Tuggerah Lakes Entrance Management Study: Stage 1 Review of Previous Studies

Report MHL2781
April 2021

Prepared for:
Central Coast Council

Cover Photograph: Tuggerah Lakes entrance 30 June 2020. Provided by Central Coast Council.

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Foreword

In July 2020, NSW government's professional specialist advisor, Manly Hydraulics Laboratory (MHL) were commissioned by Central Coast Council to undertake the Tuggerah Lakes Entrance Management Study with the aim of developing an evidence-based Interim Entrance Management Procedure for Tuggerah Lakes to reduce the risk to life, public and private infrastructure and public health. This will be aided by decision support tools providing quantitative data to facilitate a rational, proactive and informed approach to future entrance management actions.

The Tuggerah Lakes Entrance Management Study is being delivered as a series of reports for the following stages of work:

Stage 1: **Review of previous studies (this report)**

Stages 2 - 4: Entrance modelling and analysis

Assessment of entrance management options

Interim entrance management procedure and associated decision support tools

This report provides the outcomes of Stage 1 of the Tuggerah Lakes Entrance Management Study and has been released prior to the completion of subsequent stages of the project as recommended in a recent review of Central Coast Council's Lagoon and Lake Entrance Management, Policies and Practices by Gordon (2021).

This report contains a review and summary of over 25 studies from 1987 to present relevant to the context of entrance management at Tuggerah Lakes. Findings from the review have been used to provide a conceptual understanding of entrance processes and inform subsequent works and stages of the project.

The report was prepared by Matthew Phillips, Armaghan Severi and Bronson McPherson.

This report is classified as public and is available via the MHL report library.

Executive summary

Tuggerah Lakes is situated within the traditional boundaries of Darkinjung (Darkinyung) land, which extends from the Hawkesbury River in the south, Lake Macquarie in the north, the McDonald River and Wollombi up to Mt Yengo in the west and the Pacific Ocean in the East.

This report provides the outcomes of Stage 1 of the Tuggerah Lakes Entrance Management Study. It contains a review and summary of over 25 studies from 1987 to present relevant to the context of entrance management at Tuggerah Lakes. Findings from the review have been used to provide a conceptual understanding of entrance processes and inform subsequent works and stages of the project.

Tuggerah Lakes has had a long history of entrance management to alleviate flooding and water quality issues, including reports of flood damages extending back to the 1860's (PWD,1992). Managing the Tuggerah Lakes entrance continues today with the majority of the lake's low-lying foreshore now heavily urbanised and susceptible to flooding as well as placing added stressors on ecological communities.

Flooding in the area is characterised by both elevated ocean water levels and catchment runoff, with the condition of the entrance an important contributing factor controlling lake flood levels (Lawson & Treloar, 1994). While the channel does temporarily scour and widen during flood events, the typically low tidal prism of the entrance results in net infilling of sand into the entrance from the ocean with time, requiring mechanical invention to maintain open conditions.

Since 1993, Tuggerah Lakes entrance maintenance dredging works have been carried out by Council. Under the Tuggerah Lakes Estuary Management Plan dredging of 30,000 to 80,000 m^3/yr is performed when one or more of the following indicators are reached (occurring on average every 1-2 years):

- The throat of the channel at the southern tip of the sand spit at the Entrance reduced to a width of 15 m at mid tide level.
- The flood tide sand shoals threaten to block the ebb tide dominant channel along the northern/eastern side of the Entrance area.
- The flood tide shoals threaten to block the main channel east of the bridge.

Dredged material is used for replenishment at South and North Entrance beaches. In addition to periodic maintenance dredging, the NSW Government constructed a rock groyne in 2017 at South Entrance beach to enhance beach stabilisation immediately south of the entrance (Cardno, 2013).

The Tuggerah Lakes Floodplain Risk Management Study and Plan (WMAwater, 2014) noted entrance management via periodic dredging would have minor benefits including possible prevention of minor flooding, small reduction in flood peak levels and potential six-hour reduction in flood duration. Benefits of dredging are noted to diminish with time following works due to infilling and that at the time there was limited evidence justifying dredging of the entrance in terms of reducing flood damages. It was recommended as a high priority that an Entrance Management Strategy be formalised for Tuggerah Lakes to manage flooding.

A range of alternative entrance management options have been investigated as part of previous studies including entrance jet pump systems, entrance restraining walls, entrance adjustment trials, trained entrance configurations and/or various dredging work strategies (e.g., PWD, 1987; 1988; Patterson Britton and Partners, 1994; WorleyParsons, 2009; Cardno, 2013; 2015; GHD, 2019).

More recently Cardno (2015) undertook morphological modelling of the Tuggerah Lakes entrance to assess the implications of a 150 m wide dredge channel with a range of depths. The scale of dredging investigated was much larger than Council's present maintenance dredges. The study found that:

- Dredge channels would likely infill from ocean and lake ends;
- Dredging would increase conveyance and tidal exchange between the lake and ocean, with this increase limited when dredging to more than -2.5 m AHD due to the shoaled region west of The Entrance bridge;
- Dredging would result in lower average lake levels of up to 0.1 - 0.2 m with increased lake tidal range. Decreases in lower average lake levels may have ecological and recreational consequences; and
- Potential higher tidal currents with dredging at The Entrance bridge and along Terilbah reserve may result in scour and/or shoreline erosion.

Previous studies have also investigated the feasibility of different trained entrance configurations for Tuggerah Lakes (Patterson Britton and Partners, 1994; WMAwater, 2014; Cardno, 2013; 2015). Patterson Britton and Partners (1994) found that the construction of entrance training walls was impracticable due to the potential impacts on lake water levels and tidal range, increased flooding, storm surge and wave climate in the entrance and loss of upstream entrance shoals. Findings from more recent numerical model investigations of trained entrances include:

- Trained entrance configurations modelled indicate that a 250 m width not physically or economically viable to keep open, with potential adverse impacts on ecology and increased frequency of ocean inundation events (WMAwater, 2014);
- Trained entrances configurations that limit the entrance width to 100 m are likely to increase peak flood levels, the number of flood-affected properties and flood water retention time. (Cardno, 2013);
- Trained entrance configurations modelled indicate that ongoing maintenance dredging would be required to keep open (Cardno, 2013); and
- Trained entrance would decrease the rate of sediment infill from the ocean compared to without training walls (Cardno, 2015).

Although trained entrance configurations in previous numerical modelling studies have indicated that the entrance will continue to infill, experience along the NSW coast shows that when breakwaters extend deeper into offshore waters, trained entrances can transition into a self-scour regime. Nielsen and Gordon (2015) noted this behaviour at a number of trained entrances along the NSW coast.

Implications of an entrance in a self-scour regime include extensive entrance scour requiring channel erosion protection works, changes in sedimentation patterns in bays and adjacent beaches as well as significant changes to fringing ecological communities (Nielsen and Gordon, 2015). Such implications at Tuggerah Lakes entrance could result in:

- Damage and undermining of existing seawall foreshore protection at the entrance and footings of The Entrance Bridge.
- Higher high tide levels exacerbating ocean flood events in the lake including spring tides, king tides potentially coinciding with storm surge and wave setup during high wave events. The entrance in its present state currently restricts the amount of ocean flooding in the lake, protecting low-lying foreshores from more frequent inundation during coastal events with elevated ocean water levels.
- Lower low tide levels with increased exposure of mud flats and seagrass beds resulting in ecological degradation of fringing ecosystems, odour issues and recreation boating hazards.

Maintenance dredging of Tuggerah Lakes entrance has continued as a means of entrance management including recent dredges in 2018 and 2020. Recent studies have been undertaken to refine Council's dredging operations and strategies (GHD, 2019).

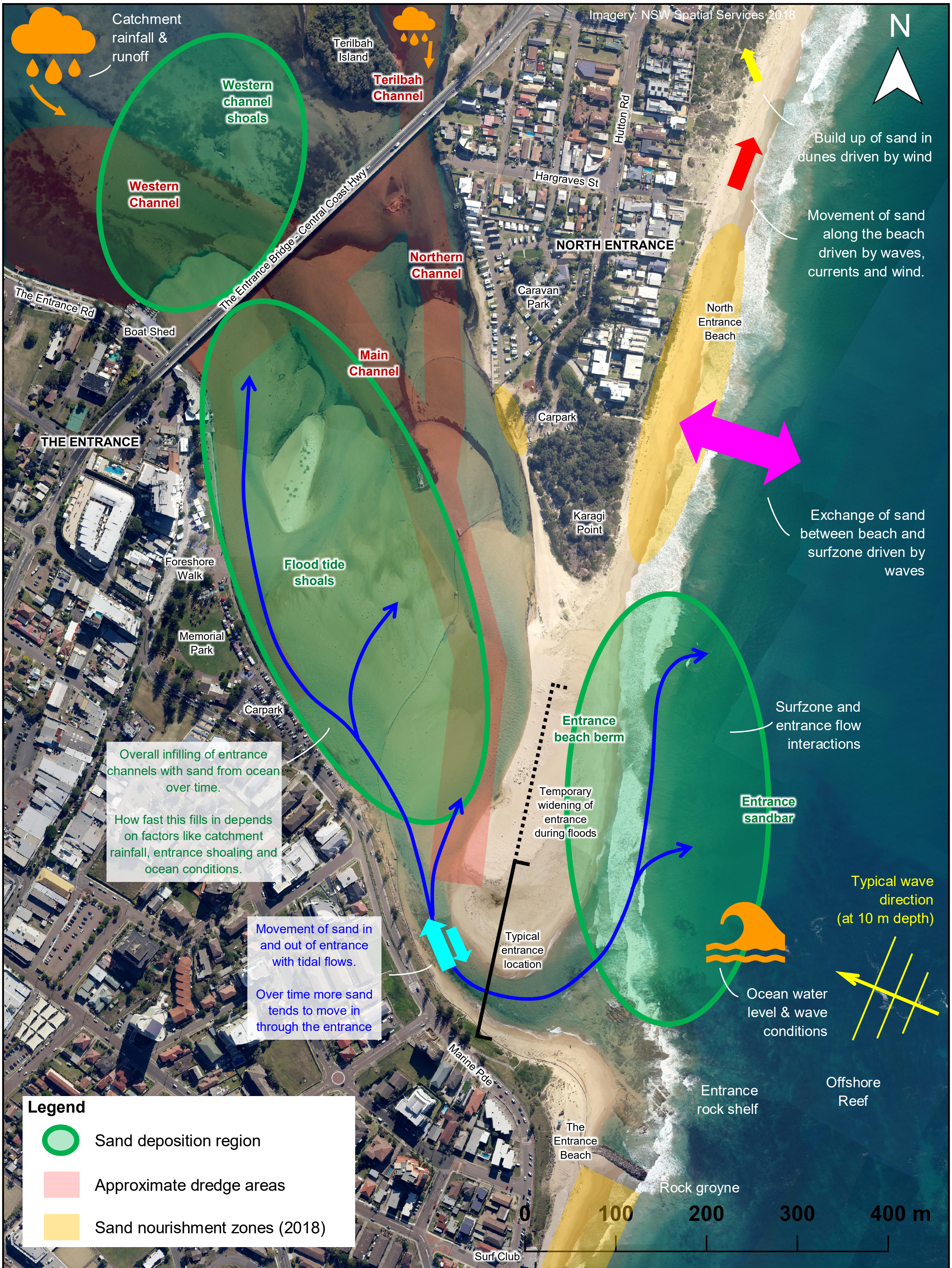
The present review of previous studies has been used to develop a conceptual model of Tuggerah Lakes entrance summarised **Figure E.1** to provide an overview of key entrance processes including sediment transport pathways, deposition regions and approximate dredging locations.

Water levels in the lake are primarily controlled by catchment runoff and ocean water levels as well as entrance conditions and shoaling processes depicted in **Figure E.1.** Flood scour processes along with ebb tide sediment transport, carry sand out of the entrance channel and deposit it offshore on the entrance sandbar or on the beach face adjacent to the entrance. In the several months after a flood, the entrance is temporarily wider than normal and the lake tidal range increases due to higher ocean-lake flushing before returning to typical values as the entrance infills with time.

Mild wave conditions and flood tide processes carry sand onshore and back into the entrance channel where it is redeposited on the flood tide shoals. These processes constrict the entrance channel and reduce the lake tidal range. The typical low tidal prism and tidal velocities of the entrance result in a net infilling of the entrance region and channels with time. Periodic dredging is currently undertaken to maintain open entrance conditions. With periods of low rainfall this rate of infilling can accelerate, with shoals building up more rapidly and the entrance becoming relatively more constricted than during wetter periods.

The condition of the entrance, including its channels, berm and shoals, acts as a primary control allowing catchment flows to drain from the lake system while also restricting the amount of ocean inundation into the lake system. Given the typical low lake level (approx. 0.3 m AHD) and low-lying surrounding foreshore, managing the entrance requires a careful balance between reducing the severity of major catchment floods while protecting the lakes from adverse ocean inundation and minimising disturbances to the inherent natural lake water level variability and ecology.

Recent flood events in February 2020 and March 2021 re-emphasise the priority for a formalised Entrance Management Strategy to manage flood risk as recommended in the Tuggerah Lakes Floodplain Risk Management Study and Plan (WMAwater, 2014); enhancing the management of the entrance in a flood ready condition that considers the complex and dynamic interactions of factors that contribute water level variability in Tuggerah Lakes.



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OVERVIEW OF PROCESSES AT TUGGERAH LAKES ENTRANCE

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Figure E.1

FigureE.1.pdf

Contents

TABLES

FIGURES

1 Introduction

1.1 Background

Tuggerah Lakes is situated within the traditional boundaries of Darkinjung (Darkinyung) land, which extends from the Hawkesbury River in the south, Lake Macquarie in the north, the McDonald River and Wollombi up to Mt Yengo in the west and the Pacific Ocean in the East.

Tuggerah Lakes comprises of a catchment area of 750 km^2 with three main waterbodies including Tuggerah Lake, Budgewoi Lake and Lake Munmorah. It is one of approximately 70 Intermittent Closed and Open Lakes and Lagoons (ICOLLs) on the NSW coastline. Today much of the low-lying area surrounding Tuggerah Lakes foreshore is developed and susceptible to flooding.

Under the NSW Flood Prone Land Policy and Floodplain Development Manual (2005), the management of flood liable land remains the responsibility of local government. Since 1993 Council has undertaken periodic dredging as shown in **Figure 1.1** of the entrance tidal shoals typically every 2-3 years or when trigger levels are met since 1993. Mechanical opening of the lagoon has occasionally been undertaken as required in effort to alleviate flooding.

The Tuggerah Lakes Floodplain Risk Management Study and Plan (FRMS) was completed in 2014 (WMAwater, 2014) and recommended as a high priority that an Entrance Management Strategy be formalised for Tuggerah Lakes to manage flooding.

In July 2020, NSW government's professional specialist advisor, Manly Hydraulics Laboratory (MHL) were commissioned by Central Coast Council to undertake the Tuggerah Lakes Entrance Management Study. The study seeks to provide an evidence-based Interim Entrance Management Procedure for Tuggerah Lakes, with outcomes expected to be an important component in assisting Council's review of the Tuggerah Lakes Flood Study (Lawson & Treloar, 1994) and Floodplain Risk Management Plan (WMAwater, 2014). The study also supports Council's transition to a Coastal Management Program under the Coastal Management Act 2016 to see thriving and resilient coastal communities living and working on a healthy coast, now and into the future.

The Tuggerah Lakes Entrance Management Study is being delivered as a series of reports for the following stages of work:

Stage 1: **Review of previous studies (this report)**

Stage 2: Entrance modelling and analysis

Assessment of entrance management options

Interim entrance management procedure and associated decision support tools

This report provides the outcomes of Stage 1 of the Tuggerah Lakes Entrance Management Study. It contains a review and summary of over 25 studies from 1987 to present relevant to the context of entrance management at Tuggerah Lakes. Findings from the review have been used to provide a conceptual understanding of entrance processes and inform subsequent works and stages of the project.

A glossary of terms is provided in **Appendix A**

Figure 1.1: Dredging of tidal shoals Tuggerah Lakes entrance in 2018. Source: NSW Spatial Services.

