Additional Morphological Modelling

The Entrance

59915021/R001

Prepared for
Wyong Shire Council

24 February 2015

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Document Information

Prepared for	Wyong Shire Council
Project Name	The Entrance
File Reference	59915021 R001 Rev1 TheEntrance.docx
Job Reference	59915021/R001
Date	24 February 2015
Version Number	Rev 2
Effective Date	24 February 2015
Date Approved:	24 February 2015

Document History

Version	Effective Date	Description of Revision	Prepared by:	Reviewed by:
A	11 December 2014	Progress Report	Arjen Overduin / Chris Beadle	Doug Treloar
0	30 January 2015	Final Report	Arjen Overduin / Chris Beadle	Doug Treloar
1	19 February 2015	Revised Final Report	Arjen Overduin / Chris Beadle	Doug Treloar
2	24 February 2015	Revised Final Report	Arjen Overduin / Chris Beadle	Doug Treloar

Glossary

Advective Transport		The transport of dissolved material by water movement.
Australian Height Datum (AHD)		A common national plane of level corresponding approximately to mean sea level.
Amenity		Those features of an estuary/beach that foster its use for various purposes, e.g. Clear water and sandy beaches make beach-side recreation attractive.
ARI		Average Recurrence Interval
Bed Load		That portion of the total sediment load that flowing water moves along the bed by the rolling or saltating of sediment particles.
Calibration		The process by which the results of a computer model are brought to agreement with observed data.
Catchment		The area draining to a site. It always relates to a particular location and may include the catchments of tributary streams as well as the main stream.
CD		Chart Datum, common datum for navigation charts - 0.92m below AHD in the Sydney coastal region. Typically Lowest Astronomical Tide.
Discharge		The rate of flow of water measured in terms of volume per unit time. It is to be distinguished from the speed or velocity of flow, which is a measure of how fast the water is moving rather than how much is flowing.
Dispersive Transport		The transport of dissolved matter through the estuary by vertical, lateral and longitudinal mixing associated with velocity shear.
Diurnal		A daily variation, as in day and night.
Ebb Tide		The outgoing tidal movement of water within an estuary.
Eddies		Large, approximately circular, swirling movements of water, often metres or tens of metres across. Eddies are caused by shear between the flow and a boundary or by flow separation from a boundary.
EIS		Environmental Impact Statement
Estuarine Processes		Those processes that affect the physical, chemical and biological behaviour of an estuary, e.g. predation, water movement, sediment movement, water quality, etc.
Estuary		An enclosed or semi-enclosed body of water having an open or intermittently open connection to coastal waters and in which water levels vary in a periodic fashion in response to ocean tides.
Flood Tide		The incoming tidal movement of water within an estuary.
Fluvial		Relating to non-tidal flows.
Fluvial Processes		The erosive and transport processes that deliver terrestrial sediment to creeks, rivers, estuaries and coastal waters.
Fluvial Sediments		Land-based sediments carried to estuarine waters by rivers.
Foreshore		The area of shore between low and high tide marks and land adjacent thereto.
Fortnightly Tides		The variation in tide levels caused by the monthly variation of Spring and Neap Tides.
Geomorphology		The study of the origin, characteristics and development of land forms.
H_s (Significant Wave Height)		H_s may be defined as the average of the highest 1/3 of wave heights in a wave record ($H_{1/3}$), or from the zeroth spectral moment (H_{mo}), though there is a difference of about 5 to 8%.
Hydraulic Regime		The variation of estuarine discharges in response to seasonal freshwater inflows and tides.
Intertidal		Pertaining to those areas of land covered by water at high tide, but exposed at low tide, e.g. intertidal habitat.
Isohaline		A line connecting those parts of a water mass having the same salinity, i.e., a contour of equal salinity levels.

Littoral Zone		An area of the coastline in which sediment movement by wave, current and wind action is prevalent.
Littoral Drift Processes		Wave, current and wind processes that facilitate the transport of water and sediments along a shoreline.
Mangroves		An intertidal plant community dominated by trees.
Marine Sediments		Sediments in sea and estuarine areas that have a marine origin.
Mathematical/ Computer Models		The mathematical representation of the physical processes involved in runoff, stream flow and estuarine/sea flows. These models are often run on computers due to the complexity of the mathematical relationships. In this report, the models referred to are mainly involved with wave and current processes.
MHL		Manly Hydraulics Laboratory
MSL		Mean Sea Level
Neap Tides		Tides with the smallest range in a monthly cycle. Neap tides occur when the sun and moon lie at right angles relative to the earth (the gravitational effects of the moon and sun act in opposition on the ocean).
NSW		New South Wales
Numerical Model		A mathematical representation of a physical, chemical or biological process of interest. Computers are often required to solve the underlying equations.
Phase Lag		Difference in time between the occurrence between high (or low water) and maximum flood (or ebb) velocity at some point in an estuary or sea area.
Salinity		The total mass of dissolved salts per unit mass of water. Seawater has a salinity of about 35g/kg or 35 parts per thousand.
Saltation		The movement of sediment particles along the bed of a water body in a series of 'hops' or 'jumps'. Turbulent fluctuations near the bed lift sediment particles off the bed and into the flow where they are carried a short distance before falling back to the bed.
Sediment Load		The quantity of sediment moved past a particular cross-section in a specified time by estuarine flow.
Semi-diurnal		A twice-daily variation, e.g. two high waters per day.
Shear Strength		The capacity of the bed sediments to resist shear stresses caused by flowing water without the movement of bed sediments. The shear strength of the bed depends upon bed material, degree of compaction, armouring,
Shear Stress		The stress exerted on the bed of an estuary by flowing water. The faster the velocity of flow the greater the shear stress.
Shoals		Shallow areas in an estuary created by the deposition and build-up of sediments.
Slack Water		The period of still water before the flood tide begins to ebb (high water slack) or the ebb tide begins to flood (low water slack).
Spring Tides		Tides with the greatest range in a monthly cycle, which occur when the sun, moon and earth are in alignment (the gravitational effects of the moon and sun act in concert on the ocean)
SS		Suspended Solids
Storm Surge		The increase in coastal water levels caused by the barometric and wind set-up effects of storms. Barometric set-up refers to the increase in coastal water levels associated with the lower atmospheric pressures characteristic of storms. Wind set-up refers to the increase in coastal water levels caused by an onshore wind driving water shoreward and piling it up against the coast.
Suspended Sediment Load		That portion of the total sediment load held in suspension by turbulent velocity fluctuations and transported by flowing water.
Tidal Amplification		The increase in the tidal range at upstream locations caused by the tidal resonance of the estuarine water body, or by a narrowing of the estuary channel.
Tidal Exchange		The proportion of the tidal prism that is flushed away and replaced with 'fresh' coastal water each tide cycle.

