Tuggerah Lakes–
The Entrance
Morphodynamic Modelling

Prepared for NSW Office of Environment and Heritage

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EXECUTIVE SUMMARY

The Tuggerah Lakes system consists of three inter-connected shallow coastal lakes (Tuggerah, Budgewoi and Munmorah) that have a weak and intermittent connection to the ocean at The Entrance. The lakes have a history of water quality issues with development of their catchments leading to increased nutrient, and to a lesser extent sediment, loads.

The lakes' entrance is currently managed through regular dredging by Wyong Council to ensure that the entrance does not close and to achieve objectives related to flooding, water quality in the lower entrance channels and recreational amenity. The dredging does not affect the general water quality in the lakes.

Previous assessments have considered the possibility of constructing a training wall or training walls at the entrance to Tuggerah Lakes with the objective of maintaining a permanent entrance to the lakes and thus improving water flows and water quality. A training wall is a permanent engineered structure (typically rock) that would constrain or direct flows into and out of the entrance.

In late 2011, Cardno Pty Ltd was commissioned by the NSW Office of Environment and Heritage to develop a numerical model of the lake system to independently assess the potential effectiveness of entrance training walls in addressing water quality issues. A detailed model was prepared using the internationally recognised Delft3D package.

The model covers the entire area of the three lakes as well as the adjacent ocean and beaches. It is able to simulate the effects of tides, waves, wind, freshwater inflows and evaporation on both water and sand movement and has been calibrated to satisfactorily reproduce the observed behaviour of the existing lakes system. This provides confidence that the model will accurately predict the effects of possible training wall configurations.

The model has been utilised to assess a number of scenarios, namely:-

- The existing case (no training wall);
- A single training wall 150 metres north of the existing southern rock wall; and
- Dual training walls at 100, 150 and 200 metres apart.

Firstly, the effect of training walls on flooding was tested by simulating the passage of a 100-years (average recurrence interval) flood. The model assessed the scour of sand from the entrance, taking account of the underlying bed rock. It was found that the single training wall and dual training wall cases with 150 and 200 metre wide openings had no significant effect on peak flood levels around the lakes.

However, the reduced entrance area simulated by the 100 metre wide opening case caused an increase in peak flood levels of about 8 centimetres. More significantly perhaps, water levels for this scenario were assessed to remain elevated for several days longer than the other scenarios. With in-excess of 1300 properties around the lakes expected to experience over floor flooding in such an event, any worsening of flood impact was considered unacceptable. Accordingly, the 100 metre spacing scenario was excluded from further modelling work.

Following the simulation of flood passage, the model was run to examine the behaviour of the entrance channels and offshore post-flood shoals for a six weeks post flood period. For all scenarios, the model indicated that the entrance would not self-scour and shoaling would commence once the flood subsided. Therefore, if Council retains its current objectives related to flooding, lower entrance water quality and recreational amenity, it is expected that maintenance dredging of the type already undertaken would need to continue because the training walls do not materially improve the scouring and transport of sediment in the entrance area – in the short to medium term.

There would, however, be a gradual accumulation of sand on North Entrance and South Entrance beaches in the immediate vicinity of the training walls, and the 'return' associated with the northern training wall would limit the extent of the erosion of Karagi Point during a flood.

After the post flood modelling was completed, water quality was then modelled in terms of lake flushing over a 13 months simulation period – the first month being required to establish dynamic equilibrium. Lake bed and entrance conditions were assumed to be fixed for this modelling in order to reduce computation time. It should be noted that the model in this configuration was representing the entrance channels as still highly scoured (following flood passage) and would therefore represent a "best case" scenario for lake flushing.

The model assessed water quality conditions for each training wall scenario as well as the existing baseline of no entrance training wall. It was found that all training wall scenarios led to virtually no change in the exchange of water between the ocean and lakes through the entrance area.

TABLE OF CONTENTS

TABLES

FIGURES

APPENDICES

Appendix A Long Reef Wave Data
Appendix B Wind, Rainfall and Lake Water Level Data
Appendix C Flood Report – Review Figures
Appendix D Physical Processes
Appendix E Dredging Plan for The Entrance

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.
Flocculate		The coalescence, through physical and chemical processes, of individual suspended particles into larger particles ('flocs').
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
NTU		Nephelometric Turbidity Units
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 and 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 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.
Tidally Varying Models		Numerical models that predict estuarine behaviour within a tidal cycle, i.e., the temporal resolution is of the order of minutes or hours.
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.
Turbidity		A measure of the ability of water to absorb light.
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.

* A number of definitions have been derived from the Estuary Management Manual (1992).

1 INTRODUCTION

1.1 Submission

This report has been prepared for the Office of Environment and Heritage (OEH) by Cardno to describe investigations undertaken for the 'Development of a Combined Hydrodynamic and Morphodynamic Numerical Model of the Tuggerah Lakes, its Entrance Channels and the adjacent ocean beaches'. It describes the background, data, study approach and outcomes of this investigation. The Primary Purpose of this investigation is to assess the efficacy of possible training of the entrance in improving the water quality of the lakes. The model may be used by Wyong Shire Council (WSC) for future entrance dredging and related morphological investigations.

1.2 Background

The Tuggerah Lakes system on the NSW Central Coast comprises a series of three inter-connected shallow coastal lagoons (Tuggerah, Budgewoi and Munmorah) that have a weak and intermittent connection to the ocean at The Entrance, see Figure 1.1.

Circulation and mixing in the lakes is largely driven by wind and the occasional catchment flooding event. Limited flushing to the open sea occurs through The Entrance and is driven by the astronomical tides, other oceanic water level events, evaporation and catchment inflows. Because the lakes are relatively shallow, the fine bed sediments are readily mobilised and transported by wind events and the consequent waves and currents. The Entrance is presently managed by regular dredging to achieve objectives set by WSC related to flooding, water quality in the lower estuary and recreational amenity. The sand dredged from the entrance channels is placed on the adjacent beaches, mainly North Entrance Beach, so that sediment from the littoral area is not removed from the coastal processes system.

The management of the entrance has been a locally controversial issue for decades. Some community members consider that a deep permanent entrance will "flush" the Lake, improve water quality and resolve widespread aesthetic issues. This has often led to calls for training of the entrance. For this reason, the option of entrance training was thoroughly considered at all stages of the preparation of the Tuggerah Lakes Estuary Management Plan (EMP) prepared by WSC (2010). .

More recently, Council received a report entitled "Entrance Dynamics and Beach Conditions at The Entrance and North Entrance Beaches" (Umwelt, 2011). The study was commissioned to examine the sediment budget linkages between the entrance channels and the adjacent beaches and to identify options to manage the sedimentary processes to minimise coastal erosion hazards. U mwelt studied the interaction between entrance management strategies and the condition of the adjacent beaches and the estuary. It cautioned that training walls "... are more likely to have a detrimental transformational impact on the hydrodynamics and fragile ecology of the Tuggerah Lakes." It did, however, recommend that Council invest in a 3D hydrodynamic and sediment transport model of the entrance area to test a range of management strategies under present and sea level rise scenarios.

At the same time, the then NSW Opposition Leader, Mr Barry O'Farrell, committed a NSW Coalition Government to funding "an engineering model to determine the location and effectiveness of a possible entrance Break Wall and the impact it would have on the health of the Tuggerah Lakes" (Liberal Party of Australia, 2011). This current study will fulfil the Government's pre-election commitment, while providing Council with a useful tool to guide future management of the entrance area.

There have been a number of other studies undertaken in the past looking at a variety of issues around The Entrance. Those documents were listed in the Brief prepared by OEH and included in the References section of this report.

1.3 Conventions

Standard direction conventions have been adopted, that is:-

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

All levels are to AHD, other than where specified otherwise.

2 STUDY OBJECTIVES

The following details were outlined in the Brief. Some modifications and additions to that description have been made by Cardno. This section includes a concise overview of the methods applied to this investigation.

2.1 Study Objectives

This study has three objectives; to develop a 2D/3D model of the lake and ocean processes, to examine the impact and effectiveness of various entrance training wall configurations, and to provide Council with a tool to inform and guide the future management of the entrance area. Actual catchment modelling was not included; rather the lake and entrance model accepts available catchment runoff inputs as part of those simulations.

In relation to the second objective, the lake/entrance model system was to be capable of testing a number of possible entrance training wall configurations and predicting their effects on lake circulation, flushing, tidal prism, tidal planes and mean water level, as well as predicting the morphological response of the entrance channels and adjacent beaches both in the short term and on time scales of decades (that is, incorporating the probable Sea Level Rise) including a selected range of entrance area dredging scenarios.

In relation to the third objective, the model system was to be able to simulate the morphological response of the entrance channels and adjacent beaches as a result of various maintenance and capital dredging strategies, as well as the outcomes of beach nourishment. The model was also to be capable of simulating the effect of these various strategies on lake flushing and circulation and be capable of carrying out these simulations for current and predicted future mean sea level conditions.

The model will be able to assist management investigations of the entrance for some years. Hence it was a requirement of this commission that all model files and input data be supplied as a part of project reporting – but not the actual software. All information that would be required by a competent consultant to enable the testing of future management options has been provided. Therefore the model system used is one with a history and expectation of ongoing support – which is the case for Delft3D, including SWAN. A software licence was not required as part of this commission. Data has been provided in industry standard model-independent formats, where they exist.

