Tuggerah Lakes Entrance Management Study

Report MHL2811
August 2022

Prepared for:
Central Coast Council

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

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Document Control

Issue/ Revision	Author	Reviewer	Approved for Issue	
			Name	Date
Draft01 (Stage 1)	A. Severi B. McPherson M. Phillips	B. McPherson	B. McPherson	Sep 2020
Draft02 (Stage 2)	M. Phillips A. Severi	B. McPherson	B. McPherson	Mar 2021
Draft03 (Stage 2)	M. Phillips A. Severi	B. McPherson	B. McPherson	Apr 2021
Draft04 (Stage 3)	M. Phillips A. Severi	B. McPherson	B. McPherson	Aug 2021
Draft05 (Stage 2)	M. Phillips	B. McPherson	B. McPherson	Sep 2021
Draft06 (Stage 4)	M. Phillips	B. McPherson	B. McPherson	Dec 2021
DraftFinal	M. Phillips A. Severi	B. McPherson	B. McPherson	May 2022
Final	M. Phillips	B. McPherson	B. McPherson	11 Aug 2022

Report classification

☒	Public	Report existence and contents publicly available.
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☐	Private	Report existence and content are strictly confidential.

Report No. MHL2811

First published as a draft in September 2020.

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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 in the following stages of work:

Stage 1: Review of previous studies

Stage 2: Entrance modelling and analysis

Stage 3: Assessment of entrance management options

Stage 4: Stakeholder workshop

Stage 5: Interim entrance management procedure and associated decision support tools

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

This report is issued as Final and is classified as publicly available.

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.

The Tuggerah Lakes Floodplain Risk Management Study and Plan (FRMSP) (WMAwater, 2014) provides management recommendations to reduce risk to life, public and private infrastructure associated with flooding. The FRMSP recommended a number of high priority actions to reduce flood risk including adaption planning for foreshore suburbs, flood emergency management planning, public education and awareness, adoption of development controls and formalising an entrance management strategy.

The present study provides the rational and development of the Tuggerah Lakes Interim Entrance Management Procedure. The procedure provides a rational decision-making framework for Central Coast Council to undertake entrance management works to the entrance throat channel and berm at Tuggerah Lakes entrance. The procedure is supported by MHL Flood (and Coastal) Intelligence Tools (MHLFIT) that utilise real-time quantitative data and predictive lake level modelling to facilitate a rational, proactive and informed approach to management actions. It provides an interim entrance management approach until an Entrance Management Strategy is formalised through the Coastal Management Program (CMP) process.

Included in this study are various stages of work that have informed the development of the Tuggerah Lakes Interim Entrance Management Procedure. These include:

- 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.
- Historical data analysis to evaluate characteristic entrance behaviour including typical lake level variability, tidal range, historical trends in entrance constriction as well as interactions between entrance configuration and lake water levels for both flood and dry-weather events.
- Development of a combined hydrology and one-dimensional entrance model to simulate water level variability in Tuggerah lakes for scenarios with varying entrance constriction, ocean water levels and catchment flows. The model was calibrated and validated to measured lake levels during flood and dry-weather events. The model was used to evaluate effects of indicative entrance channel geometry and constriction on lake level variability for both flood and dry-weather events.
- Development and assessment of potential interim entrance management options including emergency pilot channel opening, emergency berm scraping, emergency pilot channel opening and berm scraping and regular berm and pilot channel management. All options were assessed (relative to a base case of no management intervention) for flood impacts for a range of flood and dry-weather events and scenarios with varying ocean water levels and entrance conditions. A multi-criteria analysis was used to evaluate broader environmental, social and economic impacts of

each potential interim entrance management options relative to a base of no management intervention.

- Development of realtime decision support tools to inform entrance management procedures incorporating latest catchment rainfall and lake water level data, Bureau of Meteorology ADFD rainfall predictions, automated entrance tidal harmonic analysis, realtime catchment hydrological and hydraulic entrance representation, flood level predictions, on-demand scenario modelling and an interactive web user interface.

The Tuggerah Lakes Interim Entrance Management Procedure aims to reduce risk to life, public and private infrastructure associated with flooding in accordance with the FRMSP (WMAwater, 2014). Flood level reduction associated with the procedure are expected to be small (typically less than 0.2 m), however, are considered beneficial in assisting to reduce flood damages. These reductions are likely to diminish for floods coinciding with extreme coastal anomalies and/or with projected sea level rise over the next 50 - 100 years.

It is important to note that flooding in Tuggerah Lakes cannot be eliminated. The impacts of flooding will continue to be experienced even under the implementation of the proposed interim management procedure and will likely worsen with sea level rise. It is important that the community in the Tuggerah Lakes Floodplain understand their level of flood risk as well as adapt and prepare to live with the impacts of flooding. Reviewing and updating planning controls will be vital for future flood risk management in Tuggerah Lakes given the significant low-lying development situated in the Tuggerah Lakes foreshores.

The interim procedure recognises the ecological importance of the dynamic variability of the Tuggerah Lakes entrance and has developed procedures to provide tailored works for different entrance conditions. The interim procedure does not seek to maintain a permanently open entrance and the entrance channel will naturally constrict with sand, particularly during dryer periods with low rainfall and scour to a wider entrance during wetter periods with increased rainfall. The interim procedure seeks to allow natural entrance processes to operate with minimal disturbances in accordance with the *Policy and guidelines for fish habitat conservation and management* (DPI, 2013).

Entrance works are to be undertaken immediately prior to flooding to assist in providing flood risk reduction. Regular ongoing entrance berm works to continuously maintain flood-ready berm conditions were not considered to be feasible given the highly dynamic nature of the entrance, susceptibility to berm rebuilding and channel infilling processes. The interim entrance management procedure is to be reviewed following flood events as required.

It is recommended that further work as part of the Floodplain Risk Management process and Coastal Management Program include a review/provision of priority floodplain risk management controls identified in the FRMSP (WMAwater, 2014), review of sea level rise impacts on flooding and coastal inundation in Tuggerah Lakes, and investigation of entrance shoal dredging to support entrance management including recreational, environmental and social outcomes. It is also recommended that Council continue to investigate potential new technologies and methods that may improve entrance condition monitoring and support management works as they become available in the future.

Next steps should involve developing public messaging and protocols to inform the community of interim entrance procedures and when works are being undertaken. Council may wish to consider developing a public MHLFIT web interface with live rainfall, lake level and entrance monitoring data. Ongoing community engagement is to form a key component in formalising an Entrance Management Strategy as part of the CMP process.

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 Classification: Public

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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 approximately 790 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. 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 (FRMSP) (WMAwater, 2014) provides management recommendations to reduce risk to life, public and private infrastructure associated with flooding. The FRMSP recommended a number of high priority actions to reduce flood risk including adaption planning for foreshore suburbs, flood emergency management planning, public education and awareness, adoption of development controls and formalising an entrance management strategy.

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. As part of the study, an evidence-based Interim Entrance Management Procedure for Tuggerah Lakes has been developed in accordance with the objectives of the FRMSP (WMAwater, 2014) and supporting Council's transition to a Coastal Management Program (CMP) 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. This procedure seeks to provide an interim entrance management procedure until an Entrance Management Strategy is formalised through the CMP process and is to be implemented alongside of other floodplain risk management controls identified in the FRMSP (WMAwater, 2014).

The Tuggerah Lakes Entrance Management Study was delivered in the following stages of work:

Stage 1: Review of previous studies

Stage 2: Entrance modelling and analysis

Stage 3: Assessment of entrance management options

Stage 4: Key Stakeholder Consultation

Stage 5: Interim entrance management procedure and associated decision support tools

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

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

1.2 Study area

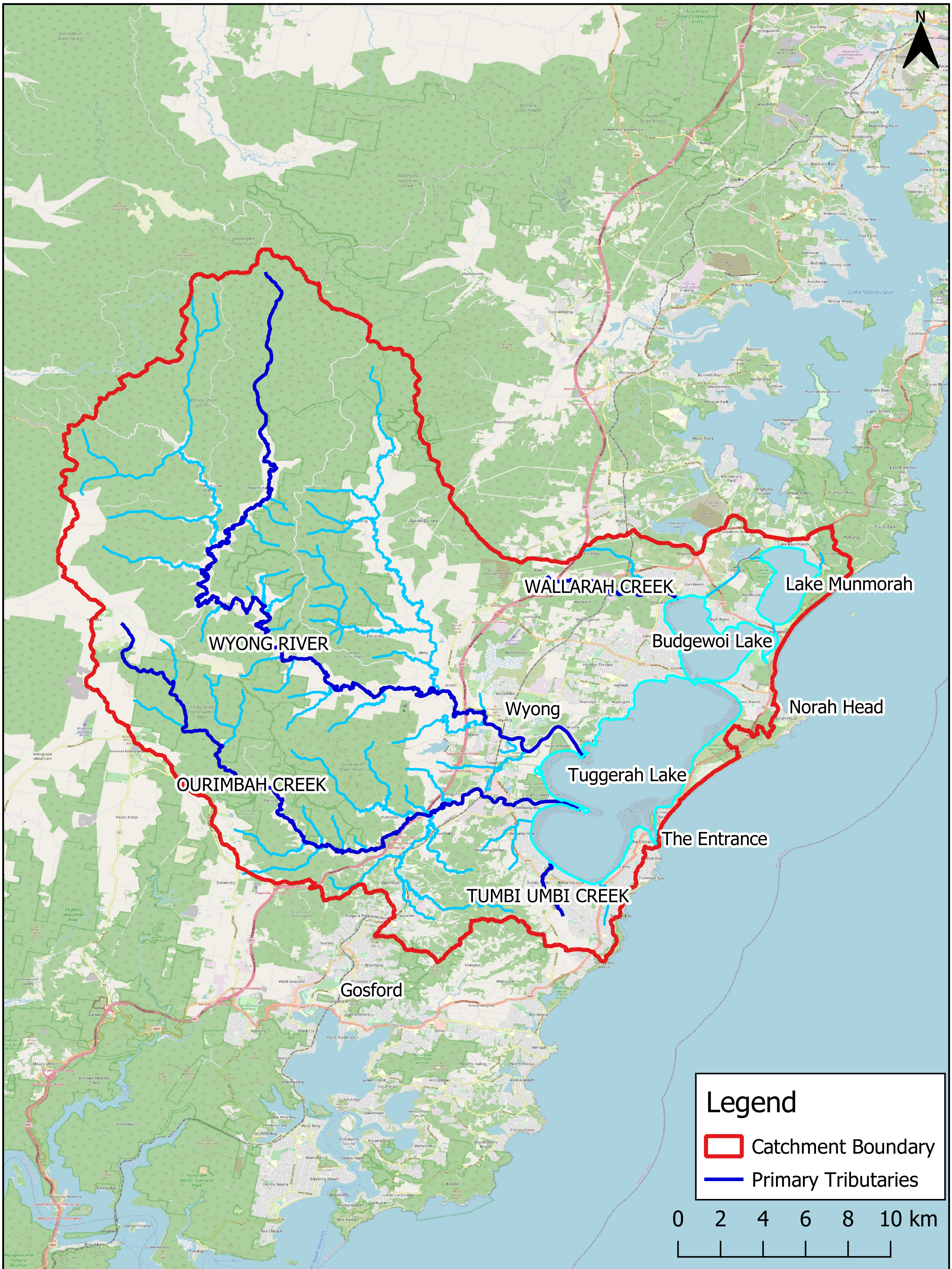
The Tuggerah Lakes system is located within the traditional boundaries of Darkinjung (Darkinyung) land on the Central Coast of NSW, approximately 80 km north of Sydney. The study area comprises three main interconnected lakes including Tuggerah Lake, Budgewoi Lake and Lake Munmorah. Tuggerah Lake is 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 a total catchment area of approximately 790 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 +4 to +6 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 during typical weather conditions. During extreme rainfall events, catchment runoff becomes the dominating factor 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 is up to 3.7 m depth at 0.3 m AHD water level (WMAwater, 2014).



NSW GOVERNMENT

TUGGERAH LAKES STUDY AREA SHOWING CATCHMENT BOUNDARY

Manly Hydraulics Laboratory

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 the collection of a variety of seafood (CSIRO, 1999). After European settlement in the 19th and 20th centuries, 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 the dredging of navigation channels in entrance shoals noted as early as 1912. Albeit the adoption of progressive technologies, manual (or mechanical) entrance opening and periodic dredging of entrance channels have continued as a long-standing adopted management practice since. Under these conditions, the channel has been 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 the 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 the 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 from 1950s to present. Sources: Umwelt (2011) and Google Earth.

1.3 Study aim and objectives

The aim of the 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.
- Undertake modelling and analysis to further an understanding of entrance behaviour and assist in the development and evaluation of an Interim Entrance Management Procedure.
- Identify and assess interim entrance management options for Tuggerah Lakes
- Develop an Interim Entrance Management Procedure and support tools to assist entrance management. Include recommendations for adaption to climate change impacts and sea-level rise.
- Provide interim entrance management recommendations that seek to:
  - Minimise the risk to life, private and public infrastructure and public health and safety.

1.4 Stakeholder consultation

Throughout all stages of this study, MHL engaged in regular project meetings and workshops with Council to gain feedback and facilitate collaboration. On the 7th of September 2021, MHL and Central Coast Council undertook a key stakeholder engagement workshop including representatives from:

- NSW Department of Planning and Environment – Biodiversity and Conservation Division
- NSW Crown Lands
- NSW Environment Protection Authority
- NSW Fisheries
- Maritime Infrastructure Delivery Office
- NSW State Emergency Services
- NSW National Parks and Wildlife Services
- Central Coast Council
- Manly Hydraulics Laboratory.

Findings from Stages 1 - 4 of the works were presented and feedback was obtained in developing and assessing interim entrance management options. Stakeholder feedback was used to refine economic, environmental and social assessment criteria for evaluating management options and provide valuable input in developing a final interim entrance management procedure. This workshop included:

- A presentation from MHL to introduce the study and the outcomes of the technical data review and modelling from previous stages of the project.
- Present and discuss all potential entrance management options.
- Highlight any issues needing resolution or clarification from parties in attendance.
- Discussion of environmental, social, economic and other constraints with respect to the potential management options.
- Consider and discuss potential support tools to inform future management actions.

The draft final version of the report was presented to key stakeholders at a workshop on the 21st June 2022 to obtain feedback used to finalise the report.

1.5 Study overview

The key stages of the present study are outlined below:

- Review of previous studies (**Section 2**)

  This section contains a review and summary of over 25 studies from 1987 to the 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.

- Modelling and analysis (**Section 3**)

  Using a combination of data analysis and flood modelling techniques, this section provides insight into entrance behaviour and water level variability for Tuggerah Lakes. Typical lake level variability, tidal range, historical trends in entrance constriction as well as interactions between entrance configuration and lake water levels for both flood and dry-weather events are addressed.

- Assessment of entrance management options (**Section 4**)

  This section provides an assessment of interim entrance management options for Tuggerah Lakes. The assessment of management options includes flood impact assessment and multi-criteria analysis against a range of environmental, social and economic criteria. A preferred interim management option is to be selected in consultation with Council and stakeholders.

- Stakeholder workshop
- Interim Entrance Management Procedure and support tools (**Section 5**)
- 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 2.3**.

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 the Tuggerah Lakes entrance in an 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 the western wall compared to the eastern wall as it is located where the rock shelf is close to the surface, shown in **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.

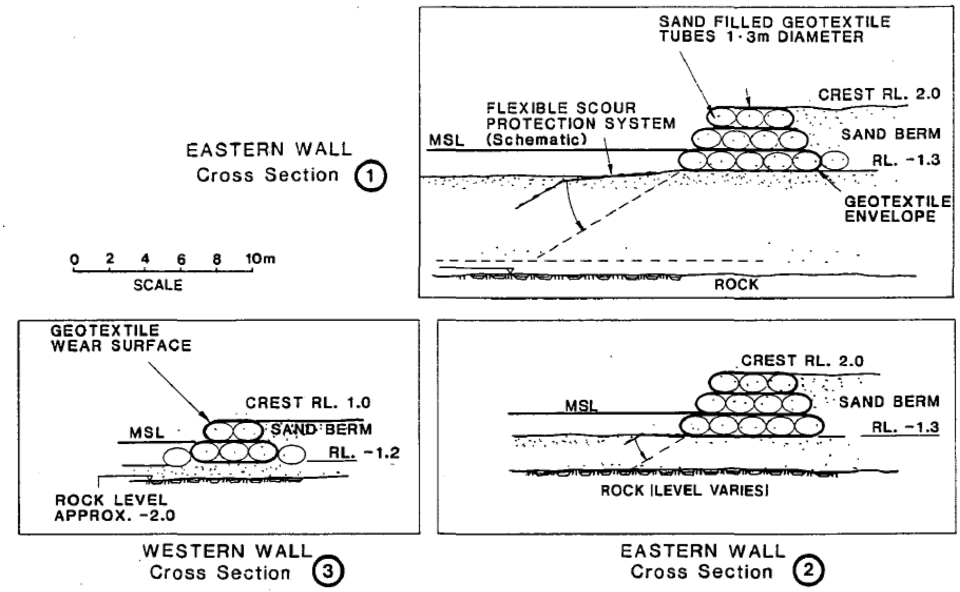


Figure 2.1: Cross-sections of the western and eastern restraining walls, reprinted from (Public Works Department, 1988).

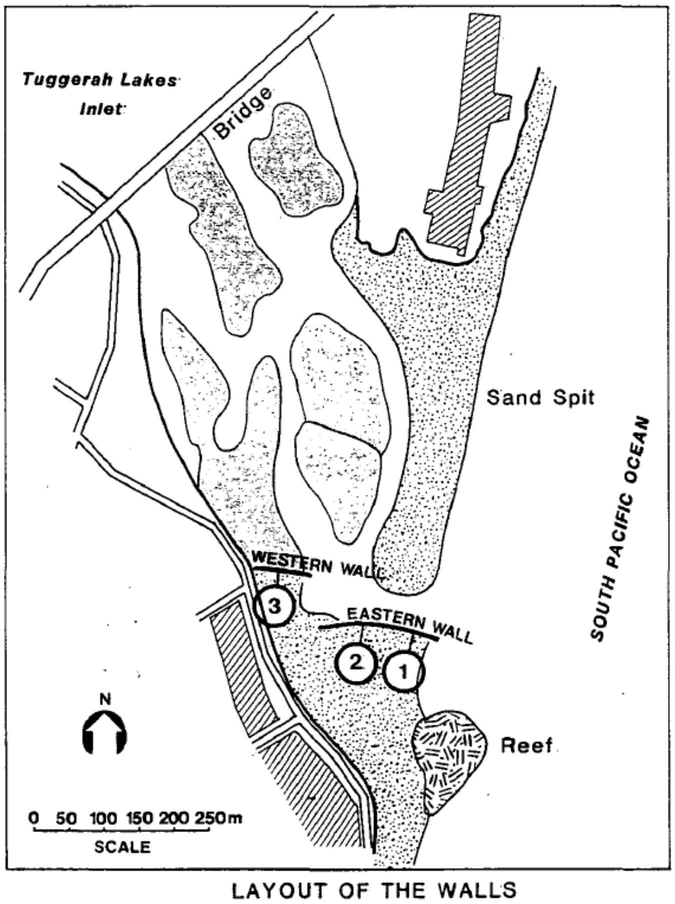


Figure 2.2: Location of the restraining walls, reprinted from (Public Works Department, 1988).

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 24 hours was the critical duration for the 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 60,000 m^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 was 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 in **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 sand mass).
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 depleted 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 dozers. • 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 for 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 in **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.

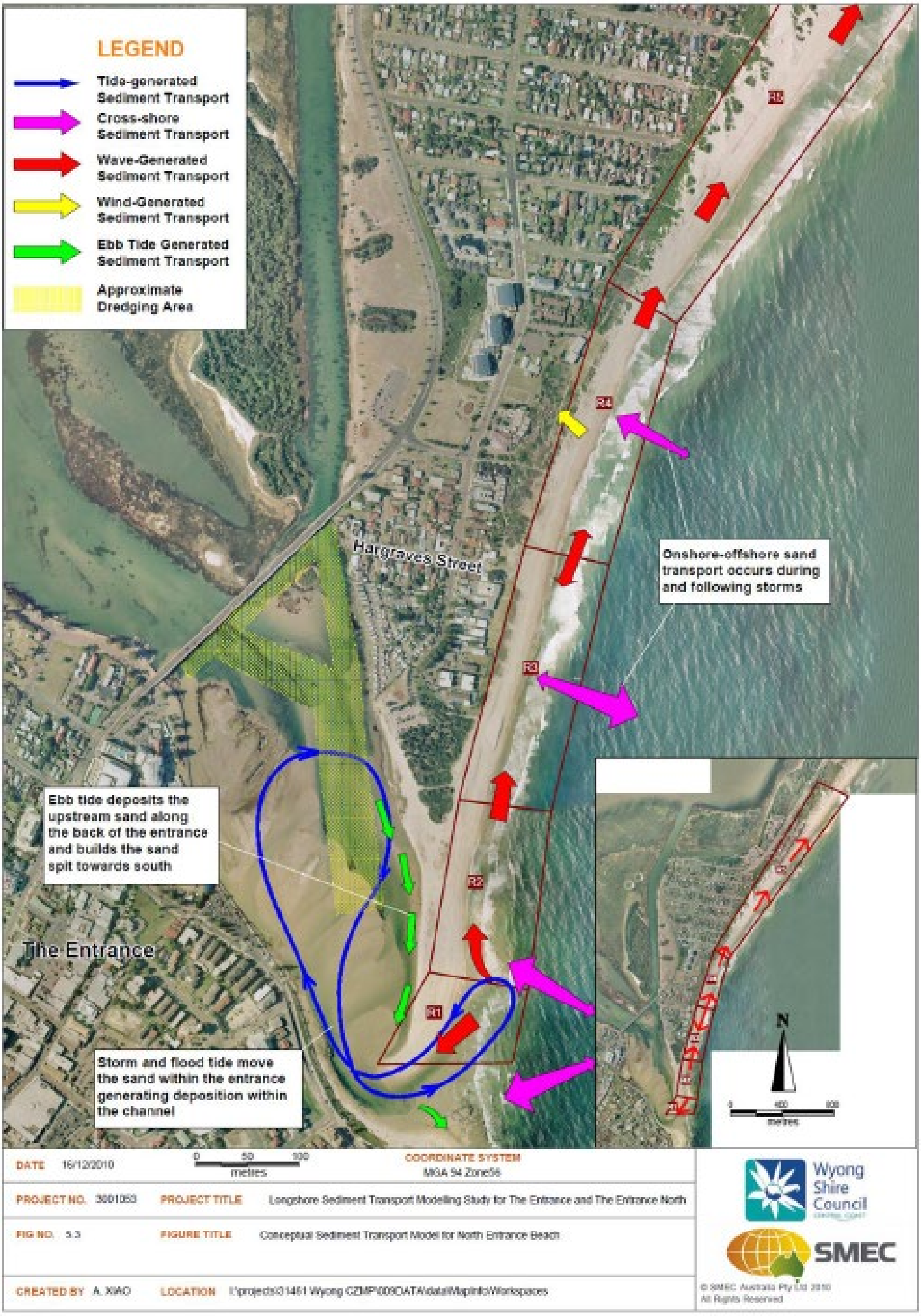


Figure 2.3: Conceptual sediment transport model for North Entrance Beach, reprinted from (SMEC, 2011).

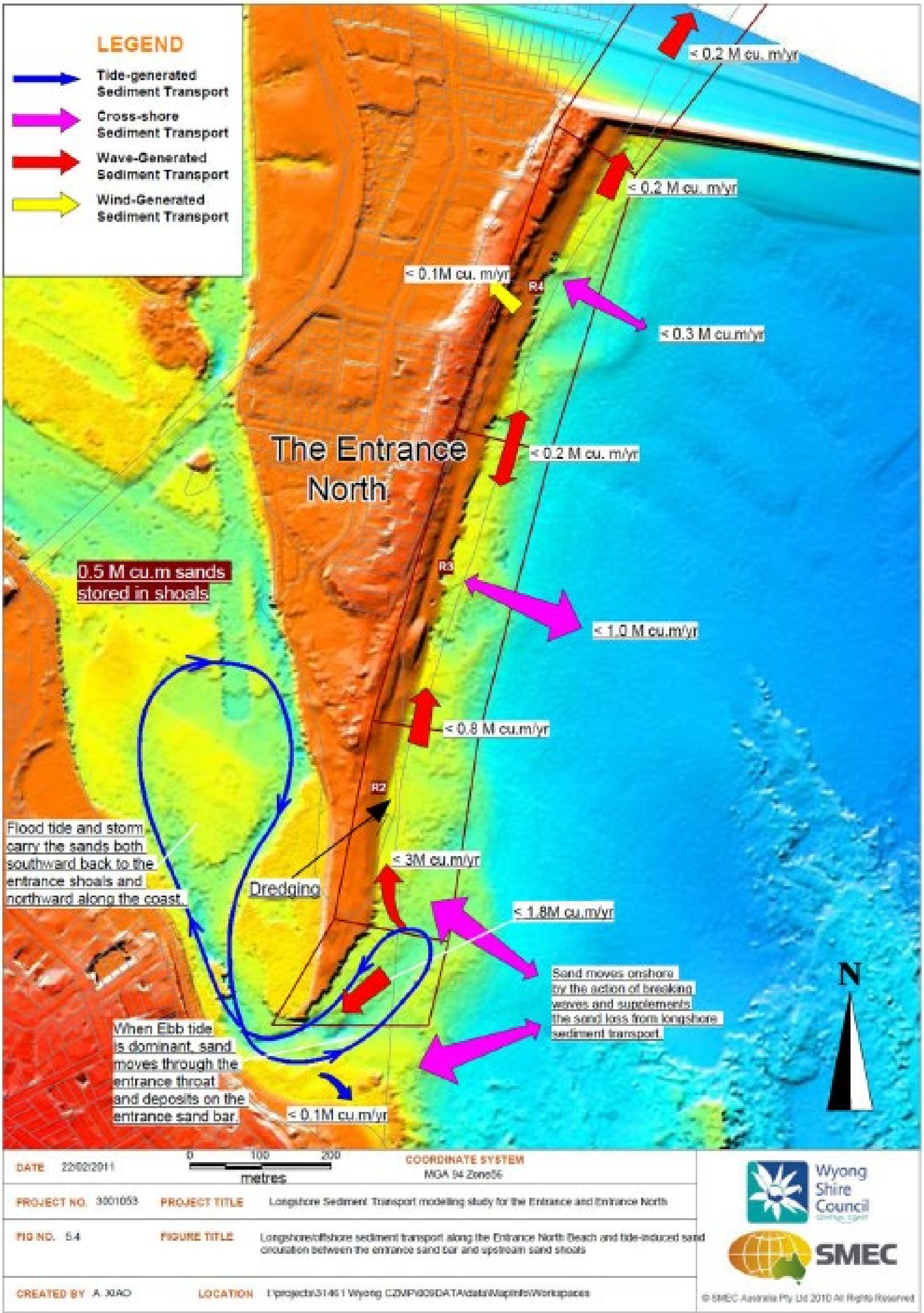


Figure 2.4: Sediment transport along the Entrance North beach, reprinted from (SMEC, 2011).

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 the 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 remain 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 the 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 the 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 the 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 the 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 a 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.

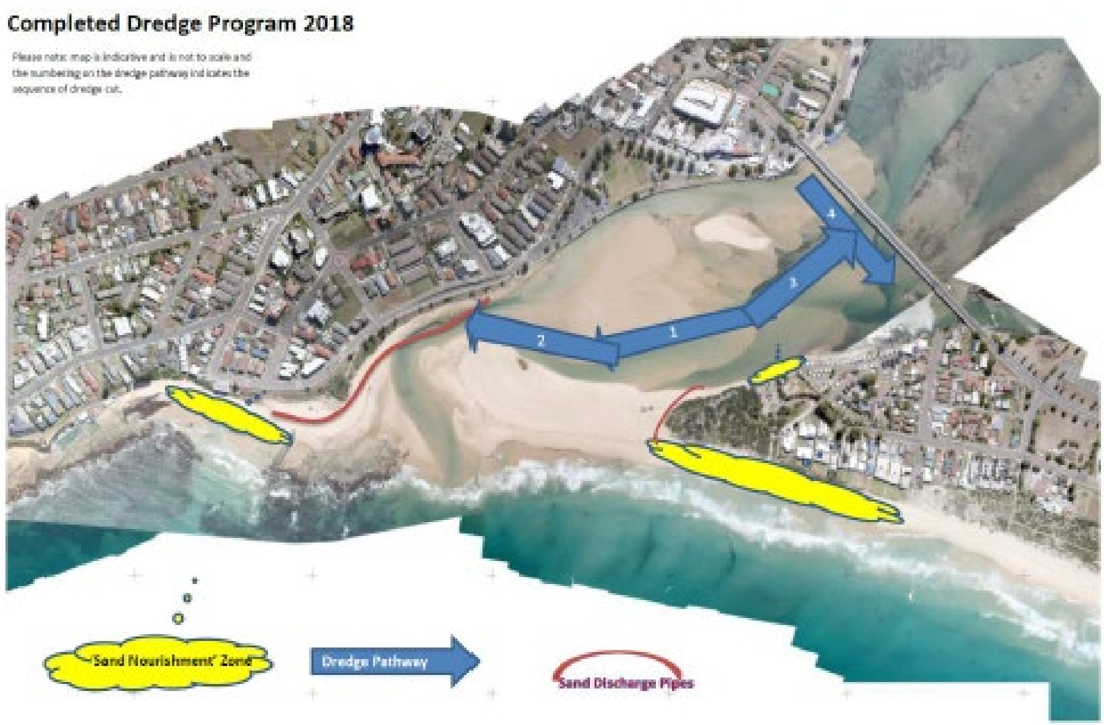


Figure **2.6: Dredge pathway and sand nourishment areas, reprinted from (GHD, 2019).**

In this study, some challenges have been identified as part of the current dredging operations including reliability and cost of ageing 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 in **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 the 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 in February 2020. WRL used LiDAR data and imagery captured by UNSW Aviation on the 11th of 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 of 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 the 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.

2.3 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 a longer duration, found to be more critical during extreme events (Lawson & Treloar, 1994). Alongside the 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 2.8 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.

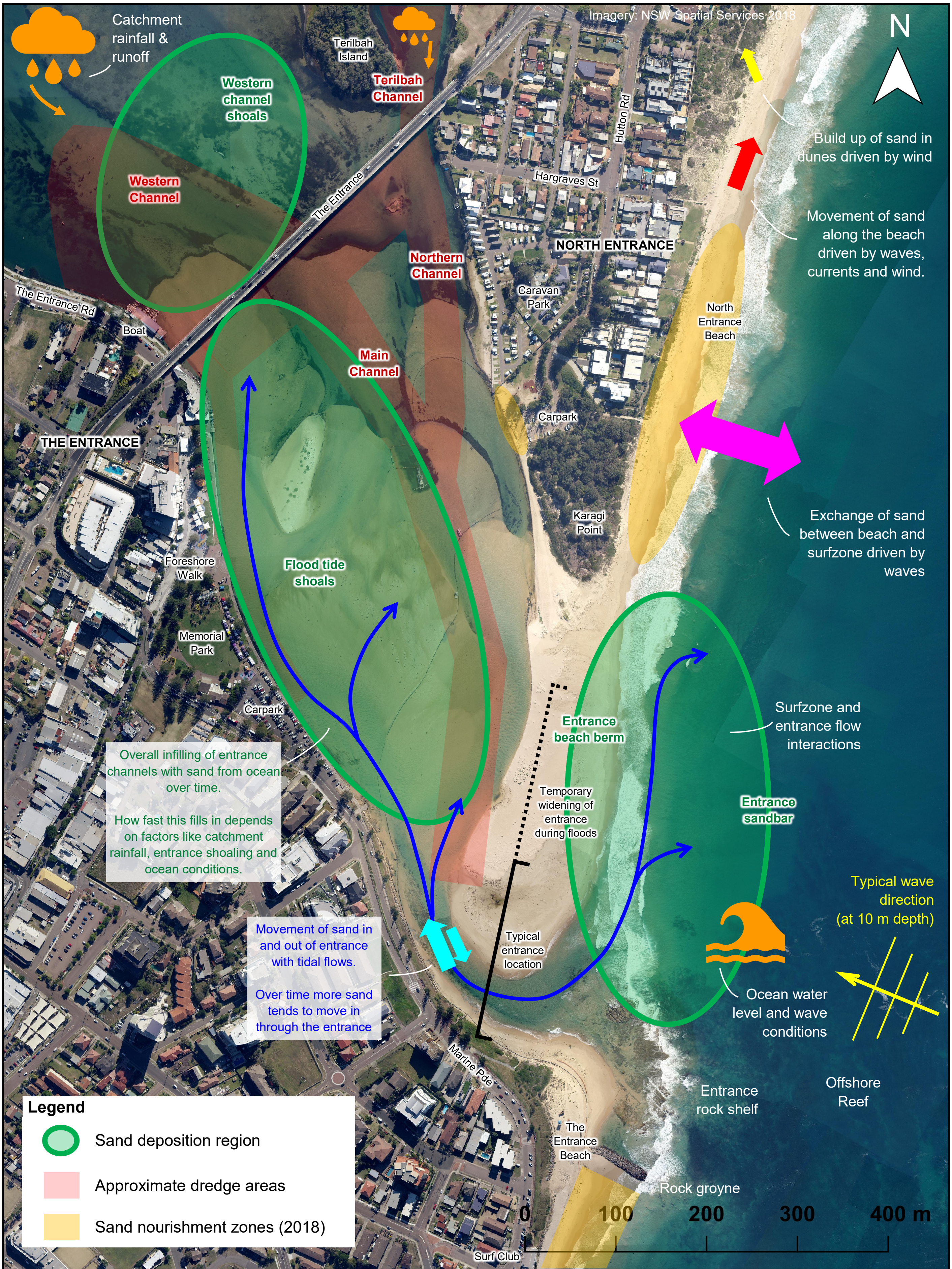
- The flood tide shoals threaten to block the main channel east of the bridge.

Dredged material from regions shown in

Figure 2.8 is used for the 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.



NSW GOVERNMENT

OVERVIEW OF PROCESSES AT TUGGERAH LAKES ENTRANCE

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Figure 2.8

Figure2.8.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 is 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 the 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 the 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.

2.3.1 Conceptual model

The review of previous studies and historical aerial imagery have been used to develop a conceptual model of the Tuggerah Lakes entrance shown in **Figure 2.9** 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 2.9**. 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.

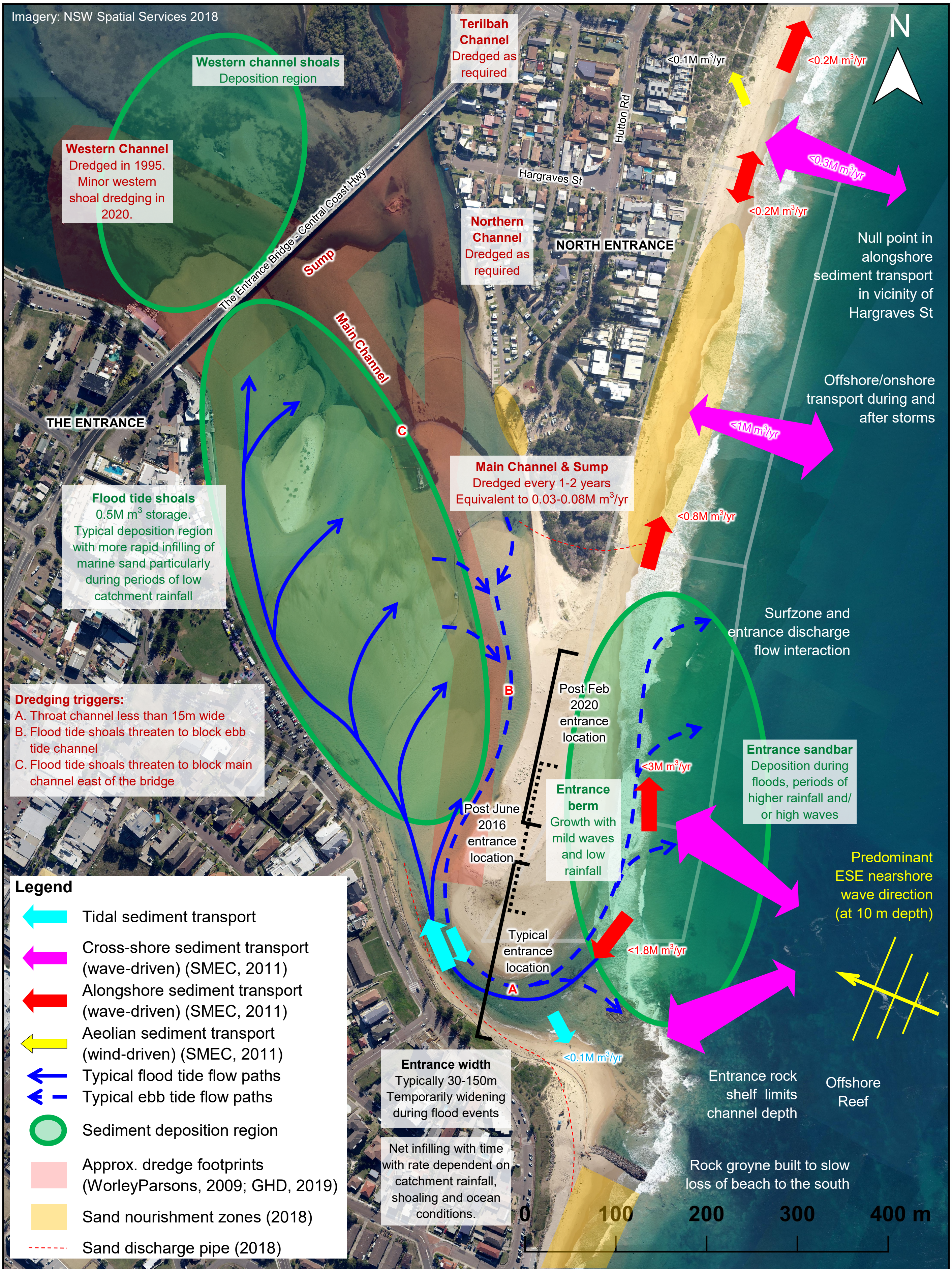
As reported by SMEC (2011), alongshore sediment transport along the open coast of the entrance is typically northward due to the predominant SSE wave climate as shown in **Figure 2.9**, with a null point in the vicinity of Hargraves St. Larger magnitude cross-shore (offshore/onshore) sediment exchanges 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 2.9**). 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 2.9**). 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 the northern end of the spit was also noted to occur in 1986 (Umwelt, 2011). Under such configurations, entrance processes depicted in **Figure 2.9** 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 natural 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.



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CONCEPTUAL MODEL OF ICOLL ENTRANCE PROCESSES AT TUGGERAH LAKES ENTRANCE

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Figure

2.9

Figure2.9.pdf

3 Entrance modelling and analysis

3.1 Preamble

Using a combination of data analysis and flood modelling techniques, this chapter provides insight into entrance behaviour and water level variability for Tuggerah Lakes. Typical lake level variability, tidal range, historical trends in entrance constriction as well as interactions between entrance configuration and lake water levels for both flood and dry-weather events are addressed.

3.2 Input datasets

Datasets used to undertake entrance modelling and historical analysis in this chapter included:

- Topographic data

Light Detection and Ranging (LiDAR) survey of the study area and its immediate surroundings was obtained for the study from ELVIS (https://elevation.fsdf.org.au/). 1 m resolution LiDAR data from the 'Gosford' dataset (NSW Spatial Services 2011-2014) was used. The accuracy of the ground information obtained from the LiDAR survey can be adversely affected by the nature and density of vegetation, the presence of varying terrain, the vicinity of buildings and/or the presence of water. The horizontal accuracy of the data is 0.8 m at 95% confidence interval, while the vertical accuracy is 0.3 m at 95% confidence interval. The terrain topography is shown in **Figure 3.1**.

- Aerial photography

The most recent available aerial imagery was obtained from Google Earth (www.googleearth.com), captured in 2021 to observe current features within the study area.

- Land zoning

Land zoning GIS spatial data was obtained from the NSW Department of Planning, Industry and Environment; shown in **Figure 3.2**.

- Water level, rainfall and flow data

Water level (15-minute recording frequency) and near-real-time rainfall stations within or in the vicinity of the study area. These gauges are tabulated in **Table 3.1** and their location is illustrated in **Figure 3.3**. Flow data records (15-minutes frequency) were obtained from WaterNSW (https://realtimedata.waternsw.com.au/) for Wyong River at Gracemere (211009) and Ourimbah Creek U/S Weir (211013) as shown in **Figure 3.3**.