Tidal Excursion		The distance travelled by a water particle from low water slack to high water slack or vice versa.
Tidal Lag		The delay between the state of the tide at the estuary mouth (e.g. high water slack) and the same state of the tide at an upstream location.
Tidal Limit		The most upstream location where a tidal rise and fall of water levels is discernible. The location of the tidal limit changes with freshwater inflows and tidal range.
Tidal Planes		A series of water levels that define standard tides, e.g. 'Mean High Water Spring' (MHWS) refers to the average high water level of spring tides.
Tidal Prism		The total volume of water moving past a fixed point in an estuary during each flood tide or ebb tide.
Tidal Propagation		The movement of the tidal wave into and out of an estuary.
Tidal Range		The difference between successive high water and low water levels. Tidal range is maximum during spring tides and minimum during neap tides.
Tides		The regular rise and fall in sea level in response to the gravitational attraction of the Sun, Moon and Earth.
Tributary		Catchment, stream or river which flows into a larger river, lake or water body
Training Walls		Walls constructed at the entrances of estuaries to improve navigability by providing a persistently open entrance.
T_z (Zero Crossing Period)		The average period of waves in a train of waves observed at a location.
Velocity Shear		The differential movement of neighbouring parcels of water brought about by frictional resistance within the flow, or at a boundary. Velocity shear causes dispersive mixing, the greater the shear (velocity gradient), the greater the mixing.
Wind Shear		The stress exerted on the water's surface by wind blowing over the water. Wind shear causes the water to pile up against downwind shores and generates secondary currents.

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Appendices

1 Introduction

In 2013 Cardno conducted a range of numerical modelling investigations of Tuggerah Lakes and The Entrance for NSW OEH – (Cardno 2013a and 2013b). The locality plan is shown in **Figures 1.1** and **1.2**. That work was carried out using a coupled wave, hydrodynamic and morphological model of the lakes system, which incorporated catchment inflows, tides, rainfall/evaporation, over-lake winds and ocean wave forcing.

Morphological processes were included in the modelling in order to investigate:-

- Scour of the entrance region during flood events; and
- Post-storm onshore sediment transport caused by waves and tidal currents.

Wyong Council's Tuggerah Lakes Estuary & Coastal Management Committee has since requested that Council engage Cardno to undertake additional modelling of The Entrance Channel in order to investigate the effects of deepening the entrance channel through dredging and removal of part of the underlying rock shelf at the lake entrance. The modelled dredging scheme is depicted in **Figure 1.3**.

Council has received a number of enquiries in relation to the predicted outcomes of the channel in the event that the rock shelf was to be removed. Council advises that the community's interest is primarily associated with increasing navigational opportunities for small vessels through the channel. At low tide the rock shelf is visible, with the outgoing water cascading over it. At this tide level the entry channel depth is approximately only 0.3m, and is virtually un-navigable, except by vessels such as jet skis and kayaks. At high tide the rock shelf at the entrance is not as evident due to the depth then being approximately 1 to 1.5m.

As part of the investigations Cardno have undertaken hydrodynamic modelling for several dredged channel scenarios covering a range of channel depths at the entrance that would allow small vessels to navigate at all stages of the tide.

This report describes the data, model systems, methods of investigation and outcomes of this engagement undertaken for Council.

Normal direction conventions have been adopted, namely that:-

- Winds and waves – coming from
- Currents – flowing towards

2 Scope of Work

2.1 Introduction

In accordance with Council's scope of work, a range of numerical modelling was undertaken, namely:-

- Coupled wave, hydrodynamic, and morphological simulations were conducted to assess changes to the channel post dredging (i.e. channel scour and infilling) – see **Section 2.2**;
- Fixed-bed hydrodynamic simulations (including tide and catchment inflows) were conducted to assess potential influence of entrance dredging on water quality in the lakes system (**Section 2.3**);
- Fixed-bed hydrodynamic simulations (including only tides) were conducted to assess the potential influence of the works on the tidal regime within the lakes system (**Section 2.4**).

Further details of the simulations are provided in the following sections.

2.2 Morphological Simulations

The morphological simulations consisted of a set of ten model runs investigating conveyance between the Tasman Sea and Tuggerah Lakes as well as morphological processes in the Entrance Channel. These simulations have been divided into the following cases:-

- No training walls;
- Fully trained entrance (nominal 150m wide channel at MSL as per Cardno, 2013a).

Five entrance dredging scenarios have been investigated for each of these cases:-

- No dredging (present day entrance condition);
- Dredged entrance - Channel bottom at -1.50m AHD (1.0m depth @Mean Low Water (MLW));
- Dredged entrance - Channel bottom at -2.50m AHD (2.0m depth @MLW);
- Dredged entrance - Channel bottom at -4.00m AHD (3.5m depth @MLW);
- Dredged entrance - Channel bottom at -5.50mAHD (5.0m depth @MLW);

For the above mentioned dredged channel simulations, the layout of each dredged channel has assumed that the requisite amount of underlying bed rock has been removed in order to achieve the required channel depth.

In reality, the removal of the rock would likely be achieved through blasting, saw cutting or other methods, and would require a comprehensive survey of the bed rock levels and extents. It should be noted that assessing the feasibility of any rock survey and removal programs required to achieve these channel depths was outside the scope of this study.

Mean Low Water has been taken to be -0.5m AHD. These simulations were run for a total of 3 months (prototype time).

2.3 Fixed-Bed Simulations

A series of ten fixed-bed hydrodynamic simulations was conducted to assess the potential influence of the proposed dredging schemes on water quality in the lakes system in terms of salinity regime. The ten fixed-bed modelling scenarios assessed the same dredging scheme combinations as the morphological simulations described in **Section 2.2**. However, these simulations excluded morphological and wave processes and had a simulation period of one year (prototype time). These simulations assumed no infilling or ongoing scour of the dredged channel.