2.2 Study Area

The model extents are sufficient to confidently predict the morphological response to entrance training wall test cases and various dredging strategies. The morphological model, comprising coupled hydrodynamic, wave and morphological modules, covers all of the entrance channels upstream to the “drop-over” in detail, the whole of the lakes for flood storage purposes in less detail, the near-shore entrance area and the adjacent beaches as far north as the northern end of Curtis Parade and south to the extent that it includes the compartment of The Entrance Beach.

The associated wave model extends offshore into deep water and into the entrance for a distance sufficient to describe wave propagation into The Entrance to a point where most ocean wave energy has been dissipated. This depends upon the degree to which the entrance is open and may be up to The Entrance Bridge in rare circumstances. Hydrodynamic and wave models were set-up and calibrated using bathymetric data provided by OEH. In this case there was no direct wave model calibration, there being no data within The Entrance. However, implicit calibration was undertaken because wave input was required to achieve reliable water level calibration within Tuggerah Lakes for the combined hydrodynamic, wave and morphological modelling system.

2.3 Boundary Conditions

Circulation and mixing in Tuggerah Lakes is dominated by wind, with the occasional freshwater catchment event having a notable effect on salinity and mixing. These factors are the primary drivers of lake circulation. It was necessary to construct time-series of fresh water inflows, together with a realistic distribution of inflow locations to facilitate the flooding events and long term flushing simulations. This data was taken from existing data sources (Manly Hydraulics Laboratory data), and a range of reports provided by OEH and WSC. For flood simulations, inflows were consistent with those used in the Tuggerah Lakes Flood Study (Lawson and Treloar, 1994 – which is still the current flood study).

The offshore boundary conditions were based on water levels (predicted tides and recorded Middle Harbour water levels) and directional wave data from the MHL Long Reef Waverider buoy site. Wind data was important also and was provided by the Bureau of Meteorology. The influence on lake flushing, in terms of salinity variations, was investigated/described using both predicted tides and measured water levels as boundary conditions for the hydrodynamic model; in order to test the importance of non-astronomical water surface variations on flushing. Coastal trapped waves and other oceanic phenomena can cause persistent periods of elevated and lowered ocean levels, both of which can cause significant influxes of high salinity ocean water to the lakes. This process is significant because of the small tidal range in the lakes and the long period of the coastal trapped waves, which leads to much less attenuation of the coastal trapped wave than of the tidal wave. Ocean storms may also cause an influx of seawater as a result of radiation stress forcing – found to be the case in Lawson and Treloar (1994) and this study – implied through the calibration process.

2.4 Assessment of Training Works

Before commencing morphological modelling it was necessary to first calibrate the hydrodynamic and morphological models. The model system was calibrated first for dry weather conditions and then for the severe flood of June 2007, the latter including entrance break-out changes – limited by bed rock that underlies the entrance area. The transport-dispersion characteristics were also 'verified' using MHL data recorded in 1996 by MHL; noting that insufficient coincident data for all important physical processes and conditions was available for calibration of the temporal salinity variation process.

Once the models were calibrated and verified, two different kinds of simulations were performed.

1. Morphological simulations that were conducted to investigate the effect of the training wall options on flood levels within the lake, as well as the morphological response of the entrance, including entrance scour and then post-flood onshore sediment transport.
2. 13 months fixed bed bathymetry simulations designed to assess the 'Best Case' effects of the training wall options on lake flushing and water quality processes using post-flood bathymetric descriptions from the 1% magnitude flood cases. It is highly improbable that the entrance would remain in a post-flood scoured condition for 13 months – accordingly these simulations represent unrealistic 'Best Case' scenarios.

For the morphological simulations, the 'Existing Entrance' and four entrance training wall configurations were modelled; one single wall and three twin wall configurations. For each of these, the morphological response for the present sea level condition was investigated for a range of catchment flood magnitudes and combined ocean wave conditions. The simulations extended until major flood-caused entrance changes ceased; using the 48-hours rainfall duration hydrographs presented in Lawson and Treloar (1994).

Entrance changes were also assessed in terms of changes in flood level (noting that this was not a flood study) and changes in wave penetration of the entrance during major storm conditions. Peak flood and ebb current vector changes were prepared also. The northern shoreline of The Entrance, near the Karagi Park caravan park, is presently affected by strong currents and shoreline erosion. Hence there was a need to quantify any changes there and potentially, similarly affected areas.

Changes in the shoreline areas near the training walls were also investigated, as well as the implications for post-storm onshore transport of sand from the offshore sand bar/shoal formed by the flood. This issue is important in that, should most of this sand bar move onshore north of a northern training wall, then entrance sand may gradually be transported from the entrance to The North Entrance shoreline as part of intermittent flood and post-event recovery processes. Some sand accretion against a southern training wall may be expected as a result of longshore transport. Also, sand may accumulate on the northern side of a northern training wall because of the gradient in wave heights between the wave-shadow area in the lee of such a structure versus the more exposed shoreline a little further north. This would lead to a southward transport of sand from southern North Entrance Beach towards the entrance and the formation of a sand fillet in that against a northern training wall.

Results have been presented in the form of plan plots and time histories of selected parameters near The Entrance and at a number of reference locations around the lake system.

Morphological updating was required for this modelling exercise so that the channel scour was included. Model calibration from the June 2007 flood event ensured that entrance scour behaviour and water level were consistent with observations from the June 2007 flood – noting that the catchment run-off hydrographs (Brennan et al, 2011) needed some modification when compared with the Lawson and Treloar (1994) runoff data for flood cases. A comparison of water level time histories at Long Jetty for the tested layouts was prepared for each flood magnitude.

Table 2.1 presents a summary of the morphological simulations specified in the Brief.

Table 2-1 Summary of Morphological Model Runs for Training Works

Sea Level	Simulation	Morphology				
		Existing	Single Training Wall	Twin Training Wall Configuration 1 150m Width	Twin Training Wall Configuration 2 200m Width	Twin Training Wall Configuration 3 100m Width
Current	One Year	✓	✓	✓	✓	✓
	5% Flood	✓	✓	✓	✓	✓
	1% Flood	✓	✓	✓	✓	✓
2100	One Year	✓	✓	✓	✓	×

The possibility of a corresponding elevated oceanic water level due to storms was taken into account in these scenarios using the June 2007 ocean storm time-series data - peak storm significant wave height of about 7m and recorded water levels at Middle Harbour. Propagating these waves shoreward to The Entrance in coupled wave and hydrodynamic modelling allows the natural ocean levels to be developed.

For the lake flushing simulations, a series of fixed bed bathymetry models were run for a period of 13 months to investigate variations in lake flushing that might arise from the various training wall options. The behaviours of the lakes' tidal prism, mean water level and circulation (as described by salinity) were assessed and compared to the baseline "Existing Entrance' case. This behaviour was modelled over a period of 13 months – the first month being required to achieve overall dynamic equilibrium. The fixed bathymetry used in these simulations was taken from the results of the 100-years ARI morphological runs described above and described in Section 6.5. The use of this fixed bed bathymetry means that these runs are somewhat unrealistic in that it is highly improbable that the entrance would remain in a post flood scoured condition for 13 months, and as such these simulations represent a "best case" scenario.

Table 2.2 presents a summary of the morphological simulations specified originally in the Brief.

Table 2-2 Summary of Water Quality Model Runs for Training Works

Sea Level	Simulation	Post Flood Entrance Bathymetry Used					
		Existing	Single Training Wall	Twin Training Wall Configuration 1 150m Width	Twin Training Wall Configuration 2 200m Width	Twin Training Wall Configuration 3 100m Width	Existing – 6 Weeks After Flood Peak
Current	100-Years ARI Flood	✓	✓	✓	✓	✓	✓

2.5 Entrance Management Investigations

The emphasis for this part of the investigation was on the local morphological response to different dredging and nourishment sand placement strategies. To achieve this, the model system must be capable of quantitatively describing the circulation and exchange of sediment between the estuarine channels (flood tide delta), the adjacent beaches and the nearshore zone.

The model system may be used to improve understanding of factors affecting sediment dynamics in the entrance area and allow Council to examine the following:-

- The effects of various dredging operations, that is, dredging a sump adjacent to The Entrance Bridge, Dredging the Terilbah Channel, the main channel and the use of a survey mark and a sand accumulation threshold to initiate dredging.
- The use of the dredged sand for beach nourishment at The Entrance and North Entrance beaches up to Curtis Parade.
- Beach scraping adjacent to Hutton Road and Curtis Parade.
- The impact of flood events and time for recovery; the effects on adjacent beaches;
- the fate of dredge spoil placed on North Entrance Beach;
- movement of the “null-point” with wave/seasonal conditions (SMEC, 2011, §2.2).
- does placement of dredge spoil at Karagi Point (as opposed to further north) increase the rate of shoaling of the entrance channels? If so, what limits should be placed on disposal in this area to maximize the efficiency of the dredging program?
- The effectiveness of sand nourishment on the shoreline inside the channel adjacent to Karagi Park.
- The effectiveness of beach nourishment inside the channel adjacent to the seawall at Memorial Park. (proposed town beach)
- Longevity and logistics of beach nourishment at The Entrance Beach
- Consideration of appropriate sand placement profiles for beach nourishment in a bid to prolong the effective protection.
- Rationalisation of dredging to minimise plant use and maximize effectiveness over the longer term using benefit versus cost considerations. Sediment sources can be introduced to simulate dredge spoil discharge.