1.2 Study area

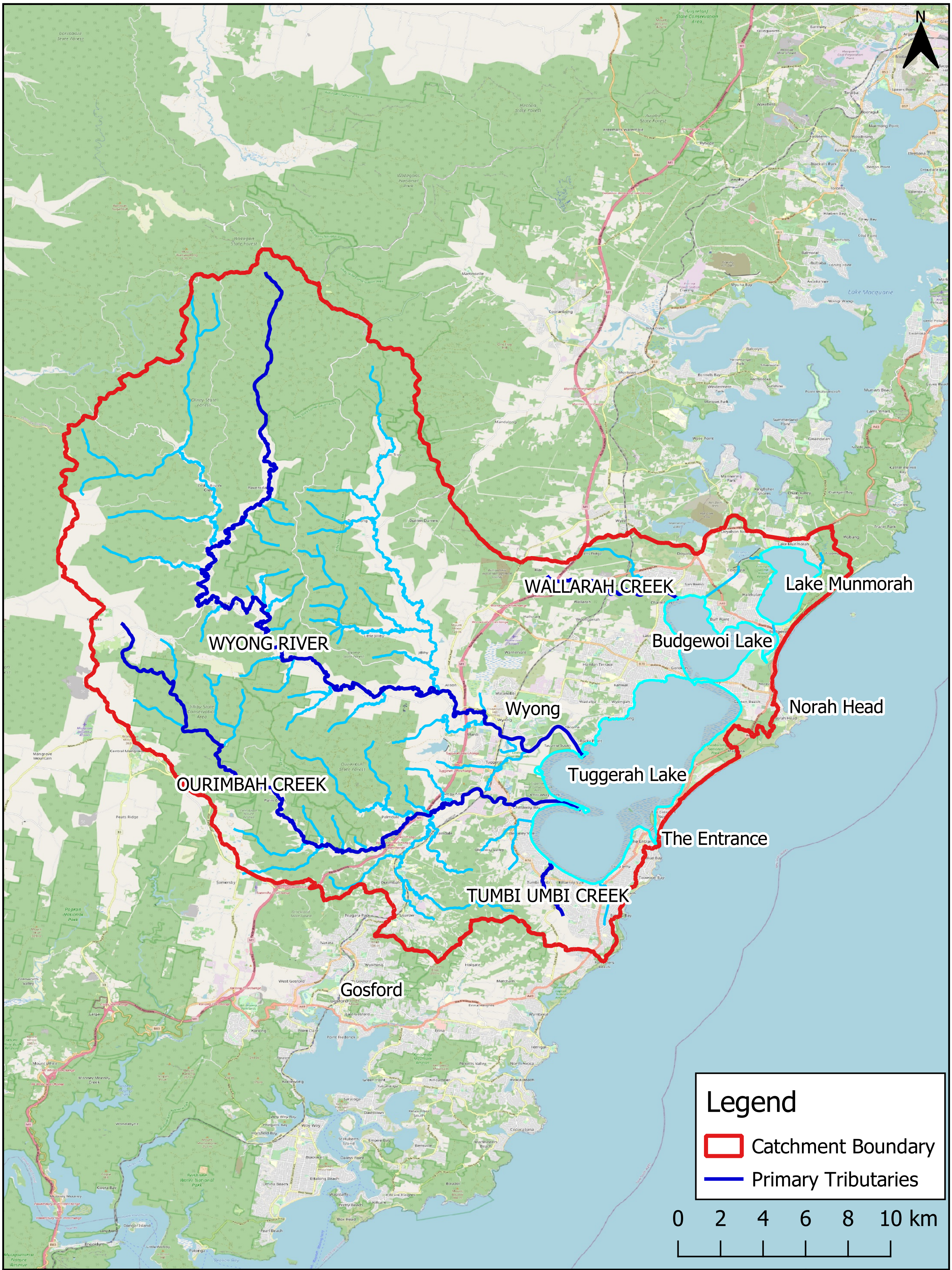
The Tuggerah Lakes system is located within the traditional boundaries of Darkinjung (Darkinyung) land on the Central Coast of NSW, approximately 80 km north of Sydney. The study area comprises three main interconnected lakes including Tuggerah Lake, Budgewoi Lake and Lake Munmorah. Tuggerah Lake is the largest of the three lakes and is connected to Budgewoi Lake and Lake Munmorah by narrow channels at Gorokan and Budgewoi. The lakes system is connected to the ocean via a single tidal channel through the barrier dune at the southern end of Tuggerah Lake. The condition of the entrance of Tuggerah Lakes, where flows exchange to/from the ocean, is dynamic and subject to entrance sediment infilling and scour, such that the estuary is classified as an Intermittently Closed and Open Lakes and Lagoon (ICOLL). The study area is shown in **Figure 1.2.**

The Tuggerah Lakes system covers the total catchment area of around 750 km^2 of which approximately 10% is covered by lakes. Wyong River, Ourimbah Creek, Tumbi Umbi Creek and Wallarah Creek are the major catchments contributing to the lakes system. Wyong River, Ourimbah Creek and Tumbi Umbi Creek drain catchment areas of approximately 447, 160 and 14 km^2 to the southern end of Tuggerah Lake, and Wallarah Creek drains catchment area of around 32 km^2 into Budgewoi Lake (WMAwater, 2014). Bio-Analysis Pty Ltd (2006) reported that around 80% of the shorelines of the Tuggerah Lakes were heavily urbanised.

Ocean tides in the region are microtidal with mean spring and neap ranges of 1.3 m and 0.8 m, respectively (Couriel et al., 2012). The regional wave climate is of moderate to high energy. Deepwater wave data collection has been undertaken off the coastline near Sydney from 1987 initially with non-directional measurements and since 1992 with directional measurements. Waves are predominantly from the SSE direction with an average significant wave height (H_s) of 1.6 m and peak wave period (T_p) of 10 s. Deepwater H_s exceeds 3 m for approximately 5% of the time and has been observed to reach up to 9 m during high energy events, most commonly driven by intense extratropical cyclones known as East Coast Lows (ECLs) that track near the coast in the Tasman Sea (Harley et al., 2017). The wave data shows that the predominant swell wave direction is south-southeast (SSE, 157.5˚TN) with over 70% of swell wave occurrences directed from the SE quadrant (SMEC, 2011). In the nearshore at 10 m water depth offshore of the entrance, waves are predominantly from the ESE with an average significant wave height of 1.5 m (Baird Australia and MHL, 2017). At the Patonga ocean water level station (212440), 20 and 100-year Average Recurrence Interval (ARI) extreme ocean water levels were estimated to be 1.39 and 1.43 m AHD, respectively (MHL, 2018).

Patterson Britton and Partners (1994) reported that the tidal range within the lakes was relatively small in the order of centimetres and average mid-tide lake levels vary between 0.2 to 0.3 m AHD due to a narrow entrance channel and shoals. However, after the occurrence of a flood event with entrance scour, tidal range can temporarily increase to approximately double typical values and average mid-tide lake levels drop to 0.1 m AHD. Tidal flows and velocities are reported to be 100 to 150 m^3/s and 1 to 2 m/s, respectively. Under the average tidal conditions and at mid-tide, the throat of the entrance was reported approximately 25 to 35 m wide and 2 to 2.5 m deep (Patterson Britton and Partners, 1994).

In 2010, MHL documented an increasing trend in average water levels in Tuggerah Lakes ranging from +3.9 to +6.4 mm/year, based on a 15-year lake water level records from 1985 to 2010. Entrance conditions and catchment runoff are the primary contributing factors controlling lake water levels. Lake levels are on average 0.3 m AHD and the corresponding average water depth is 1.9 m (WMAwater, 2014). The deepest area being reported in Lake Munmorah with up to 3.7 m depth at 0.3 m AHD water level (WMAwater, 2014).



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TUGGERAH LAKES STUDY AREA SHOWING CATCHMENT BOUNDARY

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Report MHL2781

Figure 1.2

Figure 1.2.pdf

1.2.1 Historical entrance opening and changes

Prior to European settlement in 1825, Aboriginal peoples (Darkinjung land) occupied the Tuggerah Lakes catchment area with minimal environmental impact, utilising the lakes and adjacent beaches for collection of a variety of seafoods (CSIRO, 1999). After European settlement in the 19th and 20th century, properties were acquired (originally for farming purposes) surrounding the lakes low-lying foreshore. Historical and anecdotal records during this time presented in CSIRO (1999) show that the entrance to Tuggerah Lakes would typically block up under natural conditions, remaining closed for a year or more, interrupted by the occasional flood event resulting in entrance breakout and scour.

Entrance openings were often expedited by residents whose properties and houses were impacted by flooding or by local fishermen desiring an open entrance. Entrance openings undertaken by local government to alleviate flooding are noted as early as 1915 with dredging of navigation channels in entrance shoals noted as early as 1912. Albeit adoption of progressive technologies, manual (or mechanical) entrance opening and periodic dredging of entrance channels has continued as a long-standing adopted management practise since. Under these conditions, the channel has noted to have fully closed at least 13 times in the last 100 years, for periods of up to 2-3 years (e.g., late 1930s and early 1940s) (Umwelt, 2011).

Aerial photos of Tuggerah Lakes entrance from 1941 to 2006 were examined by Umwelt (2011) to describe significant historical changes to entrance morphology. Morphological changes were found to reflect a number of factors including:

- La nina and el nino southern oscillation events and other medium to long term cycles
- Occasional extreme storm events
- Sea level rise
- Foreshore reclamation and construction of fixed foreshores
- Channel straightening and potential deepening, particularly upstream of the bridge
- Stabilisation of shoals and islands with saltmarsh, mangrove and sea grass
- Stabilisation of the mobile dune which traversed the entrance barrier spit until the late 1960s.

Selected historical aerial images are provided in **Figure 1.3** showing entrance changes from the 1950's to present. Major foreshore reclamation and stabilisation works in the entrance region noted by CSIRO (1999) and Umwelt (2011) have included:

- Late 1930's reclamation and seawall shore protection of southern foreshore east of bridge;
- Early 1960's reclamation and seawall shore protection of northern foreshore east of the bridge at North Entrance;
- Early 1980s foreshore reclamation commencing on the western side of the tidal delta; and
- Late 1980's and early 1990's straightening Terilbah channel and reclamation of foreshore to the north of the bridge. Continuing reclamation of the western shore.

The Entrance bridge was originally built in 1934 as a single lane wooden bridge, prior to the current two-laned concrete bridge being constructed in 1969 (CSIRO, 1999).

Figure 1.3: Selected historical aerial images 1950s to present. Sources: Umwelt (2011) and Google Earth.

1.3 Study aim and objectives

The aim of Tuggerah Lakes Entrance Management Study is to develop an Interim Entrance Management Procedure for Tuggerah Lakes, based on sound evidence, to reduce the risk to life, public and private infrastructure and public health (such as health issues associated with sewer overflows). This will be aided by decision support tools providing quantitative data to facilitate a rational, proactive and informed approach to future management actions.

Specific objectives of the study include:

- Consolidate, review and analyse existing information.
- Identify and address any critical knowledge or data gaps.
- Describe the processes which influence Tuggerah Lakes entrance.
- Provide recommendations that seek to:
    - Minimise the risk to life, private and public infrastructure and public health and safety.
    - Maintain or enhance water quality in Tuggerah Lakes.
    - Help improve community understanding about ICOLLs and management at The Entrance.
- Identify and evaluate management options for Tuggerah Lakes entrance.
- Investigate and describe the potential impacts of sea-level rise on Tuggerah Lakes and future entrance management.
- Evaluate the merits of dredging and entrance management.
- Engage with key stakeholders, relevant agencies and government departments.
- Develop an Interim Entrance Management Procedure.
- Investigate options and develop support tools to assist entrance management.

1.4 Study overview

Key stages of the present study are outlined below:

- Review of previous studies (**this report**)
- Modelling and analysis
- Assessment of entrance management options
- Engagement workshop
- Draft report, Interim Entrance Management Procedure and support tools
- Final report and project handover.

2 Review of Previous studies

2.1 Preamble

A review of previous studies relevant was undertaken to provide context and inform the present work as well as identify any critical knowledge gaps. A total of 29 studies over the past 43 years relevant to the management of Tuggerah Lakes Entrance were reviewed and are listed in **Table 2.1**. The breadth of studies highlights the multifaceted and complex nature of managing the Tuggerah Lakes Entrance. Numerous datasets were also reviewed including imagery, water level, rain, channel survey and asset datasets to determine suitability for the present study and to identify any data gaps. Findings from the reports are summarised in the following sections in chronological order. Key findings from the review have been synthesised into a conceptual model of ICOLL entrance behaviour in **Section 3**.

Table 2.1: List of previous work reviewed.

Year	Title	Author	Section
1987	Jet pump systems for maintaining tidal entrances	Public Works Department	2.2.1
1988	Tuggerah Lake Entrance Improvements – Entrance Restraining Wall	Public Works Department	2.2.2
1992	Tuggerah Lakes Flood Study. Compendium of Data	Public Works Department	2.2.3
1994	Tuggerah Lakes Flood Study	Lawson & Treloar	2.2.4
1994	Tuggerah Lakes Flood Study. Flood Forecasting System	Lawson & Treloar	2.2.5
1994	Tuggerah Lakes, Entrance Training Walls: Technical Discussion	Patterson Britton and Partners	2.2.6
1999	Recalibration of Tuggerah Lakes model and Evaluation of The Entrance Dredging Impacts	Lawson and Treloar	2.2.7
2005	Tuggerah Lakes Estuary Management Study	Bio-Analysis	2.2.8
2006	Tuggerah Lakes Estuary Management Plan	Bio-Analysis	2.2.9
2009	The Entrance Dredging Project Review of Environmental Factors	WorleyParsons	2.2.10
2011	Entrance Dynamics and Beach Condition at The Entrance and North Entrance Beaches	Umwelt	2.2.11
2011	Longshore Sand Transport and Tidal Inlet Stability Study for The Entrance and The Entrance North	SMEC	2.2.12
2011	Coastal Zone Management Plan for the Wyong Coastline	Umwelt	2.2.13

Year	Title	Author	Section
2013	Impact of saltmarsh rehabilitation and regrading of shorelines on nearshore condition	NSW Office of Environment and Heritage (OEH)	2.2.14
2013	Recommendations for Management of Ooze in Tuggerah Lakes	OEH	2.2.15
2013	Tuggerah Lakes Monitoring Program	OEH	2.2.16
2013	Restoration of Tuggerah Lakes through improved water quality management	OEH	2.2.17
2013	Tuggerah Lakes – The Entrance Morphodynamic Modelling. Entrance Beach Management Investigations	Cardno	2.2.18
2013	Tuggerah Lakes – The Entrance Morphodynamic Modelling	Cardno	2.2.19
2013	Report on the safety of navigation should training walls be established at the barway entry to The Entrance in NSW	Weston	2.2.20
2014	Tuggerah Lakes Floodplain Risk Management Study and Plan	WMAwater	2.2.21
2015	Additional Morphological Modelling - The Entrance	Cardno	2.2.22
2016	Review of Environmental Factors - The Entrance Rock Groyne	NSW Department of Primary Industries (DPI) – Crown Lands	2.2.23
2016	Breakwaters and training walls – The good, the bad and the ugly.	Nielsen and Gordon	2.2.24
2018	Review of the Wyong Coastal Zone Hazard Study	BMT	2.2.25
2019	The Entrance Width August 2012 to March 2019	CoastalCOMS	2.2.26
2019	The Entrance Channel Dredging Operations Feasibility Review	GHD	2.2.27
2020	Impact of February 2020 East Coast Low on Central Coast Beaches	WRL	2.2.28.1
2020	Tuggerah Lakes catchment February 2020 flood summary and historical comparison	MHL	2.2.28.2

2.2 Literature review

2.2.1 Jet pump systems for maintaining tidal entrances, Public Works Department, 1987

This study addressed the feasibility of utilising jet pumping technology at Tuggerah Lakes entrance in attempt to maintain a permanently open entrance. The study found that jet pumps would be ineffective to maintain a permanent opening in an untrained entrance environment due to the pumps being outflanked by channel migration and would require some form of training walls to stabilise the channel location. With ancillary training works, two jets located at 10 m below mean sea level, each with a capacity of 50 tonnes per hour of sand, was noted to be required to maintain a permanent non-navigable opening at Tuggerah Lakes. The report also concluded jet pumps would likely be subject to labour intensive and difficult operation due to their susceptibility to blockage by kelp and debris.

2.2.2 Tuggerah Lake Entrance Improvements – Entrance Restraining Wall, Public Works Department, 1988

This concept design report was completed for Wyong Shire Council by Public Work Department, Coast and rivers Branch in 1988 to provide advice for the design and construction of the restraining wall to maintain an open entrance for Tuggerah Lake.

The construction of the wall was reported to be an appropriate entrance management strategy by restraining the channel from migrating southward over the rock reef and improving the condition of the entrance channel. The study advised eastern and western revetments with a smaller profile for western wall compared to the eastern wall as it is located where the rock shelf is close to the surface, shown on **Figure 2.1** and **Figure 2.2**. The western wall being approximately 90 m long with a base at -1.2 m AHD and a crest level of 1.0 m AHD. The height of the wall is made up of two layers of sand filled geotextile tubes with a diameter of 1.3 m (7 tubes in the cross-section). The eastern wall being approximately 180 m long with a base at -1.3 m AHD and a crest level of 2.0 m AHD. The height of the wall is made up of three layers of sand filled geotextile tubes with a diameter of 1.3 m (12 tubes in the cross-section).