2.4 Tide-Only Simulations

In order to investigate the potential effects that dredging of the entrance channel may have on the day-to-day tidal water levels within Tuggerah Lake, an additional set of two fixed-bed simulations (excluding training walls) was undertaken:

- No Dredging (present day entrance condition);
- The Entrance Channel bottom at -5.50m AHD (5.0m depth @MLW).

In order to investigate the full range of potential changes in tidal regime, the dredge scenario representing the largest dredged volume was selected for modelling. Compared to the fixed-bed modelling undertaken to investigate flushing and morphological changes (**Section 2.3**), these two simulations were run with tide as the only boundary condition. Hence, salinity, temperature, wind, evaporation and river discharge were not taken into account – so that only the astronomical tide was considered.

3 Physical Processes

3.1 Introduction

The purpose of this section is to describe the principal coastal processes that affect morphological processes at The Entrance. These processes are:-

- Waves;
- Currents;
- Water Levels;
- Winds;
- Sediment Transport and Storm Erosion; and
- Climate Change.

3.2 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_s - significant wave height - either H_{mo} or $H_{1/3}$, which is the average of the highest 1/3 of waves in a record
- 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 upcrossings 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 of the same data.

3.2.1 Directional Spreading

Water waves also have a dominant direction of wave propagation and directional spread about that direction. This spreading can be defined by a Gaussian or generalised cosine ($\cos^n$) distribution (amongst others). There is also 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. Neither of these characteristics was addressed explicitly in this study; however, directional spreading was included in the numerical wave modelling work. Directional spreading causes the sea surface to have a more short-crested wave structure in deep water.

3.2.2 Nearshore Processes

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 and affects the hydrodynamics. 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.

3.2.3 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 as all phase speeds become more dependent on depth alone. 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.

3.2.4 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.

$$H_{max} = H_s \sqrt{(0.5 \ell n Nz)} \quad (1)$$

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

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 – noting that the constant (0.85) is really a variable:-

$H_b/d_b = 0.85$

where d_b is the breaking wave depth

3.2.5 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.

3.3 Current Processes

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

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

3.3.1 Astronomical Tides

The astronomical tides are caused by the relative motions of the Earth, Moon and Sun. 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 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.

3.3.2 Winds

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.

3.3.3 Creek Discharges

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.

3.3.4 Coastal Trapped Waves

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.

3.3.5 Near Shore Wave Processes

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.

3.4 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.

3.4.1 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.

3.4.2 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.

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.

3.4.3 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.

Within the Tuggerah Lakes system, wind set-up and set-down can result in water level variations of up to 0.2m within the lake at any given time. This process is evident in water level gauge data at Toukley (northern lake foreshore) and Long Jetty (south-eastern lake foreshore).

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 stationary inverse barometer effect.

3.4.4 Wave Set-Up

Wave set-up is described in **Section 3.2.2**.

3.4.5 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.

3.4.6 Freshwater Flows

The largest water level changes within the Tuggerah Lakes are caused by catchment inflows during major rainfall events. The major catchments delivering runoff to the lakes are the Wyong River and Ourimbah Creek. Major flood events can affect water levels in the lakes system over time scales ranging from several days to several weeks.

3.4.7 Climate Change

General scientific consensus predicts that, under enhanced greenhouse conditions, sea levels will rise in response to isothermic expansion and melting of polar-land ice shelves. Predictions of global sea level rise due to the Greenhouse effect vary considerably. It is impossible to state conclusively by how much the sea may rise, and no policy presently exists regarding the appropriate provision that should be made in the design of new coastal developments.

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.

The 4th IPCC report (2007) on climate change predicts a sea level rise of between 0.28m to 0.79m by 2100. This includes potential sea level rise should recent ice sheet melting in polar-regions continue, estimated to contribute between 0.1 and 0.2m. For engineering design purposes, Engineers Australia recommends an allowance of 0.8m for sea level rise by 2100.

3.4.8 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 along the NSW coast, 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 Pacific Decadal Oscillation (PDO).

3.5 Winds

The Tuggerah Lakes are primarily a shallow estuary system. Consequently wind driven currents are a primary source of mixing within the estuary. **Section 3.3.2** describes how wind driven current develop within the estuary.

3.6 Sediment Transport

The Tuggerah Lakes form a wave dominated barrier estuary, with the dune system separating the estuary from the ocean comprised of marine sands delivered from offshore over thousands of years.

The near shore and shoreline regions of Tuggerah Lakes are formed from marine sands and rocky headlands, with some muddy areas in the more sheltered regions. Additionally, the perimeters of some existing development works provide hard-edge areas, such as those at The Entrance.

Natural changes to the shoreline and near shore areas continue and are caused by storm waves, typically erosion, especially when they occur during periods of higher water level, and by catchment floods that deliver sediments (typically silts and clays, but also sands and other materials), to the Lakes.

Development within the Wyong region since European settlement has caused an increase in impermeable areas and consequent increases in peak flood flows and runoff volumes, leading to increased sediment yield loads.

Sediment transport is caused by the water particle motions of waves and currents that lead to a shear stress on the seabed sediment particles. In some parts of the Lakes, waves and currents cause combined shear stresses. Generally, sediment motion commences when the seabed shear stress exceeds a threshold value, which depends on particle size, density and sediment type – cohesionless (sands) or cohesive (silts and clays). Sediment may be transported as bed load or suspended load. Bed load transport is effected as a series of saltations or hops. Suspended sediment transport occurs when the turbulent mixing of the flow counteracts the fall velocity of the finer sediment particles that disperse upward from the seabed. Transport is initiated only when the shear stress exceeds the threshold.

Where a seabed is disturbed, for example, by dredging, and where the threshold condition for sediment movement is exceeded, wave and current caused sediment transport may act to restore the pre-condition of the seabed. Experience based on historical hydrographic surveys has shown that in Tuggerah Lakes, other than at near shore locations and in The Entrance shoals area, the bed of the estuary is essentially stable.

At shoreline locations sediment transport may be alongshore and/or onshore/offshore. Where waves break obliquely to the shoreline, a longshore current may cause longshore transport. Offshore transport normally occurs during a storm, with a longer term onshore transport following storm abatement. However, onshore transport may not occur in regions that generally have low wave energy, other than during ocean storms, such as within the Lakes. These regions are characterised by a flat inter-tidal area with a steep drop-off near the low tide line, and often a steep back-beach area.