- Lake bathymetry and entrance channel survey data

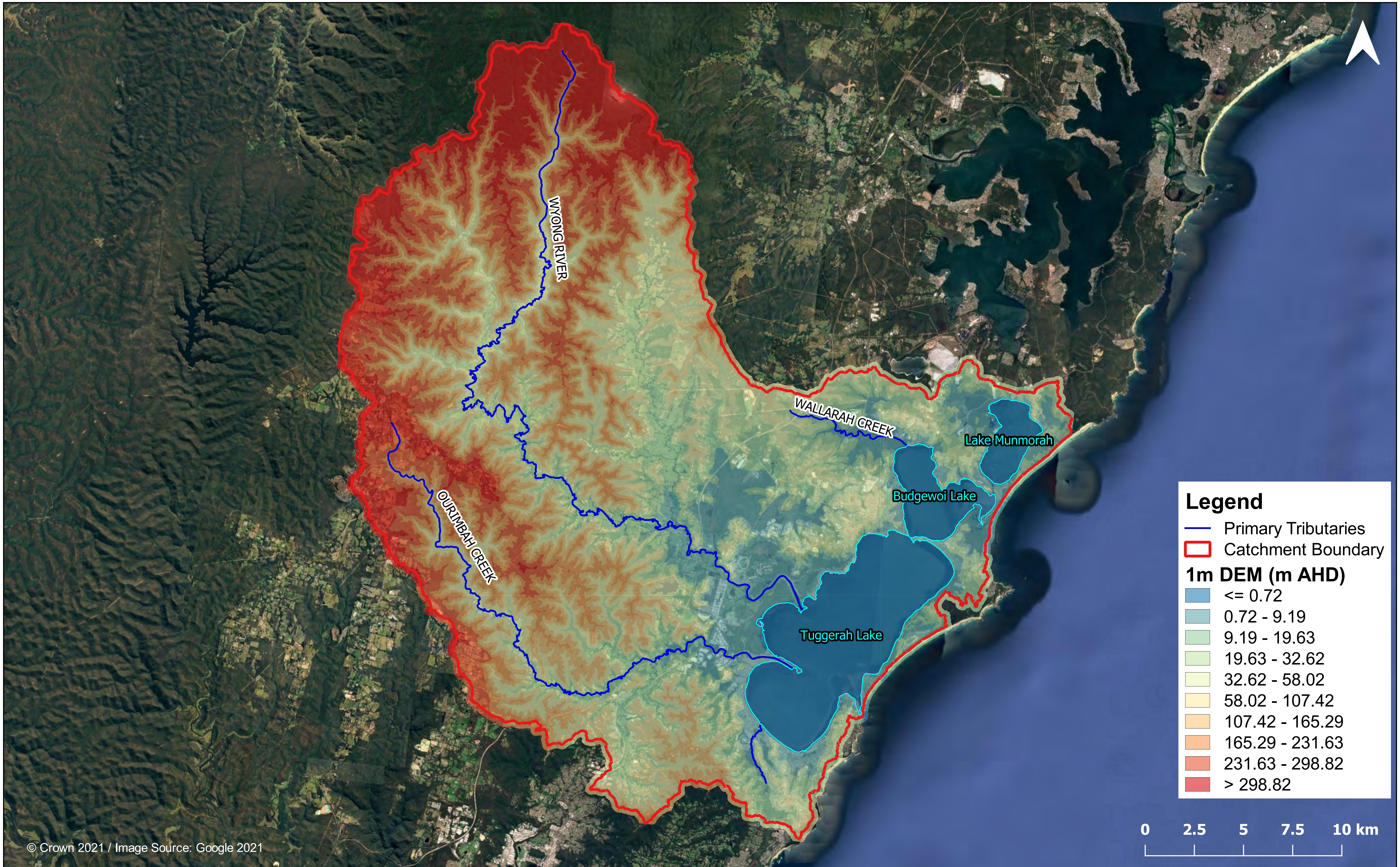
Lake bathymetry and entrance channel survey datasets were used (1975, 2011 and 2018 NSW Office of Environment and Heritage; 2018-2020 Central Coast Council).

- Further data

Additional information from the previous flood modelling studies in the Tuggerah Lakes catchment was used to inform model setup and calibration in the present study (e.g., Tuggerah Lakes Flood Study, 1994; Ourimbah Creek Catchment Flood Study, 2013; Killarney Vale/Long Jetty Catchments Overland Flood Study, 2014; Northern Lakes Flood Study, 2015; Wallarah Creek Flood Study, 2015; Tuggerah Lakes Southern Catchment Flood Study, 2015).

Table 3.1 Rainfall, water level and flow stations in vicinity of the study area.

Station Name	Station Number	Easting	Northing
Near-real-time rainfall (MHL)			
Toukley	211401	362599	6318531
WyongWeirUpstream	211417	351596	6316778
WhitemansRidge	561026	343653	6324899
Kulnura	561078	333796	6321517
HamlynTerrace	561133	357399	6319854
MardiDam	561082	351038	6314555
KangyAngy	561132	350168	6310609
BerkeleyVale	561134	353191	6309376
BateauBay	561069	358098	6305653
Lisarow	561079	348900	6305317
Yarramalong	561137	338869	6322377
Sterland	567138	342433	6315335
Warnervale(Decomm)	5SRA05	356155	6320015
Chittaway(Decomm)	561072	350336	6310109
MountElliot	561084	350646	6302980
Narara	561085	344310	6304220
Strickland	561136	345377	6305541
Wyoming	561098	346415	6302026
TerrigalReservoir	561138	355120.3	6297391
Gosford(BoM)	IDN60901	345830	6300178
Water level (MHL)			
WallarahCreekBridge	211420	360913	6323587
Toukley	211401	362599	6318531
WyongWeirUpstream	211417	351596	6316778
LeesBridge	211425	353684	6311538
LongJetty	211418	358757	6308079
TumbiUmbi	211419	355321	6307480
KangyAngy	ERTS61384	350168	6310609
Lisarow (Cutrock Creek)	212464	348883	6305388
TallTimbersLisarow	2124127	349098.6	6305933
WyongRiverU.Sbridge	61386	353247	6315353
TuggerahLakesEntrance	ERTS561001	360059.4	6309209
WyongBridgeDownstream(Decomm)	211416	353402.1	6315330
Flow (WaterNSW)			
Wyong River at Gracemere	211009	347220.3	6317541
Ourimbah Creek U/S Weir	211013	345841.2	6308872



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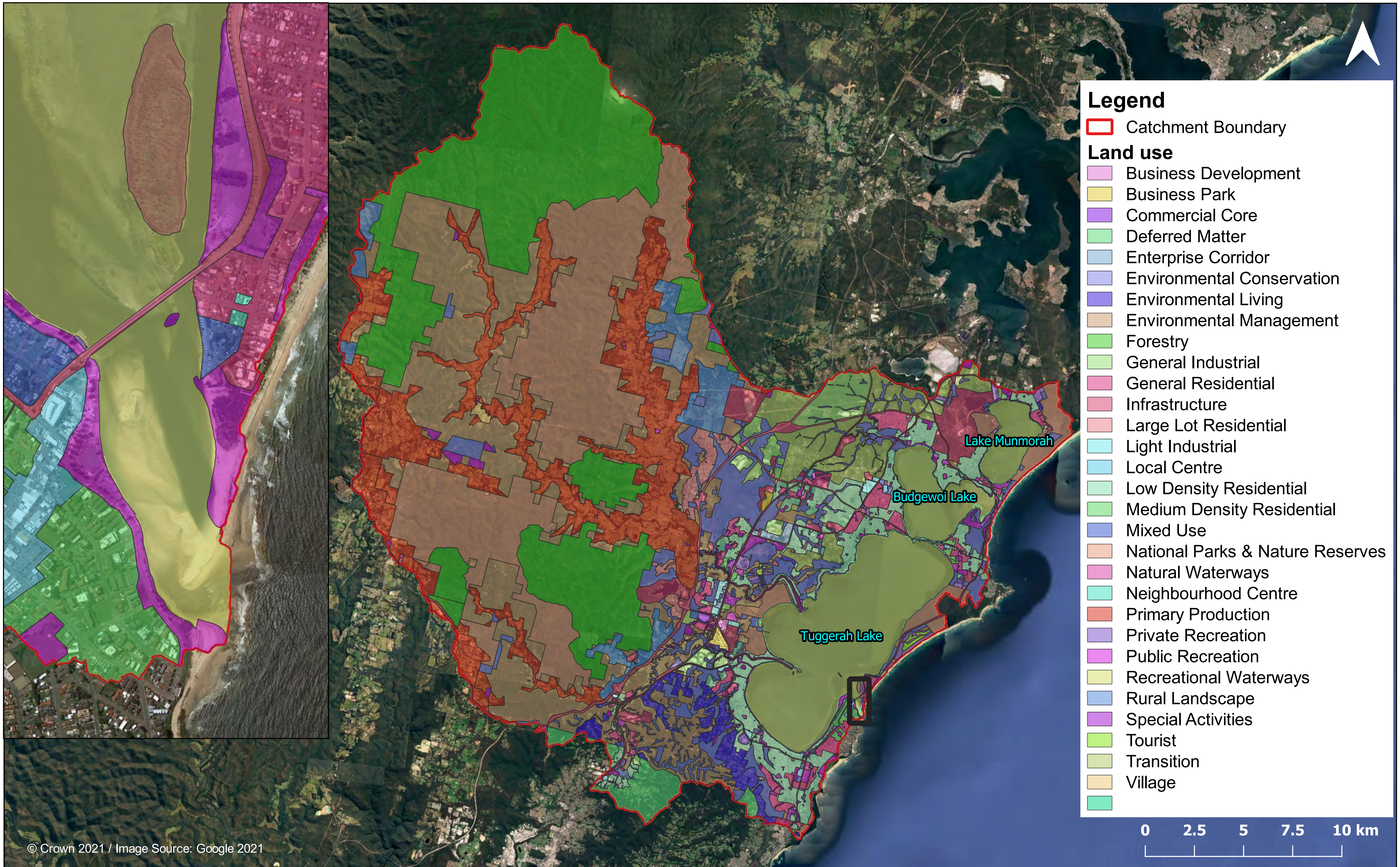
Topographic data

Report MHL 2781
Figure 3.1



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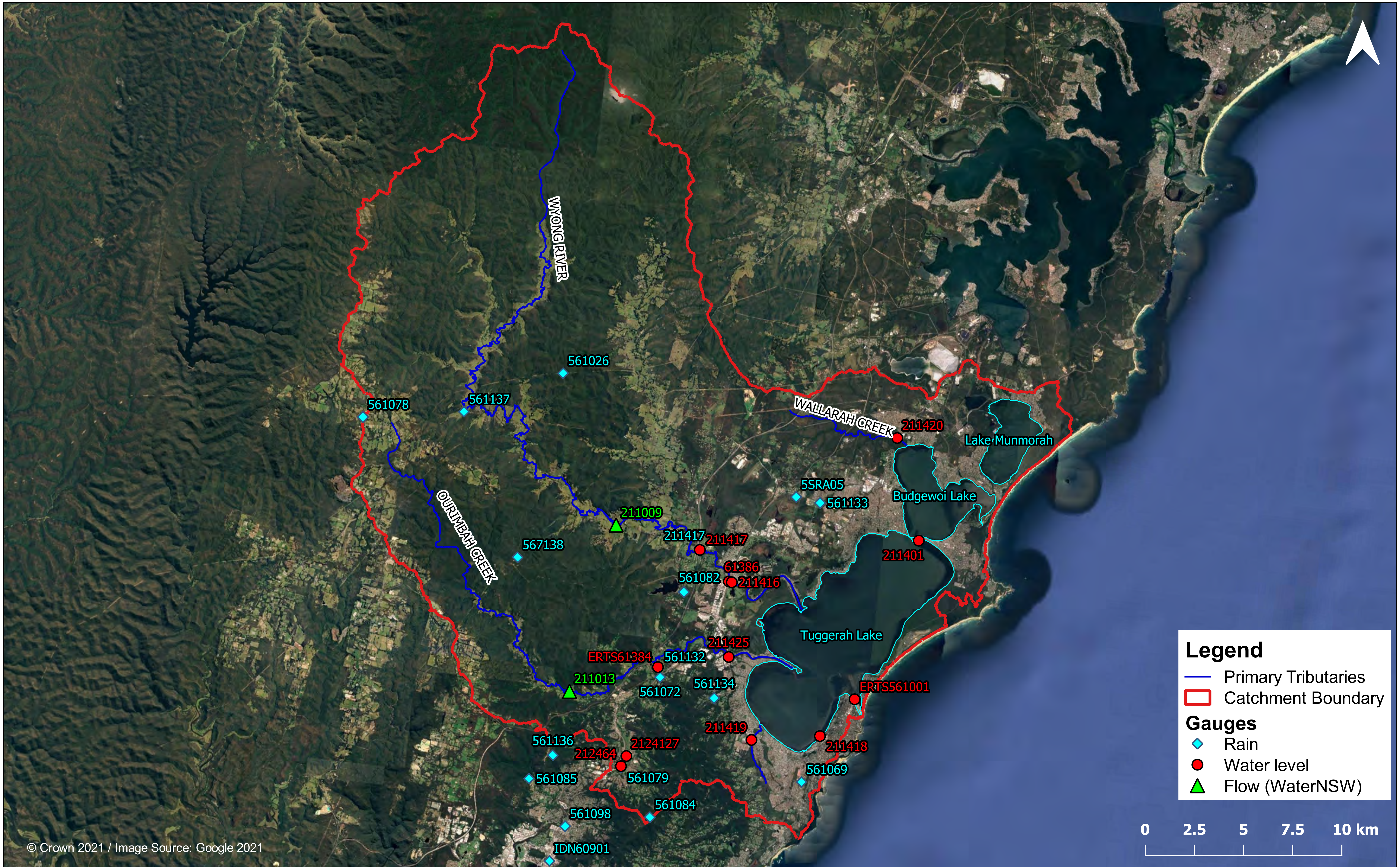
Land use zoning

Report MHL 2781
Figure 3.2



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Rainfall, discharge and water level stations

Report MHL 2781

Figure 3.3

3.3 Data analysis techniques

3.3.1 Water level analysis

A 29-year dataset of 15-minute water level records at Long Jetty (Station Number: 211418, Longitude: 151.481942 and Latitude: -33.357242) from September 1991 to September 2020 were analysed to identify typical lake levels, historical entrance behaviour and constriction. The Long Jetty gauge was used to represent lake levels in Tuggerah Lakes in the present analysis, situated relatively close to the entrance location compared to other gauges. It is noted minor differences in water level (in the order of a few centimetres) can occur between lake gauges due to wind setup. Hereafter in this report, lake water levels are in reference to the water level recorded at the Long Jetty gauge.

3.3.2 Tidal harmonic analysis

Tidal harmonic analysis was undertaken to determine the strength of tidal signal frequencies in the water level record. Tidal constituents were calculated each day using a moving 28-day analysis window corresponding to a monthly lunar cycle. As such, the results are indicative of monthly tidal response and are not a measure of day-to-day variability or rapid entrance changes occurring over shorter periods.

The magnitude of the M2 (principal lunar semi-diurnal) tidal constituent was examined to indicate tidal penetration in the entrance. An increase in the measured M2 constituent indicates an increase tidal response and entrance flushing. On the other hand, a decrease in the M2 constituent indicates reduced tidal response and entrance conditions tending towards closure. Variations in the M2 constituent were compared with water level records over periods leading up to and following flood events to identify historical entrance behaviour and constriction.

It should be noted that tidal range in the lake is relatively small and similar in magnitude to the accuracy water level data itself (±20 mm). Therefore care is required in interpreting results of tidal harmonic analysis. While the results are useful in providing an indication of long-term trends in entrance constriction, they are not to be used as a measure of day-to-day variability or entrance changes occurring over short periods of time.

3.3.3 Channel width analysis

The width of the Tuggerah Lake Entrance channel over time (at approximately 0 m AHD) was estimated using CoastalCOMS entrance width monitoring data (2012 to 2019), available entrance survey maps (September 2011, February 2018, January 2019, March and May 2020), aerial imageries obtained from Google Earth from 2007 to 2020, Planet Explorer for 2016 and 2020, as well as historical aerial imageries from 1954 to 2006 documented by Umwelt (2011).

3.4 Modelling methodology

3.4.1 Modelling overview

To model water levels in Tuggerah Lakes, the present study has adopted a Watershed Bounded Network Model (WBNM) to simulate catchment hydrology and lake inflows, combined with a one-dimensional hydraulic representation of entrance flows. This approach was selected as an efficient and cost-effective means of examining and modelling ICOLL entrance behaviour under a range of scenarios and climatic conditions. This modelling approach has been previously used to inform entrance management on Sydney's Northern Beaches, Central

Coast, Lake Macquarie, Lake Conjola and Wonboyn Lake. Along with the tidal harmonic and data analysis techniques also undertaken, the modelling can be used to predict both short-term entrance behaviour and allows for relatively fast run times to explore a high number of options and storm events.

3.4.2 Hydrological Modelling

3.4.2.1 Model description

A Watershed Bounded Network Model (WBNM 2017_001) was adopted for hydrological modelling of the Tuggerah Lakes catchment. It is an event-based hydrological model that utilises storage routing to simulate flood hydrographs based on rainfall-runoff relationships for Australian catchments (Boyd, 1979). The WBNM model has been widely adopted for similar studies in Australia including the Tuggerah Lakes Flood Study (Lawson & Treloar Pty. Ltd, 1994) and more recently the Tuggerah Lakes Southern Catchments Flood Study (WMAwater 2018). It has been used to simulate a wide range of hydrological behaviour in natural and urban catchments and requires relatively few catchment parameters in comparison to other runoff routing models. Hence WBNM model was considered appropriate for this study.

3.4.2.2 Catchment delineation

Catchment boundaries and sub-catchment areas were delineated using the GIS-based terrain analysis program *CatchmentSIM,* with topographic Lidar point data from NSW Lands and Property Information (2011-2014 LPI ALS Survey) and lake bathymetry datasets (1975 and 2018 NSW Office of Environment and Heritage). Delineated catchment boundaries, sub-catchment areas and flow paths are provided in **Figure 3.4**.

3.4.2.3 Model parameters

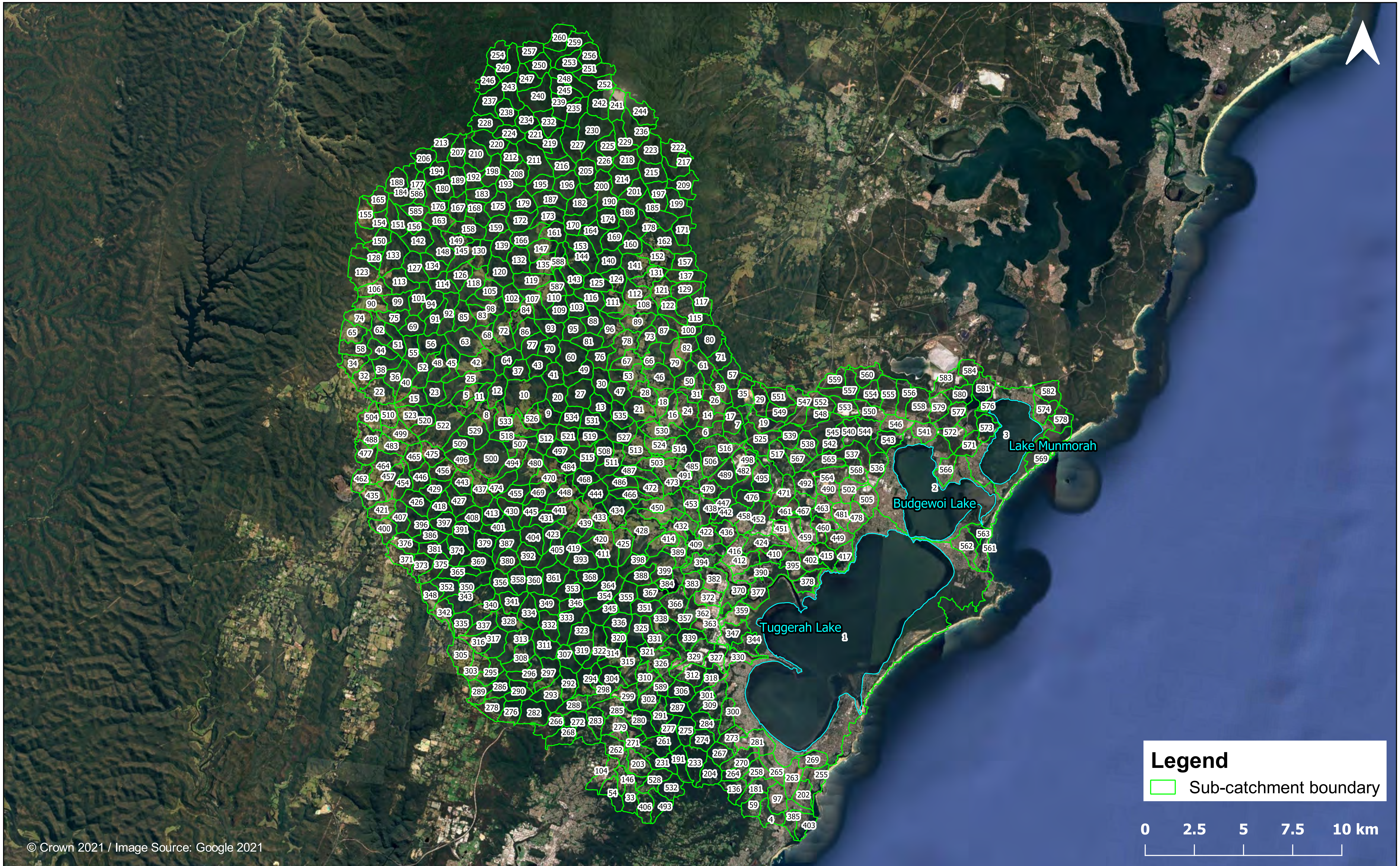
Impervious areas

The portion (%) of impervious area for each sub-catchment was estimated using spatial land zoning GIS information provided by the NSW Department of Planning and Environment and visual inspection of available aerial satellite imagery of the catchment area including roads, roof tops, carparks and built-up areas. Lake/dam water surfaces were also classed as fully impervious.

Lag parameters and flow paths

The delay or acceleration of runoff response is dependent on the physical characteristics of the catchment. These are accounted for in the WBNM model through lag parameter inputs including the lag factor (c) and impervious lag factor.

A lag parameter of 2.5 and impervious lag factor of 0.1 were adopted based on calibration results against measured flow data during flood events along the Wyong River and Ourimbah Creek tributaries (see **Section 3.4.4**). The relatively high lag parameter was adopted to capture observed flood behaviour during calibration likely characteristic of the largely undeveloped catchment. Flow paths were routed using nonlinear routing (type = R) with a value of 1.0 as recommended by Boyd et al. (2017) for natural channels and streams.



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Hydrologic model catchment delineation

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Figure 3.4

Rainfall losses

Following a recent review by WMAWater (2019), it is recommended in AR&R2019 that calibrated rainfall losses be adopted for hydrology design inputs in NSW. Calibrated continuing loss (CL) values from previous studies undertaken in the Tuggerah Lakes catchment have typically been between 1.5 - 4.5 mm/h for pervious surfaces and 0 mm/h for impervious surfaces (Tuggerah Lakes Flood Study, 1994; Ourimbah Creek Catchment Flood Study, 2013; Killarney Vale/Long Jetty Catchments Overland Flood Study, 2014; Northern Lakes Flood Study, 2015; Wallarah Creek Flood Study, 2015; Tuggerah Lakes Southern Catchment Flood Study, 2015). A continuing loss (CL) value of 3.5 mm/h for pervious and 0 mm/h for impervious surfaces was adopted based on calibration results against measured Wyong River and Ourimbah Creek flow data (see **Section 3.4.4**).

These values are consistent with typical continuing losses adopted in previous studies. Pervious initial losses (IL) in the present study varied for each calibration event and ranged from 0 - 60 mm. An impervious initial loss of 0 mm was adopted for all model runs.

3.4.3 Hydraulic entrance representation

A one-dimensional hydraulic model of the entrance was set up and calibrated to estimate the magnitude of entrance flow corresponding with different (simplified) entrance configurations. Model inputs included:

- hypsometric relationships between water levels and lake surface area derived from available bathymetry and topography datasets.
- measured and simulated ocean tide levels at the mouth of the entrance.
- entrance channel survey information provided by Council.

Entrance flows, Q (m^3/s) were estimated using empirical flow equations based on differences in ocean and lake water levels. The Mannings equation was used when the channel depth was less than ocean and lake water levels. The Mannings equation is given by

$$Q = \left(AR^{2/3}\sqrt{S}\right)/n$$

Where R is the hydraulic radius (m), S is the hydraulic grade line slope (m/m) and n is the Mannings roughness coefficient ($s/m^{1/3}$). The cross-section area of flow, A (m^2), was calculated using a simplified trapezoidal representation of the entrance channel as shown in **Figure 3.5**. A constant bank slope of 0.06 m (rise on run) was applied to all model runs, taken from 2018 Marine Lidar bathymetry data. Modelled width or entrance width is in reference to the bottom of the channel as shown in **Figure 3.5**.

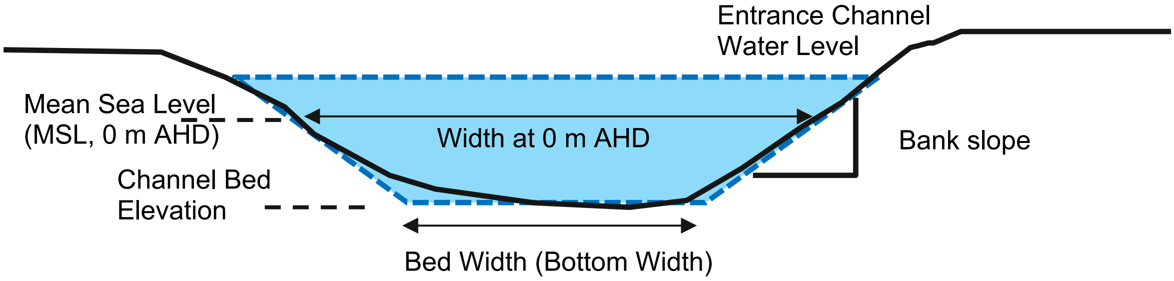


Figure 3.5: Schematic showing simplified model entrance channel geometry

Where the channel bed level was greater than either lake or ocean water level, a broad-crested weir equation was used to estimate flow, given by

$$Q = 1.69WH^{3/2}$$

Where W is the channel width (m) and H is the difference in head (m) between upstream water level and channel bed elevation.

For simulating historical events, entrance flows were computed using measured ocean tide levels at the Patonga gauge (212440, situated approximately 27 km south of the study site) and initial lake water levels at the Long Jetty gauge.

While the one-dimensional hydraulic entrance approach can efficiently help assess simplified changes in entrance geometry, it should be noted that the model does not capture more complex two-dimensional entrance behaviour such as irregularities in channel width and bed level, channel curvature, entrance channel location, and two-dimensional flow patterns. However, the model is considered suitable for the purpose of this study to help assess simplified changes in entrance geometry and will be used alongside additional data analysis techniques to help inform entrance behaviour.

The breakout and scour behaviour of each management option was developed based on calibrated entrance scour parameters in **Section 2.** Breakout behaviour (duration, scour width and depth) for each management option has been developed considering:

- Previous modelling studies at the entrance (e.g., Lawson & Treloar,1994; Cardno, 2013; 2015)
- Council's experience and knowledge of entrance scour (per Comms) including the Feb 2020 flood event.
- Insight from the scour behaviour at other NSW ICOLL entrances (e.g., Gordon, 1990; AWACS, 1994). Entrance scour behaviour was modelled to follow a similar pattern to other neighbouring lagoons (e.g., Wamberal, Terrigal, Cockrone and Avoca), though over longer durations (on the order of 20 h following works of Lawson & Treloar, 1994) noting the larger catchment size, extensive entrance shoals and prolonged flood discharges associated with the Tuggerah Lakes entrance in comparison to the smaller neighbouring lagoon catchments.

3.4.4 Model calibration

Model calibration is an essential step in the modelling process to confirm that the model can adequately simulate historical events. To undertake model calibration, it is necessary to have suitable recorded data sets against which to evaluate model outcomes. The selection of appropriate historical events for model calibration is, therefore, mostly dependent on the availability of relevant data.

Model calibration included the comparison of model results to measured lake water levels (Long Jetty) and available flow data (Ourimbah Creek and Wyong River). Entrance flow measurements from a dry-weather tidal gauging exercise in 1993 were also used to calibrate entrance model representation.

3.4.4.1 Calibration events parameters

The translation of rainfall into the runoff is directly influenced by the antecedent soil moisture conditions throughout the catchment. Rainfall losses are applied in hydrologic modelling to represent the amount of rainfall that does not contribute to runoff, primarily as a result of infiltration processes. The initial loss-continuing loss approach is widely accepted and was adopted in this study. **Table 3.2** summarised the adopted parameters used in calibration events.

Table 3.2 Summary of the model parameters for flood calibration events

Event	June 2007	February 2020	April 2015
Initial loss (mm)	60	0	40
Impervious initial loss (mm)	0	0	0
Continuing loss (mm/hr)	3.5	3.5	3.5
Lag parameter	2.5	2.5	2.5
Impervious lag parameter	0.1	0.1	0.1
Stream lag factor	1	1	1
Mannings n	0.04	0.04	0.04
Entrance channel starting width at 0 m AHD (m)	40	40	40
Entrance channel length (m)	400	400	400
Entrance channel starting bed level (m AHD)	-1	-0.5	-1

3.4.4.2 Flood calibration events

Suitable historical calibration and validation events were determined through considering the following criteria:

- Availability of flow data at Wyong River and Ourimbah Creek, continuous rainfall data within the catchment, and water level in Tuggerah Lake; and
- Inclusion of both flood and dry-weather events.

Model calibration events included:

- June 2007 flood event
- February 2002 flood event
- March 2020 dry-weather conditions (relatively open entrance)
- September 2017 dry-weather conditions (relatively constricted entrance)
- January and December 1993 dry-weather tidal gauging events

The April 2015 flood event was used for model validation.

June 2007

A comparison of recorded and simulated water levels at the Long Jetty for the 7th to 13th June 2007 event is shown in **Figure 3.6**. The figure shows a strong correlation between the simulated and recorded water levels. The peak water level at Long Jetty gauge shows a good agreement for June 2007 event, with a slightly earlier simulated flood peak. A comparison of recorded and simulated flow at Ourimbah Creek at the upstream weir (Station Number: 211013) and Wyong River at Gracemere (Station Number: 211009) for the 7th to 13th June 2007 event is shown in **Figure 3.7** and **Figure 3.8**. These figures show some overprediction of catchment flows in the model compared to measured results.

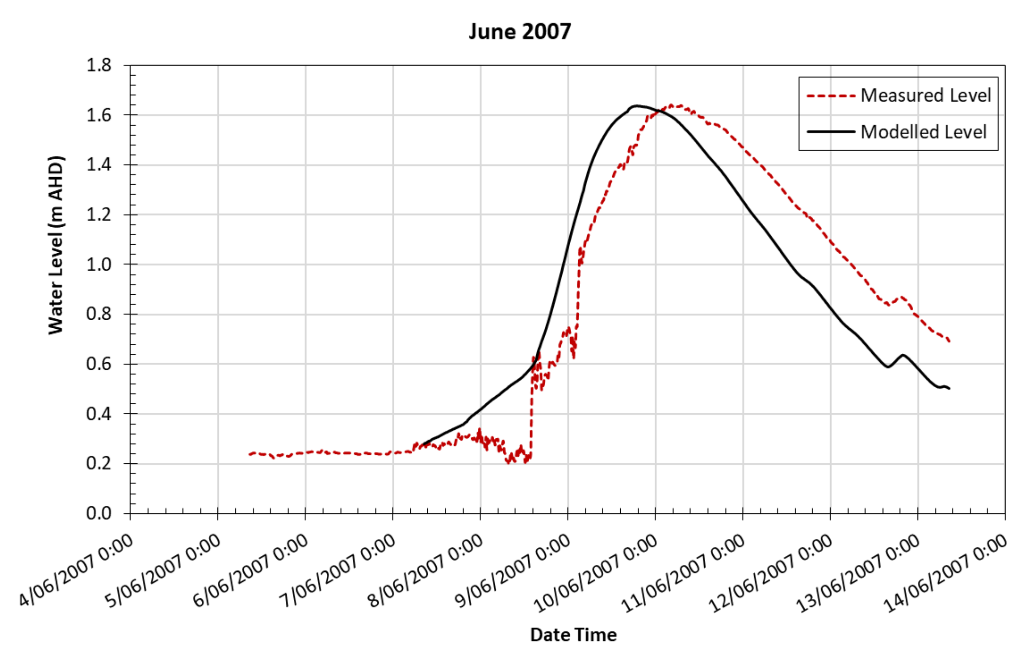


Figure 3.6: Flood calibration event June 2007 – lake water level (Long Jetty)

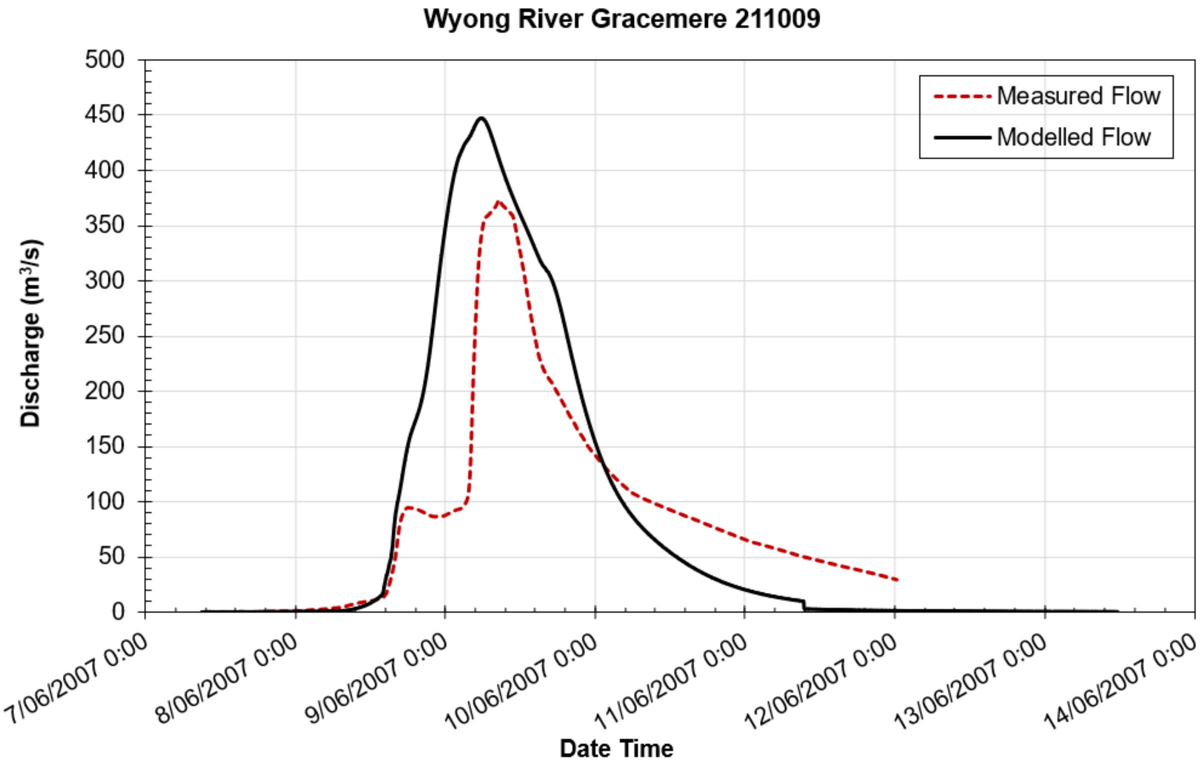


Figure 3.7: Flood calibration event June 2007 – Wyong River flow

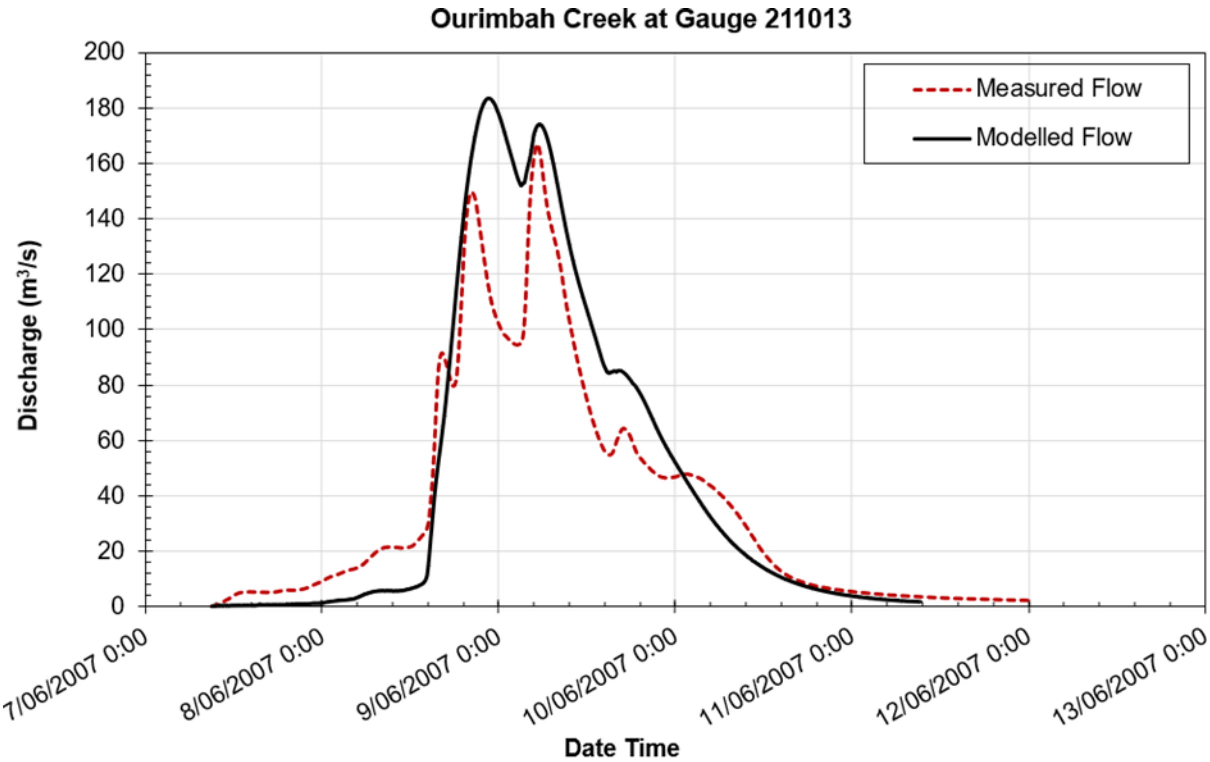


Figure 3.8: Flood calibration event June 2007 – Ourimbah Creek flow

February 2020

A comparison of recorded and simulated water levels at the Long Jetty for the 8th to 12th February 2020 event is shown in **Figure 3.9**. This figure revealed a strong correlation between the simulated and recorded water levels. The peak water level at Long Jetty gauge shows a good agreement for February 2020 event. A comparison of recorded and simulated flow at Ourimbah Creek at the upstream weir (Station Number: 211013) and Wyong River at Gracemere (Station Number: 211009) for the 8th to 12th February 2020 event is shown in **Figure 3.10** and **Figure 3.11**. These figures a good correlation between the simulated and recorded peak flow and accumulated volume at the Wyong River Gracemere gauge, with underprediction of modelled flow at the Ourimbah Creek gauge.

Poor model performance was found during efforts to simulate lake levels over the initial days of the event on the 6th and 7th February 2020, with the model substantially over-predicting catchment flows. In particular high intensity rainfall on the morning of the 6th February, shown in Sydney rain radar images in **Figure 3.12**, was found to be heavily concentrated and localised to the southern fringes of the Tuggerah Lakes catchment. This region also corresponds to where the majority of rainfall gauges used in the WBNM model are located (**Figure 3.3**), likely resulting in the overprediction of catchment flows. Due to the poor model performance on the 6th and 7th February 2020, model calibration was undertaken for 8th to 12th February 2020 with an initial loss value of zero considering the catchment was already wet.

