and wind driven currents, as well as by wave action. Even quite small wind waves that break at the shoreline can cause sediment re-suspension.

Once suspended, fine particles may be transported throughout the estuary. They ultimately settle in a more tranquil environment; in typically deeper areas. Therefore, apart from areas protected from waves, such as lake areas beyond the bridge, fine sediments will not be found.

The main parameters in the settlement and re-suspension processes are:-

w_s	setting velocity (m/s)

τ_{cd} critical shear stress for deposition (N/m^2)
τ_{ce} critical shear stress for erosion (N/m^2)
E an erosion coefficient ($g/m^2/s$) – depends on sediment consolidation

Shear stresses are related to the water particle velocities. Muddy sediments that settle on the seabed gain strength quickly due to consolidation and bio-chemical reactions in the bed. Therefore the shear stress (or velocity) needed to keep the cohesive sediments in suspension τ_{cd} is always smaller than the shear stress needed to erode the sediments from the bed τ_{ce}. The parameter E is part of site specific calibration, when re-suspension is to be considered. Thus the following regimes may occur:-

$\tau_{cd} < \tau < \tau_{ce}$ no deposition and no erosion, only pure horizontal transport
$\tau \leq \tau_{cd}$ only deposition and horizontal transport
$\tau > \tau_{ce}$ only erosion and horizontal transport

In reality, cohesive sediment transport is controlled by chemical and biological laws in addition to these physical processes. The transport is also dependent on the type of sediment and therefore analytical expressions that describe these processes are semi-empirical. Hence, much of this information has been obtained from laboratory and field experiments. Another important issue is salinity. Fine clay-particles have electrostatic properties and flocculate in saline water. The extent of flocculation depends upon the salinity and concentration of suspended particles. Where this is greater than about 0.3g/l, flocculation becomes important.

Similar processes affect the re-suspension of cohesion less sediments (sand). However, in that case, there is much less consolidation and there are no biological effects. Hence the initiation of sand movement can be described by a current speed and/or wave orbital speed and sediment size, typically the particle diameter that describes the 50% passing dimension - D_{50}. Often the seabed sediments may include sand and clay - even small proportions of clay reduce the sediment mobility.

In a natural environment these processes develop a state of quasi-equilibrium. Full equilibrium cannot be achieved because the hydro-met-ocean environment is changing constantly. However, where the form of the waterway is altered substantially by human activity, this quasi-equilibrium is disturbed.

The trend is then for the geomorphological processes to try and restore the seabed to a form consistent with the physiography of any altered waterway and the hydro-met-ocean environment. The rate of siltation will depend on the transport/suspension capacities of the tidal currents in the area. Progressive consolidation also occurs following settlement, the rate of consolidation being rapid immediately following settlement, and becoming progressively slower.

Waves also have a dominant direction of wave propagation and directional spread about that direction that can be defined by a Gaussian or generalised cosine ($\cos^n$) distribution (amongst others), and a wave grouping tendency. Directional spread is reduced by refraction as waves propagate into the shallow, near shore regions and the wave crests become more parallel with each other and the seabed contours. Although neither of these characteristics is addressed explicitly in this study, directional spreading was included in the numerical wave modelling work undertaken to describe the design wave climate along the Ettalong Beach shoreline. Directional spreading causes the sea surface to have a more short-crested wave structure in deep water.