Waterways that enter the Estuary may transport fine silt particles from the catchments to the Estuary. These fine particles eventually settle in the most tranquil regions of the Estuary. From time-to-time they may be disturbed by uncommon strong winds and consequent local sea, and then be transported to other more tranquil areas. Because nutrients may be adsorbed to these fine sediments, this process also affects the distribution of nutrients, affects light penetration and may disturb seabed plants.

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.

4 Data

A range of data items was required to set up, calibrate and operate the models applied to this investigation. They are described in Cardno (2013a) and below.

4.1 Bathymetric Data

Cardno received the following data from OEH for their previous studies at The Entrance.

- 2011 Entrance Hydrosurvey
- 2011 Bathymetric LiDAR data of the Entrance and Open Coast
- 2008 Bathymetric LiDAR data of the Entrance and Open Coast
- 1979 and 1975 Tuggerah Lakes Surveys
- 1995 Single Beam offshore bathymetric data to 60m.

Bathymetric data describing the Lakes, The Entrance area and the near shore and offshore seabed areas were required for model set up. Additionally, spatially varying seabed and sub-surface bed rock information for the entrance area was required because entrance scour during flood events is limited in depth by that natural rock structure. No differentiation was made to the layout of entrance dredging that was included in model set-up – sand or rock. However, where known rock existed, no erosion below the initial dredged seabed was allowed in the modelling.

Bed rock contour information was obtained from Public Works Department data presented in Patterson Britton & Partners (1988).

Cardno received the bathymetric data described above from OEH. A digital elevation model (DEM) of the lake and shorelines was prepared by combining these bathymetric data sets, with the most recent data taking precedence. The adopted vertical datum of the DEM was AHD.

Note that in this modelling study, the ‘existing case’ was developed using this DEM data with no entrance dredging. In Cardno (2013a) the ‘existing case’ for fixed bed modelling of lake flushing characteristics included an enlarged entrance, which was required to match the salinity data period of 1996, which pre-dated the 2011 entrance survey. Salinity levels in Tuggerah Lake are affected significantly by the entrance condition.

4.2 Wave Data

Wave data (height, period and direction parameters) for the period from 1992 to 2011 from the offshore Long Reef directional Waverider buoy was provided by Manly Hydraulics Laboratory (MHL).

4.3 Water Level Data

MHL also provided recorded water level data for Long Jetty and Toukley in Tuggerah Lake. Additionally, time-series water level data from MHL’s Middle Harbour tide gauge was provided and used as one basis for forcing the ocean boundary of the hydrodynamic model.

4.4 Wind Data

Long term recorded wind data for Mascot Airport was obtained from the Bureau of Meteorology.

Other wind data is available from Norah Head, but it contains more data gaps and the anemometer is located atop a cliff. Hence it was not applied to this study.

Comparing the Toukley (north) and Long Jetty (south) recorded water levels in Tuggerah Lake itself, one can see that water level differences between the northern and southern lake areas can be in the order of 0.6m.

These water level differences are caused by wind shear stress. Previous modelling studies undertaken in Lake Illawarra have shown that steady winds require about 3 hours in lakes of this depth to reach water level set-up equilibrium.

4.5 Rainfall/Runoff Data

Time-series rainfall data for Tuggerah were provided by MHL. Additionally estimated/modified runoff hydrographs distributed throughout the lakes were provided by OEH. The shapes, relative magnitudes and phasing of these hydrographs were based on the work of Brennan *et al.* (2011).

4.6 Sediment Data

Sediment data was taken by Cardno (two samples, as part of a previous study) at a site on the North Entrance shoreline of The Entrance, demonstrating a D_{50} particle size of 0.35mm. Particle sizes of 0.25 and 0.35mm were tested in the entrance morphological modelling to test the sensitivity of those model results to particle size and the larger size adopted for Cardno (2013a) and this project.

4.7 Salinity Data

The Lakes are generally high salinity waters, with salinity changing with catchment runoff and the condition of the entrance – higher salinity when the entrance is more 'open' and during dry periods, when evaporation (about 3mm/day on non-rain days) occurs. The most reliable data set is presented in MHL (1997), which provides salinity time-series data at many sites, some of which were adopted for transport-dispersion model set-up and verification in terms of advection-dispersion characteristics in Cardno (2013a). The lake is typically most saline near The Entrance with average salinity of 34ppt (1996), reducing to 32ppt at the northern end of Tuggerah Lake and into Lake Budgewoi.

Data presented in MHL (1997) was used to set up an initial distribution (map) of salinity for advection-dispersion investigations for lake flushing assessment.

5 Model Systems

5.1 Modelling Criteria

2D modelling was generally undertaken for these investigations because sand transport algorithms are formulated in depth-averaged flow form and the lake entrance is shallow and sandy – other than where rock occurs.

This study has adopted 2D transport-dispersion also for water quality/flushing scenarios to achieve practical computation times and because comparative investigations were required. However, Delft3D is switched easily to 3D and includes a full water quality system. This level of detail (2D) has been found to be realistic for similar estuary systems such as Brisbane Water and Lake Illawarra.

Modelling of the lake system and physical processes required coupled hydrodynamic and wave modelling, together with morphological changes to achieve reasonable calibration, acknowledging that it is generally not possible to have a completely contemporaneous field data set, especially of lake/seabed form, which changes constantly. Hence no fully contemporaneous data set was available for the model calibration described in Cardno (2013a); nevertheless, a good outcome was achieved.

5.2 Delft3D

Cardno have used the Delft3D model system to undertake the wave, hydrodynamic morphological modelling required for this investigation. Delft3D is a hydrodynamic, sediment transport and water quality modelling system developed by Deltares (formerly Delft Hydraulics) in The Netherlands. It has been applied in major coastal and ocean investigations and engineering studies throughout Australia. In the last 10-years Delft3D has led modelling innovations such as coupled online wave and hydrodynamic forcing, as well as the implementation of the latest generation of sediment transport models such as Van Rijn (2004), which are significantly more accurate than earlier models.

The Delft3D modelling system includes catchment flows, wind, pressure, tide and wave forcing, two or three-dimensional currents, stratification, rainfall/evaporation, sediment transport and water quality descriptions and is capable of using irregular, rectilinear or curvilinear coordinates.

The site is suited to the curvilinear grid and domain decomposition systems, which have enabled a detailed, yet efficient description of the flow structure in The Entrance to be prepared.