The orientation and arrangement of the walls and the crest heights were selected in a way to minimise obstruction of water view. The location of the walls is as far south as practicable to favour natural sand flushing processes, while at the same time ensuring the depth to bedrock is at least -6 m AHD in case installation of jet pumps is decided upon at some time in the future. A service life of 10 to 15 years and an initial construction cost of $580,000 (in accordance with The Entrance Channel – Studies and Reports document, $1.35 M in 2020) were estimated for implementing this measure.

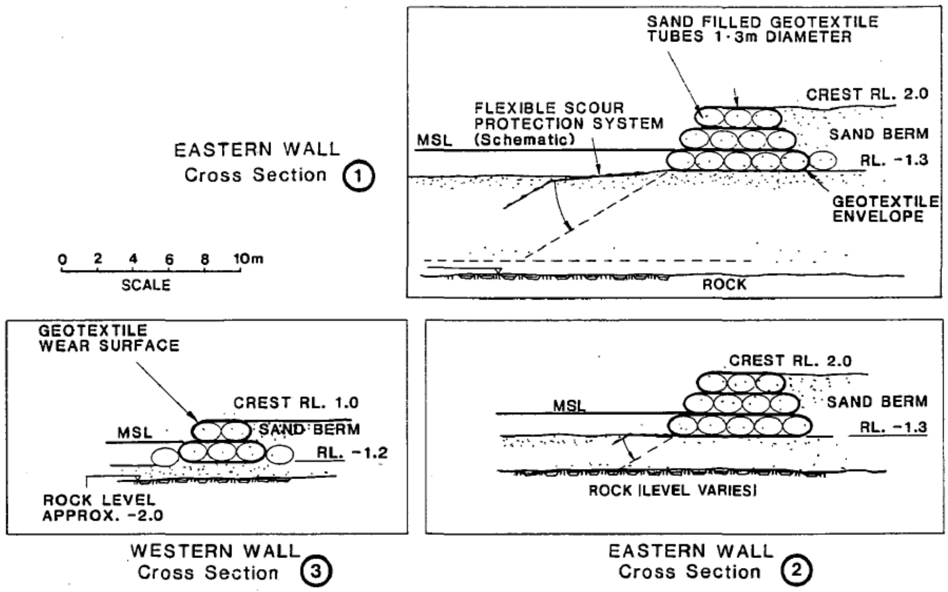


Figure 2.1: Cross-sections of the western and eastern restraining walls, reprinted from (Public Works Department, 1988).

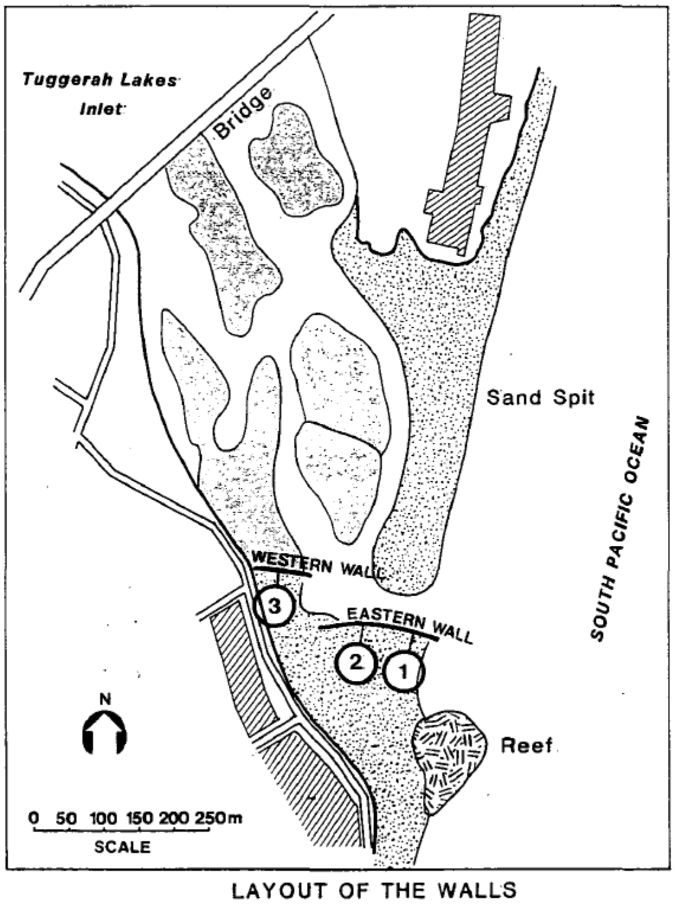


Figure 2.2: Location of the restraining walls, reprinted from (Public Works Department, 1988).

2.2.3 Tuggerah Lakes Flood Study. Compendium of Data, Public Works Department, 1992

This study provides a comprehensive description of earlier flood reports undertaken within the study area up until 1992, including the tributary creeks, flood levels from 1867 to 1992, rainfall data, weather data, and survey and mapping information.

2.2.4 Tuggerah Lakes Flood Study, Lawson & Treloar Pty. Ltd, 1994

The Flood Study Report for Tuggerah Lakes (Tuggerah, Budgewoi and Munmorah), completed for Wyong Council in September 1994 by Lawson & Treloar Pty. Ltd, was undertaken to determine the flood behaviour events with Annual Exceedance Probabilities (AEP) of 50%, 20%, 5% and 1% AEP as well as the Probable Maximum Flood (PMF). The model results from this study form the basis of Council's currently adopted flood planning levels for Tuggerah Lakes.

The flood frequency analysis was conducted based on the data collected from 1927 to 1992. The study utilised a WBNM hydrological model covering the entire catchment area and a MIKE-11 hydraulic model. The WBNM hydrological model covered the area of approximately 790 km^2 which was divided into 43 sub-catchments. The WBNM model was originally calibrated using the initial loss of 15 mm, continuing loss of 2.5 mm/hr, non-linearity parameter of n = 0.23 and lag parameter of C = 1.15. Both hydraulic and hydrological models were calibrated based on the recorded flood levels in February 1990, August 1990, and February 1992 events. Moreover, for design analysis the conditions near the entrance were obtained from an entrance breach model that was calibrated based on the historical floods.

The calibrated and validated hydrologic and hydraulic models were used to investigate flood behaviour for the 50%, 20%, 5%, 1% AEP design events (using Australian Rainfall and Runoff - ARR 1987 methodologies) and the PMF. The design flood levels were produced using the initial lake water level of 0.3 m AHD. The key findings from the report are summarised below:

- Flooding in Tuggerah Lake is influenced by both elevated ocean levels and catchment runoff. Joint probability analysis was undertaken to investigate the relationship between ocean levels, catchment runoff and wind. It was concluded that the storms producing severe rainfall on the catchment did not necessarily coincide with significant elevated ocean levels. Storm duration and entrance conditions were found to be the primary contributing factors in the propagation of the elevated ocean level. The 1% AEP flood level was modelled with ocean conditions characterised by spring tides and significant wave height of 4.5 m, with a 20 m wide initial entrance channel which scours to a wider channel during the simulated flood event.
- The results of the Flood Study showed that in 1% AEP event 48 hour was the critical duration; however, it was found that the 24 hour producing a PMF event.
- The peak flood level within the lakes system was found to be 0.91, 1.36, 1.8, 2.23 and 2.7 m AHD in 50%, 20%, 5%, 1% AEP events and PMF event, respectively.
- The Flood Study results found a significant lag time between the peak flood level upstream of Wyong and the peak water level in the lakes due to the retardation of flow through various road and railway crossings, and the substantial overbank flood storage areas in the lakes and floodplain downstream of Wyong. The entrance condition being the single most important aspect controlling flood behaviour in the lakes.

- Comparison of the peak flood level in the lake generated in the critical duration 1% AEP event (48 hrs) and 6 hrs PMF event revealed that the 1% AEP event resulted in significantly higher peak water level. This result highlights that a longer duration extreme flood is likely to be critical for Tuggerah Lakes as the volume of runoff is the principal factor in raising flood levels in the Lake system.
- The Flood Study results revealed that the water level in Tuggerah Lake rises faster than Lake Munmorah. One reasonable explanation is that the majority of the catchments drain from the southern part of the lake system via Ourimbah Creek and Wyong River into the Tuggerah Lake and the Lake Munmorah drains more slowly. However, the peak water levels are very similar and occur at roughly the same time.
- The report recommended long-term data collection at the entrance to the Pacific Ocean and streamflow gauging at the upstream river gauging stations.

2.2.5 Tuggerah Lakes Flood Study. Flood Forecasting System, Lawson & Treloar Pty. Ltd, 1994

Tuggerah Lakes flood forecasting system report was completed as a part of the Tuggerah Lakes Flood Study. A flood forecasting system was established based on the MIKE11 flood forecasting model. The FFS was commissioned in 1993 and utilised data from seven rain gauges and four river height gauges. The data are captured using the alert system. The reliability of the flood forecasting system will increase as more flood data become available and the system is recalibrated. To date, the system has not been tested in a real-time situation as it would appear it was not in operation for the June 2007 event.

2.2.6 Tuggerah Lakes Entrance Training Walls: Technical Discussion, Patterson Britton and Partners, 1994

This report was prepared for Wyong Shire Council in April 1994 by Patterson Britton and Partners to discuss the feasibility of establishing training walls at the entrance. It was documented that under average conditions, the lakes have a relatively small tidal range between 0.2 and 0.3 m above the mean sea level as a result of a narrow entrance channel and the extended upstream sand shoals. However, in the course of a major flood event, the average water level in the lake can decrease about 0.1 m and the tidal range within the lake can double.

The tidal flow ranges from 100 to150 m^3/s and tidal velocities from 1 to 2 m/s. At mid-tide and under average tidal conditions, the width of the entrance is around 25 to 35 m and the depth of the entrance is between 2.0 and 2.5 m.

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

This study discussed the impacts of implementing several measures including periodic dredging, entrance restraining wall, twin entrance training walls and twin entrance training walls with major channel dredging summarised in **Table 2.2**. Overall, it was concluded that constructing training walls considered impracticable due to the potential impacts on the water levels in the lakes and tidal range, increased flooding, storm surge and wave climate in the entrance and loss of upstream entrance shoals.

Table 2.2: Summary of entrance management approaches and their associated impacts (PBP, 1994).

Approach	Costs	Comments
Periodic dredging	• Capital cost of $0.9 million • Ongoing cost of $150000 per annum • Maintenance cost of $150000 to $300000 approximately every 4 years	• Entrance will remain unnavigable. • Entrance aesthetics and amenity maintained. • Lakes levels maintained unchanged. • Flood discharge potential maintained. • Adaptable to suit changing entrance conditions.
Entrance restraining wall	• Capital cost of $0.8 million • Ongoing cost of $250000 present value of replacement based on 10 to 15 year life. Maintenance cost of $7000 per annum	• Entrance will remain unnavigable. • Entrance aesthetics compromised. • Entrance amenity adversely impacted. • Lakes levels maintained unchanged. • Flood discharge potential maintained.
Twin entrance training walls	• Capital cost of $13 to 20 million • Maintenance cost of $1 to 1.5 million approximately every 10 years	• Entrance navigable by small recreation vessels. • Decreased average lake water level. • Potential for the erosion of North Entrance Beach. • Erosion of Entrance foreshores as a result of penetration of ocean swell. • Loss of entrance shoals. • Increased flood level. • Entrance aesthetics and amenity changed substantially. • Adverse impacts on lake foreshore habitat. • Increased lake flushing and recruitment of fish and prawns. • Ease of access for large marine animals including sharks. • Adverse construction impacts.
Twin entrance walls with major channel dredging	• Capital cost of $17 to 28 million • Maintenance cost of $1.5 to 2 million approximately every 10 years	• Entrance navigable by large vessels. • Decreased average lake water level to mean sea level. • Potential for the erosion of North Entrance Beach. • Erosion of Entrance foreshores as a result of penetration of ocean swell. • Loss of entrance shoals. • Increased flood level. • Entrance aesthetics and amenity changed substantially. • Profoundly adverse impacts on lake foreshore habitat. • Increased lake flushing and recruitment of fish and prawns. • Ease of access for large marine animals including sharks. • Adverse construction impacts.

2.2.7 Recalibration of Tuggerah Lakes model and Evaluation of The Entrance Dredging Impacts, Lawson and Treloar, 1999

This report was prepared for Wyong Shire Council in 1999 by Lawson and Treloar to investigate the impacts of widening and deepening the entrance channel on normal lake water levels.

This study investigated three options of 45 m wide channels with different dredging depths of -1.6, -3 and -4 Indian Spring Low Water (ISLW). Note that ISLW is about 0.93 m below AHD in the ocean. The outcomes of the study revealed that maintaining a channel to these dimensions would increase the mean tidal range and lower the mean lake level to between 0.15 m AHD and 0.12 m AHD, depending on the depth of dredging.

2.2.8 Tuggerah Lakes Estuary Management Study, Bio-Analysis Pty. Ltd, 2005

This report was completed for Wyong Shire Council in 2001 by Bio-Analysis Pt Ltd: Marine, Estuarine & Freshwater Ecology, to describe physical, chemical and biological patterns and identify management issues that would be the focus of a subsequent management study.

This study was prepared based on six estuary/catchment management principles to develop management objectives for the Tuggerah Lakes. These principles and objectives were summarised in **Table 2.3**.

Existing and potential issues to address the management objective for the Tuggerah Lakes include increased sediment and nutrient loads from development, erosion of creeks and banks, pollutants in stormwater runoff, reduced freshwater flow to the lakes, continuing development pressure, degraded foreshores, community perceptions, business needs and compatibility with the estuary, as well as future funding and management of the estuary.

The study investigated 27 management options shown **Table 2.4**.

Table 2.3: Principles and objectives for the Tuggerah Lakes Estuary.

Principles	Objectives
Water quality and quantity meet community needs and natural ecosystem requirements.	• Provide adequate environmental flow to sustain estuarine and riverine ecology; • Maintain water quality to protect healthy ecosystem function in the estuary and rivers; • Provide water quality in rivers and the estuary safe for primary human contact; • Maintain flow patterns while minimising flooding threat to life and property; • Provide adequate water for community water supply; and • Minimise changes to groundwater flow/stores.
The physical structure and vegetation of river, lake and wetland riparian zones are protected (and rehabilitated where required) to sustain healthy ecosystems.	• Protect, maintain & restore freshwater wetland vegetation; • Protect, maintain & restore aquatic and semi-aquatic estuarine vegetation; • Protect, maintain & restore floodplain vegetation; and • Protect, maintain & restore aquatic and riparian riverine vegetation.
Conserve the diversity of all native plant and animal species and to protect and assist the recovery of threatened and endangered species.	• The biodiversity and ecological function of the catchment shall be maintained in a manner that protects the estuary; • Minimise human disturbances that affect ecological function; • Maintain and protect environmentally significant areas and threatened species/communities; and • Ensure fishery is sustainable.
Human settlement, primary production and other land uses take place while protecting and enhancing Aboriginal cultural heritage, soil, water and ecosystem health.	• Ensure management of the estuary and catchment protects and enhances indigenous & non-indigenous cultural heritage; • Provide economically and socially justified levels of development whilst containing ecological impacts; • Support forestry, agriculture and other industries in the catchment while viability of downstream ecology is maintained; and • Protect and restore soil landscapes and improve understanding of land capability & suitability in the catchment.
The coastal zone environment is protected whilst providing for the social and economic needs of the community.	• Support existing industry where it is ecologically compatible; • Ensure any new commercial venture is socially and economically justified and is ecologically compatible with the estuary; and • Provide for public access and amenity at designated beaches and in designated recreation areas.
Improve knowledge of catchment and estuarine systems.	• Identify extent of information gaps and where appropriate undertake studies to improve understanding; and • Ensure community is pro-actively involved in estuarine health and management.

Table 2.4: Tuggerah Lakes Estuary management measures.