It was anticipated that these questions would be addressed by simulation periods of the order of one year where appropriate.

The model is capable of calculating net sediment transport into or out of the entrance, which will then provide a long-term dredging cost for cost assessment calculations. These calculations were based on a prepared scenario that included all of the important processes for a period of about two months. Time-series of sediment fluxes across a set of transects

Processes that influence the dynamic condition of the entrance are: -

- ocean wave processes
- sediment availability
- tides with evolving bed
- evolution of the entrance under catchment events, and

- the net inflow effect due to evaporation. (This latter process, although small, is equivalent to a defined constant inflow. With a surface area of 77km^2 and approximately 3mm/day of evaporation, this gives a net inflow (when open) of around 230,000m^3/day. This evaporation rate has been included in the flushing analyses.

Cardno also took into account the influence of wave stirring (and associated sediment suspension) and the state of the tide. In a lagoon system such as Tuggerah Lakes, the flood tide occurs when tide levels are above mean lake levels, which is when wave penetration is maximum (depth is greatest and waves are travelling with the flow). On the ebb tide, water levels are below mean lake levels and minimum wave penetration occurs (depth is smallest and waves are travelling against the flow). The adopted coupled model system differentiates between top and bottom of tide propagation for wave stirring and sediment transport.

3 MODEL SYSTEMS

3.1 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.

This study has adopted 2D transport-dispersion 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 has been found to be realistic for Brisbane Water and Lake Illawarra.

Modelling of the lake system and forcing 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 data set, especially of lake/seabed form, which changes constantly.

3.2 Delft3D

Cardno have used the Delft3D model system to undertake much of the numerical modelling required for this overall investigation. Delft3D is a world leading hydrodynamic, sediment transport and water quality modelling system developed by Deltares (formally Delft Hydraulics) in the Netherlands. Delft3D has been applied in major coastal and ocean investigations and engineering studies worldwide. In the field of sediment transport and morphological modelling, Delft3D is arguably the world’s leading model system. In the last 10-years Delft3D has led modelling innovations such as coupled online wave and hydrodynamic forcing, and also 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 wind, pressure, tide and wave forcing, 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 ideally to the curvilinear grid and domain decomposition systems, which have enabled a detailed, yet efficient description of the flow structure in the estuary.

The Delft3D modelling system has been applied to morphological investigations at many international locations, as well as within Australia by Cardno, other consultants and universities. It is comprised of several modules that provide the facility to undertake a range of studies. 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.

3.2.1 Hydrodynamic Numerical Scheme

The Delft3D FLOW module is based on the robust numerical finite-difference scheme developed by G. S. Stelling (1984) of the Delft Technical University in The Netherlands. Since its inception the Stelling Scheme has undergone considerable development and review by Stelling and others. Other programs utilising the Stelling scheme include the floodplain applications of Delft-FLS (WL|Delft).

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 in a rather simple way
- 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. In 3D mode, the model uses the σ coordinate system first introduced by N Phillips in 1957 for atmospheric models. The σ coordinate system is a variable layer-thickness modelling system, meaning that over the entire computational area, irrespective of the local water depth, the number of layers is constant. As a result a smooth representation of the bathymetry is obtained. Also, as opposed to fixed vertical grid size 3D models, the full definition of the 3D layering system is maintained into the shallow waters and until the computational point is dried.

From a user point of view, the construction of a 3D model from a 2D model using the σ coordinate system in Delft3D is simple and takes a matter of seconds. The model is set-up as a 2D model and the user enters the number of layers are required and the percentage of the depth for each layer. It is most common to define more resolution at the surface and at the bed where the largest vertical gradients occur. Boundary conditions can also be adjusted from depth averaged to specific discharges and concentrations per layer also.

Horizontal solution is undertaken using the Alternating Direction Implicit (ADI) method of Leendertse for shallow water equations. In the vertical direction (in 3D mode) a fully implicit time integration method is also applied. Vertical turbulence closure in Delft3D is based on the eddy viscosity concept. Rainfall and evaporation rates can be included.

3.3 Standard and Special Features

Delft3D has several pre- and post-processing tools. They include: -

- RGF-Grid – Pre-processing of grid schematisation. Includes linkage with ArcView GIS.
- Quickin – Translation of bathymetric details to the model grid. Includes linkage with ArcView GIS.

- Quickplot – Powerful post-processing and visualisation program developed in MATLAB. Visualisation of model results as spatial colour, contour and vector maps; graphing of horizontal and vertical profiles; and generation of AVI or ASCII results. It can be directly linked to MATLAB to expand post processing capabilities user developed scripts.
- DIDO – An innovative interactive grid editor and coupling tool for Delft 3D hydrodynamic simulations to Delft3D-WAQ. DIDO has the ability to aggregate hydrodynamic grid results both horizontally and vertically with horizontal aggregation generally being in areas not important to the Water Quality analysis, thus allowing considerable reduction in computational effort. It is not essential for WAQ/ECO modelling.
- Delft-3D to ArcView Translator - Tool to import results directly into Arc-View for detailed interrogation of results and enhanced visual display against GIS data such as aerial photography, cadastral and land boundaries etc.

3.3.1 Ability to Incorporate a Varying Mesh Size

Bathymetric discretisation and modelling can be undertaken in Delft3D on a rectilinear or curvilinear grid, and include domain decomposition (see Section 3.6). The Delft3D model is specifically written and most widely used 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 estuary and adjacent interconnecting channels, with less resolution in the sea 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 currents.

Additional refinement of the grid can be applied at any time during the study. The RGFGrid program, used to setup the Delft3D grid, offers a number of features to provide additional computational cell discretisation in an area of interest.

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 is very robust and stable and can simulate steep hydraulic gradients such as those which occur during entrance opening.

3.4 Wetting and Drying of Intertidal Areas

Many estuaries and embayments contain shallow intertidal areas; consequently Delft3D incorporates a robust and efficient 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 propose and use in practice 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 the characteristics of the intertidal effects 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.

3.5 Conservation of Mass

Problems with conservation of mass, such as a 'leaking mesh', do not occur within the Delft3D system. However, 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:-

- Inappropriately 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.

3.5.1 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. 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). This approach has been followed for this study.

3.6 Domain Decomposition

Delft3D provides the facility to adopt a modelling approach known as 'domain decomposition'. Domain decomposition is a 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 grid). In the case of vertical grid refinement one domain, for example, uses ten vertical layers and another domain five layers, or a single layer (depth-averaged).

Domain decomposition is widely 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.

3.7 Sediment Transport Processes

The module applied to the sediment transport analyses is the Online Sediment Module with the van Rijn 2004 sediment transport module. 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 employ 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.

3.8 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 Technical University 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.

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 and to a number of nearshore locations to the south and north of The Entrance. This latter wave data was needed for longshore sediment transport analyses required as part of this investigation.

4 DATA

A range of data items were required to set up, calibrate and operate the models applied to this investigation. They are described below.

4.1 Bathymetric Data

Following/during the inception meeting on 13 December 2011, Cardno have received the following data from OEH.

- 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 nearshore 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.

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 DEM vertical datum was AHD.

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). These data are presented in Appendix A as time-series plots.

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.

These data are shown plotted in Appendices A and B. Inspection of that data shows that there is rarely a wind-free period. 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 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, 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.

Appendix B presents time-series plots of rainfall at Tuggerah, Sydney airport wind speed and water level records at Toukley and Long Jetty.

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. 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.

Figure 4.1 shows the locations of the Tuggerah Lakes recording sites for a range of the parameters described above.

Appendix C presents selected flood hydrograph information to which reference is made later in this report.

Appendix D describes the physical processes relevant to this study.

5 ENTRANCE CHARACTERISTICS

The entrance to Tuggerah Lake and the lake system are described well in PWD (1987), and the following is based on that document.

The Tuggerah Lakes system is located in the New South Wales Central Coast region approximately 80km north of Sydney. These lakes comprise the three inter-connected lakes of Tuggerah, Munmorah and Budgewoi. The lakes have a catchment area of approximately 790km^2, of which approximately 10% is lake area.

Recent increases in development pressures have resulted in a demand to develop areas close to the lakes with water views and cooling breezes. However, these are the areas most likely to be affected by flooding from the lakes. It is estimated that 3700 lots may be affected by the 1% AEP flood level that was adopted at the time of construction of the Munmorah Power Station.

Tuggerah Lake is the largest of the three lakes and is connected to Budgewoi Lake and Lake Munmorah by narrow channels, both with road bridge crossings. The Wyong River and Ourimbah Creek catchments are the largest contributing to the lake system, and drain into the southern end of Tuggerah Lake. The lake system is connected to the ocean via a single tidal channel through the barrier dune at the southern end of Tuggerah Lake. The channel generally remains open, but closes occasionally due to littoral processes unless it is maintained open by dredging programs that have been undertaken since 1993.