All studies generally begin with the Delft3D-FLOW (hydrodynamic) module. From Delft3D-FLOW, details such as velocities, water levels, density, salinity, vertical eddy viscosity and vertical eddy diffusivity can be provided as inputs to the other modules. The wave and sediment transport modules work interactively with the FLOW module through a common communications file.

5.2.1 Hydrodynamic Numerical Scheme

The Delft3D FLOW module is based on the numerical finite-difference scheme developed by G. S. Stellling (1984) of the Delft University of Technology in The Netherlands.

The Delft3D Stelling Scheme arranges modelled variables on a staggered Arakawa C-grid. The water level points (pressure points) are designated in the centre of a continuity cell and the velocity components are perpendicular to the grid cell faces. Finite difference staggered grids have several advantages including:-

- Boundary conditions can be implemented in the scheme as basic time-series.
- It is possible to use a smaller number of discrete state variables in comparison with discretisations on non-staggered grids to obtain the same accuracy
- Staggered grids minimise spatial oscillations in the water levels.

Delft3D can be operated in 2D (vertically averaged) or 3D mode.

Horizontal solution is undertaken using the Alternating Direction Implicit (ADI) method of Leendertse for shallow water equations.

5.2.2 Ability to Incorporate a Varying Mesh Size

As mentioned previously, bathymetric discretisation and modelling can be undertaken in Delft3D on a rectilinear or curvilinear grid, and includes domain decomposition (see **Section 5.2.6**). The Delft3D model is specifically written to undertake hydrodynamic flow and transport modelling arising from tidal and meteorological forcing on a curvilinear boundary fitted grid.

The curvilinear grid system enables grid sizes to vary so that better resolution can be used within The Entrance, with less resolution in the ocean where less detail is required. Additionally, the curvilinear grid system can be better set-up to follow the flow streamlines and boundaries, thereby providing a better description of the current structure.

The domain decomposition module has been used also to prepare a fine grid area near The Entrance in order to ensure that the hydrodynamic and morphological processes are resolved adequately. The Delft3D numerical scheme can simulate steep hydraulic gradients such as those which occur during Entrance opening.

5.2.3 Wetting and Drying of Intertidal Areas

Many estuaries, lake systems and embayments contain shallow intertidal areas; consequently Delft3D incorporates a wetting and drying algorithm for handling this phenomenon. Cardno have utilised Delft3D in many applications where inter-tidal flats exist. Through experience in these areas of application, Cardno use a method of careful refinement in the intertidal areas and appropriate setting of dry depths to minimise discontinuous movement of the boundaries. This process ensures oscillations in water levels and velocities are minimised and that the characteristics of the intertidal areas are modelled accurately.

With regard to water quality modelling and conservation of mass, when a cell dries out, the substance mass is still kept within the cell. When the cell re-wets, as occurs on a rising tide, this mass is then re-diluted.

5.2.4 Conservation of Mass

Problems with conservation of mass, such as a ‘leaking mesh’, do not occur within the Delft3D system. Nevertheless, whilst the Delft3D scheme is unconditionally stable, inexperienced use of Delft3D, as with most modelling packages, can result in potential mass imbalances.

Potential causes of mass imbalance and other inaccuracies include:-

- Inappropriate large setting of the wet/dry algorithm and unrefined inter-tidal grid definition;
- Inappropriate bathymetric and boundary definition causing steep gradients;
- Inappropriate time step selection (i.e. lack of observation of the scheme’s allowable Courant Number condition) for simulation.

5.2.5 Model Boundary Conditions

The downstream model boundary has been set in the open sea in a depth of about 80m and defined as a water level and wave boundary (the latter for morphological simulations only). This boundary can also include time-series of parameters such as salinity, temperature, sediment concentration and nutrient concentration. However, it is common practice to set boundaries sufficiently distant from the active estuarine area for these parameters to be constant in time (other than water level and wave conditions) so that they don’t influence the solution. This approach has been followed for this study.

5.2.6 Domain Decomposition

Delft3D provides the facility to adopt a modelling approach known as ‘domain decomposition’. Domain decomposition is a model gridding technique in which a model is divided into several smaller model domains that are dynamically coupled with each other. The subdivision is based on the horizontal and vertical model resolution required for adequately simulating physical processes. Computations can be carried out separately, yet concurrently, on these domains. The communication between the domains takes place along internal boundaries. Computations are carried out concurrently, via parallel computing, thus reducing the turn-around time of multiple domain simulations. Domain decomposition allows for local grid refinement, both in the horizontal direction and in the vertical direction in 3D models. Grid refinement in the horizontal direction means that in one domain smaller mesh sizes (fine grid) are used than in other domains (coarse grids).

Domain decomposition is recognised as an efficient and flexible tool for the simulation of complex physical processes. The structured multi-domain approach combines the advantages of the modelling flexibility of the single-domain unstructured approach with the efficiency and accuracy of the single-domain structured approach.

5.2.7 Sediment Transport Processes

The module applied to the sediment transport analyses is the Online Sediment Module with the Van Rijn (2004) sediment transport module – cohesionless sediment. This system makes it possible to undertake time-series sediment transport modelling using combined tide, wind, wave and fresh water flows. The bed levels, water levels and currents within the wave module are updated every hour and the calculated wave conditions (wave heights and radiation stress maps) used for the next hydrodynamic phase.

Changes in currents and water levels then affect wave process calculations in the next wave model step and those new outcomes are then used in the next hydrodynamic and morphological steps. It is based on the Van Rijn (2004) sediment transport algorithm. This algorithm incorporates time varying flow conditions in the calculation of bed roughness and reference concentrations. Cardno also employs a bed-form roughness model which can be particularly important when simulating hydrodynamic and sediment transport processes in an entrance system under flood flow condition. At Lake Illawarra, Cardno has demonstrated the importance of careful selection of an appropriate bed roughness model to simulate the hydrodynamic processes in a narrow entrance system with a steep hydraulic gradient.

5.3 SWAN Wave Modelling System

The wave model Cardno used in this study is based on the third generation wind/wave modelling system, SWAN, which is incorporated as a module into the Delft3D modelling system. This model was developed at the Delft University of Technology and includes wind input (local sea cases), combined sea and swell, offshore wave parameters (swell cases), refraction, shoaling, non-linear wave-wave interaction, a full directional spectral description of wave propagation, bed friction, white capping, currents and wave breaking. SWAN also includes phase-averaged diffraction based on the model of Holthuijsen *et al.* (1993).