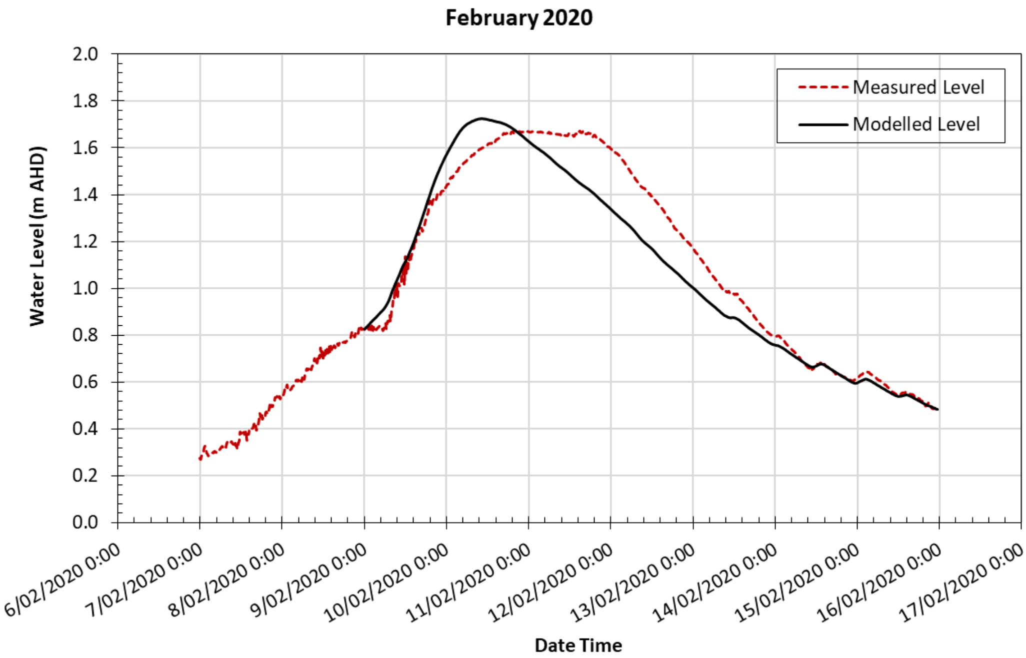


Figure 3.9: Flood calibration event February 2020 - lake water level (Long Jetty)

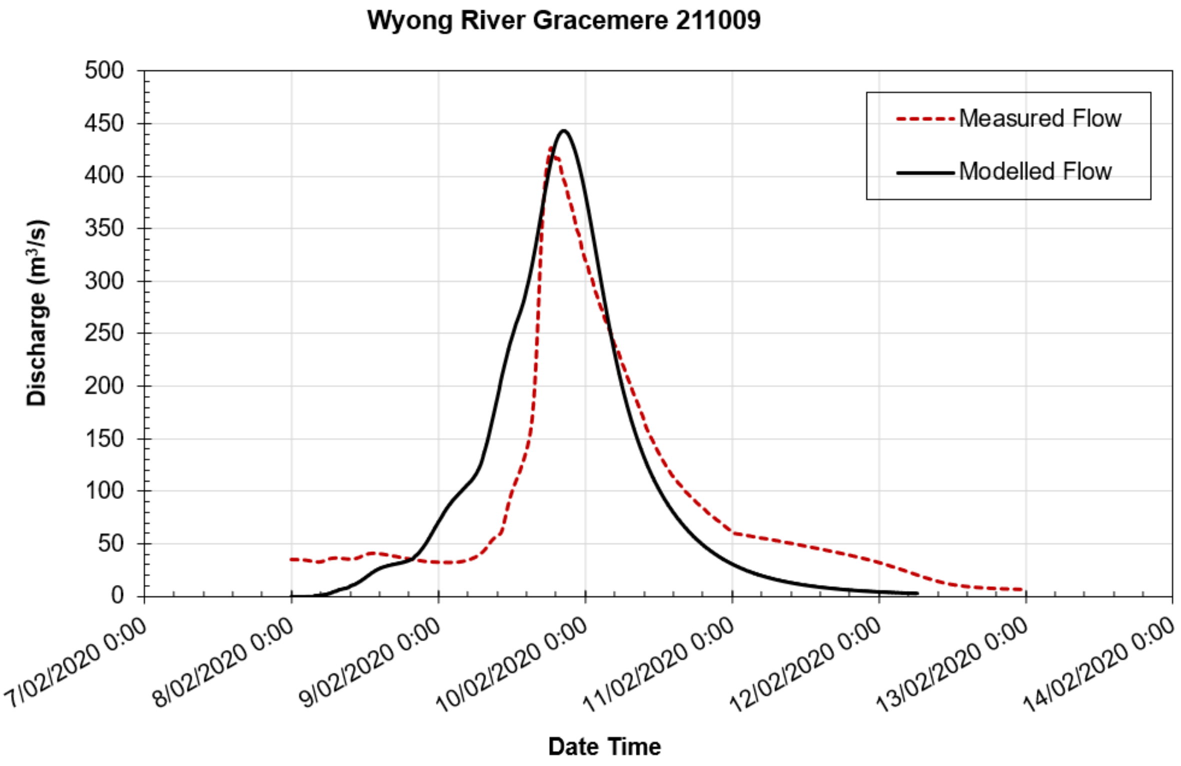


Figure 3.10: Flood calibration event February 2020 – Wyong River flow

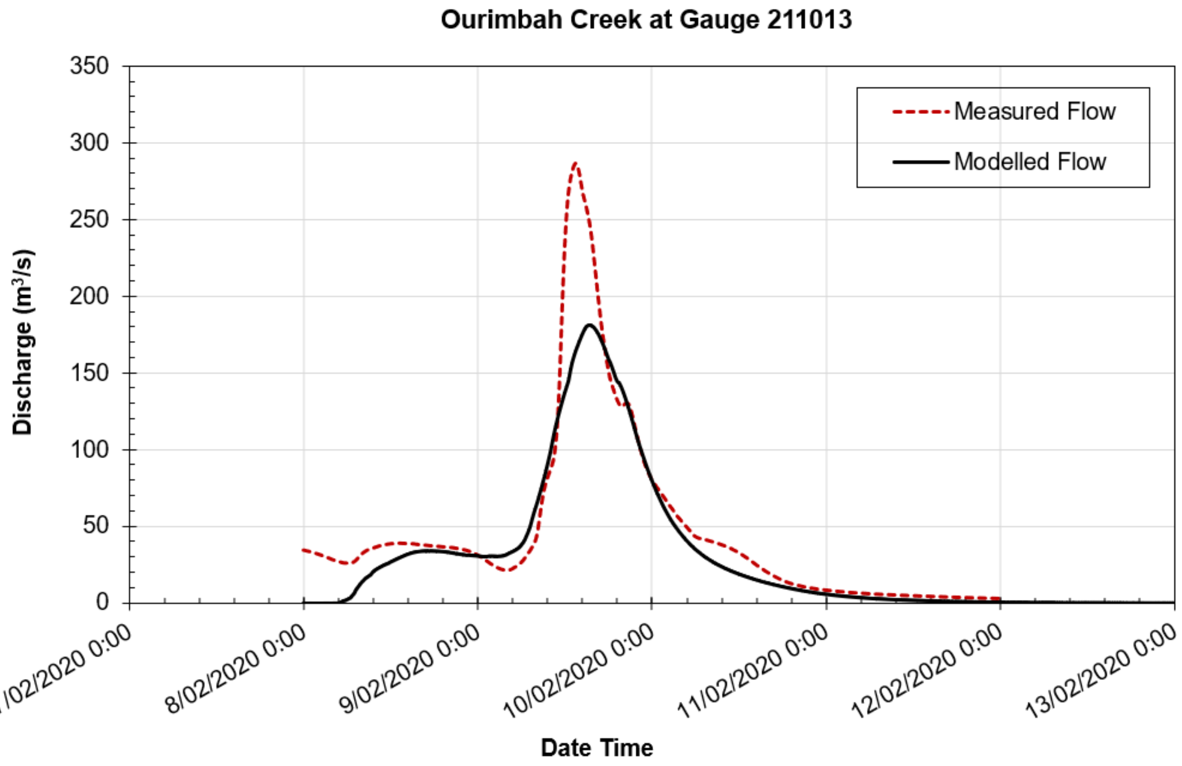


Figure 3.11: Flood calibration event February 2020 - Ourimbah Creek flow

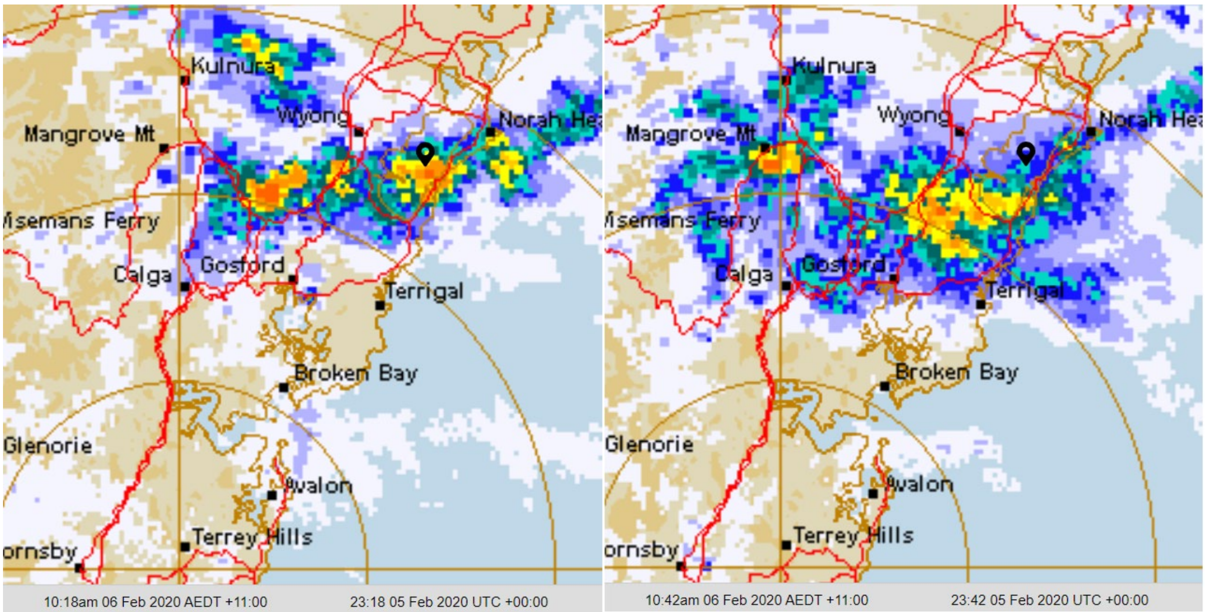


Figure 3.12: Bureau of Meteorology Sydney rain radar images 6th February 2020

3.4.4.3 Dry weather calibration events

March 2020 and September 2017

The model was calibrated against water level data for two periods on the 8th to 14th March 2020 and 10th to 13th September 2017 shown in **Figure 3.13** and **Figure 3.14**, respectively. The events are associated with variations in water level due to measured tidal ocean levels with no rainfall. A strong correlation with measured lake water levels was able to be achieved using the model including a good agreement with measured tidal variations.

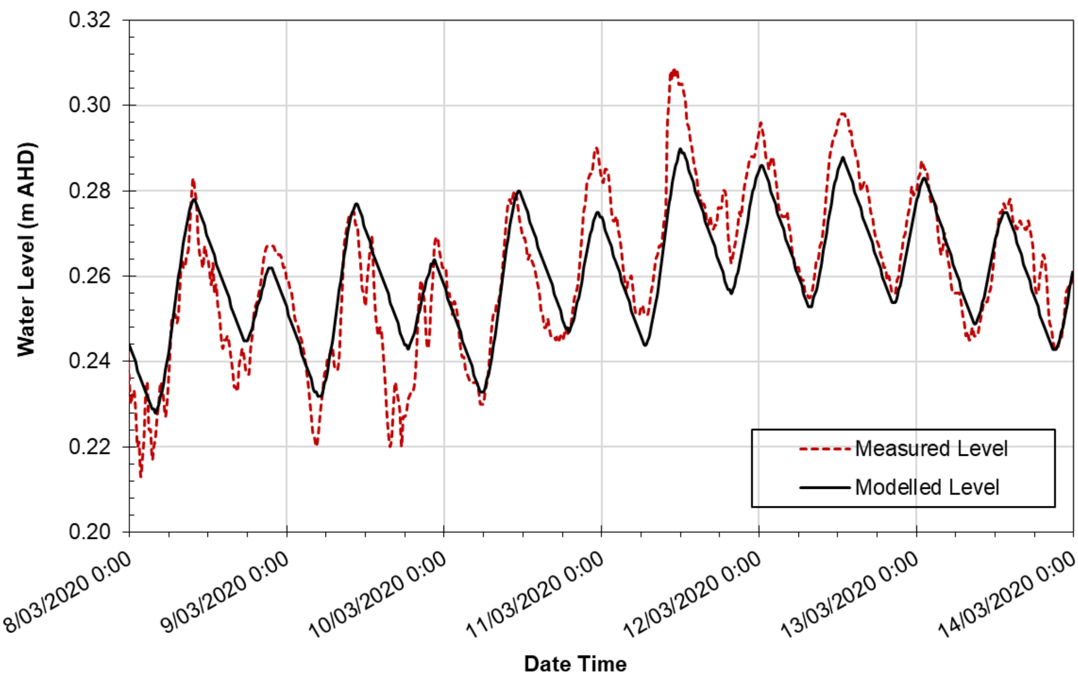


Figure 3.13: Dry weather calibration event March 2020 - lake water level (Long Jetty)

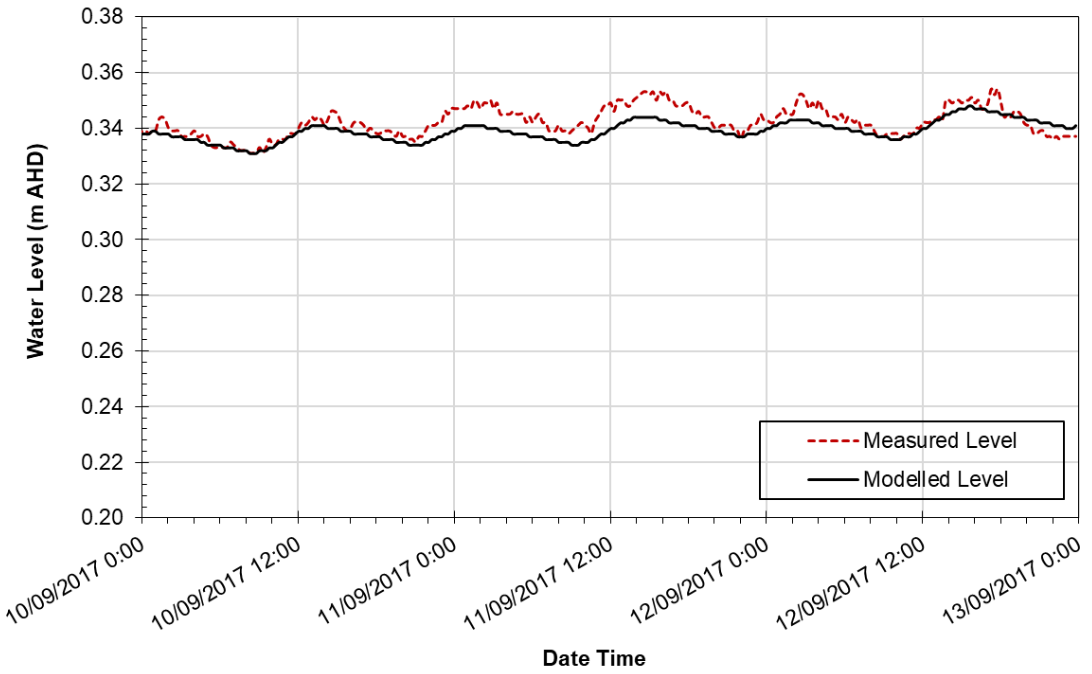


Figure 3.14: Dry weather calibration event September 2017 - lake water level (Long Jetty)

3.4.4.4 Entrance flow calibration

Entrance flows were calibrated against entrance tidal flow gauging datasets from 1993 undertaken in the entrance channel. Calibration results are provided in **Figure 3.15** and **Figure 3.16**, and are in good agreement with the entrance tidal gauging flow data.

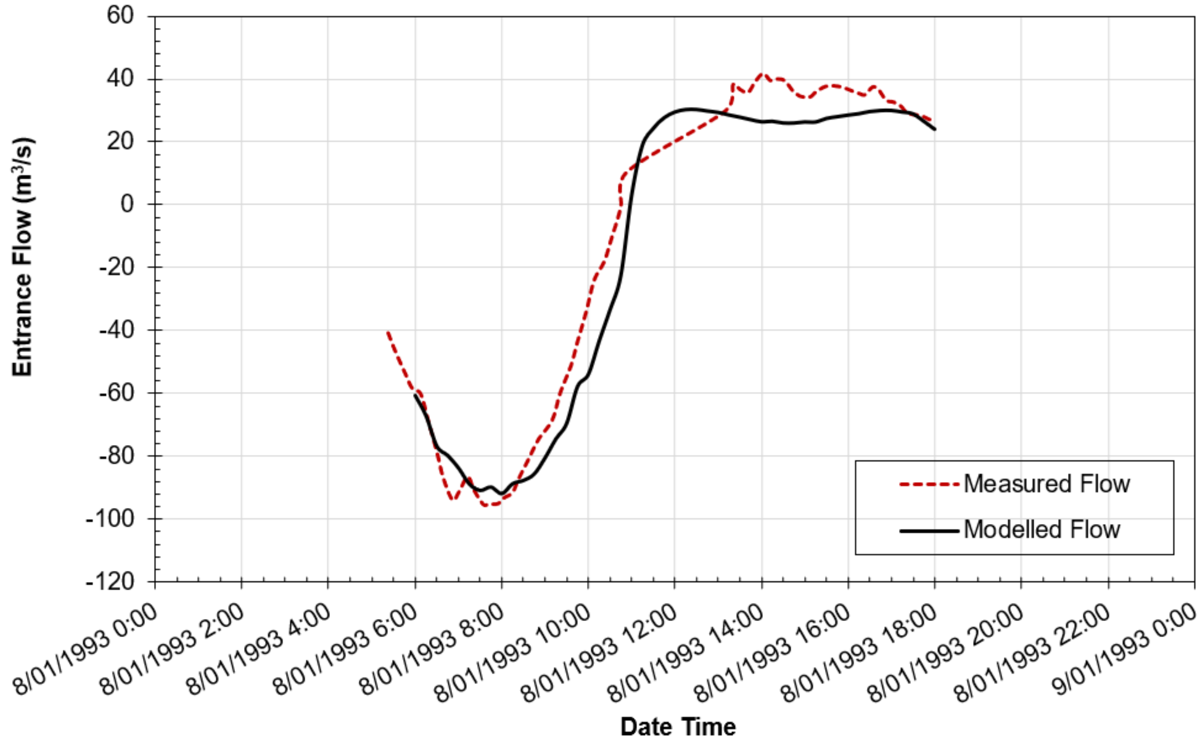


Figure 3.15: Entrance modelled vs measured flows 8th January 1993

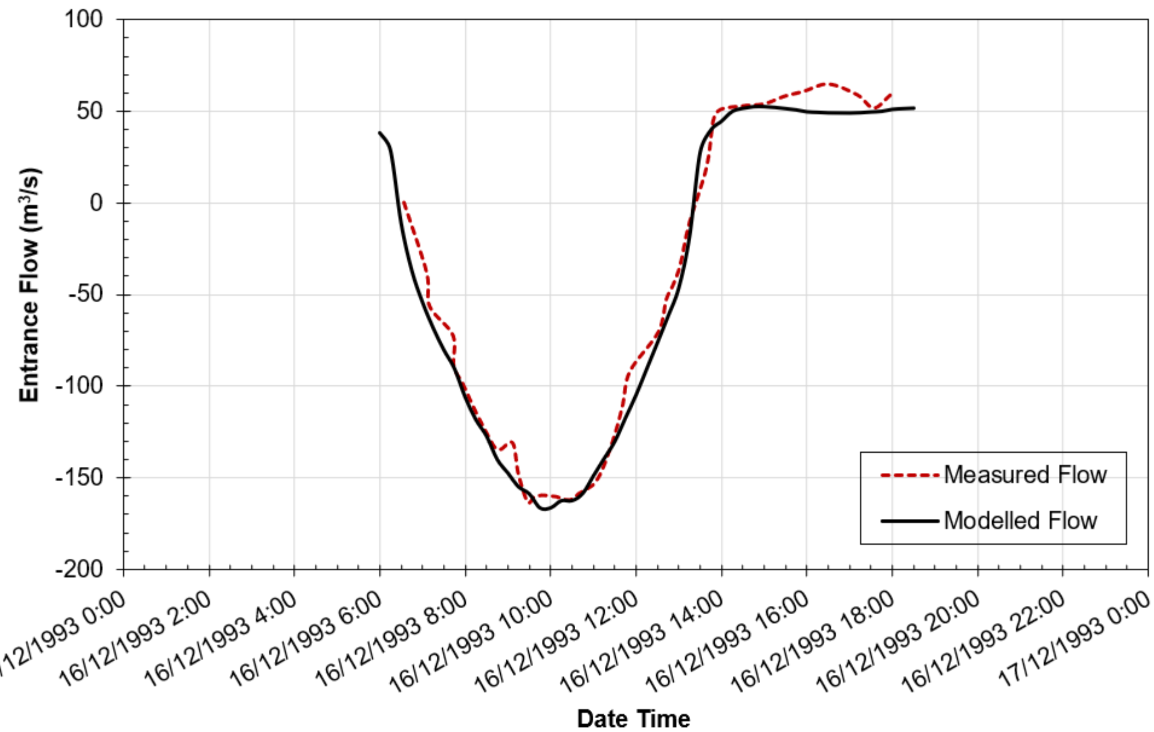


Figure 3.16: Entrance modelled vs measured flows 16th December 1993

3.4.5 Model validation

The model was validated against measured lake levels (Long Jetty gauge) in April 2015. A comparison of recorded and simulated water levels at the Long Jetty for the 21st to 27th April 2015 event is shown in **Figure 3.17**. This figure revealed a strong correlation between the simulated and recorded water levels. The peak water level at Long Jetty gauge shows a good agreement for April 2015 event.

Overall, the model was found to have sufficient accuracy in predicting historical flood and dry-weather events for the purpose of helping to assess simplified changes in entrance geometry and impacts on lake water levels. During validation and calibration, the model was able to predict peak lake levels during flood events within an accuracy of approx. 10 cm and dry weather lake levels within approx. 5 cm including tidal variations. Along with other data analysis techniques, the model will help provide insight into entrance behaviour and Tuggerah Lakes water levels.

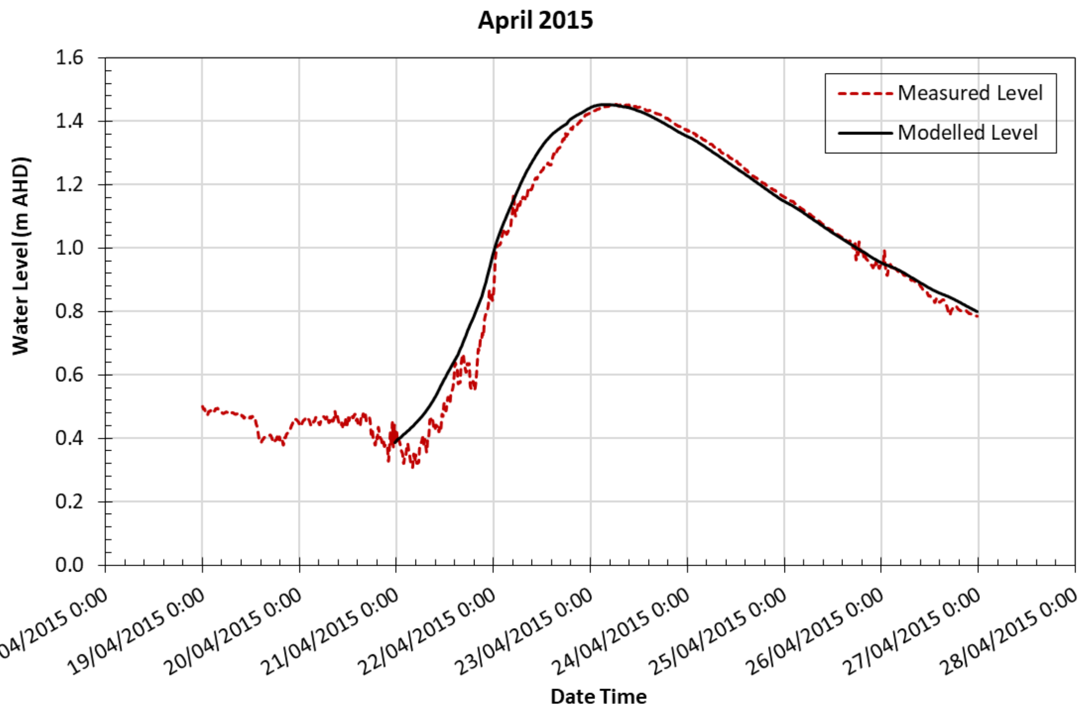


Figure 3.17: Model validation April 2015 flood event – lake water level (Long Jetty)

3.4.6 Modelled flood events for analysis

Events adopted to model of entrance behaviour during flooding included both historical flood events and design flood events from the Tuggerah Lakes Flood Study by Lawson & Treloar Pty. Ltd (1994). Events included

- 8-11 June 2007 flood event – Peak water level of 1.64 m AHD.
- 21-26 April 2015 flood event – Peak water level of 1.46 m AHD.
- 4 x Design flood events as adopted in Lawson & Treloar Pty. Ltd (1994)
    - 1% AEP – Peak water level 2.23 m AHD
    - 5% AEP – Peak water level 1.8 m AHD
    - 20% AEP – Peak water level 1.36 m AHD
    - 50% AEP – Peak water level 0.91 m AHD

Design events were modelled with a time-varying spring tide downstream boundary including storm surge anomaly as specified in Lawson & Treloar Pty. Ltd (1994). Historical events were modelling using measured ocean water levels at the Sydney tide gauge (213470). Sensitivity to increases in downstream ocean water level boundary conditions were modelled in **Section 3.5.9.**

It is noted that the above design events were also adopted more recently in the Tuggerah Lakes Floodplain Risk Management Study and Plan by WMAwater (2014). The model was also run for dry-weather periods to assess entrance flow behaviour during non-flood conditions.

3.5 Results and discussion

3.5.1 Typical lake water levels and tidal range

Water level records in Tuggerah Lakes have been recorded since September 1991 at 15-minute timesteps at the Long Jetty water level gauge (211418). The 29-year Long Jetty water level record is shown in **Figure 3.19**, alongside Berkeley Vale monthly rainfall totals, historical dredge periods and calculated Tuggerah Lakes M2 harmonic constituent. The average lake level over the 29-year monitoring period was 0.27 m AHD with 90% of observations between 0.09 m AHD and 0.5 m AHD (**Table 3.3** and **Figure 3.18**). Tidal harmonic analysis was used to estimate tidal ranges in the lake which were found to typically vary between 1-3 cm, ranging up to 15 cm following significant flood events with relatively wide open entrance conditions. The maximum tidal range in the record was observed in the months following the June 2007 flood event which saw lake levels peak at 1.64 m AHD, the highest on record within the 29-year monitoring period. Maintenance dredging was also noted to have been undertaken not long before the event in late 2006 (**Figure 3.19**), potentially further contributing to relatively high tidal penetration into the lake following the flood event.

Table 3.3: Average water level and typical tidal range in Tuggerah Lakes (at Long Jetty Gauge - 211418)

Monitoring Period	Average Lake Level	Typical Lake Tidal Range	Post-Flood Lake Tidal Range
1993 to 2020	0.27 m AHD (Between 0.09-0.50 m AHD 90% of the time)	1-3 cm	Up to 15 cm [a]

[a] Maximum lake tidal range for 1993-2020 period was observed in the initial months following June 2007 flood event.

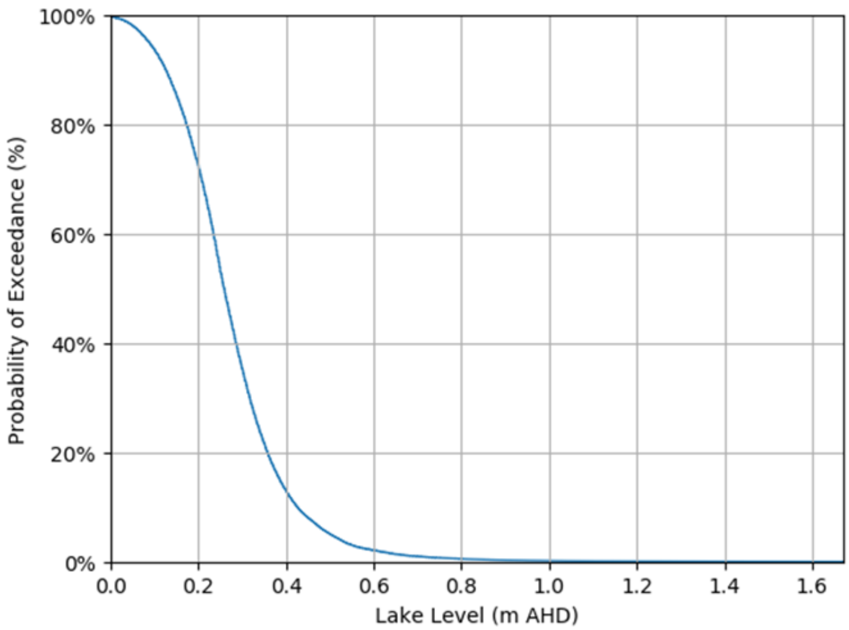


Figure 3.18: Lake level (Long Jetty gauge) exceedance probability

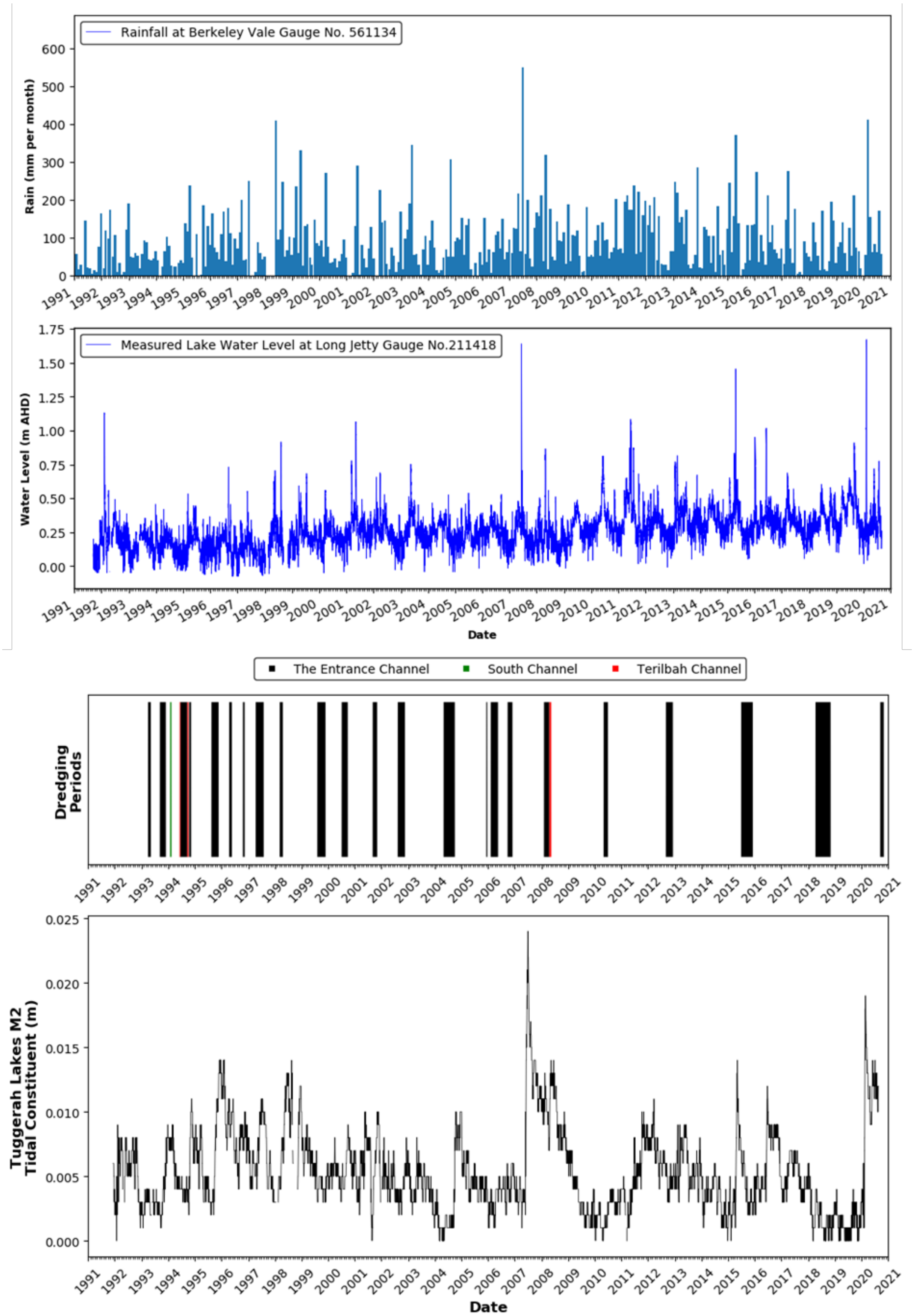


Figure 3.19: Timeseries plots (from top) of Berkeley Vale monthly rainfall totals, Tuggerah Lakes water level at Long Jetty gauge, historical dredging periods, and calculated Tuggerah Lakes M2 harmonic constituent (measured at Long Jetty gauge)

3.5.2 Characteristic entrance behaviour

Tidal harmonic analysis provides a useful means of understanding trends and patterns in entrance opening behaviour. It involves quantifying the strength of tidal signal frequencies in a coastal lake or lagoon water level record, to provide an indicator of how open or closed an entrance is to the ocean over time.

Tidal harmonic analysis was undertaken for the Long Jetty water level record in Tuggerah Lakes for the 29-year monitoring period between September 1991 to September 2020. The magnitude of the M2 tidal constituent was calculated over a 28-day monthly lunar cycle to indicate monthly entrance behaviour as is shown in **Figure 3.19**. An increase in the measured M2 constituent indicates an increase in tidal response. On the other hand, a decrease in the M2 constituent indicates reduced tidal response and entrance conditions becoming more constricted to ocean flows.

Frequency plots of M2 values from 1991 to 2020 are provided in **Figure 3.20**. M2 values were relatively small due to the small tidal variability in lake water levels. These varied between 0 (heavily constricted entrance) and 0.024 m (maximum opening) with a mean value of 0.005 m. M2 values were most often (approx. 70% of the time) between 0.002 - 0.009 m indicative of typical entrance conditions, increasing to above 0.009 m during periods of higher tidal flushing and larger entrance opening.

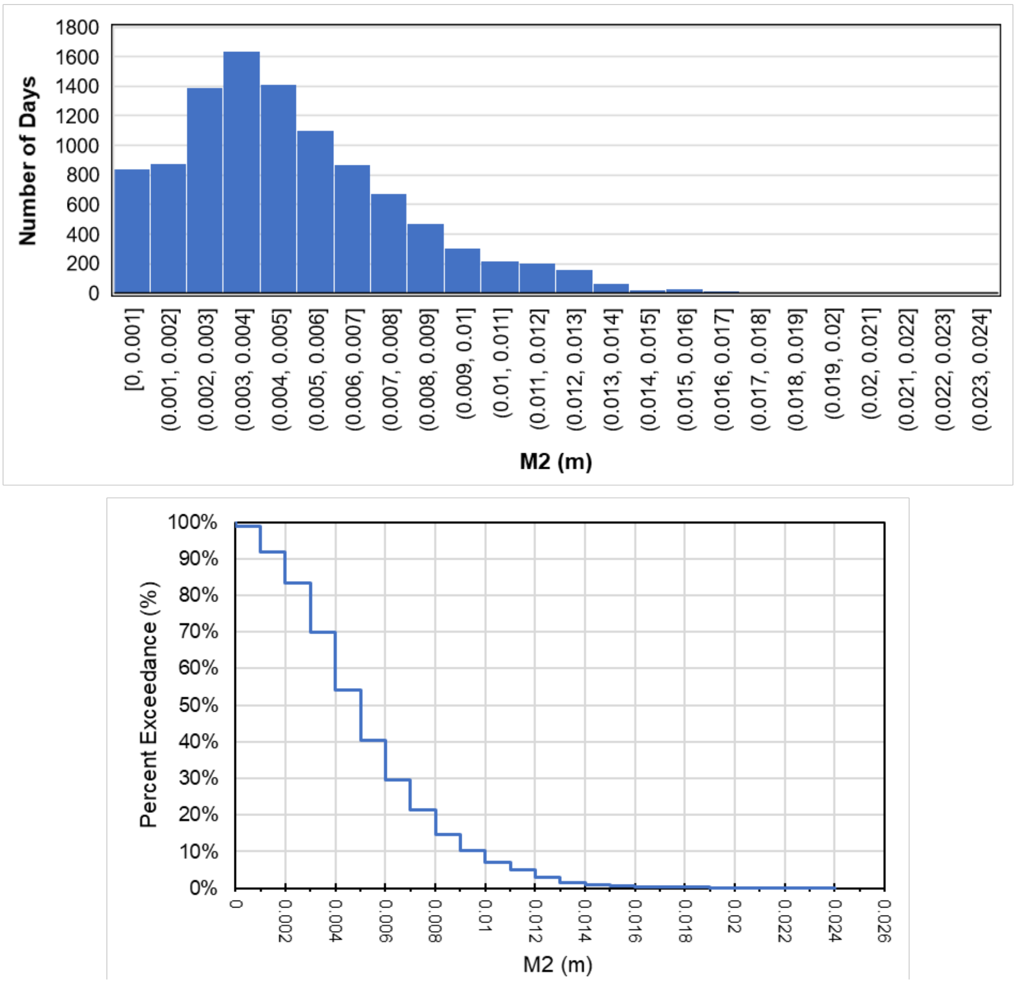


Figure 3.20: Frequency histogram of M2 tidal constituent values in Tuggerah Lakes (top) and probability of exceedance of M2 tidal constituent values (bottom)

Preliminary threshold levels in M2 values to help interpret historical entrance behaviour and constriction are shown in **Table 3.4** and **Figure 3.21.** These include preliminary thresholds for conditions associated with:

- ***Wide open entrance:*** relatively wide open entrance conditions with scoured shoals and channel typically greater than 90 m wide (at 0 m AHD) with high tidal penetration. These conditions were observed to occur occasionally following heavy rainfall and an elevated lake level typically greater than the moderate flood level classification for Tuggerah Lakes of 1.3 m AHD.
- ***Moderately open entrance:*** moderately open entrance conditions with a throat channel typically 50 - 90 m in width (at 0 m AHD), associated with moderate tidal penetration and only minor flood tide shoals in the entrance region. This was observed to be a common state of the entrance.
- ***Moderately constricted entrance:*** moderately constricted entrance conditions with a throat channel typically 20 - 50 m in width (at 0 m AHD), associated with moderately low tidal penetration and developing flood tide shoals. This was observed to be a common state of the entrance.
- ***Heavily constricted entrance:*** heavily constricted entrance conditions with a throat channel less than 20 m in width (at 0 m AHD), associated with low tidal penetration and dominant flood tide shoals filling the entrance channel. These conditions were observed to occur only occasionally, particularly with prolonged periods of low catchment rainfall.

A heavily constricted entrance may remain open to the ocean (with low entrance flows) or, with extended low rainfall, can historically enter a fifth state where the entrance channel fully closes to the ocean described below:

- ***Fully closed:*** Entrance channel completely closes to the ocean due to the progressive sediment infilling and entrance berm growth by wave activity. No flow exchange occurs between the estuary and the ocean during any tidal stage. Umwelt (2011) found that historically the entrance has been fully closed at least 13 times over the last 100 years due to the progressive sediment infilling and entrance berm growth by wave activity.

Example aerial images in **Figure 3.22** show the entrance in each of the above conditions. Also shown are key regions of entrance constriction under each condition.

Entrance width measurements (at approximately 0 m AHD) are also shown in **Figure 3.21** estimated from monitoring camera data, aerial images and entrance channel surveys. Entrance channel width was measured at the approximate region of constriction in the entrance channel throat. Entrance channel width was observed to vary from less than 20 m up to 200 m, with a median width of 56 m.

Table 3.4: Recommended M2 thresholds levels and interpretation.

Long Jetty M2 (m) (Station 211418)	Entrance tidal penetration	Frequency of occurrence	Interpretation
Less than 0.002	Minimal	Occasional particularly with prolonged dry periods	Heavily constricted entrance
0.002 to 0.005	Low	Common state of entrance	Moderately constricted entrance
0.005 to 0.009	Moderate	Common state of entrance	Moderately open entrance
Greater than 0.009	High	Occasional following heavy rainfall	Wide open entrance
0.024	Maximum since 1993	-	Maximum entrance opening since 1993. Occurred post June 2007 storm.

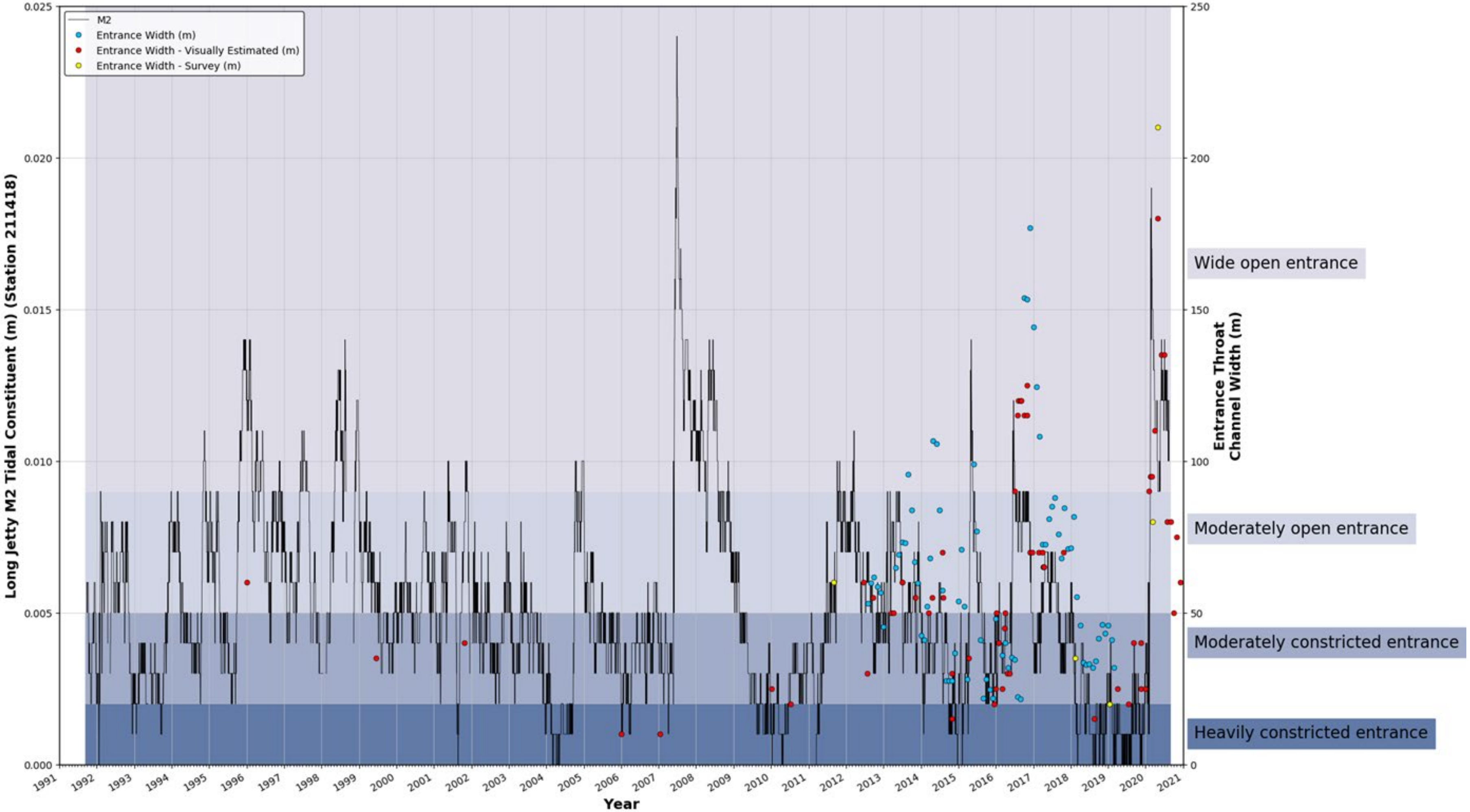


Figure 3.21: Long Jetty M2 timeseries and thresholds to interpret entrance conditions.