Tuggerah Beach extends 9km from Pelican Point to The Entrance (**Figure 1.1**). The tidal channel leading to the Tuggerah Lakes system lies immediately to the north of The Entrance adjacent to a minor rock outcrop that has some control on entrance scour depths. The three interconnected lakes in the system and their water surface areas are:-

- Tuggerah Lake – 58km^2
- Lake Budgewoi – 11km^2
- Lake Munmorah – 8km^2

The tidal range in Tuggerah Lake varies with the condition of the entrance channel and spring-neap cycles, but is typically in the order of 20mm. Budgewoi and Munmorah Lakes are virtually non-tidal. Because of the asymmetry of tidal flows in the entrance channel, the mean water level in Tuggerah Lake is tidally super-elevated 0.2m above mean sea level, but varies over the spring-neap cycle and oceanographic water level changes such as coastal trapped waves. The total area of the catchments draining to the lake system is 713km^2.

5.1 The Tidal Inlet

The inlet to Tuggerah Lake takes the form of a delta extending 2.6km from the beach line to the lake. It may be considered in two regions. They are:-

The downstream 800m from the beach to the road bridge is the entrance area and consists of unstabilised and frequently mobile sand shoals with one or more tidal channels and islets. The upstream 1.8km from the bridge to the lake proper takes the form of a fan delta, the sand in which is largely stabilised by seagrass growth.

The delta margin at the lake is not as established and in an aerial photograph shows signs of bed features formed by wave action. This is particularly so on the north-west sector which faces the longer fetches of the lake. The western sector shows many fewer wave derived features and those that are present have an orientation consistent with waves approaching from the west-north-west.

With the exception of the two islands, the upstream delta area is below lake water level. It is dissected by a number of natural channels and two narrow dredged channels, one to the north-east and one to the south-west. These channels do not maintain permanent forms.

5.2 The Entrance

5.2.1 General

The Entrance proper from the bridge to the beach is a region 800m long with a maximum width of 350m. It consists of mobile entrance shoals with one principal channel and as many as three minor channels. On the southern shore, the mobile area extends some 200m upstream of the bridge while on the northern shore it stops short of the bridge.

The downstream section of the northern shoreline comprises the sand spit known as Karagi Point. This region is susceptible to erosion during flood events.

5.2.2 Entrance Hydraulics

The entrance to Tuggerah Lakes acts as a channel with a tidal range ratio approaching zero. The tidal range in the lake is in the order of 20mm based on tidal prism/surface area calculations. Two field measurements were made by MHL on 8 October 1975 and 26 May 1976. Based on that data, for an ocean tidal range of 1.6m, the tidal prism volume was 106m^3. This is very small, but is consistent with a 5mm tide range and an approximate surface area of 35km^2 for Tuggerah Lake. This study will use a calibrated model to make other estimates, based on the most recent estuarine and ocean area survey.

The 1975 data showed the short peaked flood tide discharge and extended ebb discharge curves typical of long shallow entrances and small tidal range ratios. The super-elevation of the lake water surface was 0.21m above 0m AHD.

5.2.3 Entrance Channel Stability

These comments are based on the 1975 MHL tidal gauging exercise.

5.2.4 Peak Tidal Velocities

The 1975 data gave peak tidal velocities of 2m/s on both the ebb and flood tides. Again there was insufficient data to observe variations of the type suggested by Escoffier (1977). However, given that he suggests a critical velocity of the order of 3ft/s (0.9m/s), the data may indicate that in 1975, the channel was attempting to scour towards a stable cross section which would be of the order of twice that measured. A far more likely explanation is that although the velocities were above the critical speed, a large sediment in-feed in the entrance prohibited the full development of the section.

6 MODEL SETUP

A coupled hydrodynamic/morphological and wave modelling system based on Delft3D and SWAN has been prepared.

The hydrodynamic model includes all three lakes and extends seaward to depths in the order of 80m. This set-up ensures that the tidal prism is realistic and that all water level slope changes, wave driven currents, wind effects and morphological changes related to the entrance area will occur within the modelled region. In order to describe future entrance/seabed changes, a fine grid area that extends from the Entrance Bridge, describes the island and channel features (at the times of the surveys) and offshore to about 12m deep was set-up, with coarser grid areas adopted to describe the main lake areas and offshore. Initially this fine grid was set with a nominal grid size of 5m, but that set-up proved to be far too slow for realistic model simulations. Hence this grid area was de-refined to a nominal size of 8.3m, still fitting to the surrounding coarser grid areas of approximately 25m grid size – a factor of 3:1.

The model was set-up using the domain decomposition system so that all grids were solved dynamically at the same time-step and no boundary transfers were required. This procedure also optimises computer time. Figure 6.1a presents a plan of the hydrodynamic model grid layout. The fine grid area is shown in red, but note that it de-refines from 8.3m seaward of about the 12m depth to datum AHD. A more 'zoomed–in' image of this set-up in the region of The Entrance area can be seen in Figure 6.1b.

Figure 6.2 describes a similar nested grid system established for the SWAN wave model, with a 10m grid resolution in The Entrance. However, this model only extends part way into The Entrance because swell wave penetration into Tuggerah Lake will not be far - reduced by rocky reefs and shoals in the near shore area; as well as the formation of the entrance itself. However, water levels in the lake will be affected by shoreward wave propagation from time-to-time (radiation stress caused set-up in the lakes) and this coupled model layout provides for this process in a physically realistic and seamless manner. Sediment transport into The Entrance, especially after a flood has transported sand from the entrance area shoals into the sea, is affected by wave stirring, as well as the wave driven currents causing onshore and longshore sediment transport towards the entrance. Hence, a reliable description of wave processes is required in the entrance area.

The rock shelf that lies beneath some areas of the entrance has been included as a non-erodible, sand covered (at least initially) bar with rock set at levels according to rock contour data available in Patterson Britton (1988). There is no other reliable data describing it. The presence of this rock shelf will reduce the potential scour depth during floods and may cause the required entrance width between potential training walls to be greater than would otherwise be the case.

These model simulations were undertaken in a sequential leap-frog manner in which offshore wave conditions were updated every hour (a SWAN simulation that applies the most recent wave parameters, water levels and currents, as well as seabed level changes when morphological change is included) and then a period of hydrodynamic time-steps to model the next one hour. The hydrodynamic model uses the most recent wave parameters as the solution develops in changing tide, wind and catchment inflows. Rainfall and evaporation were applied also, according to the available timed and dated information.

Model calibration is required to confirm that the model is operating in a physically realistic manner and hence to provide confidence in the outcomes. It was not possible to calibrate the morphological modelling processes, or the longshore transport processes directly as no suitable data was available. In those cases the model outcomes for the existing bathymetry were examined to ensure that the outcomes were physically realistic.

This task was undertaken in three stages. They were:-

- Dry weather (non-flood) event
- Flood event of June 2007
- Recorded salinity data of 1996 (MHL, 1997)

The response of the lake system to tidal, wind, wave and flooding processes depends significantly on the entrance configuration, which varies continuously under natural and human forcing. Hence it was not possible to undertake these calibrations in the most rigorous sense; there being no fully contemporaneous data set.

6.1 Model Calibration – Dry Weather Water Levels

The process adopted in this calibration task is described in the sequence below:-

1. Select a period for which antecedent rainfall was low or zero, and preferably, during which low or zero wind speeds occurred. Such a calibration case, with the model driven by tides alone would allow bed friction calibration. A time period close to the 2011 entrance survey would be best also because the form of the entrance is likely to have a significant effect on entrance hydrodynamics. MHL344 (1975) shows that current speeds near the spit in the entrance area may be in the order of 1.5m/s during spring tides and sand will be very mobile there. It was not possible to fulfil all of these selection criteria because there is virtually no period of absolute calm over several days – a simulation over this period is required to demonstrate pumping-up and pumping-down of the lake level.
2. Simulation of the period from 10 to 24 January 2011 was undertaken applying a predicted tide (Fort Denison constants, >60, provided by NTC), with a Chezy bed friction factor of 45 (other friction factors were tested). No wind and wind cases were investigated, as well as applying the recorded Middle Harbour tidal water levels. **Figure 6.3** presents these results. They show that the lake system responds to the spring neap cycles by pumping up and down. The results show a bigger tidal signal than observed at the time. No wave forcing was included.
3. **Figure 6.4** shows that changing the wind friction factor had little influence on the results.
4. **Figure 6.5** shows that the predicted Sydney tide was basically 0.1m higher than the recorded Middle Harbour water levels at the time (possibly due to CTW's and barometric effects). At this stage it was not clear whether using the predicted or measured tide was the better course.

1. For **Figure 6.6**, bed friction has been changed to Manning's n (0.035 in the Lake and 0.04 through the entrance) and wave forcing has been included, together with the recorded tide and winds. This outcome is believed to provide the best (calibrated) result. The small remaining discrepancies between the calibrated model and the recorded results are most likely the result of small differences between the shape of the entrance during the recorded period and the modelled entrance shape (obtained from received LiDAR). Some uncertainty in the catchment flows, wave data at the site and wind input also affects the outcome. Moreover, the model itself cannot be considered to provide a perfect description of the hydrodynamics and morphological processes. All of these may contribute to the over-prediction of water level on and from 17 January. However, the trends are in good agreement.