SWAN includes a nested grid capability that allows coarser grids in deeper water and finer grids in shallow water where better definition of seabed form and depth are needed. Output from the model includes significant wave height, dominant wave direction, spectral peak and mean periods and (optionally) the full directional wave spectra at selected grid points.

Offshore waves were propagated into The Entrance to a point where they no longer affected sediment transport and water levels.

6 Modelling Methodology

Morphological simulations in this investigation were conducted using the same model set-up developed for, and applied in, Cardno's previous modelling investigations for The Entrance (Cardno, 2013a and b). Model grid systems set-up for the hydrodynamic and wave models are presented in **Figures 6.1** and **6.2** respectively.

6.1 Morphological Simulations

Four general, dredged-entrance morphological modelling scenarios (the dredged area extending upstream to The Sump at the Entrance Bridge, see **Figure 1.2**), as well as the existing case (no dredging) – each for fully trained and non-trained entrances, were investigated (see **Section 2.2**). Each of these ten simulations included waves, tides, winds and catchment flows over periods of about three months. These input parameters were required to describe the physical processes that include a range of met-ocean conditions.

The purpose of this modelling was to investigate the morphological evolution of the entrance channel post dredging and quantify the potential rate of sediment infilling or additional scour that may occur. Hence the intention was to investigate how much channel infill might typically occur between dredging campaigns, how much sediment might need to be removed and how much more frequently the channel might need to be dredged in order to maintain the sought navigation conditions. Moreover, the proposed dredging extends to The Entrance Bridge, and consequently the proposed works may cause seabed scour around its supporting piles; this being another important issue.

Two other model set-up details need to be noted. They are:-

- The vertical and horizontal extent of the rock sill at The Entrance is not presently well defined. Although there is a clear, straight line edge to the sill, observable near low tide, there is a much greater extent of rock beneath the sand, as determined by previous probing exercises. The extent of exposed rock changes with recent flooding history in the Tuggerah Lakes. The model was set-up on the available data (as described in the 2013a Cardno report);
- The sand bed of the entrance beyond the presently identified rock will need to be dredged to some extent also, more so for the deeper rock-cut cases. That is, batters are required for the navigation channel, which will link to existing navigable areas of The Entrance and Tuggerah Lake. Batter slopes were set at 1V:5H.

The model set-up and dredged channel layouts were agreed with Council before modelling began. **Figure 6.3** describes the model boundary conditions applied to these investigations. The period selected for modelling was based on a non-flood period and having a sufficiently long set of all input data items.

6.2 Fixed-Bed Simulations

In addition to the morphological modelling scenarios, fixed bed simulations were undertaken to investigate the effect of the proposed dredging on lake salinity and tidal planes and ranges. Similarly, these one-year fixed-bed simulations have been run for both the existing (no training walls at the entrance) and developed cases (including training walls) and comprised the same dredging scenarios for the Entrance Channel (see **Section 2.2**). **Figure 6.4** describes the model boundary conditions applied to these simulations.

6.3 Tide-Only Simulations

In order to investigate the potential effects dredging of the Entrance Channel may have on the day-to-day tidal water level within Tuggerah Lake, a set of two fixed-bed simulations (excluding training walls in both cases) has been undertaken:

- No Dredging;
- The Entrance Channel bottom at -5.50m AHD (5.0m depth @ MLW).

To maximise potential changes in tidal regime, the dredge scenario representing the largest dredged volume was selected. Compared to the fixed-bed modelling undertaken to investigate conveyance and navigability, these two simulations have been run with tide as the only boundary condition. Hence, salinity, temperature, wind, evaporation and river discharge have not been taken into account – so that the astronomical tide only is considered.

7 Results

7.1 Morphological Simulations

7.1.1 Model Results

The model results for the three month morphological simulations are presented in **Table 7-1** and **Figures 7.1** to **7.20** and describe the amount of morphological change (that is, either channel infilling or additional scour) which has occurred for each dredged channel layout post dredging over the simulation period. Note that negative infill volumes indicate scour/erosion.

In order to give an indication of the rate of morphological change for each layout, infill volumes have been presented in **Table 7-1** at both the 55% mark (approximately 50 days) and at the end of the 3 months prototype time.

Table 7-1 The Entrance - Dredged and Infill Volumes

Scenario	Dredged Volume (*10^5 m^3)	Infill Volume @55% (*10^5 m^3)	Infill Volume @3 months (10^5 m^3)	Scenario	Dredged Volume (*10^5 m^3)	Infill Volume @55% (*10^5 m^3)	Infill Volume @3 months (10^5 m^3)
No Training Walls				**Fully Trained**			
No Dredging	0.00	-0.84	-1.05	No Dredging	0.00	-0.75	-0.99
Bottom at -1.50 m AHD	1.13	-0.58	-0.65	Bottom at -1.50 m AHD	1.13	-0.50	-0.60
Bottom at -2.50 m AHD	2.61	0.26	0.35	Bottom at -2.50 m AHD	2.62	0.25	0.30
Bottom at -4.00 m AHD	4.66	1.11	1.47	Bottom at -4.00 m AHD	4.62	0.98	1.25
Bottom at -5.50 m AHD	6.34	1.51	2.09	Bottom at -5.50 m AHD	6.19	1.27	1.76

Looking at the model results of the different dredging scenarios for a non-trained entrance, the following observations are made:-

- The “No Dredging” case shows scour of the entrance – indicating that the lake was slowly “emptying” during the simulation period due to previous low frequency tidal pumping (see **Figures 7.1 - 7.2**);
- The Dredged Channel with the bottom at -1.5 m AHD shows scour of the entrance, albeit at a lower rate (see **Figures 7.3 - 7.4**);
- The highest rate of infilling occurred during the first 7 weeks (prototype time) of the simulations;
- The Dredged Channel with at bottom the -2.5 m AHD began infilling almost immediately, and after 7 weeks had infilled 10% of its dredged volume. The infill volume after completion of the three month simulation equals 13% of the dredged volume. Infilling has occurred particularly from the upstream direction. However, this process has also resulted in erosion of sediments upstream of the bridge, and in the vicinity of the bridge foundations (see **Figures 7.5 - 7.6**);
- The Dredged Channel with the bottom at -4.0 m AHD began infilling almost immediately, and after 7 weeks had infilled almost 25% of its initial dredged volume. The infill volume after completion of the three month simulation equals almost one-third of the dredged volume. Infilling has occurred predominantly from the upstream direction, resulting in erosion of sediments upstream of and at the bridge (see **Figures 7.7 - 7.8**);
- The Dredged Channel with the bottom at -5.5 m AHD began infilling almost immediately, and after 7 weeks had infilled almost 25% of its dredged volume. The infill volume after completion of the three month simulation equals almost one-third of the dredged volume. Infilling has occurred predominantly

from the upstream direction, resulting in erosion of sediments upstream of and at the bridge(see **Figures 7.9 - 7.10**);