Characteristic Entrance Conditions Entrance images from Nearmaps and Umwelt (2011)	Wide Open Entrance	Moderately Open Entrance	Moderately Constricted Entrance	Heavily Constricted Entrance	Fully Closed Entrance
	 Nov 13 2016	 Apr 29 2017	 Apr 8 2018	 Jul 15 2018	 1941
Frequency of occurrence	Occasional following heavy rainfall	Common state of entrance	Common state of entrance	Occasional with dry periods of low rainfall	Infrequent particularly with extended dry periods of low rainfall
Region of entrance constriction	Scoured throat channel and shoals	Constricting throat channel and minor flood tide shoals	Moderately constricted throat channel and developing flood tide shoals	Heavily constricted throat channel and dominant flood tide shoals	Fully closed entrance berm with no flow exchange between estuary and ocean at all stages of tidal cycle.

Figure 3.22: Characteristic Tuggerah Lakes entrance states and regions of entrance constriction.

3.5.3 Physical drivers of entrance behaviour

Further analysis was undertaken to investigate physical drivers in historic trends in entrance behaviour using M2 tidal constituent observations. Annual characteristic entrance behaviour was calculated based on the annual mean M2 value and classified following **Table 3.4.** Annual trends in entrance behaviour were analysed alongside key physical drivers including:

- Catchment rainfall data: annual catchment average rainfall data was calculated using rainfall data for gauges within the Tuggerah Lakes catchment area (see **Figure 3.3**). Annual rainfall totals were categorised as dry (< 900 mm), moderate (900 - 1200 mm) and wet (> 1200 mm) based on historical rainfall statistics.
- Dredge campaign frequency (per year): average frequency of dredge campaigns shown in **Table 3.5**, calculated on a two year basis (for the corresponding year and the year prior). The data was classified into periods with dredging undertaken more often than once per year, compared with periods where dredging was undertaken less frequently than once per year. Limited dredge volume information was available at the time of the analysis and was not included.
- Wave conditions were also qualitatively described.

A conceptual model of entrance behaviour is provided in the Stage 1 report (MHL2781, 2021) which summarises key physical drivers addressed in this section.

Catchment Rainfall

Results are presented in **Table 3.5** showing the percentage occurrence of annual trends in M2 and entrance behaviour for different annual rainfall conditions and dredge campaign frequency. Catchment rainfall was found to be a primary driver of trends in entrance behaviour. Historically during relatively wetter years (average catchment rainfall greater than 1200 mm), the entrance has been predominantly characterised by higher M2 values and more open entrance conditions. Example periods in **Figure 3.21** characterised by these conditions included 1998, 2007-8, 2011, 2015, 2020 and typically correspond with periods of more frequent moderate and major flood events.

In contrast, during dryer years (average catchment rainfall less than 900 mm) the entrance has been predominantly characterised by lower M2 values and more constricted entrance conditions. Example periods in **Figure 3.21** characterised by these conditions included 1993-4, 2004-6 and 2018-9 and correspond with periods of prolonged low catchment rainfall and less frequent occurrence of flood events. For years with moderate rainfall (900-1200 mm), the entrance has been characterised by moderate M2 values and moderate entrance opening/constriction.

Dredge campaign frequency

Dredge campaign frequency was found to have a secondary effect on catchment rainfall on annual trends in entrance behaviour. Dredging was found to be most effective in maintaining open entrance conditions with moderate to high catchment rainfall. With the entrance in a more open state during wetter years, higher dredge frequency was found to slightly increase the likelihood of wide open conditions compared to moderately open/constricted entrance conditions. For example in **Figure 3.21** during the 2007/8 period, high catchment rainfall combined with more frequent dredging resulted in the entrance being a predominantly wide open entrance compared with other years.

Table 3.5: Annual trends in average entrance behaviour

Annual rainfall totals	Dredging campaign frequency	No. of years in record	Annual Average Entrance Behaviour Percentage Occurrence (%)			
			Heavily constricted entrance	Moderately constricted entrance	Moderately open entrance	Wide open entrance
Dry (< 900 mm)	< 1 per year	1	100%	-	-	-
	>= 1 per year	6	33%	33%	33%	-
Moderate (900 - 1200 mm)	< 1 per year	9	33%	33%	33%	-
	>= 1 per year	5	-	20%	80%	-
Wet (> 1200 mm)	< 1 per year	3	-	67%	33%	-
	>= 1 per year	4	-	-	50%	50%

More frequent dredging was found to be less effective in maintaining open entrance conditions during years of low catchment rainfall. Even with higher dredge frequency, prolonged low rainfall conditions are still likely to result in the entrance being heavily constricted, as entrance shoals more quickly infill with marine sand. With the entrance in a more constricted state during dryer years, more frequent dredging may slightly increase the likelihood of the entrance being in a moderately constricted state compared to heavily constricted. In **Figure 3.21** during 2018/9 the combination of low catchment rainfall and less frequent dredging resulted in the entrance being in a predominantly heavily constricted state compared with other years on record.

Wave conditions

Wave conditions may also influence sediment ingress and beach accretion at the entrance. With the absence of catchment rainfall and low entrance outflow to the ocean, high wave events can cause substantial sand ingress into the entrance, deposited as sediment fans in shoal regions and infilling the entrance channel. Mild wave conditions tend to build up the beach, and when coupled with low rainfall, the beach berm fronting the entrance grows to constrict the entrance channel. The frequency of high-intensity rainfall events is considered a key factor in prolonging the opening of the entrance channel, through the shoals and berm.

3.5.4 Historical entrance scour events

Flood events can cause significant changes in entrance conditions, scouring the entrance shoals and berm, and widening the entrance channel. This was assessed by examining changes in average M2 tidal constituent values in the months immediately before and after floods. Larger increases in M2 are indicative of greater entrance scour due to flooding.

Changes in M2 for flood events with peak lake levels exceeding 0.6 m AHD are shown in **Table 3.6**. Flood events are ordered by the magnitude of increase in M2, calculated as the difference in average M2 value in the month immediately after compared to the month immediately before the flood. Flood events causing the largest increase in M2 and entrance scour were the June 2007, February 2020, April 2015 and June 2016 flood events. It is noted for these events that the entrance was in a moderately constricted state prior to flooding and had scoured to a wide open entrance after flooding.

Figure 3.23 shows peak flood lake levels and observed changes in M2. Increases in M2 indicative of entrance scour were observed to typically occur for flood events exceeding a threshold of approximately 0.8 m AHD in peak lake levels. Flood events with peak lake levels less than 0.8 m AHD typically were observed to result in less significant entrance scour. The degree of scour may also vary depending on the entrance condition prior to flooding and time since previous entrance channel dredging was undertaken, both shown in **Table 3.6**.

Table 3.6: Historical entrance scour events and changes in Tuggerah Lakes M2.

Flood Event	Peak Lake Level -Long Jetty (m AHD)	Months since previous dredge campaign	Average M2 before flood (m)	Average M2 after flood (m)	M2 change (m)
June 2007	1.641	6	0.003	0.019	+0.016
February 2020	1.673	15	0.003	0.015	+0.012
April 2015	1.456	28	0.003	0.010	+0.007
June 2016	1.019	6	0.004	0.010	+0.005
May 1998	0.706	1	0.007	0.012	+0.005
February 1992	1.13	Unknown	0.002	0.006	+0.004
September 2011	0.682	15	0.006	0.009	+0.003
March 2001	0.779	5	0.003	0.006	+0.003
September 1996	0.731	3	0.006	0.009	+0.002
June 2011	1.084	11	0.003	0.006	+0.002
January 2016	0.952	1	0.003	0.005	+0.002
March 2017	0.689	15	0.004	0.006	+0.002
May 2001	1.066	7	0.006	0.008	+0.002
June 2010	0.813	During campaign	0.001	0.003	+0.002
April 2011	0.651	9	0.001	0.003	+0.002
March 2013	0.816	2	0.006	0.008	+0.002
September 2019	0.911	10	0.001	0.002	+0.001
May 2003	0.753	6	0.005	0.005	+0.001
February 2015	0.653	26	0.002	0.002	+0.001
June 2019	0.652	7	0.000	0.001	+0.000
November 2013	0.674	11	0.006	0.006	+0.000
February 2002	0.657	3	0.005	0.005	+0.000
June 2018	0.604	During campaign	0.002	0.001	-0.001
April 2002	0.69	5	0.005	0.004	-0.001
July 1999	0.684	15	0.006	0.004	-0.002
June 2013	0.623	6	0.008	0.005	-0.004

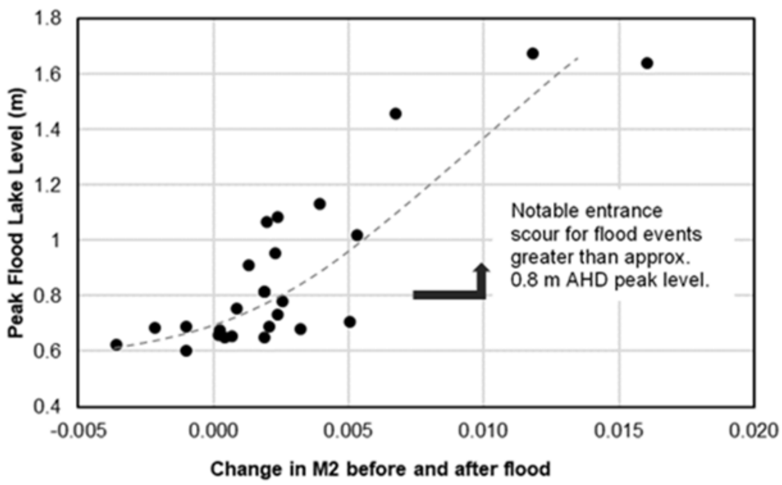


Figure 3.23: Peak flood level and observed changes in M2

3.5.5 Entrance berm and channel location

The condition of the entrance berm is another parameter governing flooding and entrance behaviour. Entrance berm levels over the past 20 years were obtained from the NSW Beach Profile Database (developed by the Water Research Laboratory UNSW on behalf of the NSW Department of Planning and Environment - www.nswbpd.wrl.unsw.edu.au), based on photogrammetry and Lidar measurements of the entrance region from 2000 to 2020. Selected beach profile locations of the entrance berm are shown in **Figure 3.24** spread approximately 80 m apart. The beach profile data was supplemented with entrance survey data provided by Council.

Where an entrance berm was present in the measured profile, the crest level was extracted and recorded in **Table 3.7**. Berm levels were observed to fluctuate over the 20-year period, with median crest levels ranging from +1.6 m AHD in the south to +3.1 m AHD in the north. The lower berm levels in the south are indicative of the entrance channel typically located close to the southern entrance embankment and entrance rock shelf (see the conceptual model in Stage 1 report MHL2781).

Umwelt (2011) found that historically the entrance has been fully closed at least 13 times over the last 100 years due to the progressive sediment infilling and entrance berm growth by wave activity. An example of a fully closed entrance is shown in **Figure 3.25**, showing the entrance in 1941 with a wide berm extending from the North Entrance to The Entrance Beach in the south. Dimensions of the berm are estimated to be approximately 100-150 m wide with crest levels between +2 to + 4 m AHD. The entrance was believed to be closed in the early 1940s for a period of 2-3 years and was likely a contributing factor to major flooding that occurred in the mid to late 1940s.

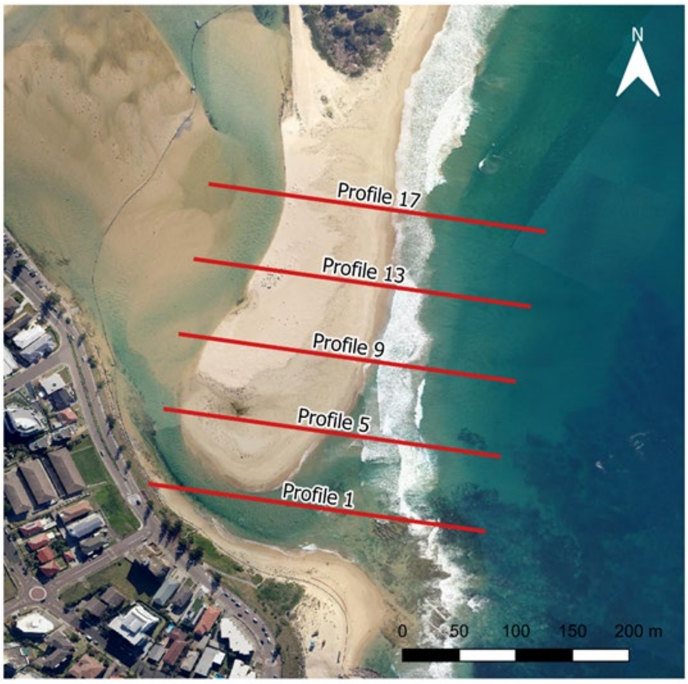


Figure 3.24: Beach profile locations of berm entrance

Table 3.7: Entrance berm crest levels

Date	Source	Entrance Berm Level (m AHD)				
		South		Mid		North
		Profile 1	Profile 5	Profile 9	Profile 13	Profile 17
29/01/2001	Profile Database	-	1.6	2.9	3.6	3.3
25/02/2006	Profile Database	-	2.3	3.7	4.0	3.8
1/09/2011	Entrance Survey	-	-	3.1	2.7	3.1
3/12/2011	Profile Database	-	-	-	2.1	-
7/06/2016	Profile Database	-	1.6	1.3	-	-
23/05/2017	Profile Database	1.6	-	1.6	2.6	2.9
7/02/2018	Entrance Survey	-	1.8	2.6	2.9	3.0
1/07/2018	OEH Marine Lidar	1.5	2.4	2.6	2.8	2.9
9/09/2018	Profile Database	1.7	2.5	2.8	3.1	3.2
16/01/2019	Entrance Survey	1.6	2.3	2.5	2.8	3.1
3/06/2019	Profile Database	1.6	2.7	2.9	3.1	3.5
9/03/2020	Entrance Survey	-	2.2	2.5	-	1.7
1/05/2020	Entrance Survey	0.8	-	-	-	-
26/06/2020	Entrance Survey	0.8	-	0.2	-	-
22/07/2020	Profile Database	1.4	-	-	-	-
	Median	*+1.6*	*+2.3*	*+2.6*	*+2.9*	*+3.1*

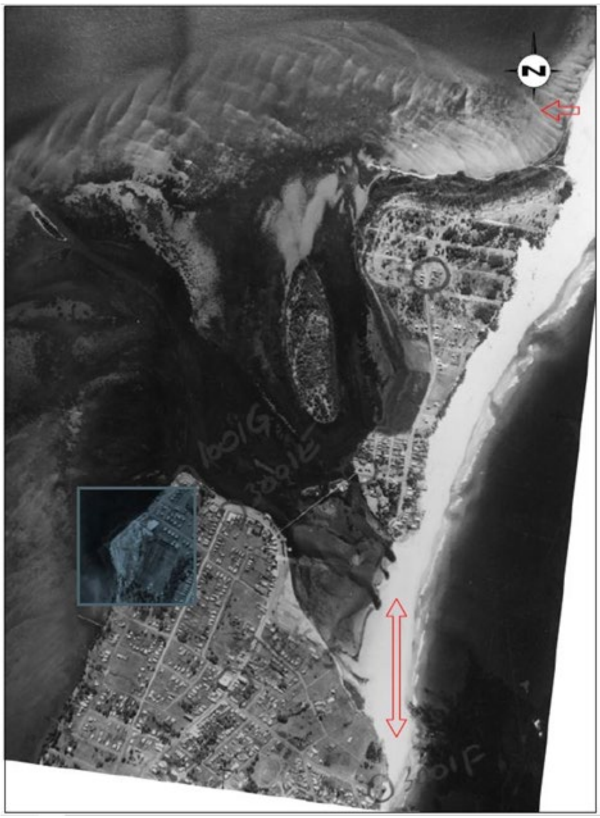


Figure 3.25: Entrance channel completely closed during 1940s with a wide entrance berm. From Umwelt (2011).

A review of available historical and aerial images (1941-present) and entrance monitoring images (2012-present) shows that the entrance channel to be typically located toward the south of the entrance berm as shown in **Figure 3.26**, adjacent to Marine Pde and opening to the ocean in the vicinity of the rock shelf. With low to moderate shoaling, the entrance channel in the south readily scours and widens to the north during floods.

It is noted that in recent years (2016-7, 2020 to present) the entrance has been located in the central region of the entrance berm compared to its typical location near the rock shelf in the south. In the months prior to the February 2020 flood event the entrance channel was open to the south but in a heavily constricted state following consecutive years of low catchment rainfall. This is shown in **Figure 3.26** in the image of the entrance in November 2019. Flood and ebb channels are seen to be poorly connected to the main throat channel due to dominant shoals in the entrance region.

Despite being open with the onset of high catchment rainfall in February 2020, the hydraulic efficiency of the entrance channel to alleviate floodwaters was likely reduced due to the presence of heavy shoaling. A secondary channel was excavated in the central region of the entrance berm as shown in **Figure 3.26** to realign the channel away from the southern side where scour impacts were placing foreshore infrastructure at risk. The mechanical opening in the central berm region was observed to readily scour and widen, reducing flows to the southern channel as the flood subsided (**Figure 3.26**). With the dominant flood tide shoals, the central berm region was observed to be a more hydraulically efficient location for mechanical opening due to its closer proximity to the remnant dredge channel in the lee of the entrance berm toward the north as shown in **Figure 3.26**. Although a more hydraulically efficient location for opening, entrance processes shift northward under such configurations and may potentially have a greater impact upon the adjacent beach and surf zone morphology compared to the typical channel location in the south adjacent to the rock shelf.

In 2016, wave overtopping resulted in a secondary channel also breaking out in the central region of the entrance berm, which then migrated back south to the rock shelf over the 1-2 years following. Entrance opening at the central to the north region of the berm was also noted to occur in 1986 (Umwelt, 2011).

3.5.5.1 Comment on impacts of rock groyne South Entrance Beach

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). 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).

Figure 3.26: Factors influencing secondary channel breakout

The likely impacts of the rock groyne on coastal processes and entrance dynamics were assessed prior to construction by Cardno (2013b). It was estimated that the rock groyne would increase the length of time that sand is retained on South Entrance Beach post nourishment by 2 - 5 years, and hence provide enhanced beach amenity in front of the surf club and other areas of the beach. The study noted that with beach nourishment the rock groyne would further widen the beach by approx. 4 m and increase the longevity of nourishment work.

It was noted in the study that the closure depth is well beyond the seaward end of the groyne and potentially not all of the sand eroded during a storm would be transported back onshore to the beach south of the groyne, with some sediment transported toward the entrance region north of the groyne. As such some nourishment would likely be required to top up the beach south of the groyne, albeit at a less frequent rate than prior to groyne construction.

Cardno (2013b) also addressed potential impacts to the beach and entrance region north of the groyne. It was noted alongshore sediment transport would be potentially impeded by the groyne preventing sediment from transporting northwards toward the entrance rock shelf (tombolo). However, it was noted that the short length of groyne would still maintain a level of sediment bypassing.

Following construction, the beach behaviour to the north of the groyne was recommended to be monitored and any loss of beach width in the area between the groyne and the entrance rock shelf (natural tombolo) was to be addressed by the placement of nourishment sand in this area from time to time during regular entrance dredging campaigns.

Since the construction of the entrance groyne in 2017, the entrance region was heavily infilled with marine sediment due to low catchment rainfall. During flooding and high waves in February 2020, a secondary channel was mechanically opened in the mid-section of the entrance berm as described in the previous section.

Any impacts of the rock groyne on entrance behaviour since construction are likely to be minimal in comparison to more significant entrance dynamics induced by catchment rainfall patterns, floods (scour and mechanical channel openings), storm erosion (entrance berm erosion) and beach recovery (entrance berm regrowth). As per the intended design, the rock groyne has likely increased the retention time of sand at The South Entrance Beach. If this is the case, volumes of dredged entrance sand placed at The South Entrance Beach (under current dredging practices) should be reduced, with surplus dredged sand to be placed north of the groyne at North Entrance Beach. Given the short length of the groyne within the active beach system and sand availability in The South Entrance Beach compartment since construction, bypassing of the groyne from south to north has likely continued to occur, with impacts on alongshore sand supply to the entrance region and North Entrance Beach expected to be relatively minor.

Detailed analysis is required to assess and confirm any potential localised impacts on the entrance channel flows in the vicinity of the rock groyne and sediment transport to North Entrance Beach. At the time of writing of the present study, Transport for NSW was conducting an Impact Assessment Study of The Entrance Rock Groyne on the entrance region and adjacent beaches (Salients, 2021). The study concluded:

> *"The following changes can be attributed to the construction of the groyne:*
>
> - *Less sand covering the rock platform to the north of the groyne.*
> - *A wider beach south of the groyne, and possibly longer retention time of this sand; with the beach being width increase being most noticeable immediately adjacent to the southern side of the groyne.*
>
> *The impacts of the groyne are limited spatially and are in line with the intended function of the groyne. Generally, changes in the vicinity of the groyne have been dwarfed by larger events within the entrance channel relating to entrance closure during drought and scour of the entrance during floods and storms in 2020 and 2021."*

Findings from Salients (2021) may be considered in the future review of the interim entrance management procedure to address maintenance of the beach and sand buffer immediately north of the rock groyne (on the southern embankment of the entrance channel near the entrance rock shelf).

 Classification: Public

3.5.6 Review of February 2020 flood event

On the 7 - 12 February 2020, a series of low-pressure troughs brought heavy rainfall over eastern NSW. A state of a natural disaster was declared for the Central Coast region on Wednesday 12 February 2020, with widespread flooding and tens of thousands of residents losing power to their homes (MHL2750, 2020).

MHL (MHL2750, 2020) provided a flood summary report and historical comparison of the February 2020 event. Rainfall intensities during the February 2020 event were found to reach up to the 1% AEP intensity at Yarramalong. The highest intensity rainfall was typically observed for durations between 24 hours and 168 hours. Sterland, Lisarow and Strickland captured the maximum observed rainfall intensities for durations of 72, 120 and 168 hours. These intensities are the highest on record since 1998 for the 72, 120 and 168 hour durations.

Water levels in Tuggerah Lakes peaked at 1.67 m AHD (Toukley gauge) near midnight on the 11th of February 2020 as shown in **Figure 3.27**. Peak lake levels were found to be within 100-300 mm of the highest lake level previously recorded since 1998 which occurred in June 2007 (MHL2750, 2020). Lake levels were above 1.3 m AHD for approximately 84 hours, with lake levels returning to typical non-flood levels by the 19th of February (**Figure 3.27**).

WRL (2020) analysed beach changes before (June 2019) and after (February 2020) the event which also brought high waves. Significant wave height recorded at the MHL Sydney waverider buoy reached up to 6.5 m from the east-south-east. The study calculated a loss of subaerial beach volume of -16 m^3/m at The Entrance SLSC and -56 m^3/m at Hutton Rd North Entrance. 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.

Changes in entrance morphology as a result of the event are described in **Section 3.5.5**. Following a period of prolonged low rainfall, the entrance mouth prior to the February event was relatively constricted as shown in **Figure 3.26**. Aerial images from June 2019 show dominant flood tide shoals and an entrance throat channel in the south poorly connected to the main dredge channel to the north.

Despite the entrance being opened to the ocean with the onset of heavy rainfall on the 7-9 February 2020, the hydraulic efficiency of the entrance channel to drain floodwaters was likely reduced due to the presence of heavy shoaling during the rise of the flood. A secondary channel was excavated in the central region of the entrance berm as shown in **Figure 3.26** to realign the channel away from the southern side where scour impacts were placing foreshore infrastructure at risk. The secondary channel was observed to scour to a width of 60 - 80 m within several hours of opening as shown in **Figure 3.28** and formed that primary entrance channel as the flood subsided (WRL, 2020). Factors influencing the success of the mechanical opening during the event are discussed in **Section 3.5.5**.

As a result of the entrance opening and scour, tidal range in Tuggerah Lakes (Long Jetty gauge) increased from less than 1 cm prior to the event to up to 8 cm after the event. Wide open entrance conditions prevailed in the subsequent months, with the two entrance channels merging to one wide channel by May 2020, located in the central region of the entrance berm. High waves in July 2020 resulted in further coastal erosion at the already depleted North Entrance Beach, threatening properties at Hutton Rd and triggering the placement of emergency rock protection on the shoreline. Lower intensity rainfall events saw lake levels rise to above 0.5 m AHD on separate occasions in May, July and October 2020. By late 2020, the entrance had slightly infilled with moderately open entrance conditions prevailing.

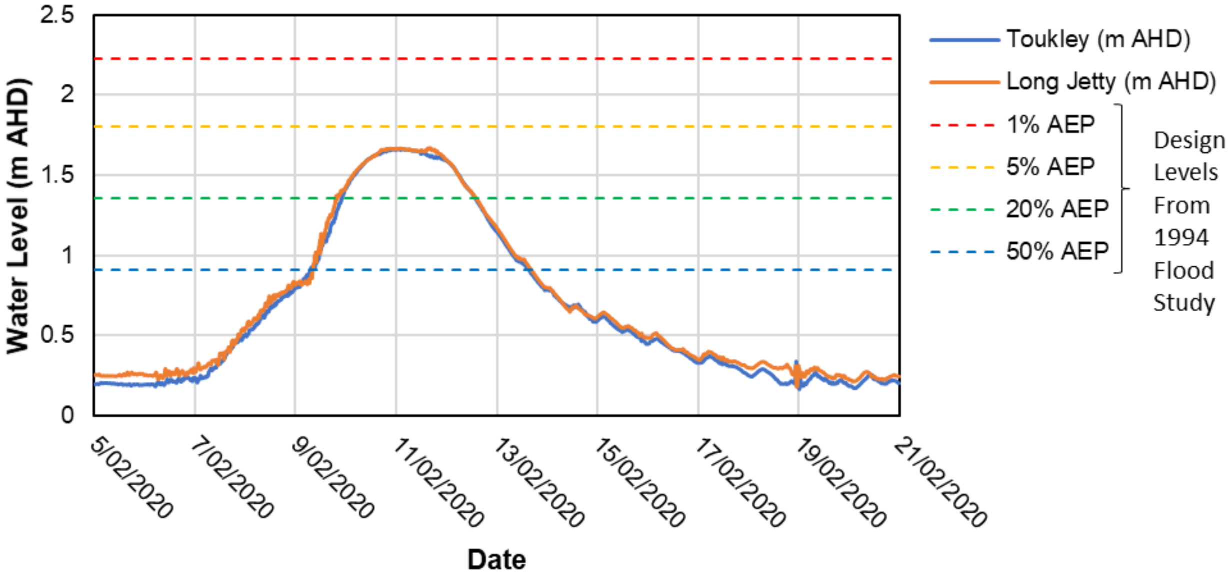


Figure 3.27: Tuggerah Lake water levels during February 2020 Flood

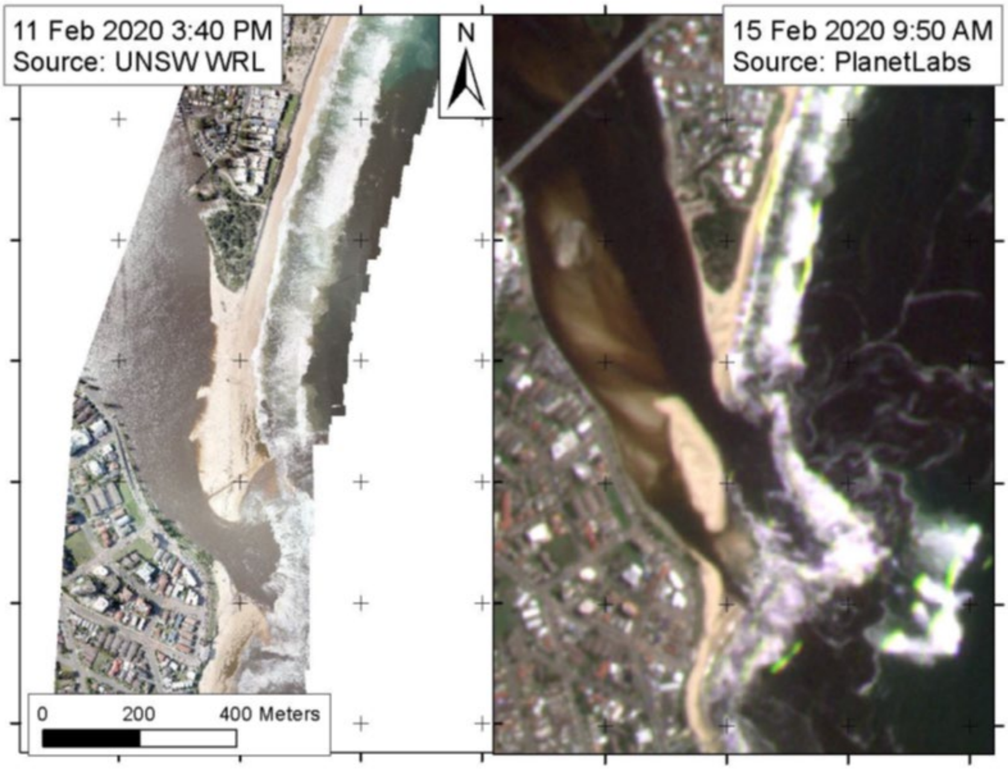


Figure 3.28: Entrance channel changes following mechanical opening in February 2020. Source: WRL (2020)

3.5.7 Brief description of March 2021 flood event

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 during the morning of the 22nd of March 2021 as shown in **Figure 3.29**. Entrance conditions before and immediately after the event are shown in the satellite imagery in **Figure 3.30**. Prior to the event the entrance was open in the central region of the berm with a width of approximately 60 m and widened to approximately 150 - 200 m by the 25th of March as shown in **Figure 3.30**. On the 19th of 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).

In comparison to the February 2020 flood, peak lake levels were approximately 0.15 m lower during the March 2021 event. 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 the ground), initial lake levels, entrance channel configuration/shoaling and ocean conditions.

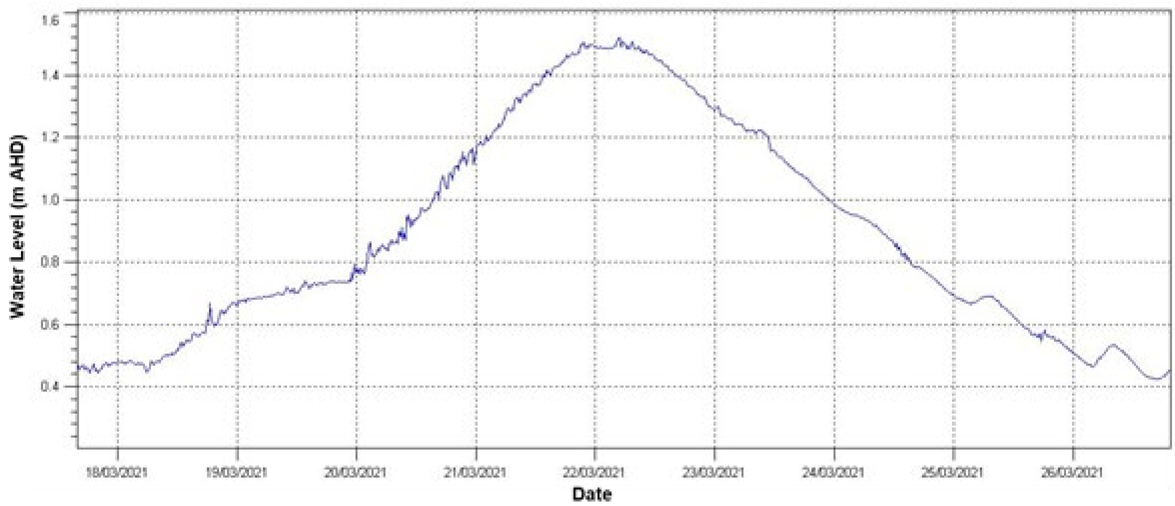


Figure 3.29: Long Jetty water level March 2021 flood event

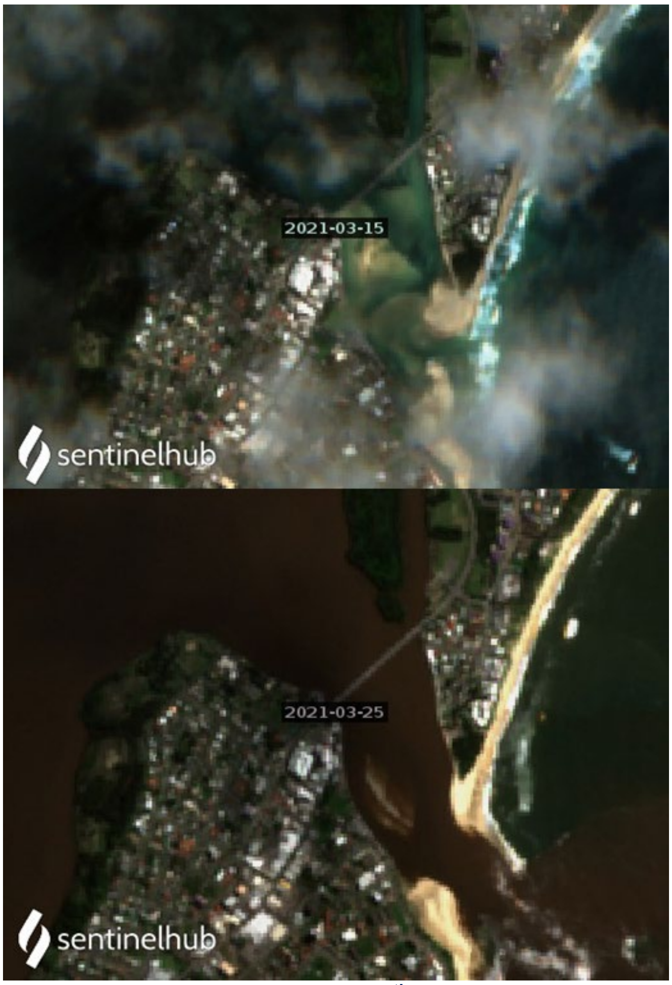


Figure 3.30: Satellite imagery of entrance before (15th March) and immediately after (25th March 2021) the March 2021 flood event. From Sentinel.

3.5.8 Effects of entrance conditions during flood events

Channel geometry and width

The model was run to examine changes in entrance width for each of the flood events listed in **Section 3.4.6**. Changes in entrance width were applied in the model by changing the width of the channel bottom in the simplified trapezoidal cross-section representation of the entrance channel shown in **Figure 3.5**. Modelled width or entrance width is hereafter in reference to the equivalent width at 0 m AHD (approximate Mean Sea Level).

Firstly for each event, the model was calibrated to a starting depth and width that best simulated either measured data in the case of historical events or design peak flood levels (Lawson & Treloar Pty. Ltd, 1994). Each event was then remodelled with different starting entrance widths (entrance width at start of flood) ranging from closed conditions to 200 m (significant post-flood scour). The model included scour of the entrance based on the results of model calibration against measured data (or design level data) for each event. Downstream ocean water level boundaries for each event are described in **Section 3.4.6**.

Modelled lake levels for events with different design catchment flows and starting entrance conditions are shown in **Figure 3.31** and summarised in **Table 3.8.** Additional model results for each event are provided in **Appendix A.** Simulated rates of rise, peak flood levels and flood duration are shown in **Table 3.8**. Flood duration was calculated as the duration with lake levels exceeding 1.3 m AHD at the Long jetty water level station.

Wider entrance widths were found to have the greatest reduction in peak water levels for larger and less frequent flood events greater than the 20% AEP event, with this effect diminishing for smaller, more frequent flood events (**Figure 3.31** and **Table 3.8**). For events greater than the 20% AEP, peak levels were found to reduce by typically 0.1 - 0.35 m for wider entrance conditions prior to flooding. Smaller reductions in peak water levels of around 0.05 - 0.15 m were observed for more frequent flood events, likely due to the greater tailwater influence of ocean water levels for such events. Overall, entrance widths prior to the flooding of 100 m (wide-open entrance occurring after high rainfall) compared to 25 m (heavily constricted entrance) were found to reduce peak water levels by 5 - 15%.

Flood duration is seen to reduce with wider entrance conditions prior to flooding for events in **Table 3.8**. Flood duration and rates of rise are also highly dependent on the temporal rainfall patterns and more prolonged rainfall distributions and may differ between historical and design events.

Table 3.8: Influence of entrance channel width on flood events (without additional ocean anomaly)

Modelled Event	Indicative starting entrance condition	Starting entrance width (m, at 0 m AHD)	Peak Flood Level (m AHD)	Rate of rise (m/hour)	Flood duration above 1.3 m AHD (hours)
June 2007	Fully Closed	Closed	2.26	0.052	82
	Heavily Constricted	25	1.67	0.053	43
	Moderately Constricted	**40**	**1.65**	**0.053**	**43**
	Moderately Open	60	1.60	0.052	41
	Wide Open	100	1.57	0.051	40
April 2015	Fully Closed	Closed	1.82	0.043	Closed
	Heavily Constricted	25	1.46	0.045	44
	Moderately Constricted	**40**	**1.45**	**0.047**	**44**
	Moderately Open	60	1.44	0.049	42
	Wide Open	100	1.34	0.055	15
1% AEP Catchment Flows	Fully Closed	Closed	2.52	0.106	49
	Heavily Constricted	25	2.25	0.108	34
	Moderately Constricted	**40**	**2.21**	**0.107**	**32**
	Moderately Open	60	2.11	0.105	30
	Wide Open	100	1.90	0.096	27
5% AEP Catchment Flows	Fully Closed	Closed	2.08	0.084	Closed
	Heavily Constricted	25	1.80	0.084	35
	Moderately Constricted	**40**	**1.77**	**0.083**	**34**
	Moderately Open	60	1.72	0.082	32
	Wide Open	100	1.61	0.077	28
20% AEP Catchment Flows	Fully Closed	Closed	1.46	0.070	Closed
	Heavily Constricted	25	1.37	0.069	19
	Moderately Constricted	**40**	**1.35**	**0.069**	**16**
	Moderately Open	60	1.31	0.068	8
	Wide Open	100	1.22	0.064	0
50% AEP Catchment Flows	Fully Closed	Closed	0.96	0.054	Na
	Heavily Constricted	25	0.93	0.054	
	Moderately Constricted	**40**	**0.92**	**0.053**	
	Moderately Open	60	0.90	0.053	
	Wide Open	100	0.84	0.051	

All events modelled with starting bed level at -1 m AHD

The starting width (in bold) corresponds to calibrated model runs for each flood event.

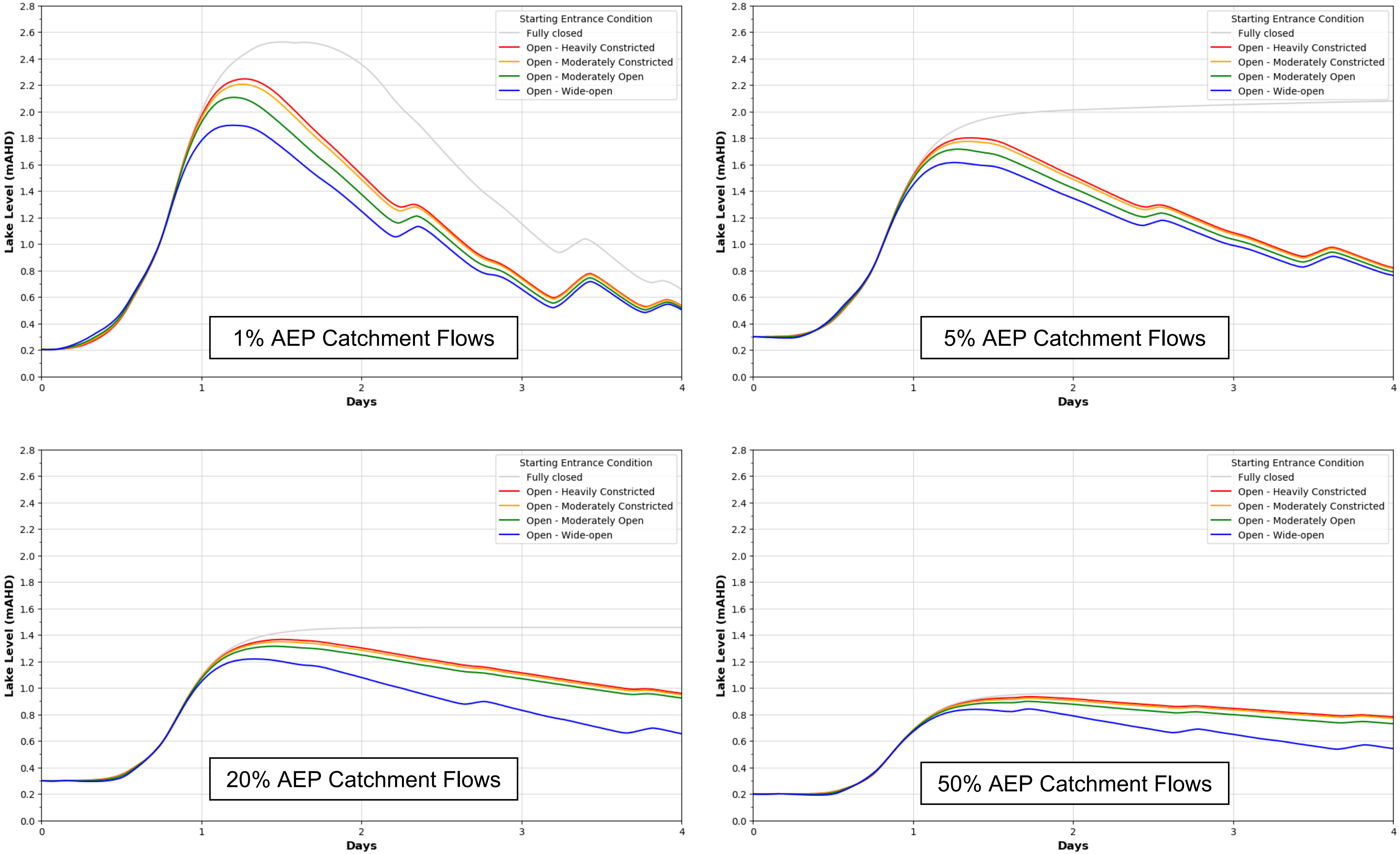


Figure 3.31: Starting entrance conditions and lake flood levels for design catchment flows

Entrance channel bed level

The model was likewise run to examine changes in entrance channel bed level for each of the flood events listed in **Section 3.4.6**. Changes in entrance channel bed levels were applied in the model by varying the depth of the entrance channel shown in **Figure 3.5**.