Item	Priority Programmes
1	Streambank rehabilitation and erosion protection
2	Stormwater management in new urban areas focussing on sediment and nutrient management, water sensitive urban design and producing more natural flows for downstream environments.
3	Retrofit stormwater interventions in existing urban areas focussing on sediment and nutrient management, contaminants and gross pollutants.
4	Undertake a programme of works to restore degraded or threatened habitat through rehabilitation, strategic land protection and active management of invasive species (e.g. weeds).
5	Foreshore management programme including identification and passive/active rehabilitation of key habitats such as saltmarsh and fringing wetlands and managing threatening processes on public and private lands.
6	Improve facilities in designated recreation areas based on community consultation including additional seating, BBQs, picnic areas, educational signage, upgraded boat ramps.
7	Limit public access to ecologically sensitive areas of the foreshore and estuary where necessary, including saltmarsh (e.g. Tuggerah Bay) and seagrass habitat (e.g. Budgewoi Sandmass).
8	Audit sub-catchments for environmental compliance including sediment/erosion and contaminant controls.
9	Develop a catchment audit process for assessing high-risk catchments and prioritising interventions.
10	Continue to monitor faecal coliforms at recreational Locations.
11	Monitor key wetlands for degradation and changes in condition.
12	Develop a population strategy that is based on what environmental changes the estuary, rivers and catchment can sustain rather than on available land.
13	Develop partnerships with universities to get innovative approaches to sustainably managing the catchment and estuary.
14	Develop partnerships with developers and business operators to get innovative approaches to managing the catchment and estuary in a sustainable manner.
15	Explore the development of a central body to oversee programmes and expenditure for estuarine management.
16	Develop funding strategies to ensure on-going and dedicated catchment and estuarine management programmes.
17	Develop strategies to identify and manage key remaining catchment habitats
18	Maintain ocean entrance dredging programme.
19	Maintain river mouth dredging on a rolling 5 years programme for Tumbi, Ourimbah, Wyong, and Wallarah/Spring Creeks.
20	Continue to maintain stormwater treatment devices ensuring performance data are collected and analysed.
21	Designate foreshore recreational areas and manage/encourage maximum recreational use and enjoyment including beach cleaning and wrack management.
22	Maintain identified foreshore rehabilitation areas, protect sensitive habitats and educate the community about the habitats.
23	Provide a process for addressing key estuarine process & management questions such as faecal coliform sources, fishery status, bioindicators, groundwater, sea-level rise and mixing.
24	Conduct appropriate research into riverine ecological processes and water quality to support environmental flow management.
25	Prepare and implement an ongoing community information and education programme about estuarine health using websites, newspapers, Council columns and field days.
26	Improve pollution source control through education of community, industry & tourists.
27	Develop incentives for the community to encourage sustainable use of water and pollutant reduction.

2.2.9 Tuggerah Lakes Estuary Management Plan, Bio-Analysis Pty Ltd, 2006

This report was prepared for Wyong Shire Council in October 2006 by Bio-Analysis Pt Ltd: Marine, Estuarine & Freshwater Ecology, to determine measures directed at maintaining and/or improving estuarine wellbeing and provide indicative cost estimates for the implementation of those measures.

The Tuggerah Lakes Estuary Management Plan provides the platform for sustainable, cooperative management of the lakes system. The 27 priority programmes from the Estuary Management Study have been grouped into four main action plans as listed below. The estuary management plan will be revised every 5 years, the following action plans required to be developed each year to set out actions, responsibility and allocate funding for the coming year.

Table 2.5: Tuggerah Lakes Estuary management plans and allocated funding.

Action Plan	Goal	Funding ($ per annum)
Water Quality	Improve the quality of stormwater from the catchment	$2,180,000
	Ensure beaches meet primary water contact requirements	$81,000
	Stabilise foreshore and streambank erosion	$640,000
	Encourage sustainable use of water	$269,000
Ecology	Improve foreshore habitat	$629,000
	Protect and restore catchment habitat	$564,000
	Protect estuary habitat	$18,000
	Learn how changes to flow in the rivers affect plants and animals in the estuary	$296,000
Socio-economics	Improve recreational facilities around the lakes and creeks	$2,200,000
	Provide estuary positive business opportunities	$127,000
	Develop sustainable targets for development	$116,000
	Maintain creek mouths for navigation and water flow	$550,000
	Maintain flow through the entrance	$432,000
Knowledge and Management	Establish an estuary management body	$381,000
	Learn more about key processes in the estuary	$343,000
	Develop partnerships with universities	$52,000
	Provide the community with current information on the estuary	$459,000

2.2.10 The Entrance Dredging Project Review of Environmental Factors, WorleyParsons, 2009

This report was prepared for Wyong Shire Council by WorleyParsons in 2009 to review the impacts of the entrance dredging project on environmental factors. It was reported that dredging allows a sustainable and local supply of material suitable for nourishment of the deleted beaches minimising the potential for erosion to the adjacent dues and reduction of impacts to associated ecosystems, infrastructure and property. However, some minor and temporary impacts were identified based on this REF and associated investigations. In this study, several management and mitigation measures were proposed for the purpose of dredging Environmental Management Plan tabulated below.

Table 2.6: Dredging projects environmental management and mitigation measures.

Action Plan	Measures
Erosion	• Dredging of Town Beach on an “as needs” basis. • Visual monitoring of the shoreline of Terilbah Island. • Dredging is not recommended in the portion of the sump in the flood tide shadow zone on the western side of Yellawa Island. • Visual monitoring of the shoreline of Yellawa Island and monitoring of the infilling of the sump by a survey. • Shaping of placed sand by dozer into a cross-shore and alongshore profile consistent with a natural accreted beach state. • Establishing cross beach survey transects for beach nourishment areas and undertaking pre- and post- dredging and beach nourishment surveys. • Carrying out the regular photogrammetric analysis as undertaken for the Coastline Management Plan (WSC, 2009). • Maintenance of a dredge log to record source, placement area and volumes of dredge material being placed.
Water quality	• Monitoring of the pH of the discharged dredge slurry within 30 minutes of the dredge commencing operation each day in accordance with EPL3200. • Regular visual monitoring of turbidity within the dredge area and at the discharge location within each beach nourishment area by the dredge crew. • The dredge master would undertake all reasonable efforts to minimise turbidity during dredging and during discharge at each beach nourishment area. • The dredge master would implement all reasonable and feasible contingency measures to minimise prolonged visible turbidity plumes.
Fuel Storage and Handling	• Regular inspection of plant and equipment to minimise the risk of oil and fuel leaks. • Display of Material Safety Data Sheets (MSDS) onboard the plant. • Carrying out of all re-fuelling and associated activities in accordance with Council’s Dredge Procedure’s Manual (Procedure Manual OS and R – 010). • Following the procedure, in order, by the dredge crew in the event of an accidental fuel spillage: Control, Contain, Notify the Supervisor, and Clean Up the spill. • Notification of the NSW Fire Brigade (call 000) and relevant Government agencies (NSW DECC EPA Group) by the Supervisor to enable removal/ treatment in a focussed and well-coordinated manner. • Fitting of the dredge with appropriate environmental controls such as absorbent pads and booms and pumping equipment. • Management of any spillages in accordance with the relevant Material Safety Data information for the material being handled.
Ecology	• Avoiding harm to all areas of saltmarsh and seagrasses outside of the immediate dredge footprint. • Application of a permit to harm marine vegetation under Section 205 of the Fisheries Management Act 1994. • Dredging of those areas to the west of the bridge during the ebb-tide. • Temporary cessation of dredging in the event of seeing Green Turtles in the vicinity of the dredge area. • Continued monitoring by Council of the arrival, breeding and nesting of Little Terns at The Entrance sand spit. • Implementing a pre-dredge survey for each area. • Identification and removal of any Bitou Bush and noxious weeds within the potential beach nourishment areas prior to the placement of dredged material.
Noise	• Restriction of working hours between 6 am and 6 pm Monday to Wednesday and between 6 am and 2.30 pm (and up to 6 pm when necessary) from Thursday to Saturday. • Selection of appropriate plant and equipment and fitting of plant and equipment with noise control devices where necessary.

Heritage	• Stopping the work in case of finding any item of potential non-indigenous heritage significance and contacting the NSW Heritage Council in accordance with the Heritage Act 1977. • Stopping the work in case of finding potential indigenous heritage significance and contacting DECC and the Local Aboriginal Land Council in accordance with the *National Parks and Wildlife Act 1974*.
Air quality	• Regular maintenance of all plants and equipment to minimise the emission of smoke, fume and other air pollutants into the atmosphere. • Suspension of use and undertaking of maintenance (if necessary) of any plant/ equipment found to be emitting visible smoke/ fumes. • Maintaining all services/ inspecting logbooks.
Amenity	• Completing works prior to the summer holiday period. • Restricting working hours between 6 am and 6 pm Monday to Wednesday and between 6 am and 2.30 pm (and up to 6 pm when necessary) from Thursday to Saturday. • Mounding of placed sand to allow oxidation and bleaching of discoloured sands. • Operating a telephone complaints line in accordance with EPL3200 during operating hours. • Notifying the public regarding the complaints telephone hotline number. • Recording of any complaints, any action taken, and any responses/follow-up contact provided to the complainant. • Manage the turbidity impacts. • All plant, equipment and waste would be removed following the operation with the exception of safety signage adjacent to the dredged channels within the estuary.
Access and safety	• Managing navigational hazards as a result of the dredge and pipeline in accordance with NSW Maritime requirements. • Signage at Picnic Point Boat Ramp and The Entrance North Boat Ramp. • Permanent signage along the foreshores of the dredge footprint. • Fencing and signing the outlet of the discharge pipeline at the time of beach nourishment activities. • Restricting public access to the nourished area until the material has been reshaped into a profile consistent with the naturally accreted beach state. • Chaining the discharge pipeline to the rock platform and signing during the placement on the Entrance Beach. • Nourishing the Entrance Beach only during periods of reduced swell height. • Requirement of two personnel to operate the dredging work. One person is also required to continually monitor the pipe outlet at the beach nourishments area during operational hours.
Waste	• Collection, temporary storage and appropriate management of all waste material retrieved from The Entrance Channel and generated during the works. • Monitoring of the beach nourishment areas during placement of dredged material and during the shaping of material with bulldozers. • Waste management would be undertaken in accordance with the philosophy of the NSW Waste Avoidance and Resource Recovery Act 2001 under a Waste Minimisation Hierarchy.

2.2.11 Entrance Dynamics and Beach Condition at The Entrance and North Entrance Beaches, Umwelt Pty Limited, 2011

This report was completed for Wyong Council in April 2011 by Umwelt Pty Limited, to investigate the sediment transport processes affecting sediment budget and coastal morphology at the North Entrance Beach and at the Entrance to Tuggerah Lake, as well as assessing a range of options to managing the sedimentary processes. This study concluded and recommended:

- Council should continue its existing dredging program;
- North Entrance Beach is receding. Placement of dredged sands on the beach will slow the recession;
- Council should not construct training walls at The Entrance as there is no investigation indicating that training walls would benefit the lake or North Entrance Beach;
- High volume dredging or removing the sand berm to a permanently wide condition are also not supported as it will cause enhanced wave penetration;
- Undertake further investigation on sand deposits at the depth of closure, inner tidal delta and sand on the inner shelf followed by more detailed modelling of sediment transport systems, a 3D hydrodynamic and sediment transport model of the entrance area.

2.2.12 Longshore Sand Transport and Tidal Inlet Stability Study for The Entrance and The Entrance North, SMEC, 2011

This report was prepared for Wyong Shire Council in March 2011, by SMEC, undertaken an investigation to understand the dynamics of the Entrance and to estimate potential longshore sediment transport rates as well as compile a conceptual sediment transport model of the Entrance and North Entrance beach. The study area covers the Entrance and several kilometres north of the Entrance along the Entrance north beach.

The evolution of Tuggerah Lake Entrance was determined through analysing the aerial images from November 1941 to March 2006. This study utilised SWAN wave transformation model to determine the longshore sediment transport rate due to the wave action over a given period of time. A conceptual sediment transport model of the Entrance area and North Entrance beach was set up based on the results of the previous calculation shown on Figure 2.3.

A predominantly northward sediment transport occurs along the North Entrance Beach due to the swell. It was observed that southward sediment transport entering the inlet at the Entrance and along the Entrance northern spit. Sand carried out by the ebb tide through the entrance channel deposits on the entrance sand bar area, whereby it becomes available for onshore transport back onto the beach. Flood tide and breaking waves carry the sands from the entrance bar both southward back to the entrance shoals and northward along the coast, with some being brought onshore by wave action. The estimated magnitudes and pathways of detailed sediment transport within the five regions along the Entrance North are shown on **Figure 2.4**.

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

The results of the sensitivity analysis revealed an increase in the average lake level when the entrance is shallower and an increase in tidal range when the entrance is wider. The length of the channel slightly decreases the tidal range and increases the water level. The water level in the lake does not exceed 0.15 m and the tidal range is around 0.2 m (only the tidal impact has been taken to account, no rainfall and fluctuation in atmospheric pressure were considered). The low tidal range within the lake and the low tidal prism cause the low velocities resulting in sand deposition within the entrance over time. If the dredging works stop eventually the entrance will close. Flood events may increase the flow at the entrance and generate erosion that would widen the entrance temporarily.

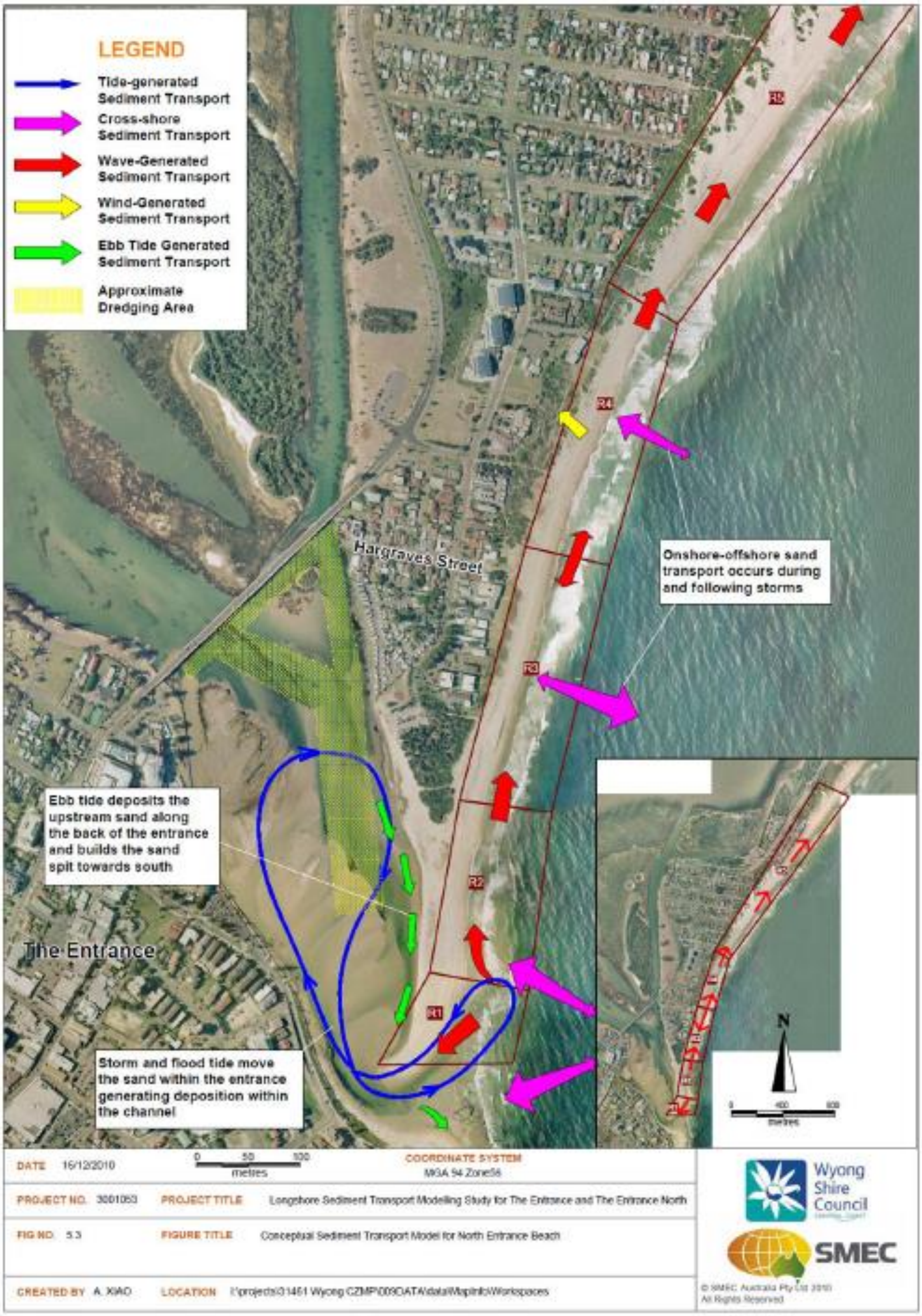


Figure 2.3: Conceptual sediment transport model for North Entrance Beach, reprinted from (SMEC, 2011).