The model was run for subsequent simulations with a map of Chezy roughness parameters equivalent to the Manning's n values, using a roughness conversion relationship that depends upon water depth (Deltares, 2011 and Henderson, 1966)). Experience has shown that applying the Chezy parameter leads to better morphological response because it does not 'attract flow' inappropriately and then lead to excessive vertical scour.

6.2 Flooding Data

It was necessary to verify the model, as best can be, by also undertaking a flood simulation. Cardno have referred to three reports in this matter. Wyong Council officers advised the inception meeting attendees that they believed that the Lawson and Treloar (1994) flood report was realistic because they had compared the results with recorded water levels for the significant rainfall/runoff event of June 2007. Department of Environment and Climate Change and Water (Brennan et al, 2011), (their *Figure 94*), shows that peak flood level in this event was about 1.6m AHD. Flood levels modelled by DECCW for this period were too low.

OEH (2011), see their *Figure 3*, provides catchment flow time-series data for the period from 1980 to 2010. Therein, peak flow to Tuggerah Lake for June 2007 is only about 320m^3/s.

Lawson and Treloar (1994), see their *Figure 7*, provides modelled catchment flow for the February 1992 flood. Combining the Wyong River and Ourimbah Creek flows, peak inflow is about 1500m^3/s – much bigger than the result shown in OEH's *Figure 3,* referenced above. Hence a likely contributing reason why the modelled flood level of OEH *Figure 94* was too low is that catchment flows were too low. Cardno have used *Figures 7* and *3* comparisons to modify the OEH catchment flows for June 2007, which is the closest-in-time flood to the 2011 survey. This procedure maintained the hydrograph shapes and inflow distribution around the lakes. These catchment and flood information figures are presented in **Appendix C** in the sequence adopted above.

That event was adopted for 'flood and morphological' verification using tides, waves, winds and fresh water inflows and comparing modelled and recorded lake water levels – which would have been affected to some extent by entrance scour during that event. This task also required an extended simulation to describe, as a first trial, the post-flood onshore sand transport at The Entrance. Model morphological parameters applied to Avoca and Wamberal lagoons, where entrance break-out calibration data was available, were adopted in the first instance.

6.3 Flood Simulation

The model system of the lakes, entrance and offshore area was run using recorded water levels from Middle Harbour, recorded wave data from Long Reef (transferred to The Entrance area) and estimated/modified runoff hydrographs distributed throughout the lakes. The shapes and phasing of these hydrographs were based on the work of Brennan et al (2011), but the actual discharges were modified according to Lawson and Treloar (1996) – increased by a factor of 5.

The model was run as a flow-wave-flow system so that the hydrodynamic and wave modelling phases used output from the other to describe the dynamically changing conditions.

Wave model time-steps were at intervals of 1 hour. Radiation stress and wave map files were then provided to the hydrodynamic model, which applied that data for the next hour of hydrodynamic modelling. The seabed was then modified and the new bed levels, water levels and current data provided to the wave model for the next hour. This procedure was repeated throughout the simulation.

Previous morphological modelling of Avoca and Wamberal Lagoons provided calibrated entrance-erosion parameters as an initial set of conditions. One of these was the lateral erosion parameter which was set at 1. This means that where a known bed level change occurs in a wet cell over one time-step, then the same level change (the increment) occurs in a neighbouring dry cell. Active cells change as water level changes and bed levels change.

Rock levels determined by PWD (Patterson Britton & Partners, 1988) were included in the morphological set-up and a sand characteristic particle size of D_{50} = 0.35mm was adopted; based on the available data. No erosion was allowed below those rock levels, but sedimentation could occur on them. Flood/morphological calibration included a period of about four days prior to the actual flood commencing in order for the seabed near the entrance to undergo some 'shake-down' to achieve dynamic equilibrium between the lake/seabed and the applied boundary conditions in order to remove lake/seabed changes that are not part of the flood event. Hence the period from 3 to 7 June was excluded from the flood caused erosion/sedimentation analysis result.

6.4 Flood Verification Results

Figures 6.7 to 6.8 present a range of results describing the outcomes from a simulation period of two months – first month shown on Figure 6.7.

There has been a loss of about 100m from Karagi Point with erosion of about 3m vertically in the entrance and an offshore bar of ≈ 2.5m height formed. The erosion channel is more east-west than the normal tidal channel that is often NNE – SSW, see Figure 1.1 - inset.

Figure 6.7 shows that modelled peak water level during the flood is realistic, as is the small post-flood tidal range at Long Jetty. Only computed daily run-off rates were available and were assigned to 1200 hours. Noting that the actual entrance form is not known for early June 2007 and the runoff hydrographs have significant uncertainty associated with them, the agreement is very good.

Figure 6.8 shows also that offshore wave conditions were high during this flood event and that there were some periods of higher waves after the main flood event. It is possible that these wave conditions would cause onshore transport and an understanding of this characteristic at The Entrance is required as part of training wall layout for concept design. That is, the intention would be to place proposed training walls where post-flood event onshore-moving sand would not be transported into the entrance, but rather onto the beaches to the north and south where it would accumulate. Unless sand is moved northward naturally from North Entrance Beach by wave action, this process would gradually widen the beach there. In order to maintain this function of 'ratchetting-out' entrance sand, entrance management would require the sand to be removed mechanically from time-to-time from North Entrance Beach to prevent excessive 'fillet' development at the southern end of North Entrance Beach and eventual sand ingress to the entrance from there.

Figure 6.9 shows that flood erosion has caused significant changes to the shoaled areas within The Entrance – period 7 to 13 June 2007. The time-series results show also that this event persisted for a period of about one month with the lake level staying at or above 0.5m AHD for about two weeks – 9 to 23 June, modelled and measured data. More entrance erosion occurred during a period of neap tides after 23 June, see Figure 6.9. Figures 6.9 and 6.9 describe the post-breakout bed level changes and the 1 month post-flood bed level changes, respectively. The offshore bar that was formed by the flood event (Figure 6.10) is clearly moving back onshore, but with a northward direction (Figure 6.11). This process changes the tidal channel to cause flow more northward than the east-west channel scoured by the flood. This is consistent with the commonly observed entrance form.

Figure 6.12 shows that adopting a finer sand of D_{50} = 0.25mm leads to a lower peak flood level by about 7cm. This is consistent with more erosion of the entrance that would occur with smaller sand particles. Although this peak flood level is slightly lower, than the D_{50}=0.35mm result, and hence closer to the Lawson and Treloar (1994) 100-years ARI flood level based on 1D modelling, that is not a reason to adopt the 0.25mm particle size for the investigations – the entrance bathymetry prior to flooding and the actual inflow hydrographs will have a bigger effect. A D_{50} of 0.35mm was used for subsequent investigations.

6.5 Flood Simulation Results

Following model calibration, a range of morphological simulations was undertaken in accordance with Table 2.1. Figure 6.13 describes the training wall layouts agreed with OEH and WSC. They are based on the general observation that floods in Tuggerah Lakes may scour channels 100 to 200m wide – though not actually measured. One principle of training walls design is that they should not increase flood levels; a second could be that they be sufficiently close to cause self-scouring. However, in practice there is conflict between these two requirements and the flood risk has been taken as the main design requirement. Hence, training wall options were originally based on northern training walls placed at nominal distances of 150 and 200m north of the existing seawall on the southern bank of the entrance. After some initial modelling it was also considered prudent to investigate a 100m wide training wall option.

These cases are shown on Figure 6.13. The southern wall would butt-up to the existing seawall. The single training wall case has been adopted to be 150m north of the southern seawall – a single southern training was not expected to be useful.

The northern training walls have significant lake-side turn-backs that could be constructed to prevent a break-through of the Karagi Point Spit in a severe storm or flood. An alternative could be to ensure a sufficient store of sand to prevent this from happening. Figure 6.14 shows that during a rare, severe major ocean storm (ESE, H_s=10m, T_p=13 seconds, storm tide 1.2m AHD), wave set-up would be sufficient to overtop the current level of southern Karagi Point. Overtopping waves could erode the low crest of this dune, a process observed on barrier islands along the east coast of the USA during severe hurricanes. Note that the wave set-up level shown in the lakes for this case is for a steady state wave simulation that implicitly provides sufficient time for the wave processes to 'fill the lake'. In reality the influence of wave forcing would be less in the lakes because the duration of the peak wave conditions would be insufficient for this full potential water level increase to occur. Nevertheless, as shown by model calibration and the May 1974 flood (with little rainfall, Lawson and Treloar, 1994), ocean waves do raise the lake level to some extent. Following initial investigations, a 100m wide, two training wall case was investigated also.

Figure 6.15 presents seabed and rock profile information for the three northern training walls.

The first stage was to set up the model scenarios using the 48-hours rainfall event hydrographs of Lawson and Treloar (1994). It was necessary to extrapolate those results to prepare the 1-year ARI case using extremal plotting and then to digitize them all to provide input for the flood modelling. Note that the Lawson and Treloar (1994) hydrographs are total catchment flows. These hydrograph flows were distributed amongst the twenty-four catchment discharge locations of Brennan et al (2011) on the basis of average catchment flow ratios in that report. These locations are shown on Figure 4.1.