As per the previous section, the model was calibrated to a starting depth and width that best simulated either measured data in the case of historical events or design peak flood levels (Lawson & Treloar Pty. Ltd, 1994). Each event was then remodelled with different entrance bed levels ranging from -0.5 m AHD to -2 m AHD. The model was also run for fully closed entrance conditions with a berm at +2.0 m AHD. Entrance breakout was triggered in the model for these scenarios when water levels exceeded the berm level by 0.2 m.

Modelled lake levels for each event are provided in **Appendix A** and summarised in **Table 3.9**. Simulated rates of rise, peak flood levels and flood duration are shown in **Table 3.9**. Similar to entrance width, lower channel bed level was found to have the greatest reduction in peak flood levels for larger flood events greater than 20% AEP, reducing peak flood levels by 0.1 0.2 m with lowering of the channel bed by 1 m. For more frequent events smaller than the 20% AEP, lowering the entrance depth had minimal impact on peak flood levels which are more influenced by ocean water level conditions. Lowering of the channel bed resulted in some reduction in rates of rise in flood level and flood durations, however to a lesser extent than compared with increases in entrance channel width.

The effects of a fully closed entrance condition on flooding are seen in the closed berm scenarios in **Table 3.9** and associated modelled lake levels in **Appendix A**. For events larger than the 20% AEP, closed berm conditions were observed to increase peak flood levels by 10-40% with significantly longer flood durations above the 1.3 m AHD threshold. For more frequent events, closed entrance conditions were found to have a less significant increase in peak flood levels, though with longer flood durations (no entrance outflow).

It should be noted that entrance channel bed levels in the southern area of the entrance opening region are influenced by the presence of the rock shelf situated at +0.5 m AHD to +1.0 m AHD (Survey of rock shelf at The Entrance, Central Coast Council, January 2020). This limits the entrance scour depth and flow patterns locally in this region.

Table 3.9: Influence of entrance channel depth on flood events

Event	Starting entrance depth (m AHD)	Peak Flood Level (m AHD)	Rate of rise (m/h)	Flood duration above 1.3 m AHD (h)
June 2007	+2 (closed)	2.26	0.052	82
	-0.5	1.67	0.053	43
	-1	**1.65**	**0.053**	**43**
	-1.5	1.60	0.052	41
	-2	1.58	0.051	40
April 2015	+2 (closed)	1.82	0.043	Closed
	-0.5	1.46	0.045	44
	-1	**1.45**	**0.047**	**44**
	-1.5	1.44	0.049	42
	-2	1.44	0.052	41
1% AEP	+2 (closed)	2.52	0.106	49
	-0.5	2.25	0.108	34
	-1	**2.21**	**0.107**	**32**
	-1.5	2.10	0.105	30
	-2	2.02	0.102	29
5% AEP	+2 (closed)	2.08	0.084	Closed
	-0.5	1.80	0.084	35
	-1	**1.77**	**0.083**	**34**
	-1.5	1.71	0.081	32
	-2	1.66	0.079	30
20% AEP	+2 (closed)	1.46	0.070	Closed
	-0.5	1.37	0.069	19
	-1	**1.35**	**0.069**	**16**
	-1.5	1.31	0.066	8
	-2	1.28	0.064	0
50% AEP	+2 (closed)	0.96	0.054	Na
	-0.5	0.93	0.054	
	-1	**0.92**	**0.053**	
	-1.5	0.90	0.052	
	-2	0.86	0.051	

The starting depth (in bold) corresponds to calibrated model runs for each flood event.

Preliminary berm breakout model results.

3.5.9 Effects of ocean water levels during flood events

Ocean water levels at the entrance of Tuggerah Lakes are a function of astronomical tides as well as a number of other non-astronomical factors including 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 (MHL2236, 2018). During catchment flood events, elevated ocean water levels can prevent floodwaters from draining and exacerbate flooding in the lake.

The model was run to examine the impacts of elevated ocean water levels for each of the flood events listed in **Section 3.4.6**. Changes in ocean water levels were applied in the model by raising the dynamic downstream ocean water level boundary (described in **Section 3.4.6**) during each simulated flood event. As per the previous sections, the model was first calibrated to a starting depth and width that best simulated either measured data in the case of historical events or design peak flood levels (Lawson & Treloar Pty. Ltd, 1994). Incremental increases of +0.2 m and +0.5 m were then applied to the downstream ocean water level boundary for each modelled flood event.

Modelled lake levels for each event are provided in **Appendix A** and summarised in **Table 3.10**. Simulated rates of rise, peak flood levels and flood duration are shown in **Table 3.10**. Increase in ocean water levels by +0.5 m was found to increase peak flood levels by up to 5% for more frequent, minor flood events. Effects of more extreme ocean water level anomalies of up to +1.1 m AHD are investigated in the assessment of interim entrance management options and are further discussed in **Section 4.4.1.**

Table 3.10:Influence of ocean water levels on flood events

Event	Increase in ocean water level above measured tides (m)	Peak Flood Level (m AHD)	Rate of rise (m/h)	Flood duration above 1.3 m AHD (h)
June 2007	+0	1.62	0.051	40
	+0.2	**1.65**	**0.053**	**43**
	+0.5	1.70	0.054	47
April 2015	+0	1.43	0.046	40
	+0.2	**1.45**	**0.047**	**44**
	+0.5	1.51	0.047	54
1% AEP	+0	2.21	0.108	32
	+0.2	**2.21**	**0.107**	**32**
	+0.5	2.21	0.106	36
5% AEP	+0	1.77	0.082	34
	+0.2	**1.77**	**0.083**	**34**
	+0.5	1.78	0.083	38
20% AEP	**+0**	**1.35**	**0.069**	**16**
	+0.2	1.35	0.069	17
	+0.5	1.38	0.068	22
50% AEP	**+0**	**0.92**	**0.053**	**N/a**
	+0.2	0.94	0.053	
	+0.5	0.97	0.052	

Values in bold correspond to calibrated model runs for each flood event.

3.5.10 Effects of entrance conditions during dry-weather events

Effects of entrance geometry during a 5-day (8 - 13 March 2020) dry-weather spring tidal cycle are plotted in **Figure 3.32** and **Figure 3.33**. During this period the entrance was relatively open due to the recent scouring of the Feb 2020 flood event in the month prior, with lake levels (Long Jetty) slightly below average at approximately 0.26 m AHD. As such the results reflect relatively high lake tidal variations, which would be less for more constricted entrance conditions and neap tidal cycles.

Simulated lake levels for a range of entrance widths (as defined in **Figure 3.5**) from 30m to 200m are shown in **Figure 3.32**, using a constant channel bed level of -1.5 m AHD based on model calibration for the dry-weather event. Increases in entrance width were observed to increase the spring tidal range in the lake, with lower low tide levels and higher high tide levels. Modelled spring tidal ranges in the lake for the 5-day event, with different entrance widths, are summarised below:

- Moderately Constricted Entrance (30 - 50 m): Modelled spring tidal range less than 3 cm
- Moderately Open Entrance (50 - 90 m): Modelled spring tidal range of up to 5 cm
- Wide Open Entrance (90 - 150 m): Modelled spring tidal range of up to 10 cm
- Rare post-flood scoured entrance (150 - 200 m): Modelled spring tidal range of up to 15 cm

Simulated lake levels for a range of entrance channel bed levels (as defined in **Figure 3.5**) from -0.5 m AHD to -3 m AHD are shown in **Figure 3.33**, using a constant entrance bed width of 50 m and 1V:15H bank slopes based on model calibration. During the 5-day spring tidal cycle, lower channel bed levels were observed to increase the spring tidal range. For the channel bed at -3 m AHD a tidal range of up to 15 cm was observed, a magnitude comparable to what is currently only experienced following major flood events. Channel bed levels deeper than -1.5 m AHD were also observed to have a reduction in lake water levels and would likely decrease average lake levels over longer time periods.

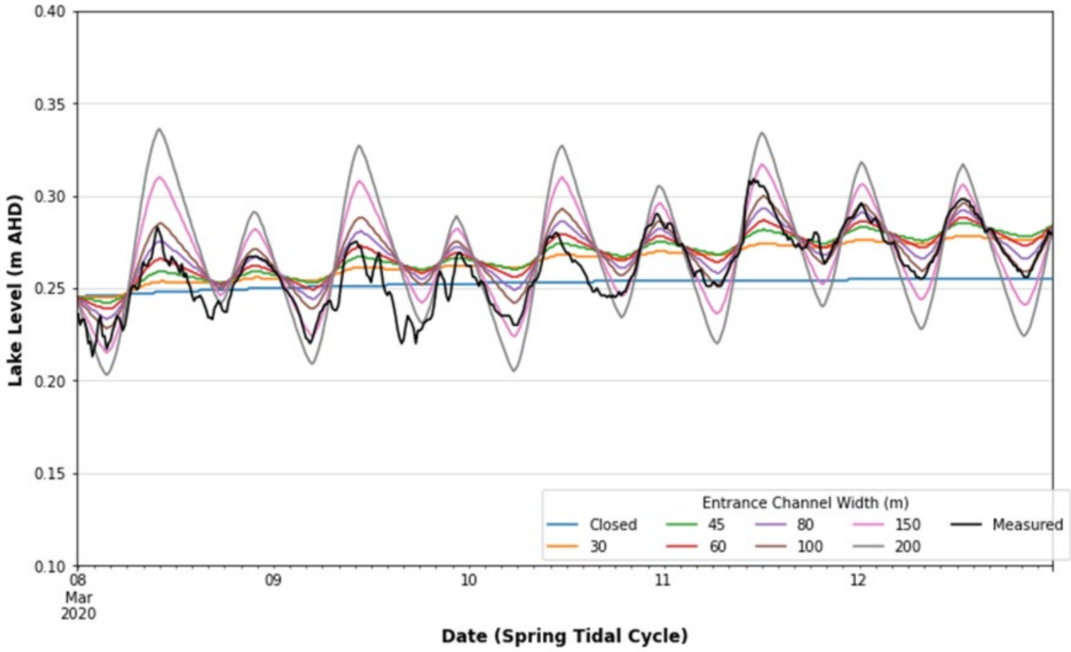


Figure 3.32: Simulated lake level during spring tidal cycle for varying entrance width with constant channel bed level at -1.5 m AHD.

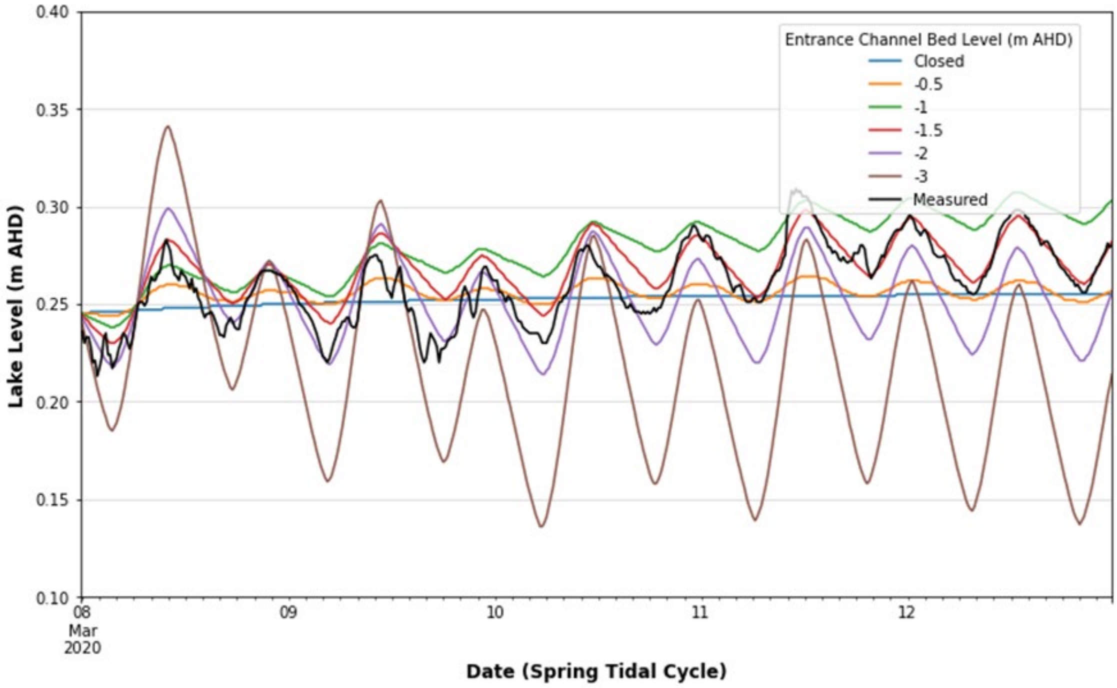


Figure 3.33: Simulated lake level during spring tidal cycle for varying entrance channel bed level.

3.5.10.1 Effects of ocean water levels post major flood events

The average lake level (+0.27 m AHD) and foreshore regions of Tuggerah Lakes are relatively low in comparison to elevated ocean water levels that can occur during large coastal events with large tides (king tides approx.+1.0 m AHD) potentially coinciding with high storm surge (approx. 0.1 to 0.4 m) and wave setup (approx. 0.5 to 1 m).

The morphology of the entrance including its channels, berm and shoals act as a primary control restricting the amount of ocean inundation into the lakes during coastal storm events. With wide open entrance conditions the risk of inundation from ocean water levels increases, compared with more constricted conditions.

In the several months following major flood events, the entrance temporarily persists in a wide open state with scoured entrance shoals and high tidal penetration as described in **Sections 3.5.1** and **3.5.2**. Following major floods, such as in June 2007 and February 2020, the tidal range in the lake can increase up to the order of 0.15 m. During these periods the risk of minor coastal inundation temporarily increases.

Figure 3.34 shows lake levels (Long Jetty gauge) in the months following the February 2020 flood, plotted alongside rainfall, measured tides (Sydney gauge), tidal residual, and nearshore significant wave height at the -10 m AHD contour fronting the entrance (transformed from offshore Sydney wave buoy data using the NSW Nearshore Wave Tool).

Minor periodic increases in lake levels on the order of 0.2 m above typical levels are observed to develop from early April and coincide with each spring tide cycle. In late May 2020, spring tides coinciding with a tidal anomaly of 0.3 m (believed to be predominantly driven by barometric effects of a low-pressure system offshore) and minor rainfall saw lake levels rise to approximately 0.7 m AHD. Large waves during this event may have resulted in some wave setup at the entrance, however, this was likely to be relatively minor in comparison to the larger contribution of ocean tides (including anomaly). The event resulted in increased wave exposure along entrance seawalls and closure of carparks due to inundation of low-lying foreshore areas.

In addition to ocean inundation, wide open entrance conditions following major floods can also lead to adverse reductions in lake levels when ocean conditions temporarily set-down due to tidal and barometric effects. This was observed in particular instances in the months following the June 2007 flood as shown in **Figure 3.35**. In late July 2007, neap tides and an extensive high-pressure system over the Tasman Sea resulted in lake levels dropping to near 0 m AHD over a period of a few days. A similar event is also noted in mid-to-late October 2007. With more frequent open entrance conditions, the reoccurrence of these events can result in increased exposure of mud flats and seagrass beds, disturbing the ecology of fringing lake ecosystems, as well as creating odour issues and recreation boating hazards for lake users.

As the entrance naturally constricts and shoals grow with time following floods, the amount of ocean penetration into the lakes is restricted and the likelihood of adverse impacts (both inundation and mud flat exposure) of coastal events reduces.

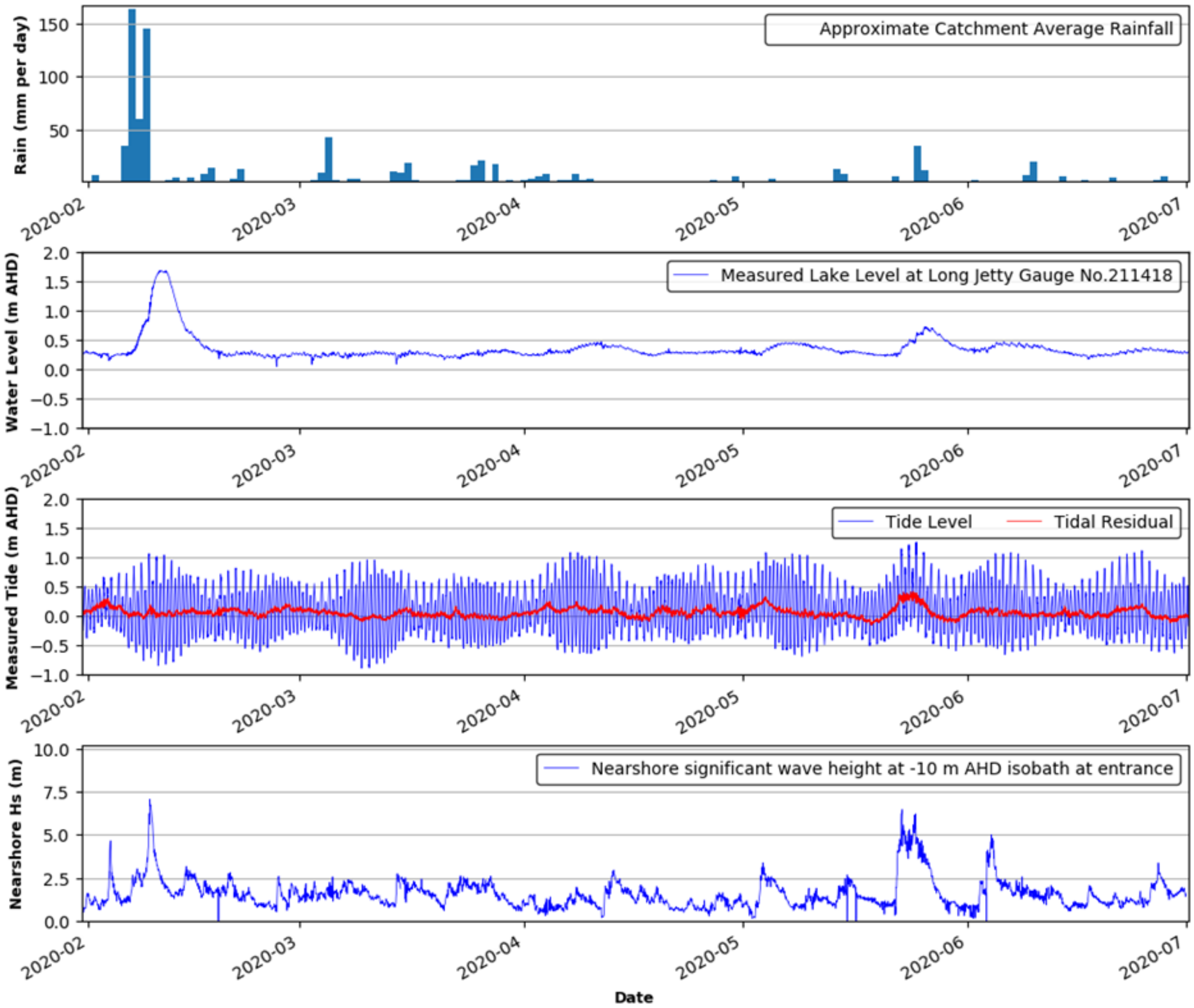


Figure 3.34: Post February 2020 flood lake levels and ocean water level conditions

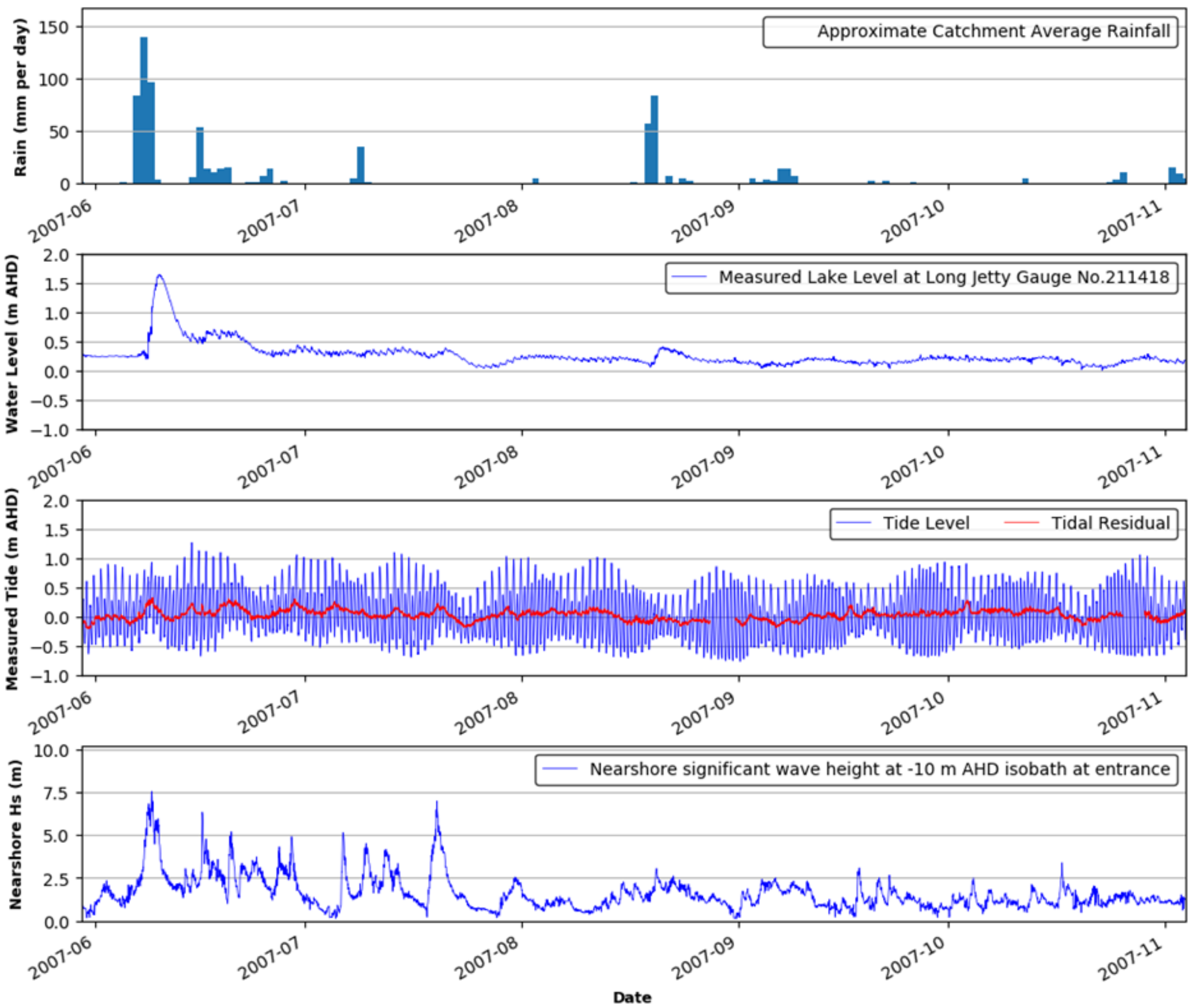


Figure 3.35: Post June 2007 flood lake levels and ocean water level conditions

3.5.11 Entrance channel flow and width relationships

In addition, the model was used to define relationships between entrance channel width and flow for the simplified entrance channel cross-section shown in **Figure 3.5**. The model was run with no catchment flows using a constant downstream ocean water level at 0 m AHD and various lake levels ranging from 0 to 2.23 m AHD (1% AEP peak flood level).

Entrance flow and channel width relationships with a constant channel bed level at -1 m AHD are shown in **Figure 3.36.** Results are similarly plotted in **Figure 3.37** with a constant channel bed level at -2 m AHD.

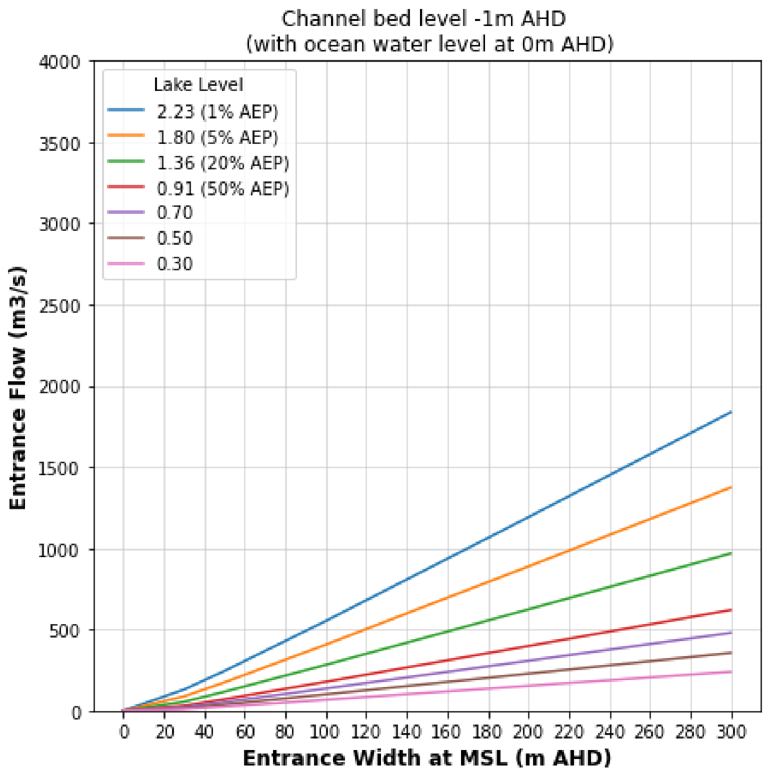


Figure 3.36: Entrance flow vs width relationships for channel bed level of -1 m AHD.

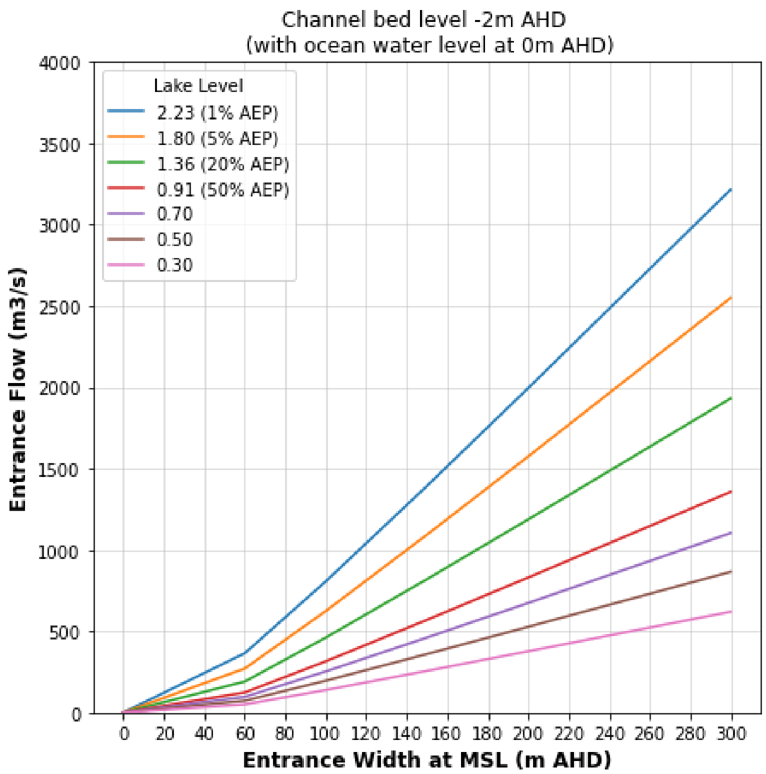


Figure 3.37: Entrance flow vs width relationships for channel bed level of -2 m AHD.

3.5.12 Review of current maintenance dredging program

Entrance dredging of navigation channels in the Tuggerah Lakes entrance shoals are noted as early as 1912 (Umwelt, 2011). Albeit the adoption of progressive technologies, manual (or mechanical) entrance opening and periodic dredging of entrance channels have continued as a long-standing adopted management practice since. Under these conditions, the channel has been 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).

In 1993 maintenance dredging of the entrance was commenced by Council as part of the Tuggerah Lakes Restoration Project. Following trial dredging investigations in 1991, a dredge strategy was developed which aimed to maintain tidal flushing and reduce risk of flooding to life and property in low-lying areas of the estuary (Worley Parsons, 2009; GHD, 2019). This strategy was adopted and refined under Council's maintenance dredging. Between 1993 and 2009 dredge campaigns dredging was carried out on "as needs" basis typically every several months to a year between campaigns.

In 2009 a Review of Environmental Factors (REF) for entrance dredging recommended campaigns be undertaken less frequently with larger dredge volumes during campaigns (WorleyParsons, 2009). Since 2009 dredging has been performed only when one or more of the following indicators are reached (Central Coast Council, 2019) – occurring on average every two to three 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.

Dredge pathways and triggers are summarised in **Figure 3.38** Channels are typically dredged to a width of 50 m and a level of 2 m below water level (RoyalHaskoning, 2020). Dredge campaigns typically transfer 30,000 - 80,000 m^3 per annum (up to 100,000 m^3) of sand from the 2.5 km of entrance shoal channels to the adjacent beaches (via sand pumping). Since the construction of The Entrance Beach Groyne and nourishment, The Entrance Beach sand has been relatively stable, such that the dredge campaigns now focus on the transfer of sand to eroded regions at North Entrance Beach (RoyalHaskoning, 2020).

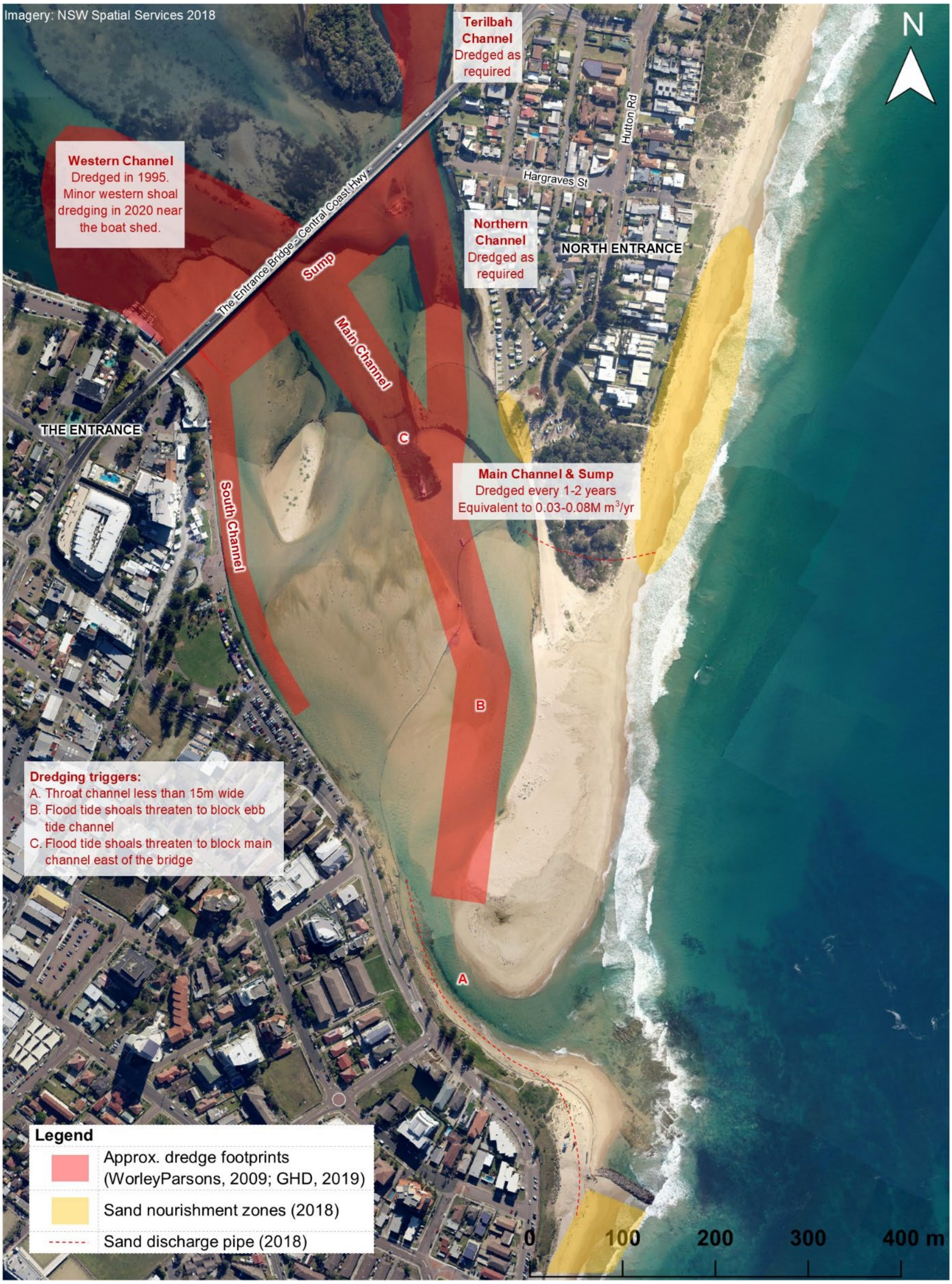


Figure 3.38: Entrance dredge pathways

Up until recently, Council used a custom-built small Cutter Suction Dredge to undertake dredging, however, this was recently decommissioned having reached the end of its serviceable life. The most recent dredging program in 2020 was undertaken using contracted staff and equipment, in addition to Council staff. The dredging program has evolved with time to comply with changing EPA requirements including dewatering of dredge slurry in sediment ponds (RoyalHaskoning, 2020). In 2020, a Review of Environmental Factors (REF) for the dredging program also indicated that dredging triggers are currently undergoing revision (RoyalHaskoning, 2020). The REF also outlines the current objectives for the Entrance Channel dredging program:

- Dredge channel areas that will help to:

  (i) extend the duration of the open/well-flushed entrance conditions,

  (ii) reduce the threat of channel scour/sedimentation to foreshore assets; and

  (iii) improve recreational boating access and amenity;

- Reuse dredged material for beneficial purposes (coastal protection, foreshore amenity, training of tidal flows) and manage dredge materials in a way that is practical for Council;
- Undertake dredging when trigger conditions are met;
- Ensure dredge planning and operations limit potential impacts to significant environmental values, including Little Tern habitat, marine vegetation and water quality.

Entrance maintenance dredging was not assessed as an interim entrance management option in this study. It is recommended that further work be undertaken to evaluate Council's current maintenance dredging operations and investigate the feasibility of a targeted maintenance dredging strategy for the Tuggerah Lakes entrance.

Modelling and assessment of interim entrance management options in the subsequent sections of this study has assumed flow connection between the main lake to entrance throat channel. This connectivity is primarily driven by catchment rainfall and supported to a secondary degree by maintenance dredging. See **Section 3.5.3** for more details regarding the physical drivers of entrance behaviour.

3.6 Summary

Using a combination of data analysis and flood modelling techniques, this chapter provides insight into entrance behaviour and water level variability for Tuggerah Lakes. A 29-year year dataset of 15-minute water level records at Long Jetty was used to calculate an average lake water level of 0.27 m AHD with 90% of observations between 0.09 m AHD and 0.5 m AHD. Typical lake tidal range varied from 1 - 3 cm, ranging up to 15 cm following significant flood events with relatively wide open entrance conditions

Tidal harmonic analysis of the Long Jetty water level record was used to understand characteristic trends in entrance behaviour highlighting main states of entrance constriction, namely:

- ***Wide open entrance:*** relatively wide open entrance conditions with scoured shoals and channel typically greater than 90 m wide (at 0 m AHD) with high tidal penetration. These conditions were observed to occur occasionally following heavy rainfall and an elevated lake level typically greater than the moderate flood level classification for Tuggerah Lakes of 1.3 m AHD.
- ***Moderately open entrance*:** moderately open entrance conditions with a throat channel typically 50 - 90 m in width (at 0 m AHD), associated with moderate tidal penetration and only minor flood tide shoals in the entrance region. This was observed to be a common state of the entrance.
- ***Moderately constricted entrance:*** moderately constricted entrance conditions with a throat channel typically 20 - 50 m in width (at 0 m AHD), associated with moderately low tidal penetration and developing flood tide shoals. This was observed to be a common state of the entrance.
- ***Heavily constricted entrance:*** heavily constricted entrance conditions with a throat channel less than 20 m in width (at 0 m AHD), associated with low tidal penetration and dominant flood tide shoals filling the entrance channel. These conditions were observed to occur only occasionally, particularly with prolonged periods of low catchment rainfall.

A heavily constricted entrance may remain open to the ocean (with low entrance flows) or, with extended low rainfall, can historically enter a fifth state where the entrance channel fully closes to the ocean described below:

- ***Fully closed:*** Entrance channel completely closes to the ocean due to the progressive sediment infilling and entrance berm growth by wave activity. No flow exchange occurs between the estuary and the ocean during any tidal stage. Umwelt (2011) found that historically the entrance has been fully closed at least 13 times over the last 100 years due to the progressive sediment infilling and entrance berm growth by wave activity.

Entrance constriction was found to be primarily driven by variations in catchment rainfall and to a lesser extent by the frequency of dredge campaigns. Flood events with peak water levels exceeding +0.8 m AHD were observed to cause an increase in tidal penetration into the lake.

Median entrance berm levels over the past 20 years range from +1.6 m AHD in the south to +3.1 m AHD in the north, with the entrance channel typically located toward the south of the entrance berm (adjacent to Marine Pde), opening to the ocean in the vicinity of the rock shelf and extending in width to the north during floods.

Information of major flooding in February 2020 was briefly reviewed highlighting a heavily constricted entrance channel with dominant shoals prior to the event. Peak lake levels during the event were found to be within 100 - 300 mm of the highest lake level previously recorded since 1998 which occurred in June 2007. Mechanical entrance opening to the north was undertaken, scouring to a width of 80 m within a few days. As a result of the scour during the flood, tidal range in Tuggerah Lakes increased from less than 1 cm prior to the event to up to 8 cm after the event. Wide open entrance conditions prevailed in the months following the event, with slight entrance infilling toward the end of 2020.

A combined hydrology and one-dimensional entrance model was setup to help assess the impact of simplified changes in entrance geometry (channel width, bed level and ocean water level) on water levels in Tuggerah Lakes. The model used a Watershed Bounded Network Model (WBNM) to simulate catchment hydrology and lake inflows and was combined with a one-dimensional hydraulic representation of the entrance. The model was calibrated and validated to predict measured lake levels during flood events and dry-weather within an accuracy of approx. 0.1 m including tidal variations (does not consider forecast model accuracy subject to input rainfall forecast variability and prevailing entrance conditions).

The impact of changes to the simplified entrance channel geometry on lake levels were examined for a range of flood events including historical and design flood events (50% AEP to 1% AEP) as well as dry-weather events. In particular, changes in modelled entrance channel width, bed level and ocean water levels were assessed.

Wider entrance conditions were found to have the greatest reduction in peak water levels, equivalent to 0.1 - 0.35 m, for larger and less frequent flood events greater than the 20% AEP event. This effect was reduced for more frequent flood events associated with the increased influence of ocean water levels on lake levels. The results highlight the effect of wider entrance conditions providing a minor reduction in the severity of major floods while demonstrating a greater influence of ocean conditions on flood levels for smaller, more frequent flood events.

Differences in entrance width during dry weather conditions were observed to increase tidal range in the lake, reaching similar magnitudes to what historically has only occurred following larger flood events when the entrance widens with flood scour. More open entrance conditions are likely to cause a higher frequency of coastal inundation during periods of elevated ocean water levels as well as more frequent exposure of shallow mudflats/seagrass beds during periods of low ocean water levels (driven by tides and barometric effects) resulting in ecological and lake amenity issues.

Similar results were observed for changes in entrance channel bed level with deeper entrances likely to induce a larger lake tidal range and also alter the average lake level. Increase in ocean water levels by +0.5 m were found to have a minor increase in peak flood levels by up to 5%. Effects of more extreme ocean water level anomalies of up to +1.1 m AHD are investigated in the assessment of interim entrance management options and are further discussed in **Section 4.4.1.**

The results demonstrate that the condition of the entrance, including its channels, berm and shoals, acts as a natural 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 careful consideration for protecting Tuggerah Lakes from adverse ocean inundation and minimising disturbances to typical lake water levels.

The findings of this chapter provide useful information to help inform characteristic entrance behaviour including typical lake level variability, tidal range, historical trends in entrance constriction as well as interactions between entrance configuration and lake water levels for both flood and dry-weather events. The work has also successfully developed a model to simulate water level variability in Tuggerah lakes for scenarios with varying entrance constriction, ocean water levels and catchment flows. The modelling and analysis will provide a useful tool to help assess potential entrance management options in further project stages.

4 Interim management options assessment

4.1 Preamble

This section provides a multi-criteria assessment of different interim management options for the entrance of Tuggerah Lakes. The main purpose of an interim entrance management strategy should be to account for critical environmental issues and facilitate an approved opening at short notice under formulated, documented and agreed procedures and criteria (DPI, 2013).

Interim management options are to be achievable in the short-term and work towards best practice for managing Tuggerah Lakes Entrance while a formalised entrance long-term entrance management strategy is yet to be established under the CMP process. Various management options have been modelled and assessed alongside a range of environmental, social and economic criteria to inform a preferred entrance management approach.

Interim management options assessed are outlined in **Table 4.1** and further described in the following section. Interim options seek to support "flood-ready" entrance berm and throat channel conditions in the event of potential flooding while maintaining the natural lake level variability of Tuggerah Lakes outside of flood events.