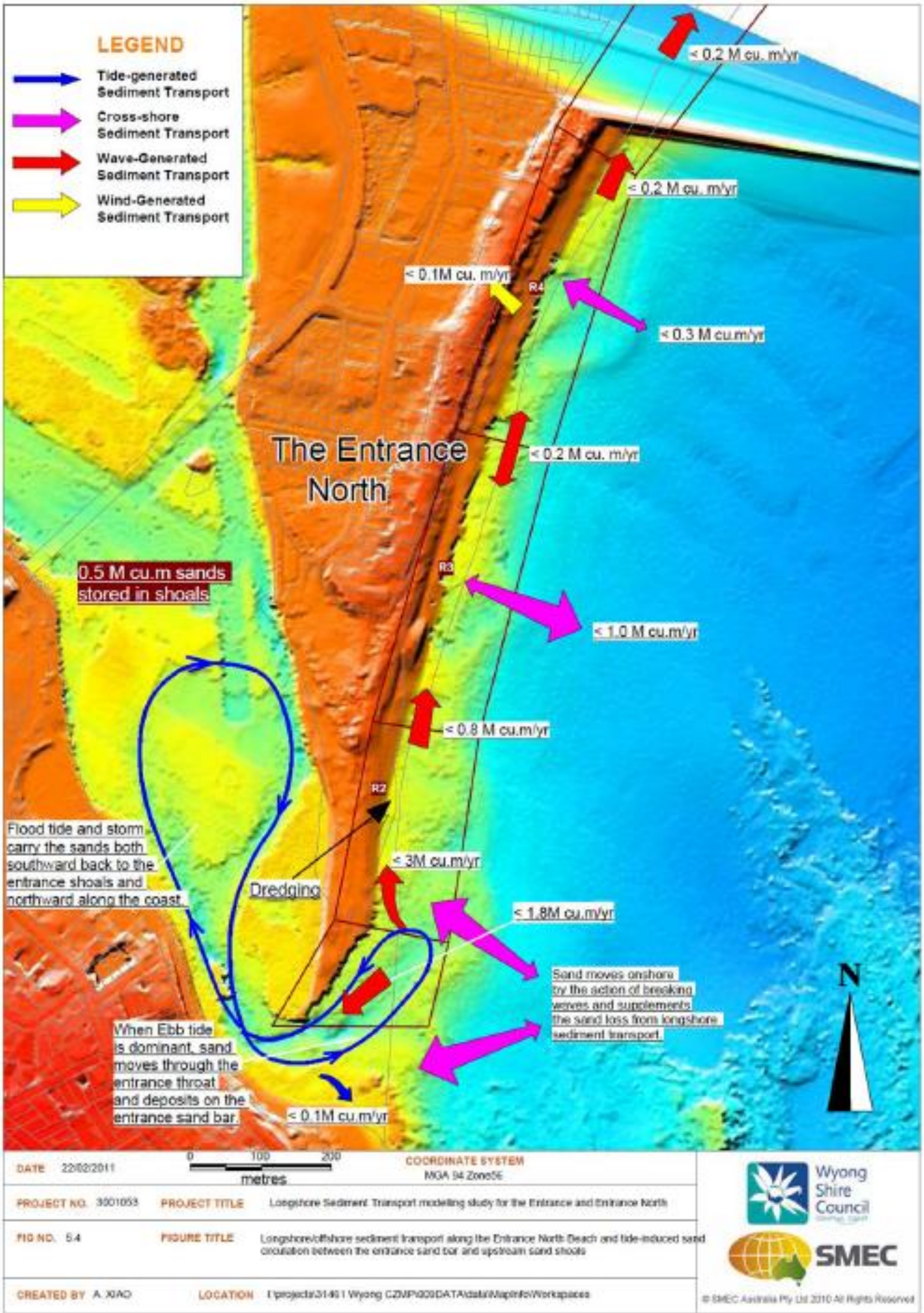


Figure 2.4: Sediment transport along the Entrance North beach, reprinted from (SMEC, 2011).

2.2.13 Coastal Zone Management Plan for the Wyong Coastline, Umwelt, 2011

The Coastal Zone Management Plan (CZMP) for Wyong Shire (Wyong CZMP 2011) was developed in partnership with the NSW Office of Environment and Heritage and prepared in accordance with the NSW Government's coastal legislation policies and guidelines at the time. The CZMP outlines strategies for managing coastal risks along the Wyong coastline from Catherine Hill Bay to Crackneck Point, with the aim of ensuring residents and visitors are able to enjoy an attractive coastal landscape now and into the future, as a place to live and work, a place for recreational activity and a place where healthy natural systems are protected.

Recommended actions in the CZMP related to Tuggerah Lakes entrance included:

- A9: Continue to dredge sand from the active tidal delta in The Entrance channel and place the sand on North Entrance beach. Some sand may also be placed on The Entrance Beach. This was recommended as an ongoing action utilising existing approvals and funding arrangements at the time.
- A67: Establish a detailed monitoring program to clarify how sand placed on North Entrance beach is redistributed and to facilitate a review to provide more effective sand retention. This was recommended as an ongoing action and included monitoring of the entrance channel, North Entrance Beach and The Entrance Beach.

2.2.14 Impact of saltmarsh rehabilitation and regrading of shorelines on nearshore condition, OEH, 2013

This report was prepared for Wyong Shire Council in June 2013 by OEH to evaluate the impact of shoreline restoration strategies on the nearshore environment. As a part of this study, a field survey was undertaken on 19th to 21st of November 2012 at Long Jetty, Berkeley Vale and Lake Munmorah.

The study outcomes revealed that saltmarsh rehabilitation and regarding shorelines have improved the condition of the nearshore environment at Long Jetty and Lake Munmorah with less black ooze formation. The Berkeley Vale sites degraded beyond the point where shoreline restoration strategies alone could have any positive impact on the nearshore zone. Regraded shorelines facilitated the delivery of some wrack onto the shore but given the huge quantities of wrack produced in the lake system, and fairly constant lake level resulting from entrance management, additional strategies are required to manage wrack volumes in the nearshore zone.

Nearshore condition at most saltmarsh sites was still poor. Degraded sediments were widespread, and macroalgal blooms were common in the nearshore waters in front of all saltmarsh sites. The results reflected the general pattern of poor water quality in nearshore waters due to the chronic input of urban stormwater with very high concentrations of nutrients. Adverse effects of nutrient and sediment inputs from adjacent stormwater drains/creeks were observed at most sites, such as heavy ooze accumulations concentrated around the mouth of stormwater drains/creeks, large volumes of oozy sediment and elevated nutrient concentrations. It was noted that shoreline restoration alone will not greatly improve the condition of the nearshore if the quality and quantity of stormwater pollution remains at the current level.

This study recommended the following measuring:

- Continuing efforts to rehabilitate saltmarsh habitat and restore low-gradient sloping shorelines around the lakes were recommended;
- Efforts to improve the nearshore condition along highly degraded areas, such as Long Jetty foreshore and the western shores of lower Tuggerah Lakes, need to focus on improving the quality and quantity of stormwater delivered to this area; and
- Once nutrient and fine sediment inputs to the nearshore are substantially reduced and nearshore waters are better flushed with lake-basin water, saltmarsh rehabilitation and shoreline restoration may further improve the condition of the nearshore.

2.2.15 Recommendations for Management of Ooze in Tuggerah Lakes, OEH, 2013

This report was prepared for Wyong Shire Council in June 2013 by OEH to prepare strategies to manage ooze in the nearshore areas. The key objectives of this study can be summarised as reducing nutrient and sediment loads entering the nearshore in stormwater runoff, transporting wrack onto shore to dry aerobically, and improving water flow in nearshore areas through increased mixing with lake and basin water.

The study recommended summarised the following strategies to manage the water quality in Tuggerah Lakes:

- Improve the quality of stormwater entering nearshore zone using multiple approaches
    - Community education and behaviour change through promoting reducing the use of nutrient-rich chemicals in the home and keeping green waste out of stormwater drains.
    - Regular cleaning/maintenance of 'wet' storm drains and gross pollutant traps
    - Seal roads and verges
    - Retrofit stormwater improvement devices
- Rehabilitate saltmarsh habitat and restore low - gradient shorelines around the lakes
- Wrack harvesting
    - Strategic harvest of offshore accumulations of wrack
    - Sensitive harvest of wrack from nearshore areas
    - Community harvest for council collection

2.2.16 Tuggerah Lakes Monitoring Program, OEH, 2013

This report was prepared for Wyong Shire Council in July 2013 by OEH to develop a dataset to effectively track estuary health and implement appropriate management measures as needed. In this program water clarity, nutrient concentration and a biological component were monitored through measuring total suspended sediment and turbidity, Chlorophyll-a and seagrass depth range, respectively.

It was observed that these parameters were consistent with NSW monitoring and reporting standards. The program outcomes revealed a lower salinity in the nearshore zone indicating the influence of stormwater runoff and groundwater discharge on the nearshore zone. A physical barrier was created between the lake basins and the nearshore zones via dense seagrass beds, macroalga growth and wrack accumulations. This physical barrier prevents mixing between the lake basins and nearshore zones. Nutrient enrichment is a major threatening factor in the nearshore zone contributing in the formation of black ooze and creating sulphidic conditions in the sediment. In the lake basins, high turbidity is the major threatening factor as a result of the resuspension of fine sediment derived from the upper catchments. High turbidity reduces light penetration and over a long-time can impede the growth of seagrass. Further monitoring was recommended to build on long-term datasets.

2.2.17 Restoration of Tuggerah Lakes through improved water quality management, OEH, 2013

This report was prepared for Wyong Shire Council in August 2013 by NSW Office of Environment and Heritage to undertake an investigation to provide information on the key components and processes driving ecosystem health and subsequently for developing management and planning strategies.

As part of this study, a hydrodynamic model was developed to represent the movement of water and material around the lakes over time and the influences by key driving forces including wind, catchment discharge and exchange with the ocean. The hydrodynamic model identified that there are two distinct hydrologic zones within the lakes: the lake basin and the nearshore zone. Seagrass beds and macroalgae growth form a physical barrier between the lake basin and nearshore zone preventing mixing between the lake basins and nearshore zones. This study recommended the following measures to manage Tuggerah Lakes water quality.

- Improve water quality of catchment runoff: sealing of roads, improve stormwater management and a reduction in nutrient and sediment loads.
- Shoreline remediation: regrading of banks and establishment of saltmarsh reserves.
- Ongoing management of stormwater quality, and in limited circumstances of wrack.

2.2.18 Tuggerah Lakes – The Entrance Morphodynamic Modelling. Entrance Beach Management Investigations, Cardno, 2013

This report was completed for NSW Office of Environment and Heritage in 2013 by Cardno, to study a range of management options for the Entrance Beaches.

The study utilised a Delft3D modelling system to study a range of management options. The model covers the entire area of the three lakes, adjacent ocean and beaches. The model was calibrated based on dry weather conditions and for the severe flood of June 2007 to replicate the observed behaviour of the existing lakes system. This study applied LITPACK coastal processes modelling system including LITDRIFT and LITLINE modules to compute longshore sediment transport and determine changes to a shoreline over a period of time. Also, SBEACH was used to describe the variations in beach amenity due to beach nourishment.

The study investigated five management options summarised below:

- Option 1: Periodic South Entrance Beach nourishment - This option consisted of periodic sand nourishment (10000 m^3) on South Entrance Beach in conjunction with Councils dredging program. This option would enhance beach amenity in front of the surf club and other areas of the beach. However, it is expected that this nourishment is required approximately every five years.

- Option 2: Short groyne at South Entrance Beach and periodic South Entrance Beach nourishment – This management option consisted of locating a 100 m long rock groyne south of the SLSC tower along with the periodic sand nourishment. This option would extend the time that sand is retained on South Entrance Beach post nourishment by 2 to 5 years. Therefore, in this option re-nourishment is required approximately every 7 to 10 years.
- Option 3: Long groyne at South Entrance Beach and periodic South Entrance Beach nourishment - This management option consisted of locating a 130 m long rock groyne approximately 400 m north of the SLSC tower along with the periodic sand nourishment. This option would extend the time that sand is retained on South Entrance Beach post nourishment by 2 to 5 years. Also, implementation of this option may cause sand being trapped gradually on the southern side of the rock groyne after each significant flood resulting in a long-term accumulation of sand on the South Entrance Beach. Therefore, in this option re-nourishment is required approximately every 7 to 10 years.
- Option 4: Northern Entrance training wall and Northern revetment wall along with periodic South Entrance Beach nourishment – This option comprises the construction of a training wall to a high crest level and a revetment along the shoreline up to Karagi Park and to the Entrance Bridge. Implementation of this option would gradually trap sand on the northern side of the training wall after each significant flood event and prevent erosion and shoreline recession inside the entrance at Karagi Park. Also, the Southern Entrance Beach nourishment would be required approximately every 5 years to enhance the beach amenity in front of the surf club and other areas of the beach.
- Option 5: Fully trained entrance along with initial South Entrance Beach Nourishment – This option involved a northern training wall and northern revetment wall on the northern side of the entrance channel, as well as a southern training wall on the southern side of the entrance channel. Implementation of the current measure would gradually trap sand on the North Entrance and South Entrance beaches. Revetment would prevent erosion and shoreline recession inside the entrance at Karagi Park. Fully trained walls would extend the time that sand is retained on South Entrance Beach after nourishment by 5 to 10 years.

This study resulted in the NSW Government – as an election commitment - building a short groyne to hold sand on The Entrance Beach.

2.2.19 Tuggerah Lakes – The Entrance Morphodynamic Modelling, Cardno, 2013

This report was prepared for NSW Office of Environment and Heritage in 2013 by Cardno, to assess the efficacy of possible training of the entrance in improving the water quality of the lakes.

The study utilised a Delft3D package to model the potential effectiveness of entrance training walls in addressing water quality issues. The model covers the entire area of the three lakes, adjacent ocean and beaches. The model was calibrated based on dry weather conditions and for the severe flood of June 2007 to replicate the observed behaviour of the existing lakes system.


Figure 2.5: Training walls investigated by Cardno 2013.

The impact of training walls on the flooding was investigated by simulating the passage of 1% AEP flood event. Several scenarios were investigated including the existing case (no training wall), a single training wall located 150 m north of the entrance training walls, dual training walls at 100, 150 and 200 m apart.

The key findings from the report on Tuggerah Lakes are summarised below:

- The study results show that the single and dual training wall scenarios with 150 and 200 m wide openings had no significant impact on peak flood levels around the lakes.
- The results revealed that limiting the entrance to a 100 m wide opening caused an increase in peak flood levels of about 0.08 m. Also, it was estimated that the water levels remain elevated for several days longer than other scenarios, with in-excess of 1300 properties around the lake expected to experience over-floor flooding. Therefore, the training wall with an opening of 100 m was discarded.
- The model was simulated for a six weeks post-flood period and its results revealed that the entrance would not self-scour and shoaling would commence once the flood subsided, highlighting that the training walls do not materially improve the scouring and transport of sediment in the entrance area in the short to medium term. However, the results show a gradual accumulation of sand on North Entrance and South Entrance beaches in the immediate vicinity of the training walls after severe flood events.
- It has been concluded that maintaining an open connection between Tuggerah Lake estuary and the ocean through training walls would not impact the flushing of the lake system, and thus would not be expected to affect water quality within the lake. Therefore, maintaining an open channel through either dredging or training walls would not significantly affect water quality in the lake.
- The results revealed that the maintenance dredging of the type already undertaken by Council should be continued.

Dredge channel infilling was simulated to be approximately 6000 m^3 after 2 months following dredging of a channel approximately 30 - 50 m with bed depth of -1.5 m AHD (dredge volume of 28,800 m^3). The infill rate was modelled to decelerate with time following dredging and was estimated to completely infill after approximately 500 days. The results were found to be in good agreement with Council's dredging program.

2.2.20 Report on the safety of navigation should training walls be established at the barway entry to The Entrance in NSW, Weston, 2013

This report was prepared by Captain Charles Weston and included in Appendix H of the Cardno (2013) study. The report provides recommendations regarding the boat navigation safety at the entrance of Tuggerah Lakes with and without training walls. Recommendations included:

- Navigating the existing bar is dangerous and should not be attempted. Actions to raise public awareness regarding these dangers are addressed including signage, pamphlets and online safety notices.
- Improved navigation offered by a trained entrance is limited by the presence of the existing rock shelf.
- Should the rock shelf be removed and the depth of the entry between training walls be increased by dredging then this would facilitate its use by larger vessels with appropriate safety signage, navigation marks and assistance of Volunteer Marine Rescue to manage navigation.