In all simulations, the ocean boundary was formed from the recorded Middle Harbour tides and waves as well as winds for the severe flood of June 2007. Peak storm H_s is about 7m, although peaking some hours before the peak of the flood. Such a severe storm (less than 100-years ARI ocean storm) could occur with the flood events as both are likely to be due to the same meteorological phenomenon (east coast lows).

No dredging of the entrance was included in these test scenarios. Some entrance dredging was undertaken during the construction of the northern training wall at Lake Illawarra, with the entrance closed to provide tranquil water during those works. Dredging of The Entrance is complicated by the presence of the rock sill and extensive sea grass beds west of The Entrance Bridge. Without a complete connection between the sea and the lake, dredging may have limited effectiveness.

6.5.1 Flood Levels

Figures 6.16a to d show the water level time-series for the sixteen flood simulations presented in Table 2.1. For the 100-years ARI flood simulation (Figure 6.16a) peak levels are about 2.3m AHD compared with 2.2m AHD (about) presented in Lawson and Treloar (1994) for the 1% AEP (100-years ARI) flood event. Given that the earlier studies were based on a 1D model and a different entrance form, the agreement between the results is remarkably similar and the current results provide a reliable basis for assessing the differences between the training wall simulation results in terms of flood level effects. Note also that the results are quite smooth, providing confidence that the model system is working reliably, especially with morphological change included in the processes.

Furthermore **Figure 6.16a** indicates that the single training wall, 150m and 200m width double-training wall options do not significantly affect the 100-years ARI flood level within the lake. However, the 100m wide training wall option increases the peak flood level by 0.08m from the modelled existing entrance condition, but more significantly, causes lake water levels to remain elevated for several days longer as the narrower entrance results in slower draining of the lake system back to normal pre-flood levels. Seventy-two hours after the peak flood level, this option still has lake level 0.4m higher than the existing entrance case does. For this reason alone the 100m wide training wall option should not be considered as a viable alternative. It would also be affected more than other options by the rock sill at the entrance.

Furthermore, **Figure 6.16b** shows similar results for the 20-years ARI flood events. Whilst the peak flood level of the 100m width training wall option is not significantly increased as it was for the 100-years ARI simulation, the persistence of elevated lake levels can been seen clearly on this figure. **Figure 6.16c** indicates that, for the 1-year ARI flood, none of the training wall layouts significantly affects the peak flood level within the lake, or the duration of elevated lake levels. **Figure 6.16d** plots the results for the 2100 climate change scenarios, wherein ocean levels have been increased by 0.9m. These results show a greater pre and post flood event tidal range – which occurs as a result of the increased tidal prism that elevated ocean water levels bring. The results also show that none of modelled training wall configurations resulted in increased flood levels.

6.5.2 Flood Induced Bathymetric Changes

In the first instance it was necessary to examine the outcomes from the Existing entrance bathymetry in order to provide a basis for comparison with the training wall options in terms of bathymetric changes. These base results are presented in **Figures 6.17** to **6.21**. **Figure 6.18** shows scouring within the entrance and a deep channel seaward of the entrance, with two main shoals further seaward. The bigger shoal is about 3m above the seabed and scour is about 4m. **Figure 6.20** describes the further bed changes between 12 and 17 June and shows that additional erosion/deposition occurred following the major flood event as lake level reduced, but stayed elevated for an extended period.

Figures 6.22 to **6.26** present similar results for the single northern training wall case. **Figure 6.23** shows that the main channel has undergone significant scouring with a deep hole at the outer end of the training wall on its southern side.

The shape of the scour channel and shoal offshore to the east-northeast are different from those developed for the post-flood Existing entrance, see **Figure 6.18**. There has been much less erosion of Karagi Point, both at the southern end and from the trunk. The scour channel is also further south. By 17 June, see **Figure 6.25**, much of this channel has been in-filled and the offshore shoal to the east-northeast is moving onshore. Compared with **Figure 6.20**, there is much less shoaling on the southern side of the entrance.

Figures 6.27 to **6.31** present results for the two training wall case, where spacing between the walls (edge to edge at 0m AHD) is 150m. The northern wall is located at the same location as the single training wall. The outcome is very similar to the single training wall case, except that shoal formation to the south is far less.

On the other hand, Figure 6.30 shows some sand accumulation on the southern side of the southern training wall, when compared with Figure 6.25.

Compared with the Existing case, there is less erosion of Karagi Point, partly caused by the presence of the turn-back wall along part of the southern end of Karagi Point. Note that, comparing Figure 6.30 with Figures 6.25 and 6.20, there is a small accumulation of sand on the southern side of the southern training wall. It is likely that flooding and entrance sediment transport processes, as well as longshore transport would gradually build a wider beach against this 'groyne', though there is limited sand on this beach. In the post-flood entrance, the tidal channel is forced to maintain a more definite east-west alignment than shown in the natural (Existing) case – compare Figures 6.31 and 6.21.

Figures 6.32 to 6.36 present the same series of model results from the case where the two training walls are 200m apart. Figure 6.33 shows that there would be some loss of sand at Karagi Point and that the scoured channel between the walls is more central that it was and more east-west in alignment than it was for the 150m wide channel case. The main flood-formed shoal lies to the east of the northern training wall and is quite elongated. Figure 6.35 shows that following the main flood period there is further erosion between the training walls, but close to the northern training wall, with some infilling of the scoured central channel. The main offshore shoal has continued to build but more slowly; and also showing a tendency to move landward. Again, the southern training wall acts as a groyne.

Figures 6.37 to 6.41 present the model results from the case where the two training walls are 100m apart. Figure 6.37 shows the location of the two training walls in relation to the underlying rock layers in the vicinity of the lake entrance, with the bulk of this rock situated near the bed surface in the training wall channel. Figure 6.38 indicates that the presence of this rock would limit the amount of scour for much of the training wall channel, with significant erosion only occurring around Karagi Point and towards the seaward end of the northern training wall. This restriction on conveyance explains the higher simulated 100-years ARI flood level in the lake, presented in Section 6.5.1.

Furthermore, results of the morphological modelling indicate that the training wall option would not be significantly self-scouring. Figure 6.50 shows the morphological changes between 17 June and 3 August for the training wall option spaced 150m apart. They show that in the 6 weeks after the flooding event has subsided, some sedimentation has occurred in the channel. This process would be likely to continue at a reducing rate until the next flooding event. As such there is likely to be a need for maintenance dredging even if training walls were implemented. Nevertheless, the volume of post-flood sand that returned to the entrance would be less than for the existing case.

6.6 Wave Penetration

An assessment of the likely effects of the training walls in changing wave penetration to The Entrance following flood abatement was based on wave conditions modelled near MHWS on 17 June. The results are presented in Figures 6.42 (Existing) to 6.46 in terms of wave heights. Figures 6.47 to 6.50 present the results in terms of differences in wave height.

Generally, wave penetration for the training wall cases is lower than it is for the existing case, because the training walls limit the scour width of the entrance and hence wave penetration. The 200m wide training wall option results in wave penetration very similar to the existing case – but slightly lower (in the order of 0.1m) because south-easterly wave energy is blocked by the southern training wall. Note that the breaking wave index used in the SWAN model was 0.8.

6.7 Lake Flushing

One possible outcome of entrance training walls, and possibly more frequent wider entrances, may be improved flushing of the lake system, principally Tuggerah Lake, because there are only narrow connections with the other lakes. Hence the flood simulation results, in terms of the 100-years ARI post-flood changed entrance bathymetric conditions, were assessed in terms of possible 'flushing capacity' change. Flushing is often used as a term to describe water quality. That is, a water body that is 'well flushed' should have better water quality; but this statement ignores the effects of contaminant loads. However, flushing is difficult to quantify in specific circumstances and water quality issues are addressed better by considering changes in a marker substance. In this case the model system has been used to investigate flushing (potential water quality improvement) in terms of salinity as it may vary over a period of one year between the Existing case, (itself run as a post-100-years ARI flood model) and the post-flood proposed training wall entrance layouts. These simulations included tidal, wind and catchment inflow forcing and were based mainly on 2009 data. Evaporation and rainfall were included.

6.7.1 Transport-Dispersion Verification

The most reliable lake-wide salinity data is presented in MHL (1997). However, the salinity distribution presented therein may not match the model set up for more recent entrance surveys or different catchment runoff. The data presented in MHL (1997) was used to establish a varying lake-wide initial distribution of salinity. The first month of simulation was used only to establish a dynamic equilibrium condition.

In the first instance the model was set-up for a 13 months simulation of the Existing case using catchment run-off, winds and tides for 2009 – 2D model. No morphological changes were included. The MHL (1997) report showed also that, apart from periods of significant catchment runoff, there was little vertical gradient in salinity. Hence 2D modelling is suitable for these long simulations.

The results of that initial simulation showed that modelled salinity within the lakes was too low, see Figure 6.51. Other simulations showed that catchment inflows had a significant effect, but that dispersion coefficient did not – within the physically realistic range. For these generally non-flood catchment flows no modification of the Brennan et al (2011) flows was made. A physical reason was sought to explain why lake salinity levels became too low, even though only comparative results between the entrance cases were needed.