Table 4.1: Summary of Tuggerah Lakes interim entrance management options

Interim entrance management option	A) Scenario 1 Fully Closed Entrance (rare entrance condition) *Description of works*	B) Scenario 2 Open Entrance: Moderately Constricted (common entrance condition) *Description of works*
1. Do Nothing	No works – Natural breakout	No works – Natural scour of existing opening
2. Emergency pilot channel opening	Pre-flood works to undertake entrance opening via pilot channel excavation through berm	Pre-flood works to undertake a secondary opening via pilot channel excavation through berm adjacent to existing opening
3. Emergency berm scraping	Pre-flood scraping of entrance berm fronting the closed primary channel	Pre-flood scraping of entrance berm adjacent to existing entrance opening
4. Emergency berm scraping & pilot channel opening	Combined options 2 + 3	Combined options 2 + 3
5. Regular berm and pilot channel management	Routine berm and pilot channel maintenance works to maintain sand levels of designated berm region	Routine berm and pilot channel maintenance works to maintain sand levels of designated berm region adjacent to existing opening

Entrance management options in **Table 4.1** have been assessed for:

a) Fully closed entrance conditions: rare (worst case) scenario most likely to occur with prolonged periods of extremely low rainfall.

b) Open entrance conditions: common entrance conditions with throat channel approximately 30 - 50 m wide channel (at 0 m AHD).

Interim options focus on the management of the entrance berm and throat channel to assist natural entrance scour processes during a flood.

Modelling and assessment of all options have assumed flow connection between the main lake to the entrance throat channel. This connectivity is primarily driven by catchment rainfall and supported to a secondary degree by maintenance dredging. See **Section 3.5.3** for more details regarding the physical drivers of entrance behaviour.

A review of Council's current entrance maintenance dredging operations is provided in **Section 3.5.12**. Entrance maintenance dredging was not assessed as an interim entrance management option. It is recommended that further work be undertaken to evaluate Council's current maintenance dredging operations and investigate the feasibility of a targeted maintenance dredging strategy for the Tuggerah Lakes entrance.

Entrance training schemes were not included in the assessment as they were considered a permanent rather than interim management solution and raise a number of environmental concerns addressed in previous studies described in **Section 2**.

4.2 Interim management options

4.2.1 Option 1) Do nothing – Base case

This option consists of allowing the entrance to behave entirely as it would under natural conditions without any management intervention. This option provides a base case to compare the effectiveness of different management options with what would occur without intervention.

Under this option, the state of the entrance prior to flooding is controlled solely by natural entrance processes. This includes the infilling of the entrance with marine sand over time, filling entrance channels and potentially fully closing to the ocean during dryer years with low rainfall. Natural breakouts and entrance scour would occur during larger flood events resetting entrance channels and open entrance conditions.

Without management intervention to alter entrance conditions prior to flooding, this option is likely to have the largest degree of flood impact during periods when the entrance is heavily constricted or closed with sand. Such a course of action may also lead to increased risk to the safety of individuals (unskilled) undertaking ad-hoc unauthorised entrance opening activities.

However, a "Do Nothing" response may be a preferred course of action when the entrance is in a sufficiently open state prior to a flood event requiring no intervention. A summary of the benefits and drawbacks of Option 1 is provided in **Table 4.2**. Entrance management costs for this option are minimal, albeit significant additional costs are expected due to damages and emergency response associated with increased flood severity.

Table 4.2: Summary of advantages and disadvantages of Option 1

Advantages	Disadvantages
• No capital costs • No changes to coastal process or natural entrance behaviour * • Minimal impacts on shorebird habitats and berm ecology • Preferred course of action when entrance is in a naturally scoured state	• Adverse flooding impacts and damages • No control over entrance management • Increased public safety risks and likelihood of ad-hoc unauthorised entrance opening activities • Low community acceptance • Does not support long-term floodplain risk management.

** It is noted that the low-lying foreshores and floodplains of Tuggerah Lakes are already highly modified from their original condition preceding development.*

4.2.2 Option 2) Emergency pilot channel opening

This option consists of emergency pilot channel works being undertaken in the lead up to a forecast flood event. Emergency works would be undertaken when a pre-defined set of criteria are met prior to a flood. For a number of ICOLL entrances along the NSW coast, emergency entrance works are triggered when the ICOLL water level exceeds a pre-defined 'trigger' level and/or when heavy rainfall and flooding are forecast.

For the purpose of assessing options in this section the following preliminary trigger criteria were adopted:

- Lake level (Long Jetty gauge) greater than or equal to +0.9 m AHD and predicted peak flood level greater than +1.3 m AHD.

Preliminary trigger criteria were determined considering the frequency of lake flood levels and corresponding flood damages reported in the Tuggerah Lakes Floodplain Risk Management Study and Plan (WMAwater, 2014). Model sensitivity to preliminary trigger levels is provided in **Section 4.4.1**. Should this option become a preferred interim management option a more detailed development of pre-defined emergency trigger criteria would be undertaken considering further aspects such as inundation of critical assets, forecast lake and ocean water levels, rate of rise of floodwaters, entrance breakout behaviour and additional workflow alerting criteria.

The nature of emergency pilot channel works will differ depending on the condition of the entrance determined by pre-flood monitoring and inspections. These are illustrated in **Figure 4.1**. During conditions with the entrance open but in a constricted state, emergency pilot channel works would be undertaken to construct a secondary mechanical channel opening through the berm, in a location allowing more efficient breakout to alleviate floodwaters and assist natural channel scour. In the rare event that the entrance is fully closed, emergency pilot channel works would be triggered to provide a mechanical opening of the main entrance through the berm prior to flooding.

These mechanical openings are typically undertaken using a backhoe excavator to dig a pilot channel from the lake to the ocean. Preliminary pilot channel dimensions for options assessment consist of a 10 m wide channel excavated to a bed level of +0.5 m AHD with a natural berm plug at its seaward edge. The berm plug would be excavated prior to a flood when the above trigger criteria are met. During the course of the flood, the pilot channel scours, becoming wider and deeper naturally, as flow increases and scours the excavated channel. Ocean water levels and the available hydraulic head difference between the lake and the ocean plays an important role in the timing and optimising of entrance opening and would be considered as part of developing emergency pilot channel opening procedures.

With the entrance in a sufficiently open state, emergency works would be on stand-by to undertake any minor works to entrance channel banks where required (e.g., minor channel realignment). Timing is a critical factor in undertaking emergency works prior to a flood event and with best practice approaches utilising real-time monitoring, forecasting and pre-flood inspections to inform the process of decision-making in carrying out emergency channel operations. A summary of the benefits and drawbacks of Option 2 is provided in **Table 4.3**.

Preliminary costings for Option 2 are estimated at $15,000 per event, assuming works are undertaken by Council internally. Preliminary costings include indicative estimates for machine hire, safety considerations, closures and communications.

Considering the probability of flood levels exceeding the preliminary adopted trigger value, this option is estimated to cost approximately $15,000 - $50,000 every 5 years.

Table 4.3: Summary of advantages and disadvantages of Option 2

Advantages	Disadvantages
• Provides mechanical entrance breakout prior to a flood event to alleviate flood severity and assist natural channel scour. • Emergency openings are commonly adopted at numerous NSW coastal ICOLLs. • Use of available monitoring and forecasting technologies to support decision-making and automated triggers • Minimal adverse impacts on natural water level variability in Tuggerah Lakes • Minimal impact on coastal processes and ecology when pilot channel located in region of typical natural entrance scour	• More reactive management of emergency opening prior to a flood event. Time-critical and opening affected by prevailing ocean and weather conditions at the time of emergency works being undertaken as plant/resource availability • Reduced benefits when entrance is already sufficiently open to the ocean prior to flooding • Reduced benefits with high ocean water level anomaly during flooding. • Potential pilot channel over-wash infilling and excavation difficulty when works coincide with high ocean water levels. • Moderate costs associated with repeat emergency works for ongoing flood events • Impacts of machinery on berm ecology during the opening

Figure 4.1: Option 2 Emergency pilot channel opening shown for open entrance in a constricted state

4.2.3 Option 3) Emergency berm scraping

This option consists of emergency berm scraping works being undertaken in the lead up to a forecast flood event. A designated region of the entrance berm is mechanically scraped to reduce the height of the sand level. Depending on the height of ocean water levels (including tides, storm surge, wave setup and other anomalies), a managed berm level would allow for water to naturally breach at a pre-determined level in the event of a flood.

Similar emergency response criteria based on forecast rainfall, predicted flood levels and best practice approaches for decision support would be adopted to trigger works similar to Option 2. Sand won during the beach scraping process could be placed on adjacent beaches (prioritising eroded regions) and levelled to match the existing beach profile such that sand is kept within the local sediment compartment.

The design berm level is selected to be lower than that of a naturally accreted berm without maintenance, but that which is feasible to mechanically achieve. Natural berm levels at the entrance of Tuggerah Lakes are described in **Section 3.5.5** and have been observed to vary on average between +1.6 to +3.1 m AHD from south to north along the entrance berm. For the purpose of assessing interim options a preliminary design berm level of +1.0 m AHD has been adopted as the preliminary level for emergency berm scraping works.

Berm scraping works would be undertaken in a designated region that:

- minimises environmental impacts to berm ecology and coastal processes
- assists natural entrance scour of the primary channel
- maintains typical channel configuration

For the purpose of assessing interim options a preliminary berm scraping region is depicted in **Figure 4.2.** During conditions with the entrance open but in a constricted state, emergency berm scraping works would extend approximately 30 m immediately adjacent to the existing channel. In the rare event that the entrance is fully closed, emergency berm scraping works would be undertaken on the berm fronting the main entrance channel.

A summary of the benefits and drawbacks of Option 3 is provided in **Table 4.4**. Preliminary costings for Option 3 are estimated at $35,000 per event, assuming works are undertaken by Council internally. Preliminary costings include indicative estimates for machine hire, safety considerations, closures and communications.

Considering the probability of flood levels exceeding the preliminary adopted trigger value, this option is estimated to cost approximately $35,000 - $100,000 every 5 years.

Figure 4.2: Option 3 Berm management

Table 4.4: Summary of advantages and disadvantages of Option 3

Advantages	Disadvantages
• Provides mechanical berm reduction prior to a flood event to alleviate flood severity and assist natural channel scour. • Use of available monitoring and forecasting technologies to support decision-making and automated triggers • Minimal adverse impacts on natural water level variability in Tuggerah Lakes • Minimal impact on coastal processes and ecology when berm scraping undertaken in region of typical natural entrance scour • Frequency of repeat works undertaken on event-by-event basis where trigger criteria are satisfied.	• More reactive management of emergency opening prior to a flood event. Time-critical and opening affected by prevailing ocean and weather conditions at the time of emergency works being undertaken as plant/resource availability. • Reduced benefits when entrance is already sufficiently open to the ocean prior to flooding • Reduced benefits with high ocean water level anomaly during flooding • Potential disturbances to berm ecology and impacts of machinery during works • Potential infilling of berm scraping region when works coincide with high ocean water levels. • No reduction of flood impacts for more frequent events below a design berm level • Moderate costs associated with repeat emergency works for ongoing flood events

4.2.4 Option 4) Emergency pilot channel opening and berm scraping

This option consists of a combination of emergency works presented in Options 2 and 3 that would be triggered in the lead up to a flood event. Indicative configuration of the works are illustrated in **Figure 4.3.** A summary of the benefits and drawbacks of Option 5 is provided in **Table 4.5.**

Preliminary costings for Option 4 are estimated at $35,000 per event, assuming works are undertaken by Council internally. Preliminary costings include indicative estimates for machine hire, safety considerations, closures and communications.

Considering the probability of flood levels exceeding the preliminary adopted trigger value, this option is estimated to cost approximately $35,000 - $100,000 every 5 years.

Table 4.5: Summary of advantages and disadvantages of Option 4

Advantages	Disadvantages
• Provides mechanical berm reduction and pilot channel opening prior to a flood event to alleviate flood severity and assist natural channel scour. • Use of available monitoring and forecasting technologies to support decision-making and automated triggers • Minimal adverse impacts on natural water level variability in Tuggerah Lakes • Minimal impact on coastal processes and ecology when berm scraping and pilot channel works undertaken in region of typical natural entrance scour • Frequency of repeat works undertaken on event-by-event basis where trigger criteria are satisfied.	• More reactive management of emergency opening prior to a flood event. Time-critical and opening affected by prevailing ocean and weather conditions at the time of emergency works being undertaken as plant/resource availability. • Reduced benefits when entrance is already sufficiently open to the ocean prior to flooding • Reduced benefits with high ocean water level anomaly during flooding • Potential disturbances to berm ecology and impacts of machinery during works • Potential infilling when works coincide with high ocean water levels. • Moderate costs associated with repeat emergency works for ongoing flood events

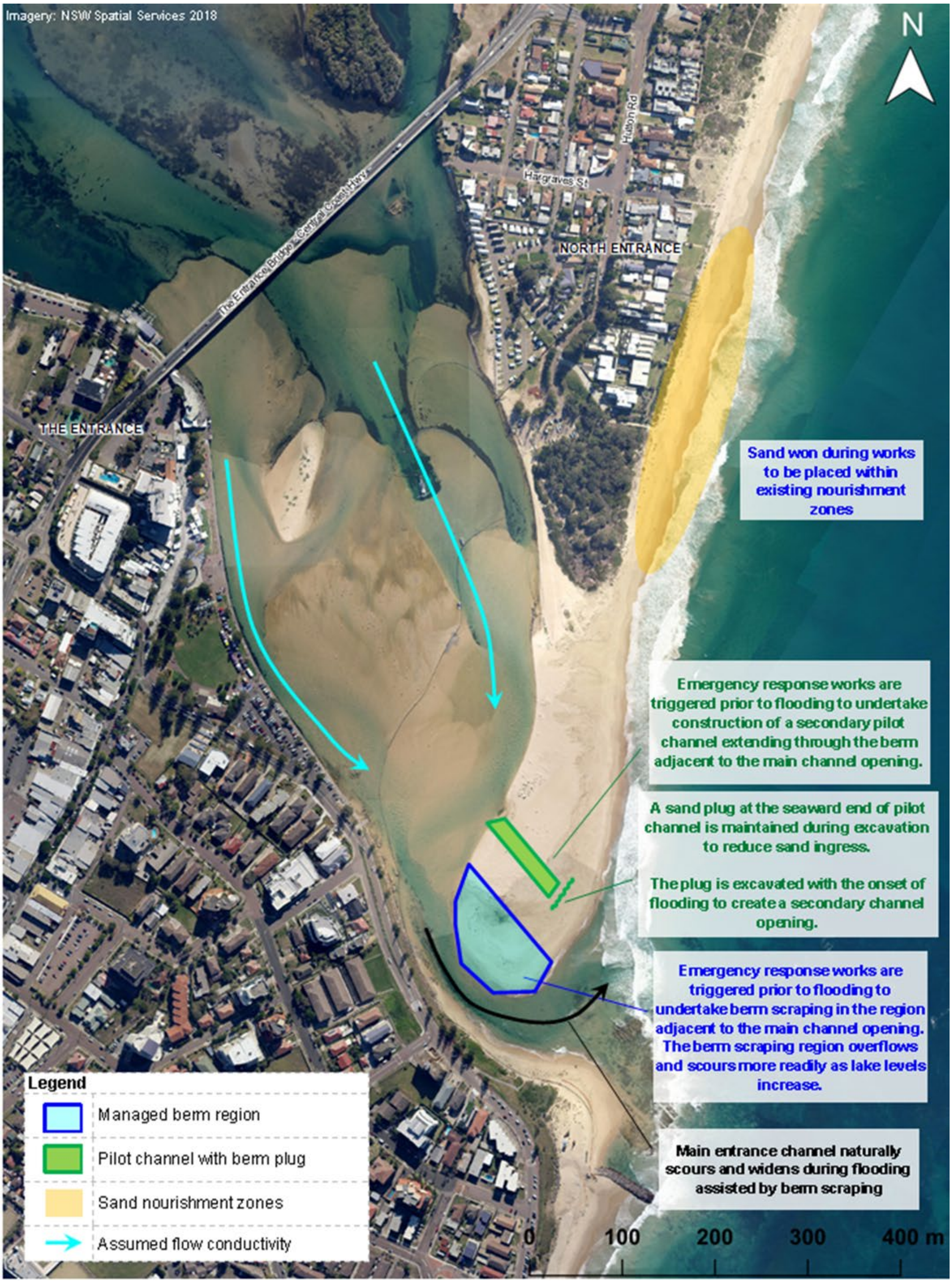


Figure 4.3: Option 4 Emergency pilot channel and berm scraping

4.2.5 Option 5) Regular berm and pilot channel management

This option consists of routine maintenance of a designated region of the entrance berm to maintain design sand levels and pilot channel. Compared to Options 2 - 4, this option provides a more proactive and labour intensive approach to preparing the entrance prior to flooding.

A designated region of the entrance berm is monitored, and its height is maintained below a design elevation via routine mechanical beach scraping. In addition, a pilot channel through the berm (similar to Option 2) would also be routinely maintained at a given depth and width, with a natural berm plug on its lake and seaward edges to prevent infilling during dry weather. These plugs would be excavated in the lead up to a flood event allowing ocean outflow and scour of the pilot channel (as per Option 2). During conditions with the entrance open but in a constricted state, the pilot channel would be located in the adjacent managed berm region next to the existing channel opening, forming a secondary opening through the berm in the event of a flood as shown in **Figure 4.4.** In the rare event of closed entrance conditions, the pilot channel would be located in the berm fronting the main entrance channel location.

Berm monitoring may be undertaken via various techniques (e.g., drones, on-ground surveys, lidar) and would be used to trigger and guide a routine berm and pilot channel maintenance program to maintain a design configuration (frequency depending on coastal processes, potentially targeted around large tidal cycles and coastal events that cause berm aggradation). Sand won during the beach scraping process could be placed on adjacent beaches (prioritising eroded regions) and levelled to match the existing beach profile such that sand is kept within the local sediment compartment.

A summary of the benefits and drawbacks of Option 5 is provided in **Table 4.6**. Noted benefits of a maintained berm and pilot channel compared to emergency response works (Options 2 - 4) include:

- Less intensive emergency response works are required in the time-limited window prior to flooding.
- Works can be scheduled and planned, and be undertaken under favourable weather and ocean conditions
- Potentially a larger region of the berm can be managed given reduced time-constraints for entrance works to be completed.

Compared to emergency response (Option 2), this option would however require increased frequency of access of machinery on and off the beach with associated environmental and social impacts. A formalised access path and procedures would be required to reduce erosion and ecological impacts.

A disadvantage of routine berm works are risks of potential high-frequency repeat works due to natural wave-drive and wind-driven berm building processes reducing the longevity of entrance works. Spring tidal cycles (occurring every 14 days) combined with lower-than-average wave conditions, tends to result in waves building the berm up in height. During the lower stages of the tidal cycle, calm waves tend to build the berm in width. High wave events may also cause sand over-wash into manged regions. Wind processes also act to move dry sand along the back of the berm which can aggrade the entrance berm with time. Under this option the frequency of repeat works, associated costs, and effectiveness would be strongly influenced by the prevalence of such processes acting between works, resulting in the natural aggradation of the scraped berm region and infilling of pilot channel works. Design and maintenance of a sand bund (removed in lead up to flood event) on the ocean side of the maintenance works may reduce some of these impacts.

For the purpose of assessing options in this section, a design sand level of +1.5 m AHD has been adopted as the preliminary level for berm management, with repeat works trigger once the berm exceeds +1.8 m AHD. This was applied to a region extending approximately 100 m into the berm immediately adjacent to the existing channel as shown in **Figure 4.4,** or fronting the primary channel in the case of a fully closed entrance. A pilot channel of similar dimensions to Option 2 would also be regularly maintained.

Preliminary costings for Option 5 are estimated at $35,000 per maintenance works, assuming works are undertaken by Council internally. Preliminary costings include indicative estimates for machine hire, safety considerations, closures and communications.

Assuming a 4 to 6 monthly window for repeat works, this option is estimated to cost in the order of $350,000 - $530,000 every 5 years.

Table 4.6: Summary of advantages and disadvantages of Option 5

Advantages	Disadvantages
• More proactive approach • Less intensive emergency response works required in the time-limited window prior to flooding. • Works can be scheduled and planned, and be undertaken under favourable weather and ocean conditions • Potentially a larger region of the berm can be managed given reduced time-constraints for entrance works to be completed. • Use of available monitoring and forecasting technologies to support decision-making and automated triggers. • Low impact on coastal processes with sand won used to alleviate coastal erosion on the adjacent beach • Minimal adverse impacts on natural water level variability in Tuggerah Lakes	• Potential environmental and social impacts of more frequent machinery on the beach • Potential minor benefits when entrance is already sufficiently open to the ocean prior to flooding • Potential reduction of the benefits with high ocean water level anomaly during flooding. • Risk of high-frequency repeat works, high costs and reduced effectiveness due to prevalence of natural berm building processes. • High costs associated with repeated maintenance works. • Increased risk of unauthorised personnel undertaken opening of pilot channel plug.

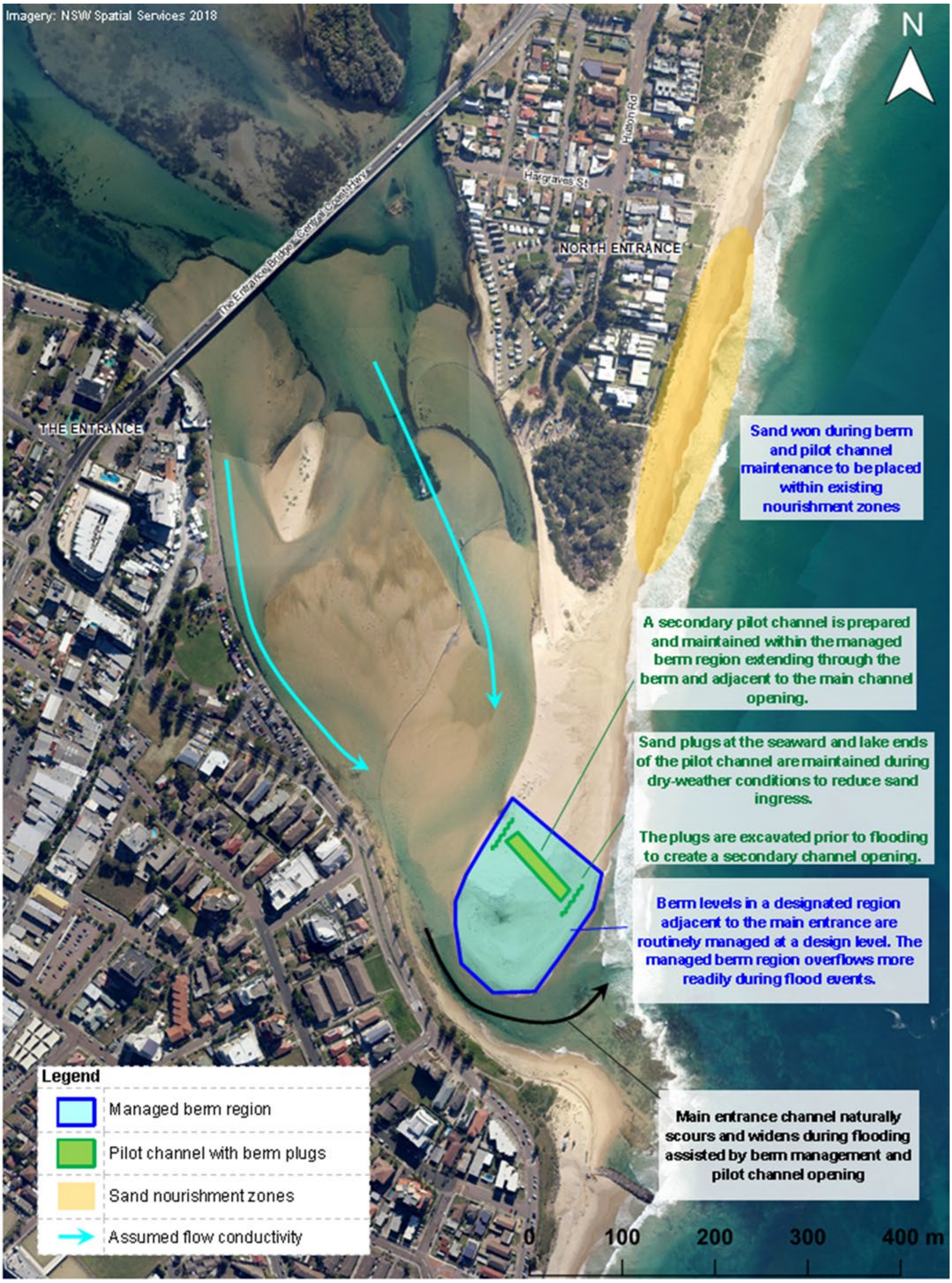


Figure 4.4: Option 5 Regular Berm and Pilot Channel Management

4.3 Methodology

4.3.1 Modelling of management options

The impacts of entrance management options (1 - 4, **Figure 4.1**) on flooding and lake levels were assessed using the flood model developed and calibrated in **Section 2**. This model allows for simplified 1D entrance channel representation to simulate impacts of management options on flooding and lake water levels. Model entrance configuration was adjusted as per **Table 4.7** to represent each of the four management options for starting entrance conditions with a) fully closed entrance and b) open entrance with a moderately constricted channel (40m wide at mean sea level).

The breakout and scour behaviour of each management option was developed based on calibrated entrance scour parameters in **Section 2.** Breakout behaviour (duration, scour width and depth) for each management option has been developed considering:

- Previous modelling studies at the entrance (e.g., Lawson & Treloar,1994; Cardno, 2013; 2015)
- Council's experience and knowledge of entrance scour (per Comms) including the Feb 2020 flood event.
- Insight from the scour behaviour at other NSW ICOLL entrances (e.g., Gordon, 1990; AWACS, 1994). Entrance scour behaviour was modelled to follow a similar pattern to other neighbouring lagoons (e.g., Wamberal, Terrigal, Cockrone and Avoca), though over longer durations (on the order of 20h following works of Lawson & Treloar, 1994) noting the larger catchment size, extensive entrance shoals and prolonged flood discharges associated with the Tuggerah Lakes entrance in comparison to the smaller neighbouring lagoon catchments.

Each of the management option (in both closed and open entrance starting states) were simulated using a total of 11 events detailed in **Table 4.8** and include:

- Design flood events (1%, 5% and 20%)
- Dry-weather coastal events with high ocean water levels
- Dry-weather events with barometric set-down
- Historical flood events (June 2007 and April 2015)

A dynamic tidal ocean water level boundary was adopted for each event and is detailed in **Table 4.8**. For design events, ocean water levels were determined in accordance with the Floodplain Risk Management Guide (OEH, 2015) and include upper and lower limits for ocean water level anomalies including wave setup.

Wave setup is the increase in downstream ocean water level due to wave breaking at the entrance. At the Tuggerah Lakes entrance, wave setup varies depending on the magnitude of nearshore wave conditions and the degree of wave breaking at the entrance. For full wave setup to develop, a significant volume of water must propagate through the entrance to the lake system. Due to the substantial volume of the Tuggerah Lakes system, wave setup impacts are relatively small under normal opening conditions (Lawson & Treloar, 1994).

Lawson & Treloar (1994) estimated wave setup at the Tuggerah Lakes entrance to be 0 - 0.45 m (0 - 7% of the offshore wave height) depending on the depth of the entrance opening. For a deeper entrance channel with reduced wave breaking, wave setup effects become minimal.

In the present study, a lower limit wave setup value of 0 m was adopted for model runs (i.e., no additional anomaly above ocean water levels). An upper limit ocean water level anomaly of 1.1 m additional anomaly was adopted and is associated with wave setup in Type C (ICOLLs and untrained entrances wave dominated estuaries) estuaries as per guidelines recommendations (OEH, 2015). This additional ocean anomaly is significantly larger than that of Lawson & Treloar (1994) and is considered a rather conservative upper limit estimate for Tuggerah Lakes (indicative of other causes of ocean level anomalies)

For historical events, measured ocean water levels were adopted with calibrated wave setup anomalies based on offshore wave data. These were found to be approximately 3 - 5% of the offshore wave height, which agrees well with the findings of Lawson & Treloar (1994).

The extent of entrance scour for each model event was limited in width and depth based on calibration scour extent with consideration given to modelled cross-sectional flow area and hydraulic radius of the entrance channel.

Table 4.7: Modelling of entrance conditions for management options

Management Option	Modelled entrance conditions prior to flood	
	a) Closed	**b) Open – Moderately Constricted**
Option 1) Do nothing	Closed main entrance channel with berm at +2 m AHD Overflow when water level exceeds berm level Natural breakout triggered when water level exceeds +0.2 m above berm *- Natural breakout widening and deepening*	Open main entrance: 40 m wide, bed level at -1 m AHD *- Natural channel widening and deepening*
Option 2) Emergency pilot channel opening	Closed main entrance channel with berm at +2 m AHD Pilot channel opening of main entrance channel triggered at +0.9 m AHD *- Initial 10 m wide, bed level at +0.5 m AHD* *- Widening and deepening with breakout*	Open main entrance: 40 m wide, bed level at -1 m AHD *- Natural widening and deepening* Secondary pilot channel opening triggered at +0.9 m AHD *- Initial 10 m wide, bed level at +0.5 m AHD* *- Widening and deepening with breakout*
Option 3) Emergency berm scraping	Closed main entrance channel with scraped berm at +1.0 m AHD Natural breakout of main channel triggered when water level exceeds +0.2 m above scraped berm level *- Widening and deepening with breakout* Overflow when water level exceeds scraped berm level of +1.0 m AHD	Open main entrance: 40 m wide, bed level at -1 m AHD *- Natural widening and deepening* Overflow when water level exceeds scraped berm level of +1.0 m AHD
Option 4) Emergency berm scraping & pilot channel opening	Closed main entrance channel with scraped berm at +1.0 m AHD Pilot channel opening of main entrance channel triggered at +0.9 m AHD *- Initial 10 m wide, bed level at +0.5 m AHD* *- Widening and deepening with breakout* Overflow when water level exceeds scraped berm level of +1.0 m AHD	Open main entrance: 40 m wide, bed level at -1 m AHD *- Natural widening and deepening* Secondary pilot channel opening triggered at +0.9 m AHD *- Initial 10 m wide, bed level at +0.5 m AHD* *- Widening and deepening with breakout* Overflow when water level exceeds scraped berm level of +1.0 m AHD
Option 5) Berm & pilot channel management	Closed main entrance channel with pilot channel and managed berm level at +1.5 m AHD Pilot channel opening triggered at +0.9 m AHD *- Initial 10 m wide, bed level at +0.5 m AHD* *- Widening and deepening with breakout* Overflow when water level exceeds managed berm level of +1.5 m AHD	Open entrance: 40 m wide, bed level at -1 m AHD *- Natural widening and deepening* Secondary pilot channel opening triggered at +0.9 m AHD *- Initial 10 m wide, bed level at +0.5 m AHD* *- Widening and deepening with breakout* Overflow when water level exceeds managed berm level of +1.5 m AHD

Table 4.8: Modelled events for impacts assessment

Event	Catchment flows	Ocean Boundary (all dynamic i.e., tidal)	Description
1	1% AEP Design Flood	1974 event	Rare flood event with rare ocean water levels
2	1% AEP Design Flood	1974 event with 1.1 m additional anomaly	Rare flood event with rare ocean water levels with large additional anomaly
3	5% AEP Design Flood	HHWS	Intermediate flood event with king tides
4	5% AEP Design Flood	HHWS with 1.1 m additional anomaly	Intermediate flood event with king tides with large additional anomaly
5	20% AEP Design Flood	HHWS	Frequent flood event with king tides
6	20% AEP Design Flood	HHWS with 1.1 m additional anomaly	Frequent flood event with king tides with large additional anomaly
7	No Rain	HHWS	Dry-weather coastal event with king tides
8	No Rain	HHWS with 1.1 m additional anomaly	Dry-weather coastal event with king tides with large additional anomaly
9	No Rain	Measured (July 2007, Sydney gauge) neap tides with barometric set-down and no additional anomaly	Dry-weather with low ocean water levels (barometric set-down)
10	June 2007 (modelled using WBNM and measured rainfall)	As measured (Sydney gauge) with minor wave setup	Intermediate historical flood event with measured ocean water levels and wave setup proportional to measured offshore wave heights.
11	April 2015 (modelled using WBNM and measured rainfall)	As measured (Sydney gauge) with minor wave setup	Frequent historical flood event with measured ocean water levels and wave setup proportional to measured offshore wave heights.

Notes:
- Catchment flows for design events were obtained from Tuggerah Lakes Flood Study (Lawson & Treloar,1994).
- Ocean boundaries for design flood events have been based on OEH (2015) guideline recommendations considering upper and lower guideline values for ocean water level anomalies (i.e., wave setup). The 1.1 m additional anomaly is associated with an upper guideline limit for wave setup associated with Type C (ICOLLs and untrained entrances) estuaries as per the above guidelines.

4.3.2 Multi-criteria assessment

4.3.2.1 Assessment criteria

A multi-criteria analysis (MCA) tool has been used to undertake a preliminary assessment of the various options described above.

The aim of this preliminary analysis was to broadly identify which potential options would be the most preferred and what specific issues may need to be managed to make them viable considering economic, environmental and social factors. The analysis involved the development of weighted assessment criteria and preliminary scoring of the expected relative performance of each potential option for each of the different assessment criteria.

Each of the entrance management strategy options was evaluated using the adopted preliminary assessment criteria and preliminary weightings as outlined in **Table 4.9**.

4.3.2.2 Scoring approach

The criteria and associated weightings were selected according to how important overall each criterion was considered to be to the success of a viable Interim Entrance Management Strategy. The sub-criteria weightings are used to determine the relative importance of each sub-criteria goal within their respective criteria category. The weighting system assigned values ranging from 1 to 5 and ranks the importance of both criteria categories and sub-criteria goals where higher scores represent greater importance as defined in **Table 4.10**. The weightings defined as part of this preliminary assessment are based on the study team's interpretation of understood values from key stakeholder discussions. Results of the MCA are also presented for equally weighted criteria to determine the impact of the weighting on indicated preferences and test sensitivity to the adopted preliminary weightings.

Table 4.9: Adopted Preliminary Assessment Criteria, Sub-criteria Goals and Weightings for the assessment of the entrance management options

Environmental Impact [5]	
Aquatic and Wetland Ecology [5]	Does not have adverse impact on aquatic ecology, marine life, and habitats including fish and prawn exchange at the Entrance. Does not increase impacts related to introduced species and harm to threatened species. Does not have adverse impact on seagrass beds, vegetation, and fringing lake ecosystems
Characteristic lake level variability and estuarine hydrodynamic processes [5]	Does not have an adverse impact on characteristic lake level variability in Tuggerah Lakes. Does not adversely impact natural ocean-estuary exchange and estuarine hydrodynamic processes.
Dune, berm and shoal ecology including Shorebird breeding [5]	Does not have an adverse impact on dune and berm ecology including sand island shoals. Does not have an adverse impact on shorebird breeding (Little Tern nesting sites). Does not have an adverse impact on Terilbah island foreshore and habitats.
Coastal Processes and Flood Behaviour [5]	
Flood Risk/Behaviour and risk to life [5]	Improve flood Risk/Behaviour and reduce the flood impacts on the community. Does the option reduce risk to life during flooding. Does not have an adverse impact on coastal inundation within the lakes.
Coastal Processes [4]	Does not adversely impact coastal processes including impacts on erosion at North Entrance beach.
Future flood risk with sea level rise [4]	Does not adversely impact future flood risk with rising sea level
Bank Erosion [4]	Does not have an adverse impact on bank erosion within the entrance region. Does not adversely impact footings of bridges, jetties, existing seawalls or wharfs due to scour.
Practicality [4]	
Plant access [3]	Minimise plant and machinery required
Approvals and policies [4]	How compatible is the option with current policies and approval processes
Technical Feasibility [5]	How feasible are the works on an ongoing basis and as an interim solution to be implemented in the short-term.
Achievability [5]	Ability to undertake works prior to a flood with potential time, safety, resource and weather constraints. This includes susceptibility to berm and channel infill processes deterring effectiveness of works.
Social / Community [4]	
Safety [5]	Does not adversely impact the safety of local residents including risk of drowning or harm to recreational users (fishing, swimmers, watercraft etc) at the entrance.
Aesthetic/Loss of natural aspect of area [4]	Does not alter natural feel or aesthetic qualities of the area
Community acceptance, perception and expectation [5]	Is the option likely to be supported by local residents in regards to acceptation, perception and expectations of managing the entrance
Recreational value [5]	Does not impact on recreational values for Tuggerah Lakes and the entrance.
Heritage [3]	Adverse impacts on heritage including Aboriginal Heritage.
Economic [5]	
Capital & Ongoing Costs [5]	Minimising capital and ongoing expenditure for the works
Flood damage reduction [5]	Impact on potential return due to reduction in flood damage
Opportunity cost [3]	Secondary benefits and solving other issues (e.g., beach nourishment)

Table 4.10: Assessment Criteria and Sub-criteria Weighting Definitions

Weighting Value	Meaning / Importance
1	Insignificant
2	Minor
3	Moderate
4	Major
5	Critical

As can be seen from the weightings assigned in **Table 4.9**, environmental impact, impact on coastal processes/flood behaviour and the relative economic impacts were weighted with slightly higher importance relative to practicality and community impacts.

Each of the options to be assessed was then scored against all of the adopted sub-criteria goals using a score between +4 and -4 as outlined in **Table 4.11**.

Table 4.11: MCA Scoring System

Score	Meaning
Compared to the Base Case, how much better or worse is the considered option at achieving the particular sub-criteria goal as given in **Table 4.9***?*	
+4	Much better than Base Case
+3	A lot better than Base Case
+2	Moderately better than Base Case
+1	A little better than Base Case
0	Same as Base Case
-1	A little worse than Base Case
-2	Moderately worse than Base Case
-3	A lot worse than Base Case
-4	Much worse than Base Case

4.4 Results and discussion of options

4.4.1 Flood impact assessment

Flood modelling results for all modelled flood events are provided in **Appendix C** and include modelled lake levels, flood peaks, duration and tangible flood damages. Flood damages were determined using floor levels and damage calculations adopted in the Tuggerah Lakes Floodplain Risk Management Study and Plan (WMAwater, 2014).

Modelled peak flood levels and associated flood damages for each management option are summarised in **Figure 4.5** and **Figure 4.6**. Equivalent annual average damages were calculated based on the 1%, 5% and 20% AEP events. To assess management options, equivalent annual average damages were calculated assuming an a) initially fully closed entrance and b) initially open and moderately constricted entrance. In reality, entrance conditions have a given probability of occurrence prior to a flood, with the latter occurring more often than the former.

Flood impacts with no additional ocean anomaly

Peak flood levels and flood damages for each management option with no additional ocean anomaly are shown in Figure 4.5. In comparison to the base case (Option 1), the largest reduction in peak flood levels and damages for the management options implemented where observed with initially closed entrance conditions. Under these conditions, the proposed interim management options were observed to reduce peak flood levels relative to the base case by approximately 0.2 - 0.3 m for the 1% and 5% AEP events and 0.05 - 0.1 m for the 20% AEP event. The largest water level reductions between each option were typically observed for Option 4. Overall, with initially closed entrance, reduction in equivalent annual average damages relative to the base case for Options 2, 3, 4 and 5 were observed to be -46%, -40%, -53% and -49% respectively.

However, most of the time, the entrance is in an open state (with varying degrees of constriction) prior to flooding. **Figure 4.5** also shows results with initially open (moderately constricted) entrance conditions. Reductions in peak flood levels were less significant for the options under these more typical entrance conditions. Under these conditions, the proposed interim management options were observed to reduce peak flood levels relative to the base case by approximately 0.05 - 0.15 m for the 1% and 5% AEP events and up to 0.05 m for the 20% AEP event. The largest water level reduction between the options was typically observed for Option 4. Overall, with initially closed entrance, reduction in equivalent annual average damages relative to the base case for Options 2, 3, 4 and 5 were observed to be -20%, -18%, -33% and -28% respectively. At best, management Option 4 was found to reduce equivalent annual average damages by $650,000 per year for these initial entrance conditions.

Peak flood levels for historical events are also plotted in **Figure 4.5**. Similar trends between management options for the historical events are observed. Under closed entrance conditions, differences between historical and design flood events are observed for Options 1 and 3. These are due to differences in catchment inflows, with historical event inflows typically of longer duration and larger volume compared to design catchment flows.

Differences in flood durations (time above +1.3 m AHD) between options are also observed in the results in **Appendix C** . For initially open entrance (moderately constricted), Options 4 and 5 were observed to have the largest reduction in flood duration above 1.3 m AHD, typically between 4 - 10 hours less than the base case for the modelled floods.

Flood impacts with +1.1 m additional ocean anomaly

The impacts of +1.1m additional ocean water level anomaly on model results are shown in **Figure 4.6.** Beneficial impacts on peak lake levels for each option are reduced with the extreme ocean water level. For initially closed entrance conditions, the management options do provide some reduction (0.1 - 0.2 m) in peak level for the larger 5% and 1% AEP events. However, for smaller events, the management options showed no reduction in peak levels. For initially open entrance conditions (moderately constricted), minimal reductions in peak flood levels were observed for all options. Overall, the results indicate that with extreme ocean water level anomalies (indicative of other causes for high ocean water levels), entrance management strategies that seek to facilitate open entrance conditions during floods (i.e., Options 2 - 5) substantially diminish, and are largely only beneficial should the entrance be fully closed prior to flooding.

Sensitivity testing

Sensitivity testing was undertaken to determine the relative flood impacts of an initial entrance in a post-flood scoured state. All model events (1 - 11) were run for an entrance starting at approximately 120 m wide (at 0 m AHD) and on average -1.5 m deep, allowing to naturally scour in depth during larger flood events.

Results for sensitivity runs with a post-flood scoured entrance without additional ocean anomaly are provided in **Figure 4.7**. As expected, this starting entrance condition provides a significant reduction in flood levels compared to the closed and moderately constricted entrance results. Compared to initially closed entrance conditions, peak lake levels are reduced by 0.3 m for the 20% AEP event and by 0.6 to 0.8 m for larger flood events with the post-flood scoured state. Compared to the initially open entrance (moderately constricted), peak lake levels are reduced by 0.2 - 0.4 m with the post-flood scoured state.