2.2.21 Tuggerah Lakes Floodplain Risk Management Study and Plan, WMAwater, 2014

WMAwater was commissioned by Wyong Shire Council in November 2014 to prepare Tuggerah Lakes floodplain risk management study and plan. The study utilised a calibrated and verified WBNM hydrological model and a MIKE11 1D hydraulic model developed as part of the Flood Study in 1994 to investigate several flood risk management measures. WBNM model was used to calculate flows based on the rainfall over the entire catchment area. The outcomes of WBNM model were input to a MIKE11 model to determine the water level in the Lakes. This report recommended several options to manage flooding in Tuggerah Lakes, which led to a short-list of 14 actions, tabulated in **Table 2.7**.

The Floodplain Risk Management Plan also investigated a range of options which were not recommended for implementation. One of these investigated options aimed at increasing the capacity of the entrance channel under two scenarios including:

- Scenario A: a 250 m wide (dredged to -1 m AHD) channel from the road bridge to the ocean; and
- Scenario B: as above plus removal of the beach berm at the entrance.

Table 2.7: Proposed floodplain risk management options.

Priority	Measure	Description
High	Adaption Planning for foreshore suburbs	Detailed investigation into the long-term land use planning for low-lying lands that feasibly cannot be protected against future sea-level rise by structural measures.
	Flood Emergency Management Planning	SES should confirm any evacuation procedure that can be realistically achieved and will not endanger lives.
	Public Education and Raising Flood Awareness	-
	Development of management plan for vulnerable water and sewer assets	Develop a management plan for vulnerable water and sewer assets which had been turned off during significant flood events as well as minor evens.
	Formalise an entrance management strategy to manage flooding	Aiming to include emergency entrance opening for the management of flooding considering sea-level rise and its impact on geomorphic and environmental characteristics of the area.
	Develop asset management procedures for the Wilfred Barrett Drive levee	Develop asset management procedures for the levee of Wilfred Barrett Drive as well as the stormwater outlets and rubber backflow valves.
	Update Section 149(2) planning certificates	-
	Address and manage local frequent flooding issues	Investigate and manage measures to address the local flooding issues identified and recorded after significant floods.
	Maintenance of water level and rainfall gauges	Ensure the existing water level and rainfall gauges in the catchment are in working order at all times.
	Undertake transfer of all relevant flood related information to the community Insurance Council of Australia and NSW State Emergency Service	Provide the Insurance Council of Australia and NSW State Emergency Service with the updated flood maps and flood related information.
Medium	Review Tuggerah Lakes Flood Study and Floodplain Risk Management Plan	Review could include assessment of wind wave run up along with sea-level rise in Tuggerah Lakes, assessment of recommended entrance management measures.
Low	Assess and manage the risk of electrocution during floods	Risk of electrocution should be addressed and managed by both the asset owner and electricity provider due to the high risk of electrocution during floods.
	Investigate opportunities for house raising	Raise the vulnerable properties above the flood planning level within the floodplain of Tuggerah Lake.
	Develop specific flood related controls for existing and future tourist parks	Address and manage the risk to the safety of occupants and damage to structures.

It was concluded that increasing the capacity of the entrance channel through implementing scenario A would lower peak flood levels in 1% AEP events by up to 0.31 m (reducing the water level from 2.23 m to 1.92 m). Also, scenario B resulted in lower peak flood levels in 1% AEP events by up to 0.45 m (reducing from 2.23 m AHD to 1.78 m AHD). Although enlarging the entrance channel would reduce the peak water level for the 1% AEP event, this measure was not recommended for the following reasons:

- Maintaining a fully open channel of these dimensions is not physically or economically viable;
- Adverse environmental impacts on Tuggerah Lakes ecosystem;
- Adverse impacts on local tourist industry;
- Potential adverse ocean wave impacts in the entrance channel;
- Potential negative impacts on the local coastal environment; and
- Concerns about the need to better consider scenarios that consider the impacts of large ocean swell events, which may produce higher levels in the lakes.

The report also acknowledged the subsequent work carried out by Cardno in 2013, which found that training walls less than 150 m wide would make flooding worse.

2.2.22 Additional Morphological Modelling - The Entrance, Cardno, 2015

This report was prepared for Wyong Shire Council in February 2015 by Cardno, to investigate the impacts of deepening the entrance channel through dredging and removal of part of the underlying rock at the lake entrance.

Cardno utilised a calibrated Delft3D modelling system developed for the OEH by Cardno (2013) to undertake the wave, hydrodynamic morphological modelling required for this investigation.

This study simulated the following cases:

- No training walls;
- Fully trained entrance (150 m wide channel)

Five entrance dredging scenarios were investigated for each of the above cases including no dredging, dredging entrance channel bottom at -1.5, -2.5, -4, -5.5 m AHD corresponding to 1, 2, 3.5 and 5 m depth at mean low water, respectively. The key outcomes of the investigations revealed that:

- Infill would initiate almost immediately from both the upstream and downstream ends of the dredged channels;
- Training walls would decrease the rate of infill from the downstream end (the ocean);
- Training walls would not have significant impact on water quality and water level in the lakes system compared to the modelled dredging channels without training walls;
- Dredging channel would increase the conveyance and tidal exchange between the lake and ocean, as well as increase lake salinity. There is a positive relationship between the conveyance increases and channel depth. However, these increases are limited by the shoaled region upstream of the bridge;

- Dredging channel would result in lower mean water level in the lake by up to 0.1 to 0.2 m. On the other hand, it would increase the lake tidal range resulting in higher high tide levels and lower low tide levels;
- Dredging channel would result in higher tidal current speeds upstream of the Entrance Bridge. It may result in scour around the Entrance Bride foundation and in the long term it may cause the shoreline and channel changes along the Terilbah Reserve; and
- The reduction in the mean water level in the lake may cause ecological and recreational consequences.

2.2.23 Review of Environmental Factors - The Entrance Rock Groyne. NSW Crown Lands, 2016

In 2017, a rock groyne was constructed by the NSW State Government at South Entrance Beach just south of the entrance region (NSW DPI, 2016). This report provides an overview of the design of the rock groyne and assessment of its environmental impacts. The groyne is composed of 2 layers of basalt primary armour (median diameter d_{50} = 1.2 m) and is approximately 100 m long extending from the existing revetment wall seaward to a depth of -0.6 m AHD.

The rock groyne was built with the intended benefit to provide an increased length of time that sand stays on the beach and hence maintain amenity and recreational access to the beach than would otherwise be the case before nourishment is required due to natural coastal processes (NSW DPI, 2016). As a result of the likely increased sand retention on the South Entrance Beach, the beach was expected to be on average wider, reducing the impacts of beach erosion and recession due to sea level rise (NSW DPI, 2016). The likely impacts of the rock groyne on coastal processes and entrance dynamics were assessed prior to construction by Cardno (2013b) and are described in Stage 2 works of the present study.

2.2.24 Breakwaters and training walls – The good, the bad and the ugly, Nielsen and Gordon, 2016

This paper was presented at the 2016 NSW Coastal Conference and addresses the potential long-term impacts of entrance breakwaters and training walls on coastal and estuary processes utilising examples and experience on the NSW coast. The excerpt of the conclusions is provided below:

> *Breakwaters constructed at estuary entrances have the potential to alter fundamental coastal and estuary processes inducing changes that may take centuries to resolve. While many beneficial and adverse impacts of breakwater construction have been well-known for many years, such as the improvements to navigation and flood mitigation and the interruption to littoral drift transport causing down-drift erosion, some impacts have not been understood and have been identified only recently, such as:*
>
> - *Breakwaters can change local wave transformation patterns, inducing large scale changes to beach alignments;*
> - *Breakwaters and training walls can enhance tidal conveyance, tripping estuaries into an unstable scouring mode.*

Such changes invariably have benefits, the reasons for which they were designed. However, such benefits invariably are accompanied by adverse impacts, many of which have included:

- *Coastal erosion and loss of development and infrastructure;*
- *Channel scour leading to damage to infrastructure and development and loss of seagrass;*
- *Dangerous boating conditions causing injury and death;*
- *Changes to and loss of fringing marine habitat impacting fisheries; and*
- *Sediment deposition smothering seagrass.*

A broader understanding and consideration of the impacts of breakwater and training wall construction is warranted.

The presentation noted that the construction of training walls at The Entrance would likely result in coastal realignment with increased erosion potential along North Entrance Beach.

2.2.25 Review of the Wyong Coastal Zone Hazard Study, BMT, 2018

BMT prepared this report for Central Coast Council in November 2018 to revise the coastal and geotechnical hazard elements applied in SMEC (2010) and SCE (2010) studies and undertake the future coastal hazard assessment for no sea level scenario in accordance with Council current interim sea-level policy.

- The results revealed that beach orientation and exposure are the main contributing factors in the variation of beach erosion hazards across the Wyong coastline.
- This study revealed that the preferential weathering of the sedimentary layers occurring at the cliff toe slopes are the primary reason contributing to the recession of the rocky cliff faces along Wyong's coast.
- The outcome of the wave runup hazard analysis for a design storm conducted by SMEC (2010) revealed a gradual increase of runup level around 6 and 7 m AHD with the maximum level of 8.1 m AHD at North Entrance.

2.2.26 The Entrance Width August 2012 to March 2019, CoastalCOMS, 2019

This report was completed for Central Coast Council in 2019 by CoastalCOMS to summarise the methodologies utilised to collect and process timeX imagery of the entrance. This report included the Wyong Entrance timeX imagery and the average entrance width from August 2012 to March 2019.

2.2.27 The Entrance Channel Dredging Operations Feasibility Review, GHD, 2019

This report was prepared for Central Coast Council in August 2019, by GHD to study a range of measures including maintenance of the existing dredge, purchase of new dredging equipment, external dredging contractor, entrance training walls, alternative dredging technology, entrance adjustment trial. Also, this report provided an overview of dredging requirements described below:

In 1993, as part of the Tuggerah Lakes Restoration Project, dredging works were carried out for the first time by Council. The primary purposes of dredging works were described below:

- to maintain the exchange of water between Tuggerah Lakes estuary and the ocean;

- to reduce the risk of flooding to life and property in low lying areas around the Tuggerah Lakes estuary;
- to prevent degradation of water quality within Tuggerah Lakes and preserve the existing ecological values of the Tuggerah Lakes estuary;
- to provide sand nourishment aiding in erosion and coastal protection and improving recreational amenity.

Council's Waterways and Coastal Protection (WCP) unit performs dredging works using a small Cutter Suction Dredge owned by Council. During the period between the dredging campaigns, WCP staff operate Council's wrack and algal collection equipment.

Council's dredging campaigns have been undertaken as needed - basically yearly and usually take three to four months to be completed. The amount of material to be removed during dredging campaigns depends on the build-up of sand in the channel. A dredging campaign can involve the removal of approximately 30000 m^3 to 80000 m^3 per annum (up to 100000 m^3).

The new dredging campaign is similar to the previous campaign with moderate refinements to count for the additional dredging requirements as needed to meet the goals. Dredging is undertaken as below:

- Annual dredging of the main channel to the east of the road bridge, the northern channel through the flood tide shoal and the southern tip of the main sandpit.
- Biennial dredging of the northern channel just downstream of the road bridge.
- Dredging as required for the Terilbah Channel (every five years), the main channel to the west of the road bridge (most recently in 1995), occasional dredging of a sump perpendicular to the south of the main channel and the flood dominate southern channel.

Following the recommendation from the Tuggerah Lakes Estuary Management Plan, dredging is performed only when one or more of the following indicators are reached (Central Coast Council, 2019) – on average every one to two years:

- The throat of the channel at the southern tip of the sand spit at the Entrance reduced to a width of 15 m at mid-tide level.
- The flood tide sand shoals threaten to block the ebb tide dominant channel along the northern/eastern side of the Entrance area.
- The flood tide shoals threaten to block the main channel east of the bridge.

In 2018, dredging works were performed due to the flood tide sand shoals threaten to block the ebb tide dominant channel along the northern/eastern side of the Entrance area – shown on **Figure 2.6**. The extracted materials were pumped and placed at the areas of the Entrance, North Entrance beaches and inside the channel fronting Dunleith Caravan Park and Karagi car park.

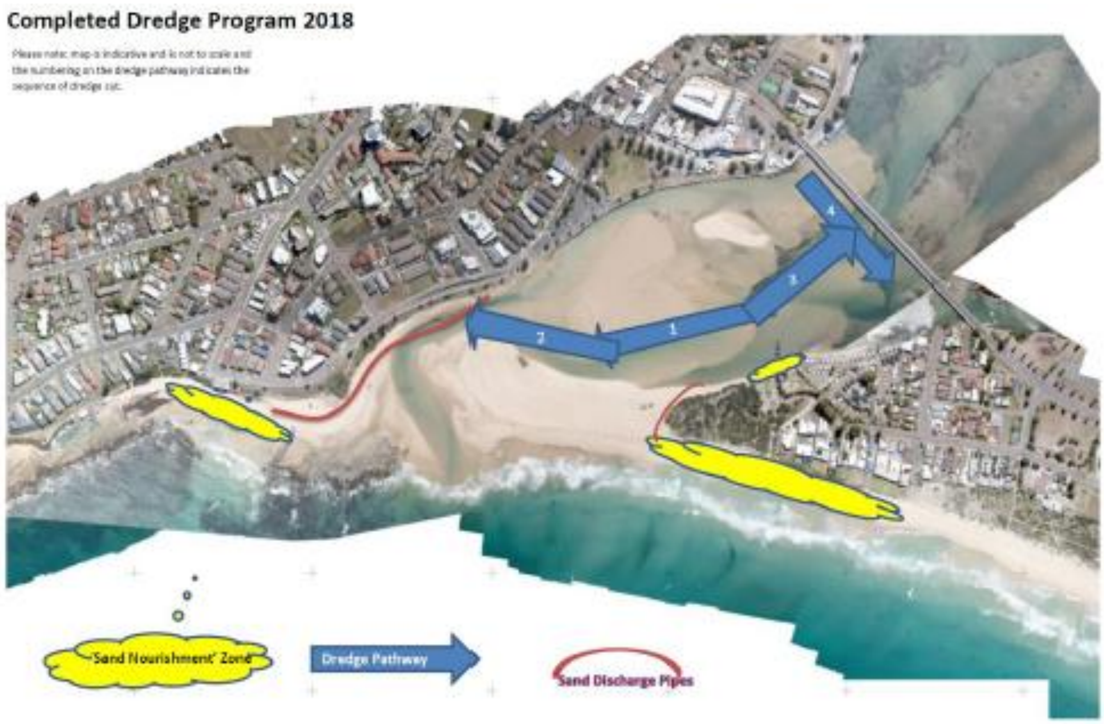


Figure **2.6: Dredge pathway and sand nourishment areas, reprinted from (GHD, 2019).**

In this study, some challenges have been identified as part of the current dredging operations including reliability and cost of aging equipment, limited capacity of dewatering and placement areas, environmental and social impacts of dredging, and compliance with licences and approvals.

As a part of this study, a range of alternative dredging work strategies were investigated including maintenance of the existing dredge, purchase of new dredging equipment, external dredging contractor, fully trained entrance as shown on **Figure 2.7**, alternative dredging technology such as sand shifter and an entrance adjustment trial. **Table 2.8** summarises the outcomes of the assessment of each method on required criteria.

It has been reported that Council's existing dredge has reached its original budgeted serviceable life. Although Council is able to keep operating the existing dredge, there are a number of challenges that need to be managed to ensure the cost-effective and environmentally sensitive completion of the future dredging campaigns. This report recommended that Council progress with undertaking an entrance adjustment trial along with emergency entrance berm clearing operations using land-based equipment; engaging an external dredging contractor to undertake trial dredging works, as well as purchase of a modern dredging equipment. Also, it has been noted that the final selection of an option required additional investigations and consultation with a number of internal and external stakeholders.

Figure 2.7: Fully trained entrance wall at the Entrance channel, reprinted from (GHD, 2019).

Table 2.8: Summary of the comparison of the investigated options (GHD, 2019).