An examination of the total annual catchment inflows for 1996 and 2009 showed that those volumes were similar, however, the annual mean lake level was about 0.1m lower in 1996 than in 2009. That is, the entrance was more open in 1996; allowing a greater salt influx from tidal exchange at that time. Hence catchment flows were not likely to be the cause, but rather the form of the entrance and degree of conveyance was the constraint on salt influx. A range of tests was conducted in which the entrance was widened in order to achieve the lower 1996 mean lake level. Figure 6.51 shows the changes in modelled salinity in the lake when the entrance is widened to allow more tidal exchange. The intention here was to demonstrate this effect only. The mean lake level was lower in this simulation, but not as low as recorded in 1996.

Figure 6.52 shows the difference in salinity that is achieved when a measured tide is used instead of a predicted tide. This recorded tide includes processes such as coastal trapped waves. Ocean water influx to the lakes is affected by longer period rises and falls in MSL that are not affected by the narrow entrance, which attenuates water level variations of tidal frequency, but less so for longer period oceanic water level variations such as coastal trapped waves and barometric effects. The difference is in the order of 1ppt over the year.

The outcome of this analysis has shown that realistic variations in lake-wide salinity could be achieved when there is contemporaneous entrance survey, and recorded run-off data and 'offshore' water level data. Nevertheless, the model will be able to describe the differences between the trained wall and Existing cases.

6.7.2 Transport-Dispersion Results

Figure 6.53 presents annual time-series of salinity for all cases in which the post-100-years ARI floods have scoured the entrance up to the end of 12 June 2007 (equivalent time). No morphological changes were included. The winds, catchment flows and tides were the same as those adopted for model verification. In principle, any improvements arising from the training walls would likely be at the maxima in these simulations – most scoured.

These results show that there is no improvement in lake flushing arising from construction of training walls.

6.8 Tidal Plane Changes

As part of the assessment of the potential improvement in lake hydraulics that might occur with training wall construction, Cardno has also conducted an analysis of the effect of the post 100yrs-ARI breakout entrance condition upon tidal planes within the lake (and thus tidal attenuation through the Entrance Channel). In order to do this, models were run for more than 2 months with no catchment inflows, winds, waves or morphology included as part of the modelling. These processes were excluded in order to isolate the effect of the entrance condition upon tidal attenuation from them. It should be noted that the omission of morphology means that these runs describe a best case, no infilling scenario – and hence only describe the tidal attenuation in the immediate aftermath of a 100years-ARI event – even though in many floods an extended period of elevated lake level will cause ongoing entrance scour, as happened in June 2007.

The fixed bed bathymetries used for these simulations were taken from the corresponding morphological runs – approximately 4 days after peak flood levels within the lakes.

The results presented in **Table 6.1** below indicate that there are no significant variations in tidal planes between the different training wall configuration cases and the existing entrance condition. In fact they are lower – see **Section 6.9**.

Table 6-1 Summary of Tidal Planes

Tidal Plane (mAHD)	Entrance Condition Post 100-years-ARI Event			
	Existing	Single Training Wall	150m Training Wall Configuration	200m Training Wall Configuration
HAT	0.294	0.276	0.269	0.282
MHWS	0.205	0.197	0.193	0.201
MHWN	0.196	0.189	0.186	0.193
MWL	0.178	0.172	0.169	0.175
MLWN	0.160	0.155	0.153	0.158
MLWS	0.151	0.147	0.145	0.150
ISLW	0.128	0.126	0.125	0.129
Spring Tide Range (m) (MHWS-MLWS)	0.054	0.049	0.048	0.051

6.9 Tidal Prism and Excursion Changes

In addition to extracting tidal planes, tidal prisms were extracted from the results of these two month simulations. These tidal prism volumes can be found in **Table 6.2** below. The tidal prism is the volume of water that enters an estuary on flood tide and leaves on ebb tide – albeit complicated by the neap-spring tidal pumping process.

The results indicate that the training wall configurations actually reduce the tidal prism from that of the existing layout. This outcome can be attributed to the locations of the northern training wall options in relation to the underlying rock layer located at the channel entrance. **Figures 6.54** to **6.56** show that there is a significant rock layer located in the south of the entrance channel. This limits the scour in the southern part of the entrance channel and, under existing conditions a 100years-ARI catchment event will scour naturally 100-250m to the north of this, where the rock layers are a little lower.

However, when the training wall configurations are in place, the presence of these structures restricts the natural lateral scour zone to the north of the rock, and hence reduces the natural scour width. Normally this would only act to increase the scour depth, but rock is present in this zone (only deeper), and the cross-sectional scour is limited, and hence the post-flood tidal prism is reduced marginally from that of the existing entrance condition.

Hence it can be seen that as a result of this, twin training wall configuration 1 results in the largest decrease in tidal prism, as these training wall as 150m apart. By comparison training wall configuration two results in only a slightly reduced tidal prism, as the northern training wall in this configuration is located further 50m to the north and the resultant scour width (and cross-sectional area) is increased.

Table 6-2 Summary of Tidal Prism Results

Tidal Flow	Tidal Prism ($x10^6m^3$)			
	Existing	Single Training Wall	150m Training Wall Configuration	200m Training Wall Configuration
Ebb	-3.61	-3.31	-3.22	-3.39
Flood	3.63	3.32	3.23	3.41

These tidal prism results are consistent with the spring tidal range results given in Table 6.1.

Note that these results show only small, but consistent changes. This outcome confirms also that the hydraulic entrance to Tuggerah Lake is not just the relatively small area at The Entrance, but includes the entire waterway over the approximate 2.6km from The Entrance to the Lake. Hence even significant changes in the seabed at the entrance will have virtually no effect on overall lake/entrance hydraulics and flushing. .

Figures 6.57 and 6.58 show the ebb and flood current vectors at a period towards the end of the 2 month flood simulations for the Existing and 150 dual training wall cases. They show that the training wall scenario results in slightly smaller currents through the entrance channel. This is consistent with the tidal prism results shown in Table 6.2 above.

6.10 Sediment Exchange

The morphological modelling undertaken for this investigation has shown that Tuggerah lakes flood events transport large volumes of sand from the ‘entrance’ into the near shore area. Following storm abatement onshore propagating swell transfers much of this sand back onshore to the north and south of the entrance as well as into the entrance leading to a more closed waterway at The Entrance.

Construction of two training walls may trap some of this sand on The Entrance and North Entrance Beaches. There would be improved beach amenity and reduced erosion hazard, respectively, but this would likely be a slow process, on North Entrance Beach, especially.

Previous investigations at this site report that there is a longshore transport ‘null’ point’ on North Entrance Beach. Figure 6.59 presents post-flood current vectors – caused by tides, waves, winds, freshwater flow, about 11 days after the peak of the flood, for the Existing and 150m wide dual training wall cases. These results show strong transport into the entrance, a null point about 200m north of The Entrance on North Entrance Beach and an otherwise northerly transport caused by wave conditions at that time. This flow structure is consistent with the conceptual model of sediment transport processes at this site.

The results also show that there would be a tendency for a beach to develop against the southern training wall and for a wider beach to form on North Entrance Beach. This process would gradually 'ratchet' sand out of the waterway between the Entrance Bridge and the sea. However, once The Entrance beach became full it would not assist this process further. On the other hand, the North Entrance beach has a much greater capacity to store sand over many years. A widening of this beach would reduce the erosion hazard at North Entrance. This would be a slow process, as experience at Lake Illawarra demonstrates. The capacity of this beach to store sand would gradually diminish. However, this sand 'ratchetting' process would not improve lake flushing to any great extent, as discussed above.

6.11 Entrance Scour

Another aspect of this project was to investigate the continued scour of the entrance following the design 100-years ARI flood and to describe the shoreward transport of the flood-formed shoal in order to determine whether or not the trained entrances would be self-scouring. Figures 6.60 to 6.63 show that for three of the design options only limited sedimentation occurs within the entrance channel for a period of about 6 weeks over the post-flood period. This process can be attributed to the slightly elevated water level that persists within the lake for some weeks after the flood (superimposed over the cyclical spring-neap tidal pumping of the lake). It should be noted here that the existing entrance condition actually has the deepest post-flood scour channel. This is because, as previously mentioned, the training wall options constrain the breakout to lie over the predominant rock layers where scour depth is limited. However the existing entrance condition allows the entrance breakout to occur slightly further north, through Karagi Point where the rock lies deeper, and is less influential in determining scour depth. For all cases sedimentation occurs predominantly to the west and east of the main channel.

7 ENTRANCE DREDGING

7.1 Background

Wyong Shire Council undertakes dredging of The Entrance Channel between The Entrance Bridge and the rock sill that underlies the entrance at the coastline every 1 or 2 years. This work is undertaken using Council's own dredge and the extracted sand is placed commonly on North Entrance Beach using a fixed dredged spoil disposal pipeline. This work is intended to reduce flood peaks (by requiring less sand to be removed by a flood), improve tidal exchange and reduce the storm erosion hazard on North Entrance Beach. In at least one instance the dredged sand was discharged to the South Entrance Beach where it is understood to have improved beach amenity for two to three years. This dredging may also reduce the tidal flow in the Terilbah Channel, thereby reducing current speeds in the region of Karagi Park caravan park. Tidal current speeds in this area may be in the order of 1m/s – observed on-site by Cardno, 6 June 2013. **Figure 7.1** provides an indication of the dredge works that extend east along the channel from the sump at the bridge to the entrance sill.