- It was also observed that an increase in conveyance resulted in higher current speeds upstream of The Entrance Bridge, including in the Terilbah Channel. This increase in current speeds may, in the long term, cause increased foreshore erosion along the Terilbah Reserve and changes to channel navigability

7.1.1 Discussion

The model results show that the infill or scour volume after three months is smaller for a fully trained Entrance than for a non-trained Entrance, ranging from about 5% less for the “No Dredging” case to about 15% for the dredged channel with the bottom at -5.50 m AHD. The presence of the training walls has prevented some marine sediment from entering the entrance, causing the rate of infill of the dredged channels from the downstream end (the ocean) to be slowed. This is consistent with the finding of Cardno (2013a).

It should be noted that the observed rates of infilling would be expected to slow with time, as the trapping efficiency of sediments decreases as the channel gradually infills. This trend is already visible when comparing the intermediate infill/scour volumes (with the model at approximately 55% completed) with the infill and scour volumes after three months (see **Table 7-1**).

Infilling of the channel for these simulations was observed as occurring from both directions (that is, from both downstream (ocean side) infilling during flood tides as well as upstream (lake side) entrance channel sediment infilling during ebb tides). This can be attributed to the greater conveyance afforded by the dredged channels, resulting in the erosion of sediments upstream of the dredged channel - with these sediments then being deposited into the channel during ebb tides. This upstream erosion may have implications for the foundations of the Entrance Bridge.

7.2 Fixed-Bed Simulations

7.2.1 Model Results

Results for model output locations A, B and C (see **Figure 7.21**) in the form of salinity and water level time-series are presented in **Figures 7.22** to **7.27**. A comparison between the two dredged cases (excluding and including training walls) shows that the presence of training walls has no significant effect on the modelled outcomes, but that the presence of training walls causes a marginal increase in head loss and pumping up of lake levels, in the order of about 1cm – see **Figures 7.28** to **7.33**. This effect is most noticeable for the non-dredged entrance cases.

The analysis of these water level time-series shows that the tidal prism (and hence conveyance between the lakes and the ocean) increases with the magnitude of dredging (see **Table 7-2**). However, the results also showed that the relative increases in conveyance diminish with increased dredged depth. That is, significant increases in conveyance are achieved by dredging to -1.5m AHD or -2.5m AHD, but gradually smaller increases are achieved by dredging deeper.

This observation can be attributed to the fact that dredging only extends from the Lakes entrance to The Entrance Bridge, while the entrance shoals upstream of the bridge still act to constrict flow into and out of the lakes. The extent of tidal channel between the ocean and The Entrance Bridge is smaller than the extent between the bridge and the Lake. Therefore increased entrance dredging causes a proportionately smaller increase in conveyance.

Table 7-2 Typical Tidal Prism Results

Tidal Flow	Tidal Prism (x10^{6}m^3)									
	Excluding Training Walls					Including Training Walls				
	No Dredging	@-1.5*	@-2.5	@-4.0	@-5.5	No Dredging	@-1.5	@-2.5	@-4.0	@-5.5
Ebb	-0.94	-2.24	-3.20	-3.74	-3.92	-0.93	-2.15	-3.13	-3.68	-3.91
Flood	0.74	2.04	3.01	3.53	3.75	0.72	1.95	2.94	3.49	3.72

*Datum AHD

The water level time-series show that a dredged entrance channel causes increased conveyance between the ocean and the lake, thereby increasing the tidal range and decreasing the mean water level within Tuggerah Lake by ~10 to 15cm, but up to ~20cm from time-to-time. The change in mean water level caused by the various entrance dredging depth alternatives is significant, but gradually diminishes with increasing dredged depth. That is, a dredged channel of -1.5m AHD would result in a significant decrease in mean lake water level, but dredging deeper still would only have minimal additional effect on water levels.

This is most noticeable during fresh water inflow events; see, for example, the mid-February 2010 period on **Figure 7.25**. During this time the 'flood level' is lower in the lakes, and is lowest for the deepest dredged case and not as low for the least dredged case – to -1.5m AHD.

By comparison, similar modelling of Council's current dredging regime, undertaken every 1 to 2 years, conducted in Cardno (2013a) showed only a minor increase in entrance conveyance (Figure 7.2 of Cardno, 2013a). This difference can be explained by comparing The Entrance channel bathymetry utilised in each study. In Cardno (2013a), the 'existing' bathymetry of The Entrance Channel was altered in order to calibrate the model in terms of salinity time-series recorded in 1996, whereas for the present set of simulations, the actual survey of 2011 was used unaltered (see **Appendix A**). Regardless, the results of the present simulations are intended for comparative purposes, to highlight the influence of the proposed dredging regimes, with and without training walls.

In terms of the spatial variability of the modelled water levels within Tuggerah Lake, comparison of the water levels at model output locations A and C reveals only slight differences (mostly caused by wind setup) in mean lake water level through the lakes systems.

Figures 7.26 and **7.27** show that the increase in lake salinity caused by the entrance dredging depth alternatives is significant, but gradually diminishes with increasing dredged depth. That is, there is a large difference between the 'no-dredging' and -1.5m AHD dredged cases (red and yellow lines), a smaller difference between the -1.5m and -2.5m AHD cases (yellow and green lines) and so on. There is virtually no difference between the -4.0m and -5.5m AHD dredged cases. This diminishing change in salinity is limited by:

- The ocean salinity of 35ppt; and
- Increased entrance dredging only causing a proportionately smaller increase in conveyance.