Criteria	Performance	Environment	Legislative requirement	Health and Safety	Cultural and Social	Cost	Risk Assessment
Maintenance of Council's existing dredge	Existing production rates of 60 m^3/hr could be maintained. Fuel burn rates would not meet modern industry standards.	Impacts generally as assessed in the 2009 REF. Few improvement options with the exception of GHG emissions which exceed modern industry standards	Differing Council and NSW EPA interpretations of the approval conditions led to stop work notice issued in 2018. EPA discussions are ongoing.	Aging equipment can present HSE issues however Council has comprehensive plans and management measures in place.	Differing opinions within the community regarding the need for and scale of dredging works.	Recent trends in increasing repair and maintenance costs expected to continue as more components require repair or replacement	Key risks relate to the costs of major repairs and availability of the dredge during these periods.
Purchase new dredging equipment	Smaller modern dredges can achieve similar production rates offered by the Council's current dredge.	An upgrade is not expected to alter the impacts of dredging works on the biodiversity, coastal habitats or morphology in the region.	Subject to the same licenses and approvals as the current dredge. Additional approval is required for wrack collection.	Subject to the same health and safety risks and control measures.	Some improvement to operational noise levels.	High initial cost and lower ongoing operational and maintenance costs than the existing dredge.	Future tightening of environmental controls may render dredging more costly or potentially unfeasible.
External dredging contractor	Expected to complete the work in a timely, cost-effective and environmentally sensitive manner.	Not expected to alter the impacts of dredging works on the biodiversity, coastal habitats or morphology in the region.	Subject to the same licenses and approvals as Council's existing dredging operations	Largely subject to the same health and safety risks and control measures as current activities	Negligible difference and expected to generate the least community concern.	Higher cost per cubic metre of sediment and mobilisation and demobilisation costs. Council will not be liable for maintenance costs.	Greater risk of standby costs and variations.

Criteria	Performance	Environment	Legislative requirement	Health and Safety	Cultural and Social	Cost	Risk Assessment
Entrance training walls	Likely not to self-scour and maintenance dredging would still be required.	Expected to have minor long-term impacts on the biodiversity, coastal habitats and/or morphology in the region, though some would be positive.	Extensive approvals would be required from multiple consent authorities.	Construction is expected to produce risks to health and safety which can be managed.	Negatively impact on the overall aesthetics of the region. Construction will impede on beach recreation.	Extremely high initial cost. The most recent study estimated construction of $43 million in 2013	Availability of suitable size and quality armour rock has proven to be an issue. Council still requires mitigating current dredging risks.
Alternative dredging technology	A mobile Sand shifter could be expected to move around 180 m3/hr under similar circumstances. Wrack and seagrass could be a hindrance.	Not expected to alter the impacts of dredging works on the biodiversity, coastal habitats or morphology in the region.	Subject to the same licenses and approvals as Council's existing dredging operations	Fencing and signage required to address drowning hazard around intake.	Negligible. Some improvement to operational noise levels.	A mobile Sand shifter would be more cost-effective than traditional dredging campaigns, though a fixed bypass system would be cost-prohibitive.	Similar to those associated with the current operations. Limited flexibility may fail to achieve the current benefits of dredging works.
Entrance adjustment trial	With a berm height set, it is likely that the entrance will self-scour during flooding events.	Timelines and intensities for the outcomes are unknown and difficult to quantify without the completion of detailed studies.	The Council should seek legal advice regarding dredging responsibilities and potential liability associated with the impacts of temporary cessation of dredging works.	Monitoring water quality parameters should be undertaken.	A number of community groups passionate about the dredging of The Entrance and improvement of water quality.	Lowest cost of the five options.	Significant risks to Council regarding community perceptions.

2.2.28 Recent Flood Events – February 2020 and March 2021

Recent flood events in February 2020 and March 2021 re-emphasise the priority for a formalised Entrance Management Strategy to manage flood risk as recommended in the Tuggerah Lakes Floodplain Risk Management Study and Plan (WMAwater, 2014). Entrance conditions prior to the February 2020 flood were open to the ocean via a channel at the southern region of the berm near the entrance rock shelf. However, after consecutive years of low rainfall conditions the entrance region was relatively constricted with dominant flood tide shoals and a relatively dry catchment. Heavy catchment rainfall saw water levels in Tuggerah Lakes peak at 1.67 m AHD (Toukley gauge) near midnight on 11 February 2020, within 100 - 300 mm of the highest lake level previously recorded since 1998 which occurred in June 2007 (MHL2750, 2020). During the event, a secondary channel was excavated in the central region of the entrance berm to realign the channel away from the southern side where scour impacts were placing foreshore infrastructure at risk. This secondary channel scoured to a width of 80 m within a few days and formed that primary entrance channel as the flood subsided (WRL, 2020).

More recently in March 2021, widespread heavy rainfall resulted in flooding across numerous NSW coastal rivers and estuaries. Water levels in Tuggerah Lakes reached 1.52 m AHD at the Long Jetty gauge on the 22nd March 2021, slightly lower than the February 2020 event. Inspection of satellite imagery (from Stage 2 works) indicates that prior to the event the entrance was open in the central region of the berm with a width of approximately 60 - 80 m and widened to approximately 150 - 200 m by the 25th March. On the 19th March 2021, Council undertook precautionary emergency works to straighten the entrance flow path and slightly widen the entrance channel by excavating some of the sand on the northern bank of the entrance channel (Central Coast Council per comms).

Factors influencing the difference in flood level and behaviour between each event include rainfall patterns (intensity, volume and temporal/spatial distributions), initial wetness of the catchment (influencing how much rainfall can sink into ground), initial lake levels, entrance channel configuration/shoaling and ocean conditions. A more detailed review of the February 2020 and March 2021 event is provided in Stage 2 works.

Both events highlight the need for a formalised entrance management strategy that maintains the entrance (including its berm, channels and shoals) in a flood ready condition to better alleviate the impacts of flooding, while maintaining protection from ocean inundation and minimising any disturbances to characteristic lake water level fluctuations.

Related Studies

2.2.28.1 Impact of February 2020 East Coast Low on Central Coast Beaches, WRL, 2020

This report was prepared for Central Coast Council in March 2020, by WRL to quantify the impact of a large east coast low (ECL) storm of February 2020. WRL used LiDAR data and imagery captured by UNSW Aviation on the 11th February 2020 immediately after the storm at low tide over key locations including Budgewoi, Hargraves Beach, Shelly Beach, Wamberal Terrigal and Avoca Beach.

The February 2020 storm occurred between the 7th to 10th February 2020 and produced a peak offshore wave height of 6.5 m from an east-south-east direction with an estimated average recurrence interval period (ARI) of 20 to 50 years. The outcomes of the analysis at The Entrance estimated subaerial sand volume losses of -16 to -102 m^3/m between The Entrance SLSC and Curtis Pde during the event. The available sand buffer fronting property boundaries at Hutton Rd and Curtis Pde was left critically low (less than 10% of design storm demand) following the event. The study also provided satellite imagery of entrance changes during the February 2020 flood event including images before and after mechanical opening of a secondary channel in the central region of the entrance berm.

2.2.28.2 MHL2750 – Tuggerah Lakes catchment February 2020 flood summary and historical comparison, MHL, 2020

This report was prepared for Central Coast Council in May 2020 by MHL to provide a summary of the collected data during the flood event in February 2020 including rainfall and water level gauges in the Tuggerah Lakes catchment. The results indicated that the rainfall intensities reached up to the 1% AEP intensity at Yarramalong. Also, the results revealed that the peak water level in Tuggerah Lakes was 1.67 m AHD during the February 2020 event. Peak water levels were within 0.1 to 0.3 m of the highest recorded water level since 1998 occurring in June 2007.

3 Summary and conceptual model

Tuggerah Lakes has had a long history of entrance management to alleviate flooding and water quality issues, including reports of flood damages extending back to the 1860's (PWD, 1992). Managing the Tuggerah Lakes entrance continues today with the majority of the lake's low-lying foreshore now heavily urbanised and susceptible to flooding as well as placing added stressors on ecological communities.

Flooding in the area is characterised by both elevated ocean levels and catchment runoff, with storms of longer duration found to be more critical during extreme events (Lawson & Treloar, 1994). Alongside condition of the entrance, found to be a primary contributing factor controlling lake flood levels,

While the channel does temporarily scour and widen during flood events, increasing the lake tidal range by a factor of two, the typically low tidal prism of the entrance results in net marine sediment infilling over time, requiring mechanical invention to maintain open conditions. An overview of entrance processes for the Tuggerah Lakes entrance is provided in **Figure 3.1** showing typical regions of deposition and primary sediment transport mechanisms.

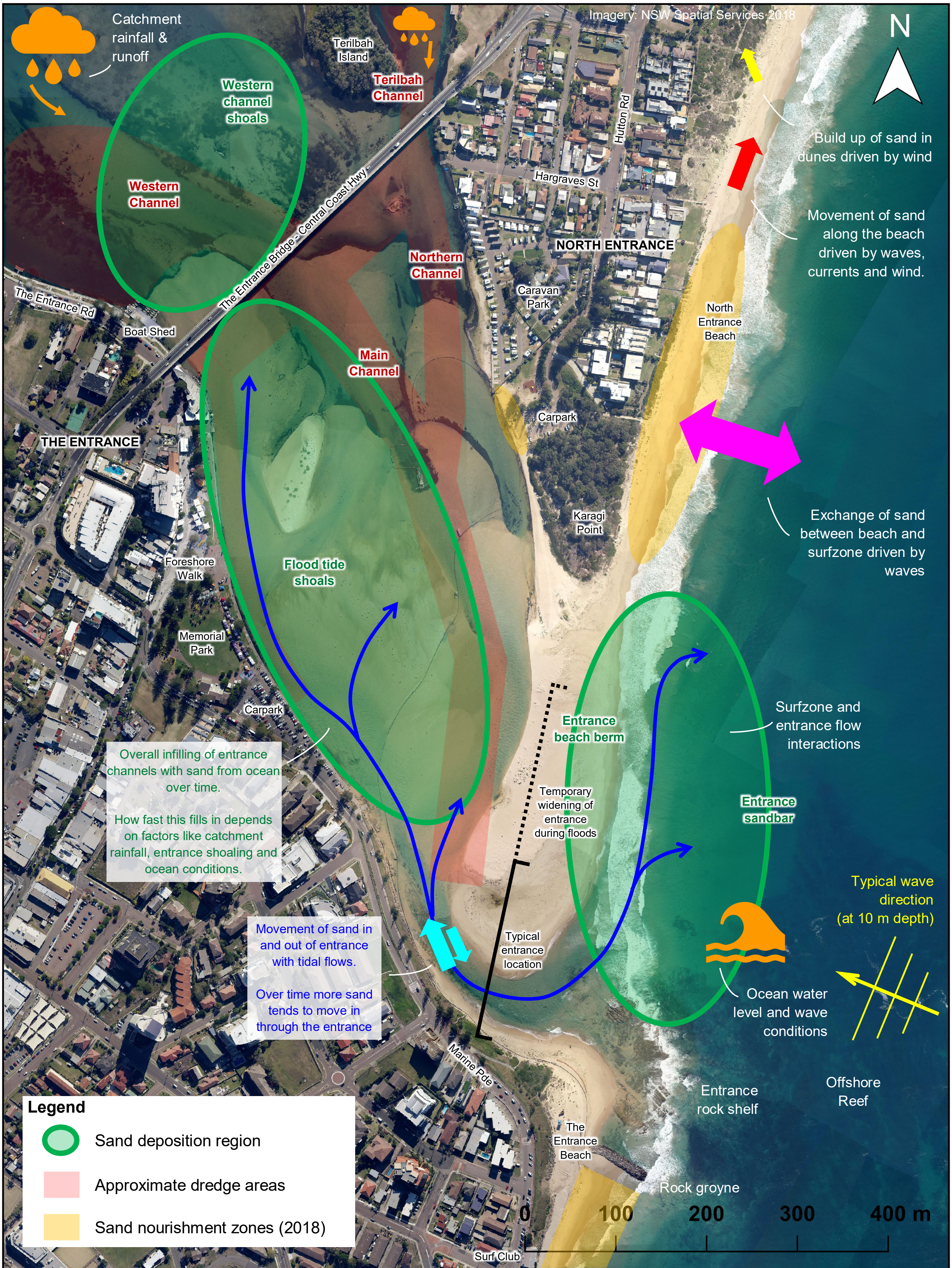
Since 1993, Tuggerah Lakes entrance maintenance dredging works have been carried out by Council. Under the Tuggerah Lakes Estuary Management Plan dredging of 30,000 to 80,000 m^3/yr is performed when one or more of the following indicators are reached (occurring on average every 1-2 years):

- The throat of the channel at the southern tip of the sand spit at the Entrance reduced to a width of 15 m at mid-tide level.
- The flood tide sand shoals threaten to block the ebb tide dominant channel along the northern/eastern side of the Entrance area.
- The flood tide shoals threaten to block the main channel east of the bridge.

Dredged material from regions shown in **Figure 3.1** is used for nourishment of South and North Entrance beaches. In addition to periodic maintenance dredging, the NSW Government constructed a rock groyne in 2017 at South Entrance beach to enhance beach stabilisation immediately south of the entrance (Cardno, 2013).

The Tuggerah Lakes Estuary Management Study and Plan recommended maintaining open entrance conditions and ocean tidal exchange to assist in managing water quality in the lake system (Bio-Analysis, 2006).

The Tuggerah Lakes Floodplain Risk Management Study and Plan (WMAwater, 2014) noted entrance management via periodic dredging would have no adverse effect on flooding except for potentially increasing the likelihood of ocean inundation compared with a non-dredged entrance. The study noted minor benefits of the maintenance dredging including possible prevention of minor flooding, a small reduction in flood peak levels of up to 0.03 m and potentially 6 hours reduction in duration of inundation. Benefits of dredging are noted to diminish with time following works due to infilling and that at the time there was limited evidence justifying dredging of the entrance in terms of reducing flood damages. It was recommended as a high priority that an Entrance Management Strategy be formalised for Tuggerah Lakes to manage flooding.



OVERVIEW OF PROCESSES AT TUGGERAH LAKES ENTRANCE

Manly Hydraulics Laboratory

Report MHL2781

Figure 3.1

Figure3.1.pdf

A range of alternative entrance management options have been investigated as part of previous studies including entrance jet pump systems, entrance restraining walls, entrance adjustment trial, trained entrance configurations and/or various dredging work strategies (e.g., PWD, 1987; 1988; Patterson Britton and Partners, 1994; WorleyParsons, 2009; Cardno, 2013; 2015; GHD, 2019).

More recently Cardno (2015) undertook morphological modelling of the Tuggerah Lakes entrance to assess the implications of a 150 m wide dredge channel with depths ranging from -5.5 to -1.5 m AHD. The scale of dredging investigated was much larger than Council's present maintenance dredges. The study found that:

- Dredge channels would likely infill from ocean and lake ends.
- Dredging would increase conveyance and tidal exchange between the lake and ocean, with this increase limited when dredging to more than -2.5 m AHD due to the shoaled region west of The Entrance bridge.
- Dredging would result in lower average lake levels of up to 0.1 - 0.2 m with an increased lake tidal range. Decreases in lower average lake levels may have ecological and recreational consequences.
- Potential higher tidal currents with dredging at The Entrance bridge and along Terilbah reserve may result in scour and/or shoreline erosion.

Previous studies have also investigated the feasibility of different trained entrance configurations for Tuggerah Lakes (Patterson Britton and Partners, 1994; WMAwater, 2014; Cardno, 2013; 2015). Patterson Britton and Partners (1994) found that the construction of entrance training walls was impracticable due to the potential impacts on lake water levels and tidal range, increased flooding, storm surge and wave climate in the entrance and loss of upstream entrance shoals. Findings from more recent numerical model investigations of trained entrances include:

- Trained entrance configurations modelled indicate that a 250 m width not physically or economically viable to keep open, with potential adverse impacts on ecology and increased frequency of ocean inundation events (WMAwater, 2014);
- Trained entrances that limit the width to 100 m are likely to increase peak flood levels, the number of flood-affected properties and flood water retention time. (Cardno, 2013);
- Trained entrance configurations modelled indicated that ongoing maintenance dredging would be required to keep open (Cardno, 2013); and
- Trained entrance would decrease the rate of sediment infill from the ocean compared to without training walls (Cardno, 2015).

Although trained entrance configurations in the previous modelling studies have indicated that the entrance will continue to infill, experience along the NSW coast show that when breakwaters extend deeper into offshore waters, trained entrances can transition into a self-scour regime. Nielsen and Gordon (2015) noted this behaviour at a number of trained entrances along the NSW coast.

Implications of an entrance in a self-scour regime include extensive entrance scour requiring channel erosion protection works, changes in sedimentation patterns in bays and adjacent beaches as well as significant changes to fringing ecological communities (Nielsen and Gordon, 2015). Such implications at Tuggerah entrance could result in:

- Damage and undermining of existing seawall foreshore protection at the entrance and footings of The Entrance Bridge.
- Higher high tide levels exacerbating ocean flood events in the lake including spring tides, king tides potentially coinciding with storm surge and wave setup during high wave events. The entrance in its present state currently restricts the amount of ocean flooding in the lake, protecting low-lying foreshores from more frequent inundation during coastal events with elevated ocean water levels.
- Lower low tide levels with increased exposure of mud flats and seagrass beds resulting in ecological degradation of fringing ecosystems, odour issues and recreation boating hazards.