Results for sensitivity runs with a post-flood scoured entrance with a +1.1 m additional ocean anomaly are also provided in **Figure 4.7**. The results again show that with increased ocean anomaly the benefits of a post-flood scoured entrance also diminish, particularly for smaller flood events less than the 5% AEP.

The sensitivity results suggest that in the absence of large ocean anomalies, a post-flood scoured state is the most desirable starting entrance condition prior to flooding. In such a case, minimal entrance management works would be required (other than potential minor stand-by emergency works). The benefit of entrance management works becomes greater realised for more constricted starting entrance conditions.

Preceding catchment rainfall is a primary factor governing how open an entrance is prior to flooding. See **Section 3.5.3** for more details regarding the physical drivers of entrance behaviour.

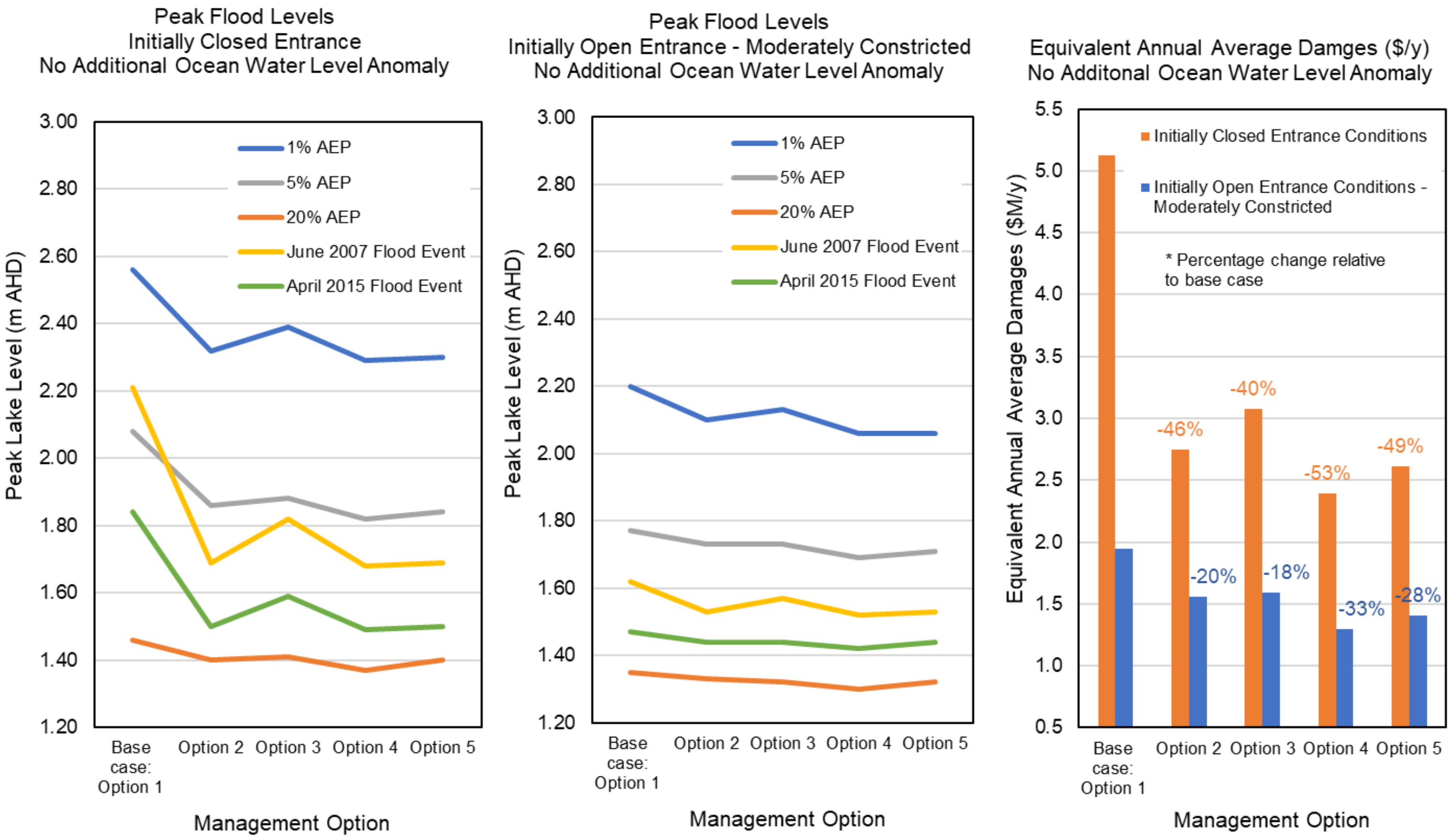


Figure 4.5: Modelled peak water level and flood damages for events with no additional ocean anomaly (1, 3, 5, 10 and 11)

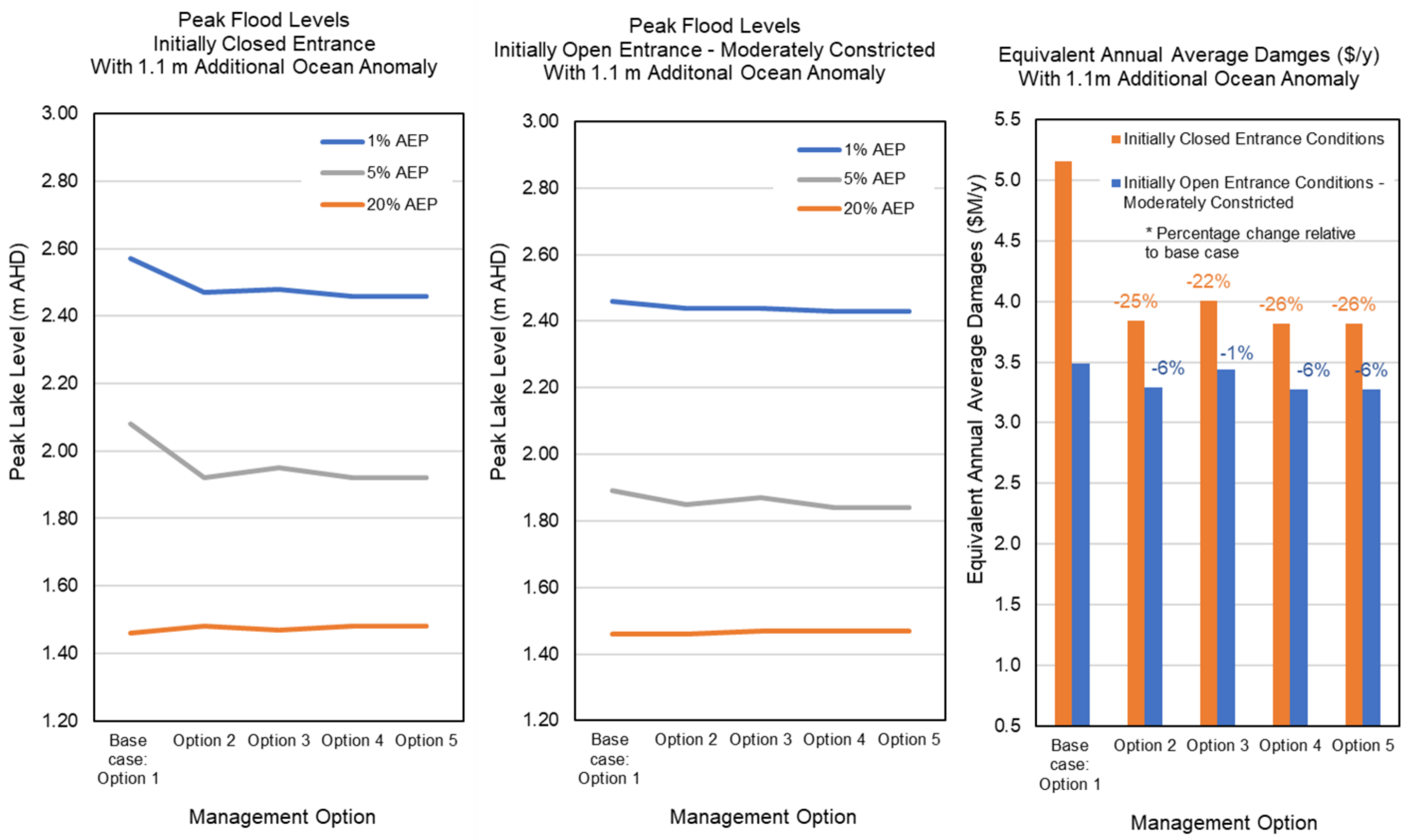


Figure 4.6: Modelled peak water level and flood damages for events with 1.1 m additional ocean anomaly (2, 4, 6)

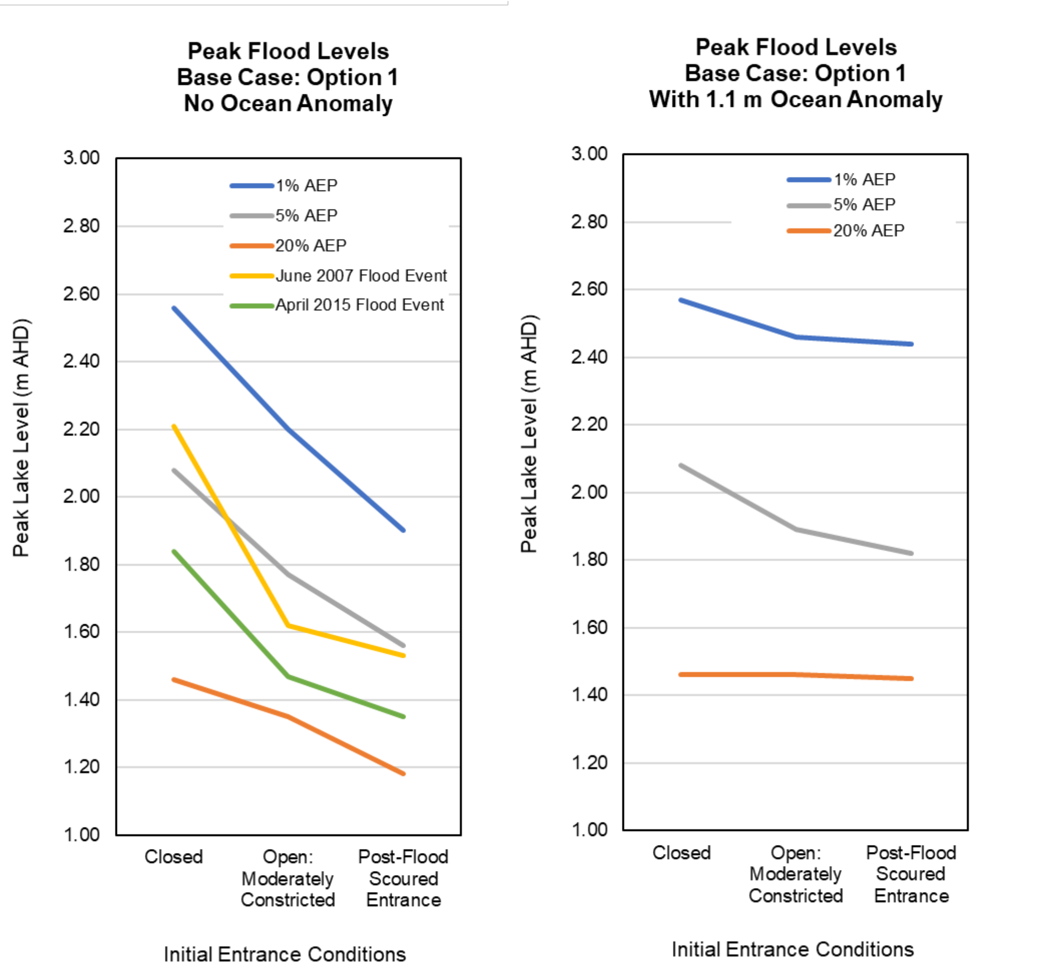


Figure 4.7: Sensitivity testing for post-flood scoured entrance conditions

4.4.2 Dry-weather impact assessment

The model was used to simulate the performance of management options under three dry-weather (no catchment flows) events:

- Event 7: King tides - HHWS Spring Solstice tides reaching approximately +1 m AHD.
- Event 8: Large coastal event with king tides and +1.1 m additional ocean anomaly. This is indicative of coastal events with king tides and extreme additional ocean anomaly (i.e., storm surge, wave setup, other causes of high ocean water levels etc)
- Event 9: Neap tides with barometric set-down. Event where ocean water levels reduce due to small tides and strong high-pressure systems.

Results for each of the dry-weather events are shown in **Figure 4.8**. All management options are observed to result in similar characteristic lake level variability as per the base case with a moderately constricted open entrance. During king tides (event 7) this results in minor lake level fluctuations (a few centimetres) typical of constricted entrance conditions. With post-flood scoured entrance conditions, water levels are observed to decrease slightly and fluctuate several centimetres with the tide.

With the additional ocean anomaly in Event 8, lake levels are observed to increase during sequential high tides increasing by +0.1 - 0.2 m in total over a course of a few days. Such coastal events provide significant oceanic flushing into the entrance region and lake system when considering the volume of this lake level increase. The magnitude of the flushing and lake level rise is shown to be larger with post-flood scoured entrance conditions, with lake levels reaching up to +0.3 - 0.5 m above typical lake levels. Minor flooding of low-lying foreshore areas and increased wave penetration into the entrance region may be experienced during such events (e.g., May 2020, see **Section 3.5.10.1**).

Effects of event 9 are also plotted in **Figure 4.8**. This event shows temporary reductions in lake levels over a course of a few days as a result of barometric (high pressure) set-down of ocean water levels. With post-flood scoured entrance conditions, lake levels are observed to reduce by 0.2 - 0.3 m (approaching MSL) and remain below 0.1 m AHD for several days. Such events would likely expose numerous seagrass beds, mangroves and mudflats located in shallow waters within the lake. A less significant reduction in lake levels is observed for the moderately constricted entrance condition management scenarios, with lake levels remaining at more typical levels above 0.2 m AHD.

The results for event 8 and 9 for the post-flood scoured entrance condition demonstrate the sensitivity of dry-weather lake level variability to entrance conditions. Major changes to the entrance configuration outside of its natural state (i.e., trained entrances, major dredging) would increase the magnitude and frequency of such dry-weather events with significant changes to entrance hydrodynamics, lake level variability and lake ecology. Such changes would likely be detrimental to the ecology of seagrass (Zostera, Halophila, Ruppia) and saltmarsh habitats that line the lakes shallow foreshores and mudflats. Alternatively, for the interim management options proposed, these events are allowed to continue to occur on a natural cycle without alteration.

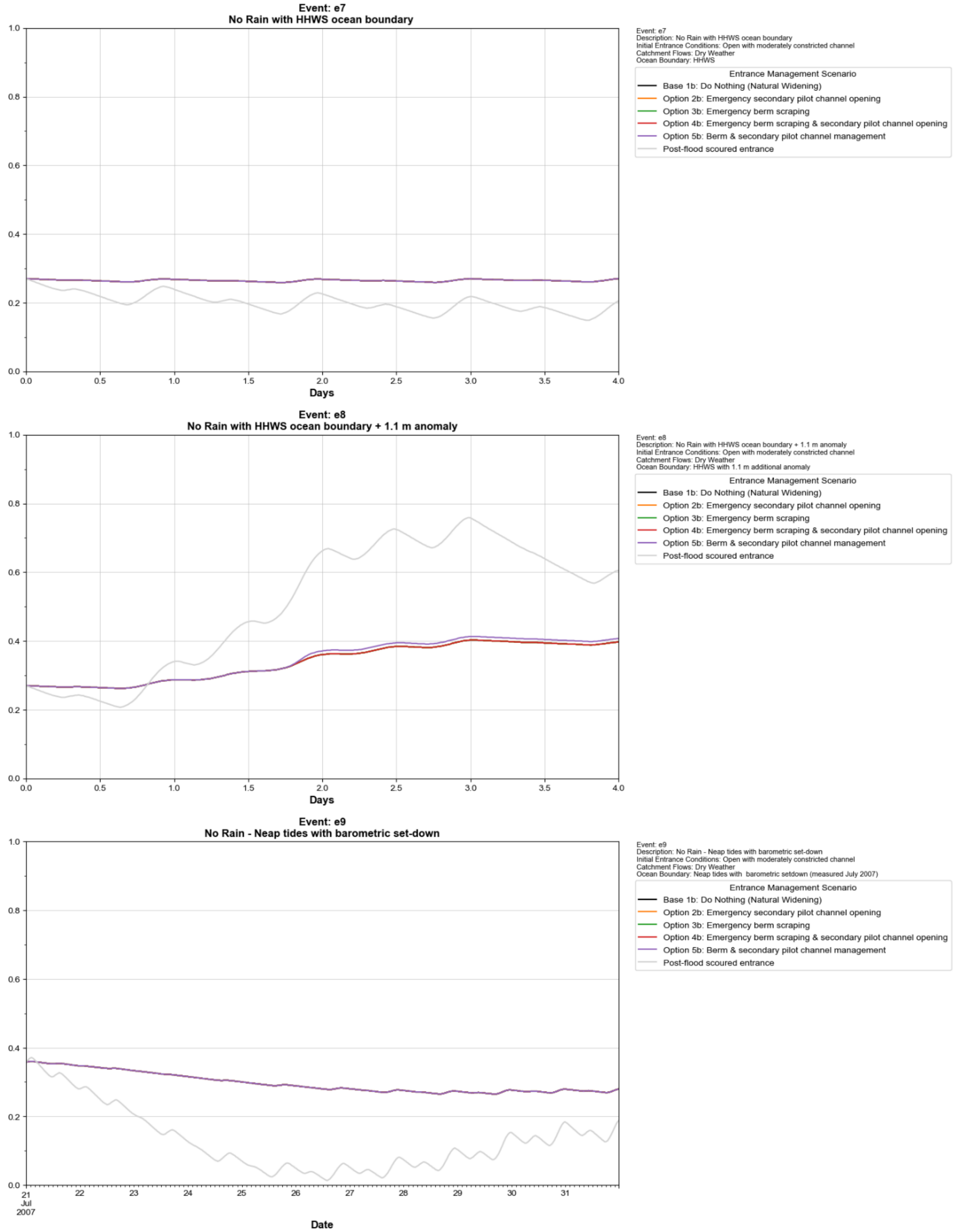


Figure 4.8: Model Lake level for dry-weather events and ocean anomalies

4.4.3 Multi-criteria assessment

Results of the preliminary MCA are summarised in **Figure 4.10** and **Figure 4.9**, with a detailed breakdown of sub-criteria assessment scoring provided in **Appendix D** .

The findings indicate emergency response options (Options 2 - 4) as preferred options compared to the routine berm and pilot channel management (Option 5). While Option 5 does provide similar reductions in flood risk to the emergency response options, it was considered less feasible and more expensive due to risks of high-frequency repeat works associated with the dynamic nature of the entrance and susceptibility to natural berm rebuilding and channel infilling processes between works. All options have minimal impact on the natural estuarine hydrodynamic process. Works are to be undertaken with appropriate environmental controls to minimise risk to shorebird breeding and berm ecology.

The main advantage of these options is the reduction in flood severity and damages for flood events without extreme coastal anomalies. Due to the high levels of development located on the Tuggerah Lakes floodplain, minor reductions in peak flood levels under these scenarios would result in a reduced amount of flood damages. The benefits of these management options are likely to diminish for floods coinciding with extreme coastal anomalies and/or with projected sea level rise over the next 50 - 100 years. Benefits also diminish when the entrance is already in a post-storm scoured condition requiring no management intervention.

It is important to note that none of the interim options, nor a wide open, post-flood scoured entrance, eliminate the risk of flooding. The impacts of flooding will continue to be experienced even under the implementation of the proposed management options and will likely worsen with sea level rise. It is important that the community in the Tuggerah Lakes Floodplain understand their level of flood risk as well as adapt and prepare to living with the impacts of flooding.

Emergency interim management options would be implemented prior to a flood event when certain trigger criteria are met (detailed in **Section 5**). Real-time monitoring, onsite inspection prior to works and flood-forecasting tools are considered key components in implementing an interim management solution and support decision-making and operational procedures. Further environmental aspects, adaption of management options for climate change, land zoning and relevant policies are outlined in **Section 5.**

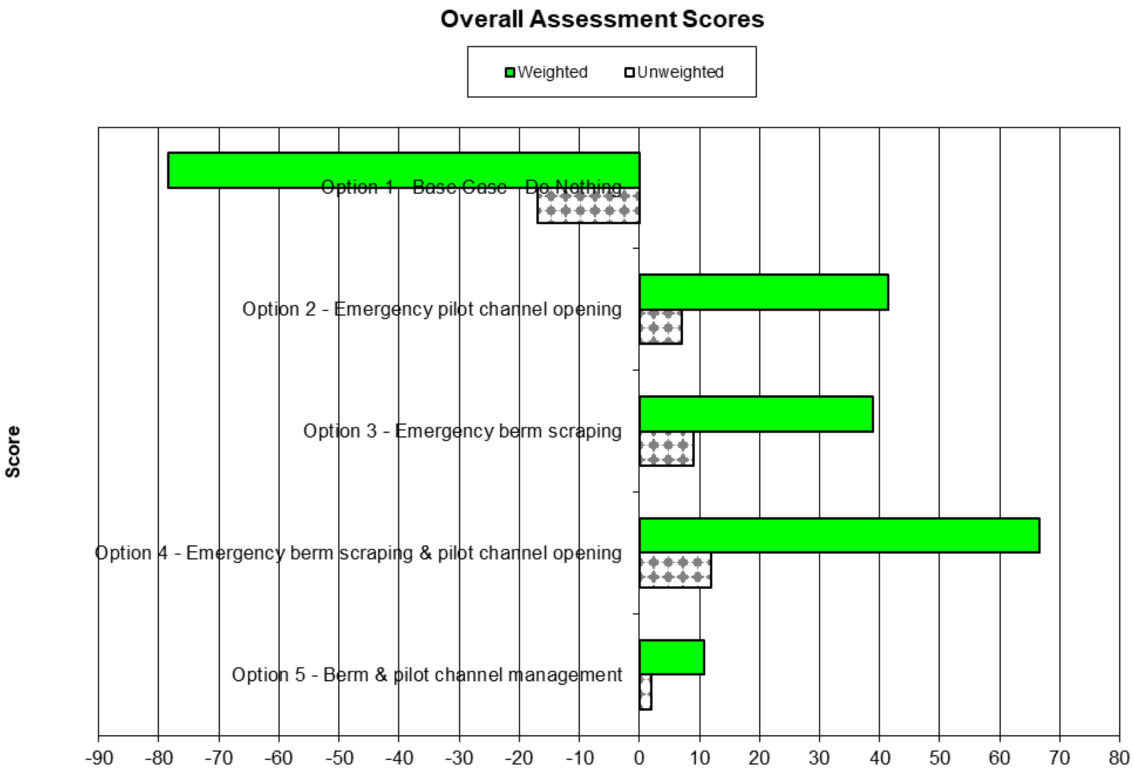


Figure 4.10: Overall MCA Assessment Scores

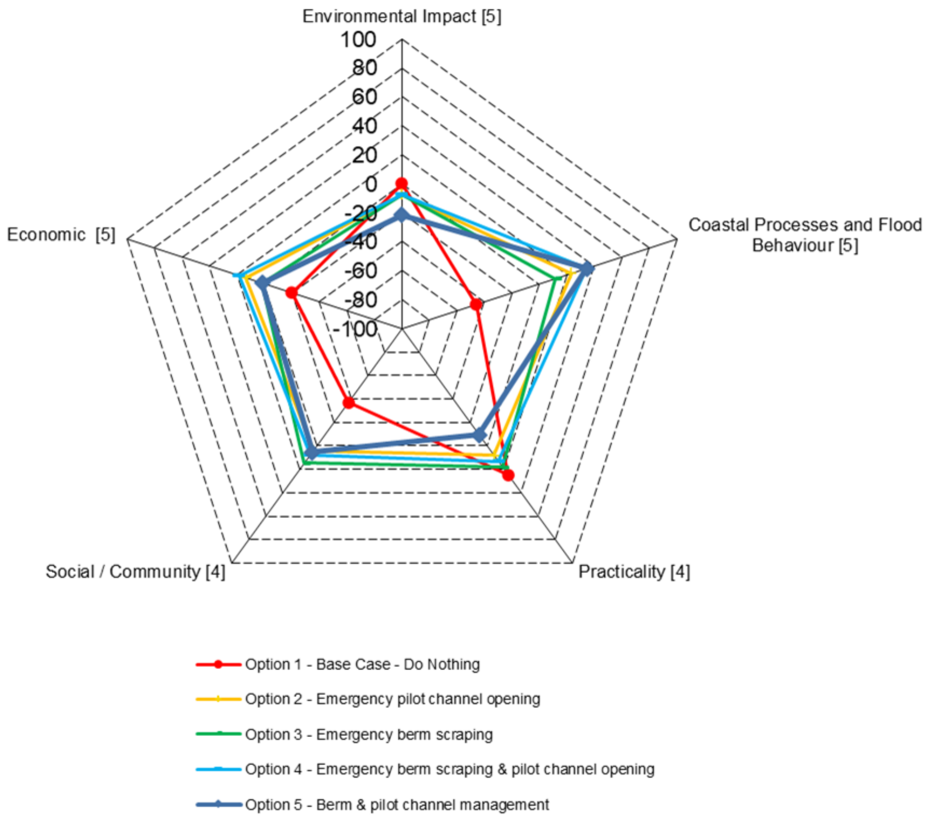


Figure 4.9: Breakdown of MCA results for criteria

4.5 Summary

Modelling of interim management options for the Tuggerah Lakes entrance has been undertaken to assess impacts on flooding and lake level variability under a range of events. Multi-criteria analysis was undertaken to assess interim management options against a range of environmental, social and economic criteria to determine a preferred approach.

The findings indicate emergency response options (Options 2 - 4) as preferred options compared to routine berm and pilot channel management (Option 5). While Option 5 does provide similar reductions in flood risk to the emergency response options, it was considered less feasible and more expensive due to risks of high-frequency repeat works associated with the dynamic nature of the entrance and susceptibility to natural berm rebuilding and channel infilling processes between works. All options have minimal impact on the natural estuarine hydrodynamic process. Works are to be undertaken with appropriate environmental controls to minimise risk to shorebird breeding and berm ecology.

Of the emergency response options, Option 4 (Emergency berm scraping and pilot channel opening) provided the greatest reduction in flood levels of up to 0.1 - 0.2 m for a typical moderately constricted open channel prior to flooding and up to 0.3 m for a fully closed entrance prior to flooding. While flood level reductions associated with the interim procedures are small (typically less than 0.2 m), these are considered beneficial in assisting to reduce flood damages given the highly developed low-lying foreshores of Tuggerah Lakes. Due to the high levels of development located on the Tuggerah Lakes floodplain, minor reductions in peak flood levels under these scenarios would result in a reduced amount of flood damages. Less intensive emergency Options 2 and 3, may be preferred over Option 4 when the entrance is in less of a constricted state prior to flooding and the relative benefits of each to Option 4 are similar.

The main advantage of all interim management options is a minor reduction in flood severity and damages for flood events without extreme coastal anomalies. The benefits of these management options are likely to diminish for floods coinciding with extreme coastal anomalies and/or with projected sea level rise over the next 50 - 100 years. Benefits also diminish when the entrance is already in a post-storm scoured condition requiring no management intervention.

It is important to note that none of the interim options, nor a wide open, post-flood scoured entrance, eliminate the risk of flooding. The impacts of flooding will continue to be experienced even under the implementation of the proposed management options and will likely worsen with sea level rise. It is important that the community in the Tuggerah Lakes Floodplain understand their level of flood risk as well as adapt and prepare to live with the impacts of flooding.

The following section provides details of a preferred interim Entrance Management Strategy based on the options proposed and assessed.

5 Interim Entrance Management Procedure

5.1 Procedure context and objective

Under the NSW Flood Prone Land Policy and Floodplain Development Manual (2005), the management of flood liable land remains the responsibility of local government. The Tuggerah Lakes Floodplain Risk Management Study and Plan (FRMSP) (WMAwater, 2014) provides management recommendations to reduce risk to life, public and private infrastructure associated with flooding. The FRMSP recommended a number of high priority actions to reduce flood risk including adaption planning for foreshore suburbs, flood emergency management planning, public education and awareness, adoption of development controls and formalising an entrance management strategy.

This procedure seeks to provide an evidence-based Interim Entrance Management Procedure for Tuggerah Lakes in accordance with the objectives of the FRMSP and supporting Council's transition to a Coastal Management Program (CMP) 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 procedure is an interim entrance management procedure until an Entrance Management Strategy is formalised through the CMP process.

The main purpose of an interim entrance management strategy should be to account for critical environmental issues and facilitate an approved opening at short notice under formulated, documented and agreed procedures and criteria (DPI, 2013). The Tuggerah Lakes Interim Entrance Management Procedure provides a rational decision-making framework for Central Coast Council to undertake entrance management works to the entrance throat channel and berm at the Tuggerah Lakes entrance. The procedure is supported by decision support tools that utilising real-time quantitative data to facilitate a rational, proactive and informed approach to management actions.

The primary objective of the interim procedure is to reduce risk to life, public and private infrastructure associated with flooding in accordance with the FRMSP (WMAwater, 2014). Flood level reductions associated with the procedure have been modelled in the development of the procedure and are expected to be small (typically less than 0.2 m, varying depending on antecedent entrance conditions and flood severity), however, are considered beneficial in assisting to reduce flood damages.

It is important to note that flooding in Tuggerah Lakes cannot be eliminated. The impacts of flooding will continue to be experienced even under the implementation of the proposed interim management procedure and will likely worsen with sea level rise. It is important that the community in the Tuggerah Lakes Floodplain understand their level of flood risk as well as adapt and prepare to live with the impacts of flooding. The interim procedure is to be implemented alongside other floodplain risk management controls identified in the FRMSP (WMAwater, 2014) to further reduce flood risk.

The interim procedure does not seek to maintain a permanently open entrance. The entrance channel will naturally constrict with sand particularly during dryer periods with low rainfall while scour to a wider entrance during wetter periods with increased rainfall. The interim procedure recognises this dynamic variability of Tuggerah Lakes entrance and has been developed to provide tailored works for different entrance conditions. These works are to be undertaken immediately prior to flooding to assist in providing minor flood risk reduction. Outside of flood events the interim procedure seeks to minimise disturbances to the natural hydraulic characteristics of the Tuggerah Lakes entrance.

The interim procedure has been developed based on the review of previous studies, analysis of historical data, modelling assessment and stakeholder consultation undertaken in the present Tuggerah Lakes Entrance Management Study.

5.2 Description of procedure

5.2.1 Characteristic conditions of Tuggerah Lakes entrance

The condition of the Tuggerah Lakes entrance channel and shoals is dynamic and continuously shaped by catchment and coastal processes including rainfall, ocean waves, and tides. By analysing tidal signals (M2 constituent) in the Lake water levels and investigating historical satellite imagery and surveys, the Tuggerah Lakes Entrance Management Study (MHL, 2022) classified the condition of the Tuggerah Lakes entrance into characteristic states shown in **Table 5.1** and **Figure 5.1**:

- ***Wide open entrance:*** relatively wide open entrance conditions with scoured shoals and channel typically greater than 90 m wide (at 0 m AHD) with high tidal penetration. These conditions were observed to occur occasionally following heavy rainfall and an elevated lake level typically greater than the moderate flood level classification for Tuggerah Lakes of 1.3 m AHD.
- ***Moderately open entrance:*** moderately open entrance conditions with a throat channel typically 50 - 90 m in width (at 0 m AHD), associated with moderate tidal penetration and only minor flood tide shoals in the entrance region. This was observed to be a common state of the entrance.
- ***Moderately constricted entrance*:** moderately constricted entrance conditions with a throat channel typically 20 - 50 m in width (at 0 m AHD), associated with moderately low tidal penetration and developing flood tide shoals. This was observed to be a common state of the entrance.
- ***Heavily constricted entrance:*** heavily constricted entrance conditions with a throat channel less than 20 m in width (at 0 m AHD), associated with low tidal penetration and dominant flood tide shoals filling the entrance channel. These conditions were observed to occur only occasionally, particularly with prolonged periods of low catchment rainfall.

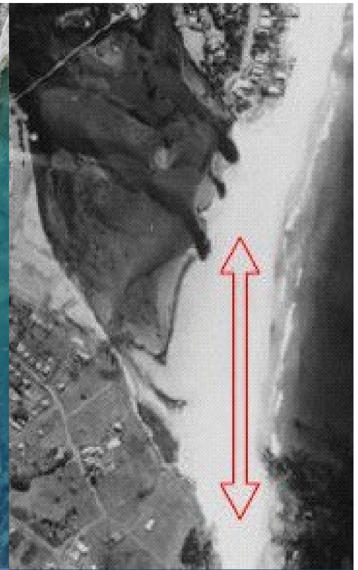
A heavily constricted entrance may remain open to the ocean (with low entrance flows) or, with extended low rainfall, can historically enter a fifth state where the entrance channel fully closes to the ocean described below:

- ***Fully closed*:** Entrance channel completely closes to the ocean due to the progressive sediment infilling and entrance berm growth by wave activity. No flow exchange occurs between the estuary and the ocean during any tidal stage.

Example satellite images in **Table 5.1** show the entrance in each of the above conditions and historical trends in classification over the last 29 years using tidal harmonic analysis are shown in **Figure 5.1**.

The interim procedure recognises the dynamic variability of the Tuggerah Lakes entrance and has been developed to provide tailored works for each of the different characteristic entrance states described above.

Table 5.1: Characteristic entrance conditions

Entrance images from Nearmaps and Umwelt (2011)	 Nov 13 2016	 Apr 29 2017	 Apr 8 2018	 Jul 15 2018	 1941
Characteristic Entrance Conditions	**Wide Open Entrance**	**Moderately Open Entrance**	**Moderately Constricted Entrance**	**Heavily Constricted Entrance**	**Fully Closed Entrance**
Frequency of occurrence	Occasional following heavy rainfall	Common state of entrance	Common state of entrance	Occasional with dry periods of low rainfall	Infrequent and associated with extended dry periods of low rainfall
Entrance tidal penetration	High	Moderate	Low	Minimal	No flow exchange between estuary and ocean during any tidal stage
Typical entrance throat channel width at MSL (m)	Greater than 90 m	50-90 m	20-50 m	1-20 m	0 m
Typical M2 at The Entrance Bridge (m)	Greater than 0.03 m	0.015 -0.03 m	0.005 -0.015 m	Less than 0.005 m	Less than 0.005 m

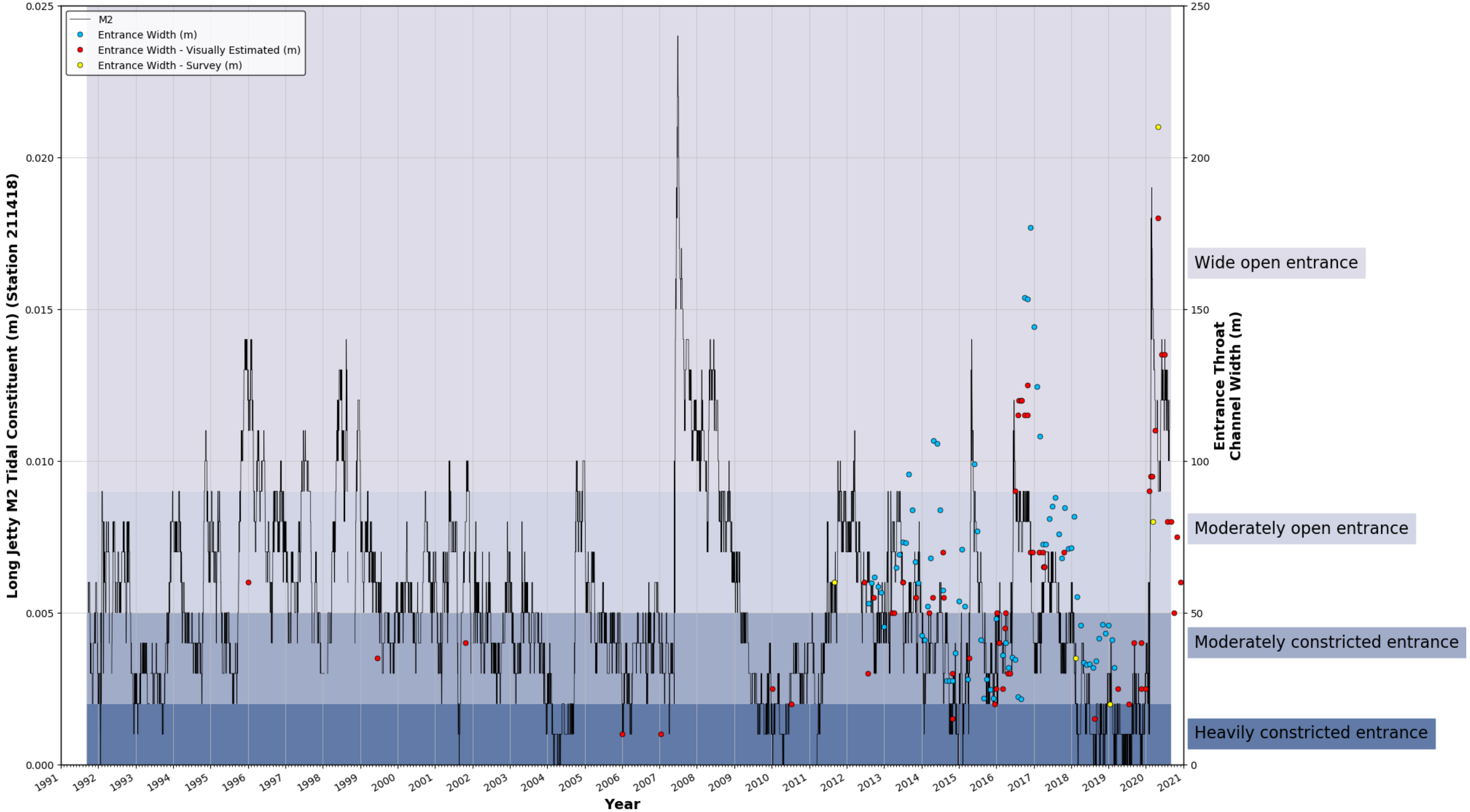


Figure 5.1: Trends in characteristic entrance conditions 1991 - 2020 using tidal harmonics and entrance width

5.2.2 Entrance condition monitoring and classification

The dynamic condition of the entrance channel and shoals is an important factor in determining what course of action is taken under the interim procedure. The entrance throat channel and shoal can be classified into five typical states or conditions (Tuggerah Lakes Entrance Management Study, 2022). These include wide open, moderately open, moderately constricted, and heavily constricted entrance conditions as shown in **Table 5.1**.

Under the interim entrance procedure, the condition of the entrance is to be continually monitored through the use of:

- Real-time tidal harmonic analysis of tidal fluctuations in the water level signal at The Entrance Bridge (Station number 561001)

  Tidal harmonic analysis provides a useful means of understanding trends and patterns in entrance opening behaviour. It involves quantifying the strength of tidal signal frequencies in a coastal lake or lagoon water level record, to provide an indicator of how open or closed an entrance is to the ocean over time. An increase in the measured M2 constituent indicates an increase in tidal response. On the other hand, a decrease in the M2 constituent indicates reduced tidal response and entrance conditions becoming more constricted to ocean flows.

  Entrance condition monitoring under the interim procedure will be supported by real-time harmonic analysis of tidal fluctuations in the water level signal at The Entrance Bridge (Station number 561001). The M2 tidal constituent is to be calculated each day using a moving 28-day analysis window (monthly lunar cycle) to provide ongoing monitoring of monthly trends in entrance conditions. M2 values and entrance behaviour between 1991 - 2020 are shown in **Figure 5.1**.

  Preliminary M2 thresholds for entrance condition classification were determined based on the 29-year harmonic analysis of Long Jetty water level records presented in **Section 3.5.2**. Correlation analysis between M2 at Long Jetty and The Entrance Bridge was used to determine the preliminary M2 thresholds, with the M2 signal at The Entrance Bridge proposed to be used for decision-support to inform the interim procedure.

- Width estimates of the entrance throat channel

  Estimates of the width of the entrance throat channel at 0 m AHD will be undertaken from satellite imagery and/or site inspections. Preliminary thresholds of entrance throat width (at 0 m AHD) for entrance condition classification were determined based on surveys and visual estimates from historical satellite imagery presented in **Section 3.5.2**. Entrance throat channel width (at 0 m AHD) and entrance behaviour between 1991 - 2020 are shown in **Figure 5.1**.

Preliminary thresholds for entrance condition classification are shown in Flow Chart A (**Figure 5.2**) with the more constricted classification from either M2 or channel width estimates used to indicate prevailing entrance state. It should be noted that M2 is calculated over a 28-day window and provides indication of monthly trends in entrance behaviour and does not capture shorter day-to-day variability. As such these thresholds intend to provide a first-pass proxy of entrance conditions and are to be supplemented by a more detailed site inspection of the entrance condition (including throat and shoal channel locations, berm heights and width, shorebird nesting locations, condition of access paths to entrance berm etc.) prior to works being undertaken to inform works of onsite specifications. It is recommended that the procedure be supplemented by a periodic entrance survey program (topography and bathymetry) to inform and optimise future entrance management.

Preliminary thresholds for entrance condition classification may be reviewed and refined as required to improve entrance condition classification. Monitoring of entrance conditions under the interim procedure is supported by MHL's established network of gauges throughout the Tuggerah Lakes catchment and live visualisation/decision support via Council's MHL Flood and Coastal Intelligences Tool (MHLFIT) webpage (see **Section 5.3.2**). It is recommended that Council continue to investigate potential new technologies and methods that may improve entrance condition classification as they become available in the future.

Depending on the prevailing condition of the entrance, different entrance management procedures will be undertaken as listed in Flow Chart A (**Figure 5.2**). These management actions are detailed in the following section.