Figure 7.28 to **7.30** compare the no-dredging case and the -1.5m and -2.5m AHD dredged cases for output locations A, B and C for the cases that include and exclude the training walls. There is virtually no difference in terms of training walls or not, but a remarkable difference in terms of salinity change between the two dredged depths. On the contrary, there is little difference in salinity between the -4m and -5.5m AHD cases.

It is important to re-iterate that as these are fixed bed simulations, they are conservative in their depiction of increased conveyance as they assume no dredged channel infilling for the 12 months of simulation, which is unlikely – as shown by the morphological modelling results.

7.2.2 Discussion

The modelled dredged configurations of the Entrance Channel, including sand and rock removal would:-

- Increase conveyance;
- Decrease mean lake water level; and
- Increase lake salinity.

Significant changes in these modelled parameters were observed by dredging to -1.5m AHD and -2.5m AHD, however, dredging deeper only resulted in minor additional changes. This can be attributed to the fact that whilst tidal conveyance increases with channel depth, these increases diminish due to the fact that the dredged channel extends only to the bridge – and conveyance is still restricted by the shoaled regions upstream of the bridge.

A reduction in mean lake water level may have a number of ecological and recreational consequences, such as a greater exposure of the mudflat areas, increased odours from decaying wrack (at least initially), reduced aesthetics and potentially reduced recreational opportunities and commercial fishing catch. Navigational issues within the lakes would need to be considered, notably at jetties and boat-ramps where less draft would be available.

The presence of the training wall had only minimal effects upon tidal conveyance and salinity, due to the fact that the simulations were fixed-bed runs (morphological processes have been excluded), assuming no infilling of the dredged channel. Therefore, these results can be considered conservative; in reality the dredged channel will gradually infill (as the results of the morphological simulations indicate, and as happens after significant flood events now), and the presence of the training walls is likely to slow the rate of infilling – see **Section 7.1**.

7.3 Tide-Only Simulations

7.3.1 Harmonic Analysis

A one-year modelled water level time-series inside Tuggerah Lake (model output location B, see **Figure 7.21**) served as input for a harmonic analysis to describe the changes in the major constituents and tidal planes. The resulting tidal constituents and their associated amplitudes were used to calculate Mean High Water Springs (MHWS) and Mean Low Water Springs (MLWS) for this semi-diurnal tidal site (see **Table 7-3**) – based on M_2 and S_2, as per Australian National Tide Tables advice.

Table 7-3 Tuggerah Lake Tidal Planes

Tidal Planes	Mean Modelled Water Level (m AHD)	MHWS (m wrt mean)	MLWS (m wrt mean)
No Dredging	0.27	+0.04	-0.04
Bottom at -5.50mAHD	0.17	+0.28	-0.28

7.3.2 Discussion

As for the previous fixed-bed simulation, the water level time-series show that the dredged Entrance Channel leads to increased conveyance between the ocean and the lakes, thereby decreasing the average tidal water level inside Tuggerah Lake by ~10cm (see **Table 7-3** and **Figure 7.34**). **Figures 7.22** to **7.33** show that when other processes are included, such as wave forcing, wind and catchment flows, the water level may be lower by about 0.2m for a significant amount of the time.

The increased conveyance also increases the tidal range. Depending on foreshore slopes, this will have varying effects on the intertidal areas around Tuggerah Lakes. Note that high tide would be higher (0.45m AHD and low tide would be lower (-0.11m AHD). Note also that the 'real' mean lake level is affected by the spring-neap tidal variation, catchment flows, evaporation and wave conditions and that spring neap tidal variations still cause tidal pumping changes.

Once more, it is important to re-iterate that as these are fixed bed simulations, they are conservative in their depiction of increased conveyance (and therefore of changing tidal planes) because they assume no dredged channel infilling for the 12 months of simulation, which is unlikely.

8 Concluding Remarks

This report describes the outcomes of a range of mobile bed and fixed bed numerical model simulations undertaken to investigate the potential effects of entrance training walls and entrance dredging at The Entrance, Tuggerah, NSW. This work has been based on the calibrated Delft3D model system developed for the Office of Environment and Heritage by Cardno. Training wall layout was adopted to be the same as that developed in Cardno (2013a) at 150m apart.

Entrance training walls and four dredged depth options were investigated to describe the following matters:-

- The likely changes in lake flushing;
- The rate of dredged area infill and the characterisation of that process;
- The likely effect of the training walls on flushing, water levels and dredged area infill rate;
- The likely effect on tidal planes in the lakes; and
- The likely effects on salinity in the lakes.

Based on the results of the modelling, the following conclusions have been made:-

<u>Morphology:</u>

- The dredged channels would begin to infill almost immediately from both the upstream and downstream ends;
- The rate of infill from the downstream end (the ocean) would be slower if training walls were constructed;

<u>Water Quality:</u>

- Comparison of simulations undertaken with and without the training walls showed little difference with regards to water quality and water levels in the lakes system;
- The dredged channel schemes would increase the conveyance and tidal exchange between the lake and ocean, and increase lake salinity (at least in the short term). Conveyance increases with channel depth, but such increases are limited by the shoaled region upstream of the bridge, which continues to act as a tidal constriction. For this reason significant changes to mean lake water level and salinity would be observed by dredging to -1.5m AHD or -2.5m AHD, but any additional effects observed by dredging deeper than that would likely be minor.
- The dredged channel schemes would decrease the mean lake level (at least in the short term) by up to 10-20cm, but would result in higher high tide levels (and lower low tide levels) by increasing the lake tidal range. This may cause

<u>Additional Impacts:</u>

- The increase in conveyance provided by the dredged channels would result in higher tidal current speeds upstream of the Entrance Bridge, which in turn:-
  - May result in scour around the Entrance Bridge foundations;
  - May result in shoreline and channel change along Terilbah Reserve (in the long term);
- A reduction in mean lake water level may have a number of ecological and recreational consequences, in the form of exposure of the mudflat areas and potentially reduced recreational opportunities and commercial fishing catch. Navigational issues within the lakes would need to be considered, notably at jetties and boat-ramps where less draft would be available.

Note that the scale of dredging investigated is much greater than Council undertakes presently.

Should one of the test cases prove attractive to Council, then Cardno advises that additional, detailed investigations of the rock sill need to be undertaken; before undertaking more detailed modelling. Dredging upstream of The Entrance Bridge would need to be addressed also for lake-to-sea navigation – if potentially viable.

9 References

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