The dredged channel is typically 30 to 50m wide, where initially narrower, and cut to -1.5m AHD. The work takes several months to complete.

The most recent round of dredging conducted by Council occurred during November/December 2012. Council confirm that approximately 28,800m^3 of sand was dredged during this time. Spoil was disposed-of in two different locations. Council confirms that the first location was outside the entrance on North Entrance Beach, but only as far north as 1 Hutton Road. A site inspection on 6h June 2013 indicated that the second disposal location was inside the entrance, along the shoreline from Karagi Point to the caravan park. Council advised that:-

"*We did pump a significant amount to the ocean side, however we directed the dissipater at the outlet to ensure where possible the beach neither eroded nor accreted and that the sand travelled offshore to re-establish banks. Therefore the sand pumped to that side is not easily visible, and we believe a significant volume of it would have travelled south to The Entrance Beach at the time. The ocean bed was not surveyed.*" (pers. comm. L. Sulkowski and A. Beavis, 12 June 2013 – Chris Beadle (Cardno).

The location of the null point is discussed further in Cardno (2013). **Appendix E** (developed from Worley Parsons, 2009), provides some general description of Council's dredging operations and the purpose of the works.

7.2 Hydrodynamic and Morphological Modelling

Council have provided Cardno with pre-and post-dredging seabed surveys from this aforementioned round of dredging. These data sets were combined with the DEM established for this study to provide pre- and post-dredging model systems. The following set of model simulations was undertaken:-

1. One-year fixed bed simulations with pre and then post dredging bathymetries. These simulations were conducted in order to compare tidal prisms, salinity time-series in Tuggerah Lake and Terilbah Channel/South Channel flows and any changes caused by the dredging. These simulations were used to describe the change in lake flushing arising from the dredging work.

2. Morphological simulations of the June 2007 flood event (using methodology described in **Section 6.5**), using the pre and then post dredging entrance bathymetries. This modelling was conducted in order to compare peak flood levels and post-flood hydrograph forms in order to assess the benefit of entrance dredging in reducing peak flood levels.

3. A two-month morphological simulation incorporating post-dredging survey, ambient waves (H_s = 1.5m, T_z = 6 seconds from the south-east, tides (predicted Middle Harbour tides) and morphological processes. This simulation was conducted in order to describe the morphological changes that occur to the dredged channel and rates of infill in 'normal, non-flood' conditions.

The results of these simulations are discussed below.

7.3 Entrance Tidal Prism and Lake Flushing

The results of the one-year fixed bed bathymetric simulations can be seen in **Figure 7.2**. They show that the dredging increases the conveyance between the lake and the ocean and drops the lake water level by approximately 1cm. This increase in conveyance results in a slight increase in lake salinity for the post dredging simulation. **Table 7-1** indicates that the entrance dredging increases the tidal prism of the lake by approximately 5 to 10%. However, this result can be considered conservative as the fixed bed simulations assume no infilling of the dredged channel, which is considered likely to occur over a one year period, to a significant extent.

Table 7-1 Summary of Tidal Prism Results

Tidal Flow	Tidal Prism (x10^6 m^3)	
	Pre Dredging	Post Dredging
Ebb	-3.14	-3.37
Flood	3.21	3.44

Additionally, the results of the modelling indicate how the dredging at the entrance affects the current structure during ebb and flood tides. One purpose behind the dredging is understood to be that deepening of the entrance (upstream of the rock sill), may reduce tidal currents in the Terilbah Channel and hence reduce erosion of the eastern bank of the entrance near Karagi Park, which has historically been prone to erosion from tidal currents, as well as flood events.

The results of these simulations are presented in the form of current vector plots in **Figures** 7.3 to 7.6. Additionally, time-series current magnitudes and directions are presented for three points in **Figures** 7.7 to 7.9. These results indicate minimal alteration of tidal currents in the Terilbah Channel and along the bank of Karagi Park, but with reductions in flood and ebb speeds of about 0.1m/s near Karagi Park (Point B). On the western side the ebb tide currents increase by about 0.2m/s (Point C0. The results do show, however, some significant reduction in tidal current magnitudes in the direct vicinity of the dredged channel. This change will contribute to re-sedimentation of the dredged channel.

The results indicate that the most prominent alteration to the currents is a reduction in current speeds directly over the areas of dredging, but very little change near Karagi Park.

7.4 Flood Attenuation

The results of the June 2007 morphological simulations indicate that the entrance dredging his minimal effect upon peak flood levels within the lake. **Figure** 7.10 shows the time-series of water levels at Long Jetty for the two simulations. This figure indicates that the entrance dredging reduced the peak flood level within the lake by approximately 3cm, but this reduction increases to approximately 5cm during the flood tail period. The June 2007 simulation is likely to be about a 15 to 20-years ARI event, depending on whether this assessment is made on peak level, flood volume or flood duration parameters.

This outcome indicates that the scour limitation imposed by the underlying rock sill at the entrance is more influential on the peak lake flood level than the entrance bathymetry between the bridge and the entrance – noting also that a much greater area of shallow water lies west of the bridge. While the dredging did reduce the flood levels by requiring less sand to be removed by the modelled flood, the effect of this was only minimal, and indicates that the current dredging scheme may not be an effective means of reducing severe lake flood levels.

Other potential dredging schemes and catchment flood scenarios were not tested.

7.5 Long Term Dredged Channel Behaviour

The other simulation conducted was a 2-months morphological simulation, which was undertaken in order to assess the morphological changes to the dredged channel and the rates of channel infill following completion of the dredging work. As mentioned in **Section** 7.1, approximately 28,800m^3 was dredged during the November/December 2012 dredging program. The results of this simulation show that over the 2 months of simulation, the dredged channel has filled in approximately 6000m^3 (approximately 20%).

It is not likely, however, that this rate of infilling would continue indefinitely until the dredge channel was filled. The rate of infill would slow over time because as the channel fills–in its trapping efficiency reduces. . Hence there is some level of uncertainty regarding the use of the models results to project the time taken for the channel to fill completely. **Figure** 7.11 shows how the rate of infilling slows over the 2 months model simulation period. Extrapolating this decelerating fill-rate forward in time indicates that the dredged channel is likely to in-fill in approximately 500 days. This assessment is consistent with Council's dredging plan of every 1 to 2 years.

This figure should be taken as only an approximate guide, as the rate of dredged channel infill is highly variable, and susceptible to pronounced changes resulting from the offshore wave conditions as well as the intensity and frequency catchment rainfall events.

8 CONCLUDING REMARKS

The model system developed for this investigation and funded by OEH has been well calibrated and verified for non-flood and flood cases. The outcomes are very sensitive to the entrance bathymetric form and all relevant physical processes need to be included – winds and waves, catchment inflows and the offshore tide, including other oceanic processes, such as coastal trapped waves. The purpose of this modelling tool was to provide a basis for testing a range of possible entrance training wall options in terms of entrance morphological differences and then potential improvements in lake flushing. An additional outcome of the modelling was to develop an investigation tool that could be used to examine the likely outcomes of entrance dredging scenarios in terms of improving lake flushing; thereby assisting Wyong Shire Council.

The range of entrance training wall cases tested has shown that they:-

- would not increase flood levels (if spaced at 150m or more apart), and
- could lead to the gradual formation of a beach on the southern side of a southern training wall, and
- could gradually reduce the erosion hazard on southern North Entrance Beach through the gradual accumulation of sand on that beach This area is likely to be localised, and
- could prevent major erosion of the southern end of Karagi Point during a flood, as a result of the proposed turn back sections of the northern training walls, and
- could possibly cause minimally higher waves to enter the estuary, slightly lower currents on the northern side, and
- would lead to virtually no change in lake water quality, and
- would require that maintenance dredging of the type already undertaken by Council to continue.

It is noted that WSC currently undertake dredging about every 2 years in prescribed channel areas east of The Entrance Bridge. No dredging is currently undertaken west of the bridge, though it is understood that northern and southern channels have been dredged in the past – Terilbah and Main Channels, see Figure 7.1. These channels and shoals located west of The Entrance Bridge are understood to be quite stable and covered with sea grass.

Some trained entrances undergo long term gradual changes, for example, Swansea Channel and Wallis Lake where continuing changes, not all for the better, occur. Although the entrance to Lake Illawarra has remained open for some years following the construction of training walls, strong currents that occur on the northern side of that entrance have caused recent shoreline erosion. That outcome may have also been partly caused by the increased rainfall that has occurred over past few years, but a more closed entrance would likely have reduced that shoreline erosion.

Investigations of the effects of Council's entrance area dredging program show very little reduction in peak flood level and change in lake flushing. However, the work does provide protection to the Karagi Point estuarine shoreline and North Entrance Beach, and on some occasions, to South Entrance Beach.

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