Maintenance dredging of Tuggerah Lakes entrance has continued as a means of entrance management including recent dredges in 2018 and 2020. Recent studies have been undertaken to refine Council's dredging operations and strategies (GHD, 2019).

Recent flood events in February 2020 and March 2021 re-emphasise the priority for a formalised Entrance Management Strategy to manage flood risk as recommended in the Tuggerah Lakes Floodplain Risk Management Study and Plan (WMAwater, 2014); enhancing the management of the entrance in a flood ready condition that considers the complex and dynamic interactions of factors that contribute water level variability in Tuggerah Lakes.

3.1 Conceptual model

The review of previous studies and historical aerial imagery have been used to develop a conceptual model of Tuggerah Lakes entrance shown in **Figure 3.2** summarising key ICOLL entrance processes including sediment transport pathways, deposition regions and approximate dredging locations. Sediment transport rates are provided from SMEC (2011).

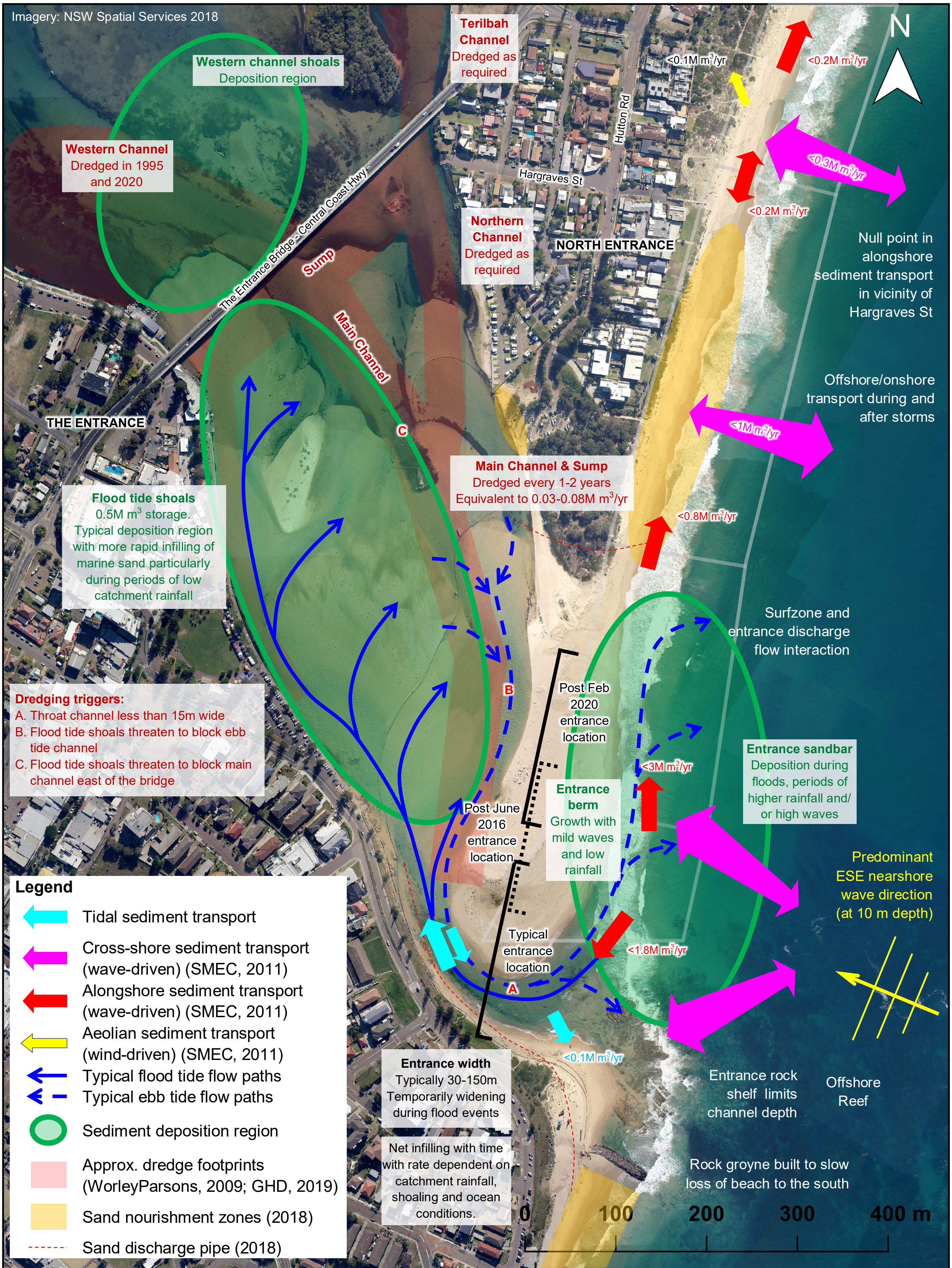
Water levels in the lake are primarily controlled by catchment runoff and ocean water levels as well as entrance conditions and shoaling processes depicted in **Figure 3.2**. With a more constricted entrance (shallower and narrower), water levels in the lake are on average higher and the tidal range smaller. After a flood and/or entrance dredging, the entrance temporarily widens and the lake tidal range increases due to ocean-lake flushing, before returning to typical values as the entrance infills with time.

As reported by SMEC (2011), alongshore sediment transport along the open coast of the entrance is typically northward due to the predominant SSE wave climate as shown in **Figure 3.2**, with a null point in the vicinity of Hargraves St. Larger magnitude cross-shore (offshore/onshore) sediment exchanges occur due to high wave energy events and are associated with beach erosion subsequent recovery cycles. Closer to the entrance channel the alongshore sediment transport tends south indicating entrance infilling (**Figure 3.2**). Surf zone and flood tide processes carry sediment onshore and into the entrance channel where it is deposited on flood tide shoals.

During periods of high rainfall and flooding, the entrance region temporarily scours and widens. Scour depth at the southern region of the entrance is limited by the presence of a rock shelf exposed at low tide. These processes along with ebb tide sediment transport, carry sediment out of the entrance channel and deposit it offshore on the entrance sandbar or on the beach face adjacent to the entrance (**Figure 3.2**). Mild wave conditions and flood tide processes carry sediment onshore and back into the entrance channel where it is redeposited on the flood tide shoals. These processes constrict the entrance channel and reduce the lake tidal range. The typical low tidal prism and tidal velocities of the entrance result in a net infilling of the entrance with time. Periodic dredging equivalent to approximately 30,000 to 80,000 m^3/yr is required to maintain open entrance conditions. With periods of low rainfall this rate of infilling can accelerate, with shoals building up more rapidly and the entrance becoming relatively more constricted than during wetter periods.

It should be noted that in recent years the entrance channel opening has been located in the central region of the entrance berm compared to its typical location near the rocks shelf in the south. In 2016, wave overtopping resulted in the breaking out of a secondary entrance in the central region of the spit, which then migrated back south to the rock shelf over the 1-2 years following. A secondary entrance was mechanically opened at the central region of the spit during the February 2020 flood event, which with the subsequent infilling of the southern channel, formed the main entrance channel after the flood event. Entrance opening in the central to northern end of the spit was also noted to occur in 1986 (Umwelt, 2011). Under such configurations, entrance processes depicted in **Figure 3.2** shift northward potentially impacting upon the adjacent beach and surf zone morphology.

The condition of the entrance, including its channels, berm and shoals, acts as a primary control allowing catchment flows to drain from the lake system while also restricting the amount of ocean inundation into the lake system. Given the typical low lake level (approx. 0.3 m AHD) and low-lying surrounding foreshore, managing the entrance requires a careful balance between reducing the severity of major catchment floods while protecting the lakes from adverse ocean inundation and minimising disturbances to typical lake water levels.



NSW GOVERNMENT

CONCEPTUAL MODEL OF ICOLL ENTRANCE PROCESSES AT TUGGERAH LAKES ENTRANCE

Manly Hydraulics Laboratory

Report MHL2781

Figure

3.2

Figure3.2.pdf

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Appendix A Glossary of terms

Aeolian sediment transport	Movement of sand by wind-driven processes. This is a primary process responsible for dune formation and growth.
AEP	Annual Exceedance Probability
Alongshore sediment transport	Movement of sand along the length of a beach driven by waves and currents.
ARI	Average Recurrence Interval
Australian Height Datum (AHD)	Is a geodetic datum for altitude measurement in Australia. According to Geoscience Australia, in 1971 the mean sea level for 1966-1968 was assigned a value of zero on the Australian Height Datum for 30 tide gauges around the coast of the Australian continent. The resulting datum surface has been termed the Australian Height Datum (AHD) and was adopted by the National Mapping Council as the datum to which all vertical control for mapping is to be referred.
Beach Face	Region of the beach that is situated between the dry beach (often flatter) berm and the low-tide seaward limit of the shoreline. This region is frequently wetted by varying tide and wave runup (or swash) processes.
Bed Load	That portion of the total sediment load that flowing water moves along the bed by the rolling or saltating of sediment particles.
Berm	The dry and often near-planar region of the beach, extending seaward of the foredune and separated from the steeper and wetted beachface. The condition of the berm is dynamic, eroding and rebuilding with waves as well as flood processes when fronting an estuary entrance.
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 mainstream.
Catchment Runoff	The amount of rainfall which ends up as stream flow, also known as 'rainfall excess ', since it is the amount remaining after accounting for other processes such as evaporation and infiltration.
Coastal amenity	Those features of a coastal environment (lake/estuary/beach) that foster its use for various purposes, e.g. Clear water and sandy beaches make beach-side recreation attractive.

Coastal morphology	The (study of the) form, shape and structure of coastal systems or subsystems such as a beach, estuary entrance or bedform.
Cross-shore sediment transport	Movement of sand onshore and offshore between the subaerial beach and surfzone driven by waves and currents.
Deposition	The sedimentary process by which transported sand or sediment is arrested and builds up in a certain location or formation.
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.
Diurnal	Having a period or cycle of approximately one tidal day. Thus, the tide is said to be diurnal when only one high water and one low water occur during a tidal day, and the tidal current is said to be diurnal when there is a single flood and a single ebb period of a reversing current in the tidal day. A rotary current is diurnal if it changes its direction through all points of the compass once each tidal day. A diurnal constituent is one which has a single period in the constituent day. The symbol for such a constituent is the subscript 1.
East Coast Low (ECL)	East Coast Lows (ECL) are intense low-pressure systems which occur on average several times each year off the eastern coast of Australia, in particular southern Queensland, NSW and eastern Victoria. Although they can occur at any time of the year, they are more common during autumn and winter with a maximum frequency in June. East Coast Lows will often intensify rapidly overnight making them one of the more dangerous weather systems to affect the NSW coast. East Coast Lows are also observed off the coast of Africa and America and are sometimes known as east coast cyclones.
Ebb Tide	The outgoing tidal movement of water within an estuary.
Estuary	An embayment of the coast in which fresh river water entering at its head mixes with the relatively saline ocean water. When tidal action is the dominant mixing agent it is usually termed a tidal estuary. Also, the lower reaches and mouth of a river emptying directly into the sea where tidal mixing takes place. The latter is sometimes called a river estuary.
Flood Tide	The incoming tidal movement of water within an estuary.
Foreshore	The area of shore between low and high tide marks and land adjacent thereto.

Harmonic analysis	Process of measuring or calculating the relative amplitudes and frequencies of all the significant harmonic components present in a given wave form.
Indian Spring Low Water	A datum originated by Professor G. H. Darwin when investigating the tides of India. It is an elevation depressed below Mean Sea Level by an amount equal to the sum of the amplitudes of tidal harmonic constituents.
Intertidal	Pertaining to those areas of land covered by water at high tide, but exposed at low tide, e.g. intertidal habitat.
King Tide	A non-scientific term used to describe especially high tide events occurring twice a year around early January and early July. They occur when the earth, sun and moon are in alignment and when the sun is closest and furthest from the earth (perihelion and aphelion respectively).
Littoral Zone	An area of the coastline in which sediment movement by wave, current and wind action is prevalent.
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.
Mean Sea Level (MSL)	The arithmetic mean of the water level heights at the tidal station observed over a period of time (preferably 19 years).
Neap Tide	Tides of decreased range or tidal currents of decreased speed occurring semi-monthly as the result of the moon being in quadrature. The neap range (Np) of the tide is the average range occurring at the time of neap tides and is most conveniently computed from the harmonic constants. It is smaller than the mean range where the type of tide is either semi-diurnal or mixed and is of no practical significance where the type of tide is predominantly diurnal. The average height of the high waters of the neap tide is called neap high water or high-water neaps (MHWN) and the average height of the corresponding low waters is called neap low water or low water neaps (MLWN).
Numerical Model	A mathematical representation of a physical, chemical or biological process of interest. Computers are often required to solve the underlying equations.
Ocean Inundation	Flooding due to elevated ocean water levels and waves including tides, storm surge, wave setup, wave overtopping and sea level rise.

Ocean water level	The average elevation of the surface of the ocean over a period of time. This is a function of astronomical tides as well as a number of other non-astronomical factors such as barometric effects (low and high pressure systems), wind stress (also known as storm surge when combined with barometric effects), wave setup, ocean currents and coastal trapped waves.
Peak Wave Period (T_P)	Peak period of the energy spectrum in a wave record.
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
Sand Nourishment	Supply of sand to a beach system from an external source to increase the recreational value and/or to compensate for the effect of shore erosion by feeding sand on the beach.
Sand Replenishment	Transfer of sand from an accreted to an eroded area within a sediment compartment to increase the recreational value and/or to compensate for the effect of shore erosion.
Sandbar	A sand body (often submerged or partially exposed) situated in shallower waters than the surrounding bed elevations. Sandbars are shaped by waves, tidal currents and flood processes (at estuary entrances), situated offshore in the surfzone and at estuary entrance regions.
Scour	Erosion caused by the acceleration of flow and vortices induced by an obstruction (structure or natural feature) to flow.
Semi-diurnal	Having a period or cycle of approximately one-half of a tidal day. The predominant type of tide throughout the world is semi-diurnal, with two high waters and two low waters each tidal day. The tidal current is said to be semi-diurnal when there are two flood and two ebb periods each day. A semi-diurnal constituent has two maxima and two minima each constituent day, and its symbol is the subscript 2.
Shoals	Shallow areas in an estuary created by the deposition and build-up of sediments.
Significant Wave Height (H_s)	Hs may be defined as the average of the highest 1/3 of wave heights in a wave record, or from the zeroth spectral moment, though there is a difference of about 5 to 8%.
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 of increased range or tidal currents of increased speed occurring semi-monthly as the result of the moon being new or full. The spring range (Sg) of tide is the average range occurring at the time of spring tides and is most conveniently computed from the harmonic constants. It is larger than the mean range where the type of tide is either semi-diurnal or mixed, and is of no practical significance where the type of tide is predominantly diurnal. The average height of the high waters of the spring tides is called spring high water or mean high water springs (MHWS) and the average height of the corresponding low waters is called spring low water or mean low water springs (MLWS).
Storm Surge	The local change in the elevation of the ocean along a shore due to a storm. The storm surge is measured by subtracting the astronomic tidal elevation from the total elevation. It typically has a duration of a few hours. Since wind generated waves ride on top of the storm surge (and are not included in the definition), the total instantaneous elevation may greatly exceed the predicted storm surge plus astronomic tide. It is potentially catastrophic, especially on low-lying coasts with gently sloping offshore topography.
Surfzone	The region of the beach where the depth of water causes waves to break and move as wave bores (collapsed, broken or white-water waves) toward the shore.
Tidal Current/Flows	A horizontal movement of the water caused by gravitational interactions between the sun, moon and earth. The horizontal component of the particulate motion of a tidal wave. Part of the same general movement of the sea that is manifested in the vertical rise and fall called tide.
Tidal Exchange	The proportion of the tidal prism that is flushed away and replaced with 'fresh' coastal water each tide cycle.
Tidal Prism	The total volume of water moving past a fixed point in an estuary during each flood tide or ebb tide.
Tidal Range	The difference in height between consecutive high and low waters. The mean range is the difference in height between mean high water and mean low water. The great diurnal range or diurnal range is the difference in height between mean higher high water and mean lower low water. For other ranges see spring, neap, perigean, apogean, and tropic tides; and tropic ranges.

Tide	The periodic rise and fall of the water resulting from gravitational interactions between sun, moon and earth. The vertical component of the particulate motion of a tidal wave. Although the accompanying horizontal movement of the water is part of the same phenomenon, it is preferable to designate this motion as tidal current.
Tide (Water Level) Gauge	An instrument for measuring the rise and fall of the tide (water level).
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.
Wave Direction	The direction from which ocean waves approach a location. Generally, the principal wave direction is represented by the direction that corresponds to the peak period of the energy spectrum.
Wave Setup	The elevation of the mean water level at the shoreline due to wave breaking in the surfzone

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