FLOW CHART A

Entrance Condition Monitoring

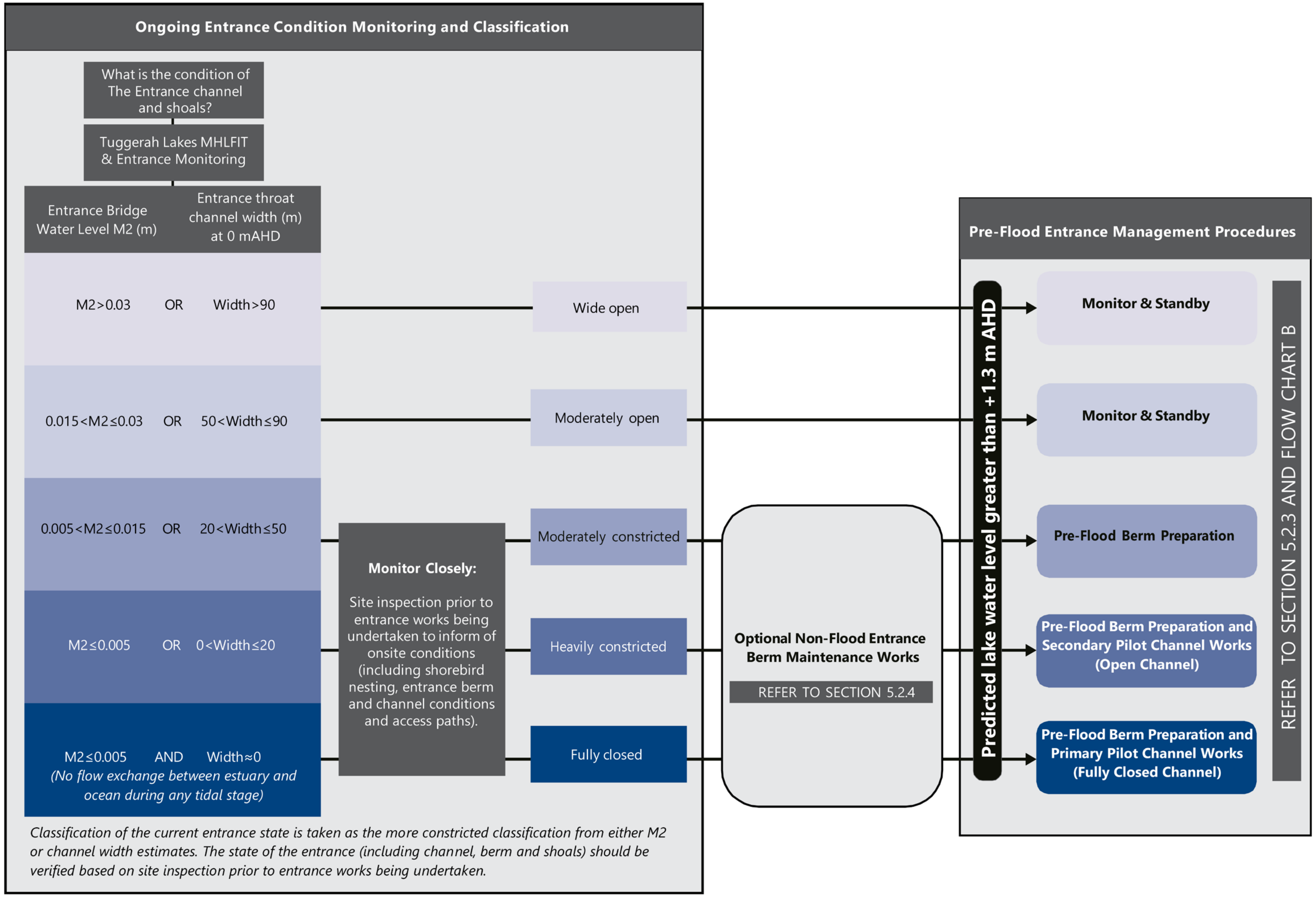


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Figure 5.2: FLOW CHART A - Entrance condition monitoring

5.2.3 Pre-flood entrance management procedures

An interim entrance management procedure for the indicative time window (approximately 3 - 5 days) prior to a possible flood event is presented in Flow Chart B (**Figure 5.3**). This provides an interim decision-making framework to guide entrance management in the days prior to possible flooding. The following sections detail different aspects Flow Chart B including flood warning, flood predictions, trigger levels and entrance management procedures for different entrance conditions.

Pre-flood entrance management procedures may not proceed should wave and weather conditions be too dangerous to undertake the works, site access to the entrance berm is not possible or there is a high degree of uncertainty for the forecast weather event.

Regular ongoing entrance works to continuously maintain flood-ready conditions were not considered to be feasible given the highly dynamic nature of the entrance including berm rebuilding and channel infilling processes. Optional non-flood entrance berm management works are outlined in **Section 5.2.3.4**.

5.2.3.1 Flood warning

The Bureau of Meteorology (BoM) issue a Flood Watch for Tuggerah Lakes and/or a Severe Weather Warning for very heavy rainfall that may lead to flood flashing in the area. In this event, Council is to continue to monitor BoM rainfall, flood forecasts and warnings, and be aware of measured water levels and rainfall within the catchment via the BoM website and Council's MHLFIT website (relevant BoM web links will be provided via Council's MHLFIT website, see **Section 5.3**).

Flood level prediction tools available via the MHLFIT website will also assist Council in estimating forecasted peak flood levels in Tuggerah Lakes. Decision-support tools include real-time flood modelling utilising the BoM's Australian Digital Forecast Database (ADFD) rainfall predictions, flood extent mapping, inundation hazard, as well as user defined scenario modelling to help inform flood predictions. The MHLFIT tool currently provides a four-day lake level prediction outlook using ADFD catchment rainfall forecasts. Monitoring and real-time decision support for the interim entrance procedure are discussed more in **Section 5.3**.

Upon issue of a severe weather warning and/or flood watch, Council is to:

- confirm and place resources required for entrance works on standby,
- undertake entrance site inspections as required,
- confirm any details of procedures based on the prevailing entrance condition including consultations with relevant authorities and environmental controls related to shorebird breeding (see **Section 5.7**),
- continue to monitor BoM forecasts and warnings
- continue to monitor flood level predictions via the MHLFIT website

It is important to note that MHLFIT lake level predictions have been developed for the purpose of decision support for the Tuggerah Lakes Interim Entrance Management Procedure. MHLFIT lake level predictions do not include prediction of overland catchment flooding, stormwater flow connectivity, hydraulic structures or wind setup. Flood warning information for Tuggerah Lakes should be obtained from the Bureau of Meteorology (BoM).

5.2.3.2 Triggers levels

Estimates of peak flood level predictions for Tuggerah Lakes are to be undertaken and reviewed in the lead up to a flood event, supported by available flood warning information outlined in **Section 5.2.3.1**.

Interim entrance procedures outlined in the following section will be triggered when the forecast flood (using the BoM ADFD forecast for 25% chance of rainfall exceedance) is predicted to peak with a level greater than +1.3 m AHD in Tuggerah Lakes. Should predicted levels be less than +1.3 m AHD, Council will continue to monitor the forecast, flood predictions and measured rainfall and water levels for any changes that may lead to flooding greater than the adopted trigger value. Council may wish to proceed with undertaking the entrance procedures on a precautionary basis in the event where there is a high degree of uncertainty in forecast rainfall and/or peak flood levels.

The predicted peak flood level trigger of +1.3 m AHD has been determined in consultation with Council and relevant stakeholders and is equivalent to the recently reviewed moderate flood level classification for Tuggerah Lakes at Long Jetty. The adopted trigger level is just below a 20% AEP[1] flood level (+1.36 m AHD) for Tuggerah Lakes (Lawson & Treloar Pty. Ltd, 1994).

[1] Annual Exceedance Probability.

FLOW CHART B
Pre-Flood Entrance Management Actions

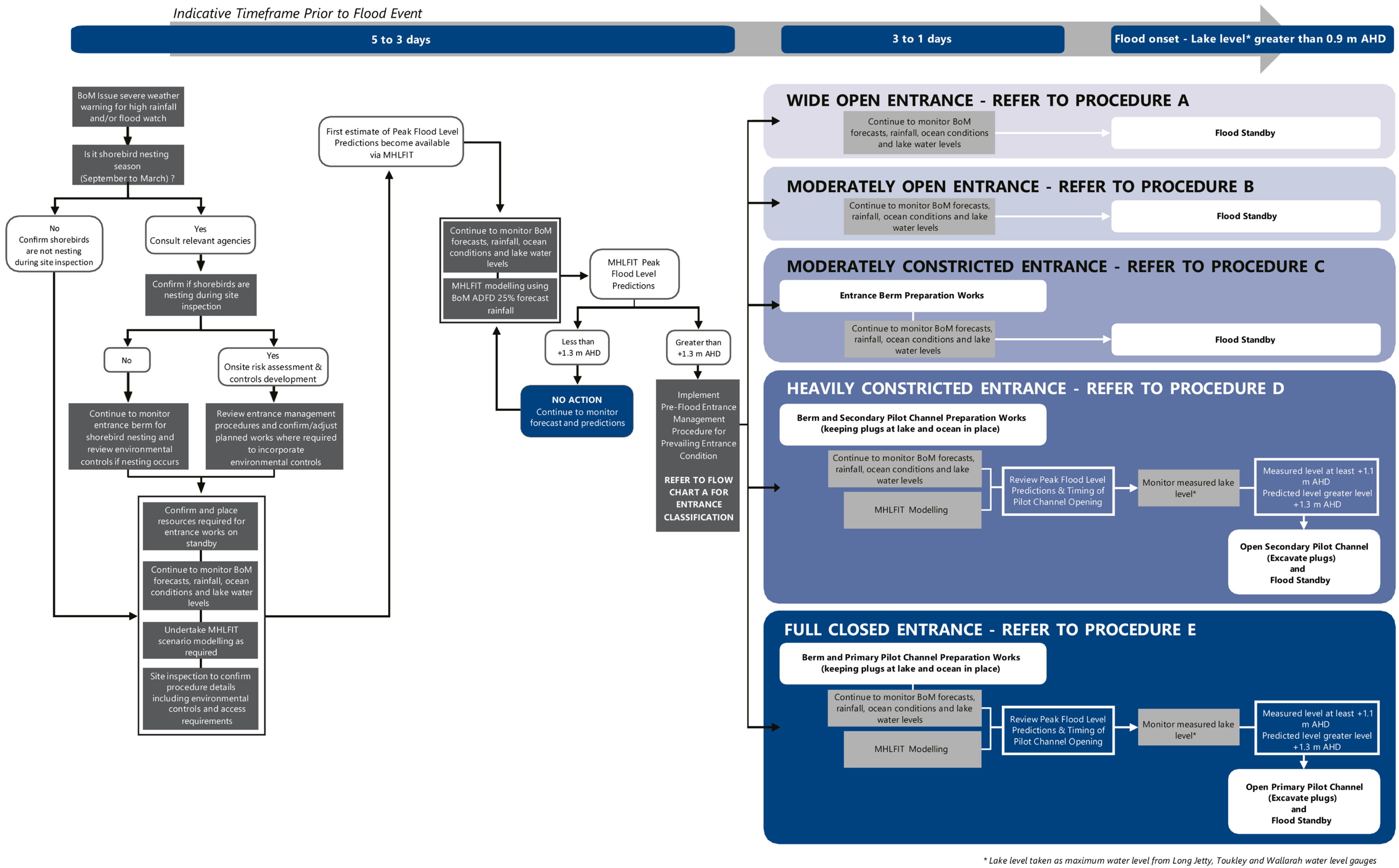


Figure 5.3: FLOW CHART B Pre-flood interim entrance management actions

5.2.3.3 Entrance management procedures prior to flooding

Entrance condition monitoring will be undertaken following **Section 5.2.1**. Depending on the prevailing condition of the entrance, different management procedures will be undertaken prior to flooding as outlined below.

Procedure A

Entrance condition: Wide open entrance

Criteria:

1) The Entrance Bridge M2: Greater than 0.03 m; OR
   Entrance throat channel width at 0 m AHD: Greater than 90 m;

AND

2) Predicted peak flood level in Tuggerah Lakes (using the BoM ADFD forecast for 25% chance of rainfall exceedance): Greater than +1.3 m AHD

Procedure: Monitor and Standby

- Maintain resources on flood stand-by and monitor entrance throat channel for adverse changes.
- Continue to monitor forecast, flood predictions as well as measured rainfall and water levels.

Procedure B

Entrance condition: Moderately open entrance

Criteria:

1) The Entrance Bridge M2: 0.015 - 0.03 m; OR
   Entrance throat channel width at 0 m AHD: 50 - 90 m;

AND

2) Predicted peak flood level in Tuggerah Lakes (using the BoM ADFD forecast for 25% chance of rainfall exceedance): Greater than +1.3 m AHD

Procedure: Monitor and Standby

- Maintain resources on flood stand-by and monitor entrance throat channel for adverse changes.
- Continue to monitor forecast, flood predictions as well as measured rainfall and water levels.

Procedure C

Entrance condition: Moderately constricted entrance

Criteria:

1) The Entrance Bridge M2: 0.005 - 0.015 m; OR
   Entrance throat channel width at 0 m AHD: 20 - 50 m;

AND

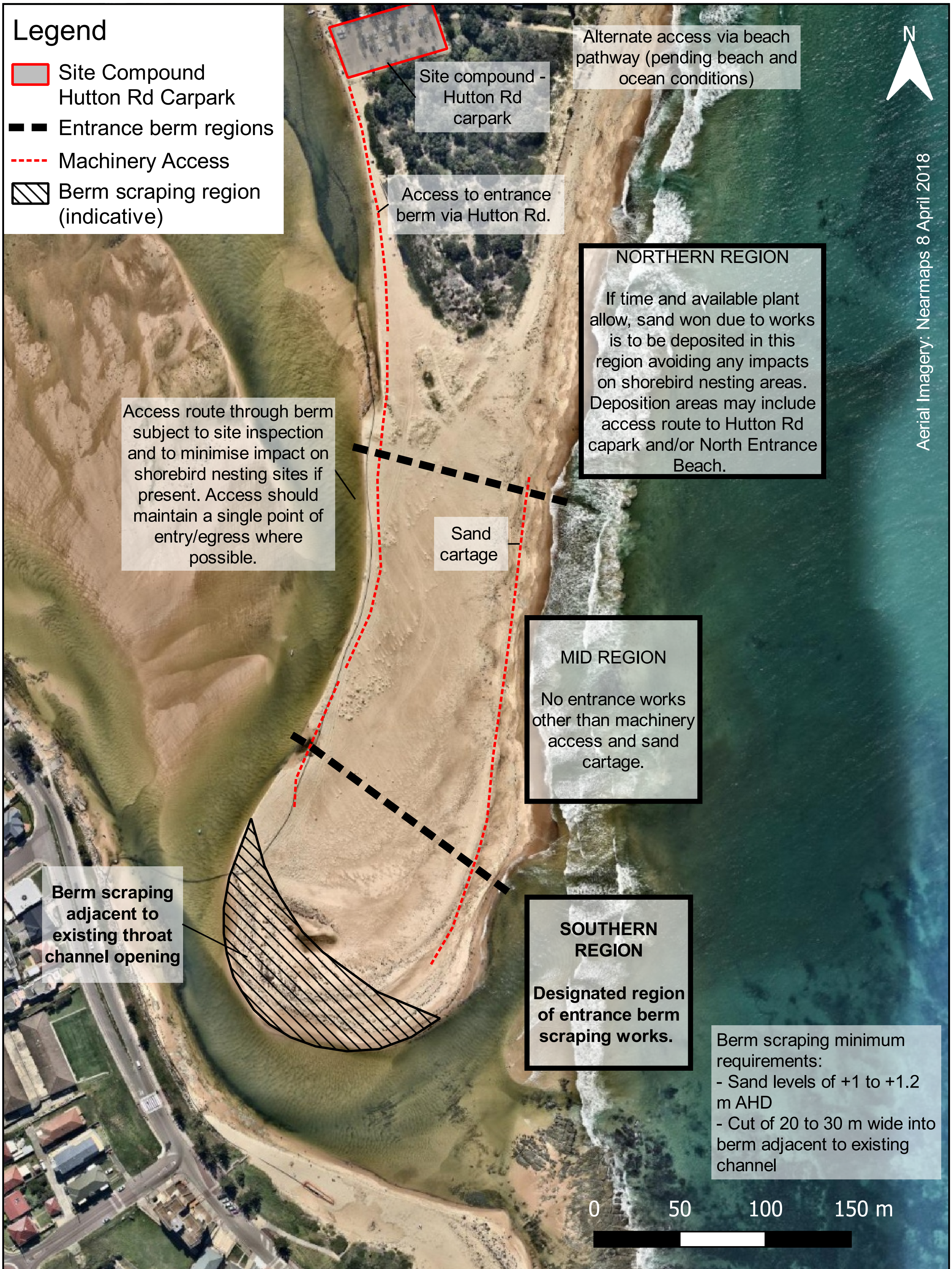
2) Predicted peak flood level in Tuggerah Lakes (using the BoM ADFD forecast for 25% chance of rainfall exceedance): Greater than +1.3 m AHD

Procedure: Berm Preparation Works

- Berm preparation works involve the lowering of sand levels by mechanical scraping along the banks immediately adjacent to the existing throat channel opening as illustrated in **Figure 5.4**.
- Berm preparation works should ideally be undertaken around low tide windows within the 1 - 3 days prior to flooding.
- Berm preparation works should be limited to the designated area in the southern region shown in **Figure 5.4**.
- Minimum requirements for berm scraping include:
  - A scraped sand level of +1 to +1.2 m AHD.
  - Cut of 20-30 m wide or more into the berm immediately adjacent to the banks of the existing opening as illustrated in **Figure 5.4**.
  - Edges of the scraped region should be graded to a slope of 1V:3H or flatter for safety.
- Sand won due to works is to be deposited in the northern region in **Figure 5.4** and avoid any impacts on shorebird nesting areas. If time and available plant allow deposition areas may include:
  - North Entrance Beach (prioritising eroded regions) and placed at the toe of the foredune.
  - Accessway from Hutton Rd carpark.
  - Where prior environmental assessment and approvals allow, sand won may also be used to support establishment of shorebird nesting areas.

  Otherwise, sand could be deposited on the adjacent berm on the northern side of the works, placed outside the area of impending entrance scour and spread so as to not impede entrance flow.

- Berm works should be avoided during shorebird nesting periods where possible. When this is not possible, exclusion zones and additional controls may be required to minimise impacts. These should be determined via onsite inspections, consultation with qualified professionals and environmental assessments prior to undertaking works outlined in **Section 5.6**.
- Machinery access to the entrance berm is to be undertaken via the designated accessway shown in **Figure 5.4** extending from the Hutton Rd carpark. Council is to regularly maintain access to the entrance berm in this area to support entrance management works. Alternate access may also be possible via the North Entrance Beach accessway on the northern side of the carpark, pending favourable beach and ocean conditions.
- Addition entrance berm management works may be undertaken outside of flooding to support environmental and social outcomes (see **Section 5.2.3.4**).
- Pre and post photographs of works are to be undertaken by Council.
- After completion of works, maintain resources on flood stand-by and monitor entrance throat channel for adverse changes. Continue to monitor forecast, flood predictions as well as measured rainfall and water levels.
- Should time, plant and/or prevailing conditions inhibit berm scraping works to be undertaken effectively, secondary pilot channel excavation may be used an alternative approach, with works located adjacent to the existing throat channel opening in the southern region of the entrance berm shown in **Figure 5.4.** Secondary pilot channel works should be undertaken in accordance with those detailed in Procedure D.



NSW GOVERNMENT

MODERATELY CONSTRICTED ENTRANCE - PROCEDURE C (INDICATIVE)

UNDERTAKEN PRIOR TO PREDICTED FLOODING GREATER THAN +1.3 M AHD IN TUGGERAH LAKES

Manly Hydraulics Laboratory

Report MHL2811
Figure
5.4

Report Figure

Procedure D

Entrance condition: Heavily constricted entrance

Criteria:

1) The Entrance Bridge M2: Less than 0.005 m; OR
   Entrance throat channel width at 0 m AHD: 1 - 20 m;

AND

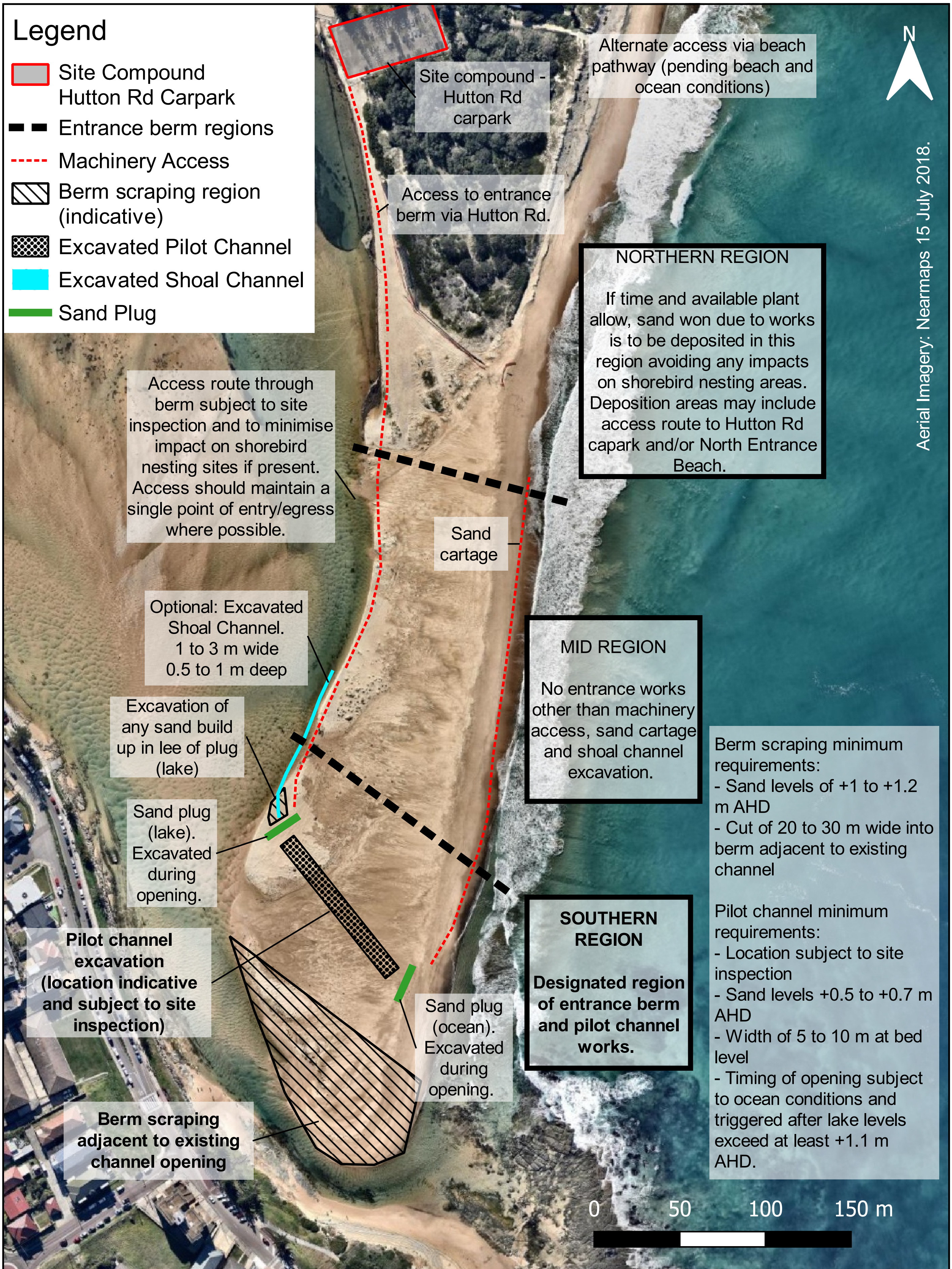
2) Predicted peak flood level in Tuggerah Lakes (using the BoM ADFD forecast for 25% chance of rainfall exceedance): Greater than +1.3 m AHD

Procedure: Berm Preparation and Secondary Pilot Channel Works (Open Channel)

- Berm works involve the lowering of sand levels by mechanical scraping along the banks immediately adjacent to the existing throat channel opening. This is to be supplemented by the construction of a pilot channel through the berm as a secondary channel adjacent to the existing channel opening. Indicative berm scraping and pilot channel works are outlined in **Figure 5.5**.
- Berm and pilot channel preparation works should be limited to the designated area in the southern region shown in **Figure 5.5**.
- Berm and pilot channel preparation works should ideally be undertaken around low tide windows within the 1 - 3 days with the pilot channel end plugs (lake and ocean) kept in place.
- Minimum requirements for berm scraping include:
  - a scraped sand level of +1 to +1.2 m AHD.
  - Cut of 20 - 30 m wide or more into the berm immediately adjacent to the banks of the existing opening as illustrated in **Figure 5.5**.
- The pilot channel location/orientation within the designated area of the southern region (**Figure 5.5**) is to be determined via site inspection prior to works being undertaken. The pilot channel location should aim to maximise flow conveyance between entrance shoal channels and ocean.
- Optional pilot channel works may consider excavation of a narrow channel at low-tide through shoaled areas as in **Figure 5.5** to improve flow connectivity to the pilot channel. Requirements for low-tide shoal channel excavation is subject onsite inspection prior to works.
- Minimum requirements for pilot channel excavation include:
  - Excavation of a pilot channel with a bed channel width of 5-10 m and bed level at +0.5 to +0.7 m AHD.
  - Sand plugs (crest at least +2.5 m AHD, with higher crest during elevated ocean conditions) are to remain in place at lake and ocean ends during and after excavation to minimise sand ingress prior to opening (see below regarding timing of opening) as shown in **Figure 5.5**.

- Opening of the pilot channel is to be undertaken after measured lake levels are at least +1.1 m AHD. Depending on the coastal conditions a successful pilot channel opening may need to wait for the lake level to be above the predicted high tide level to account for wave run up and tidal anomaly from storm surge, otherwise, the pilot channel is likely to close on the incoming high tide. Council is to utilise the MHLFIT decision support tool to inform favourable timing for opening of the pilot channel after this trigger has been met. MHLFIT decision support for pilot channel opening is described in **Section 5.3** and factors both lake, ocean and berm conditions on opening hydraulic efficiency. Measured lake level for determining pilot channel opening is to be taken as the maximum water level recorded from Long Jetty (211418), Toukley (211401) and Wallarah (211420) gauges.
- Opening of the pilot channel is to be undertaken via mechanical excavation of sand plugs.
- Sand won due to works is to be deposited in the northern region in **Figure 5.5** and avoid any impacts on shorebird nesting areas. If time and available plant allow deposition areas may include:
    - North Entrance Beach (prioritising eroded regions) and placed at the toe of the foredune.
    - Accessway from Hutton Rd carpark.
    - Where prior environmental assessment and approvals allow, sand won may also be used to support the establishment of shorebird nesting areas.

  Otherwise, sand could be deposited on the adjacent berm on the northern side of the works, placed outside the area of impending entrance scour and spread so as to not impede entrance flow.
- Berm and pilot channel preparation works should be avoided during shorebird nesting periods where possible. When this is not possible, exclusion zones and additional controls may be required to minimise impacts. These should be determined via onsite inspections, consultation with qualified professionals and environmental assessments prior to undertaking works outlined in **Section 5.6**.
- Machinery access to the entrance berm is to be undertaken via the designated accessway shown in **Figure 5.5** extending from the Hutton Rd carpark. Council is to regularly maintain access to the entrance berm in this area to support entrance management works. Alternate access may also be possible via the North Entrance Beach accessway on the northern side of the carpark, pending favourable beach and ocean conditions.
- Addition entrance berm management works may be undertaken outside of flooding to support environmental and social outcomes (see **Section 5.2.3.4**)
- Pre and post photographs of works are to be undertaken by Council.
- After completion of works, maintain resources on flood stand-by and monitor entrance throat channel for adverse changes. Continue to monitor forecast, flood predictions as well as measured rainfall and water levels.



NSW GOVERNMENT

HEAVILY CONSTRICTED ENTRANCE - PROCEDURE D (INDICATIVE)

UNDERTAKEN PRIOR TO PREDICTED FLOODING GREATER THAN +1.3 M AHD IN TUGGERAH LAKES

Manly Hydraulics Laboratory

Report MHL2811
Figure
5.5

Report Figure

Procedure E

Entrance condition: Fully closed entrance

1) The Entrance Bridge M2: Less than 0.005 m; AND
   Entrance throat channel width at 0 m AHD: Approx. 0 m;

AND

2) Predicted peak flood level in Tuggerah Lakes (using the BoM ADFD forecast for 25% chance of rainfall exceedance): Greater than +1.3 m AHD

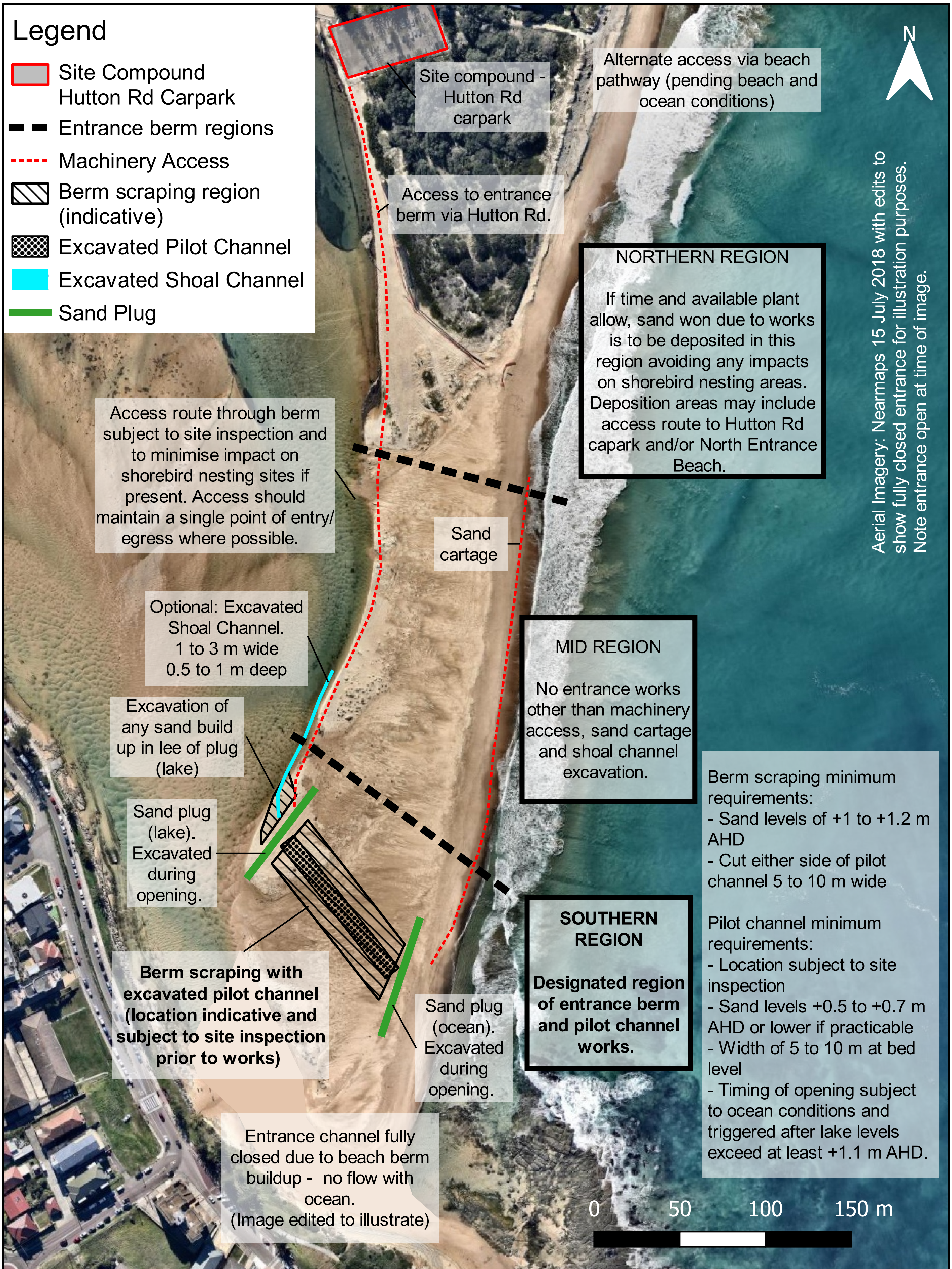
Procedure: Berm Preparation and Primary Pilot Channel Works (Fully Closed Channel)

- Undertake berm and pilot channel preparation works as outlined in **Figure 5.6**. This involves lowering of sand levels by mechanical scraping construction of a pilot channel through the berm located fronting the closed main channel.
- Berm and pilot channel preparation works should be limited to the designated area in the southern region shown in **Figure 5.6**.
- Berm and pilot channel preparation works should ideally be undertaken around low tide windows within the 1-3 days with the pilot channel end plugs (lake and ocean) kept in place.
- Berm scraping should aim to achieve:
  - a sand level of +1 to +1.2 m AHD or lower if practicable.
  - a minimum 20-30 m wide or more cut into the berm adjacent to the pilot channel (**Figure 5.6**).
- The pilot channel location/orientation within the designated area (**Figure 5.6**) is to be determined via site inspection prior to works being undertaken should aim to maximise flow conveyance between entrance shoal channels and ocean.
- Minimum requirements for pilot channel excavation include:
  - Excavation of a pilot channel with a bed channel width of 5-10 m and bed level at +0.5 to +0.7 m AHD or lower if practicable.
  - Sand plugs (crest at least +1.5 m AHD depending on ocean conditions) are to remain in place at lake and ocean ends during and after excavation to minimise sand ingress prior to opening (see below regarding timing of opening).
- Opening of the pilot channel is to be undertaken after measured lake levels are at least +1.1 m AHD. Depending on the coastal conditions a successful pilot channel opening may need to wait for the lake level to be above the predicted high tide level to account for wave run up and tidal anomaly from storm surge, otherwise, the pilot channel is likely to close on the incoming high tide. Council is to utilise the MHLFIT decision support tool to inform favourable timing for opening of the pilot channel after this trigger has been met. MHLFIT decision support for pilot channel opening is described in Section **5.3** and factors both lake, ocean and berm conditions on opening hydraulic efficiency. Measured lake level for determining pilot channel opening is to be taken as

the maximum water level recorded from Long Jetty (211418), Toukley (211401) and Wallarah (211420) gauges.

- Opening of the pilot channel is to be undertaken via mechanical excavation of sand plugs.
- Sand won due to works is to be deposited in the northern region in **Figure 5.6** and avoid any impacts on shorebird nesting areas. If time and available plant allow deposition areas may include:
    - North Entrance Beach (prioritising eroded regions) and placed at the toe of the foredune.
    - Accessway from Hutton Rd carpark.
    - Where prior environmental assessment and approvals allow, sand won may also be used to support the establishment of shorebird nesting areas.

  Otherwise, sand could be deposited on the adjacent berm on the northern side of the works, placed outside the area of impending entrance scour and spread so as to not impede entrance flow.
- Berm and pilot channel preparation works should be avoided during shorebird nesting periods where possible. When this is not possible, exclusion zones and additional controls may be required to minimise impacts. These should be determined via onsite inspections, consultation with qualified professionals and environmental assessments prior to undertaking works outlined in **Section 5.6**.
- Machinery access to the entrance berm is to be undertaken via the designated accessway shown in **Figure 5.6** extending from the Hutton Rd carpark. Council is to regularly maintain access to the entrance berm in this area to support entrance management works. Alternate access may also be possible via the North Entrance Beach accessway on the northern side of the carpark, pending favourable beach and ocean conditions.
- Addition entrance berm management works may be undertaken outside of flooding to support environmental and social outcomes (see **Section 5.2.3.4**)
- Pre and post photographs of works are to be undertaken by Council.
- After completion of works, maintain resources on flood stand-by and monitor entrance throat channel for adverse changes. Continue to monitor forecast, flood predictions as well as measured rainfall and water levels.



NSW GOVERNMENT

FULLY CLOSED ENTRANCE - PROCEDURE E (INDICATIVE)

UNDERTAKEN PRIOR TO PREDICTED FLOODING GREATER THAN +1.3 M AHD IN TUGGERAH LAKES

Manly Hydraulics Laboratory

Report MHL2811
Figure
5.6

Report Figure

5.2.3.4 Designated area of entrance works

The designated area for entrance berm scraping and pilot channel works (Procedure C, D and E) is illustrated in **Figure 5.4** - **Figure 5.6** and is located in the southern region of the entrance berm. This region promotes a typical entrance channel configuration with the opening against the southern shore and a characteristic entrance berm that increases in height from south to north. The designated area is prone to scour during flooding as the entrance channel widens naturally and is typically outside shorebird nesting areas (to be confirmed via site inspection, consultation with qualified professionals and environmental assessments prior to works).

Entrance berm scraping and pilot channel works are not to be undertaken in the mid to northern regions of the entrance berm in order to minimise potential impacts on shorebird nesting areas and coastal processes at the North Entrance Beach.

5.2.3.5 Wave and coastal effects

Flood events may coincide with elevated ocean water levels with high wave activity and large tides. During high energy ocean conditions, entrance works may not proceed because it is deemed unsafe. In the case that works can proceed safely, entrance works during high wave activity are to consider where appropriate:

- Undertaking works around low tide
- Avoid driving machinery in the regions of wave runup on the ocean side of the berm.
- Maintain (or form) an elevated sand bund on the ocean side of berm scraping works (Procedure C, D and E) to reduce wave overwash and sand ingress while entrance works are being undertaken. Once works are completed the sand bund may be removed via excavation.
- Increasing sand plug crest heights on pilot channels as required (Procedure D and E) to reduce berm overwash and sand ingress during works and prior to opening.

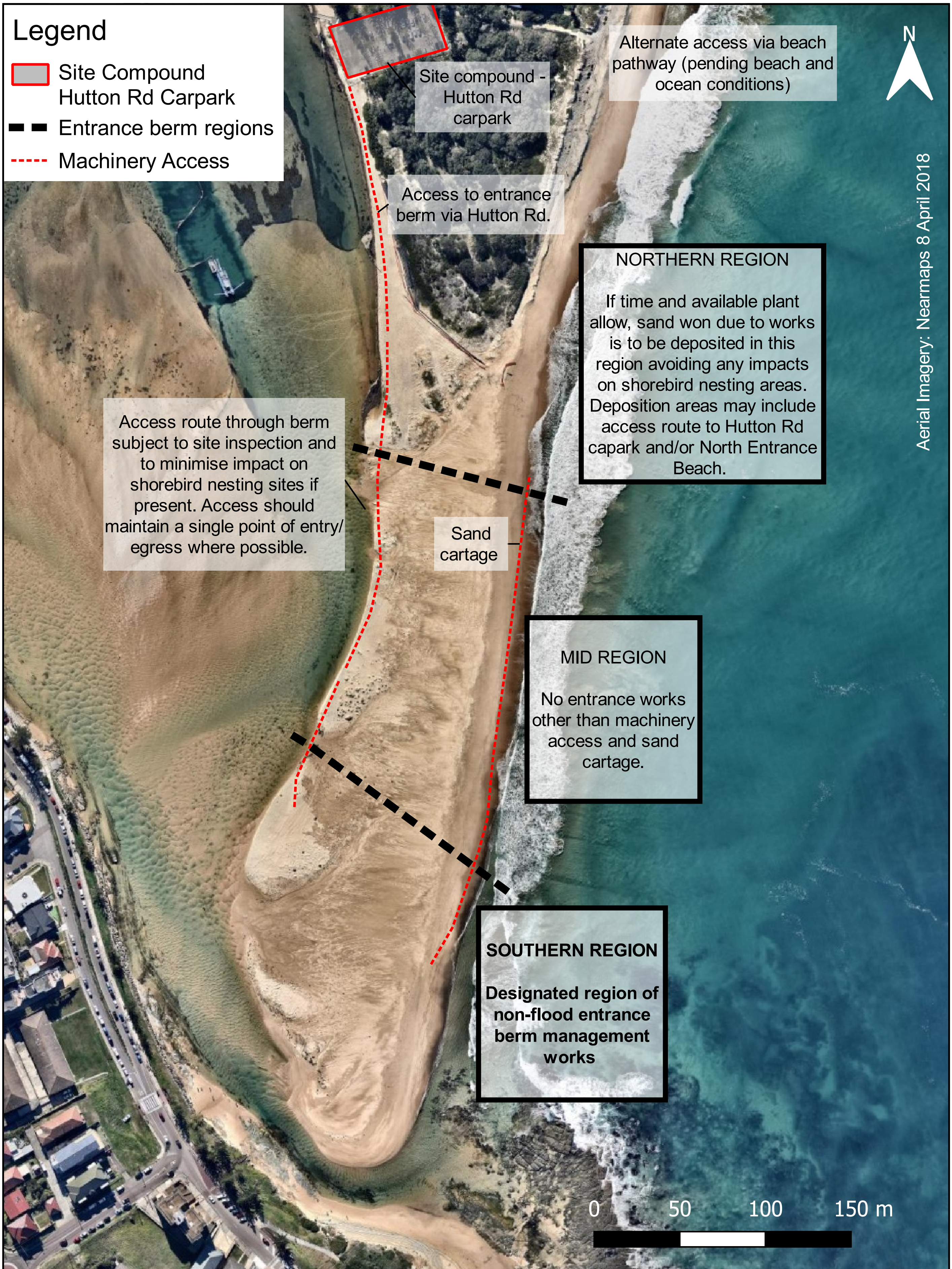
Effects of ocean conditions including tides, tidal anomalies and wave setup on predicted flooding are factored into the MHLFIT lake level predictions. Opening of the pilot channel is to be undertaken after measured lake levels are at least +1.1 m AHD. Depending on the coastal conditions a successful pilot channel opening may need to wait for the lake level to be above the predicted high tide level to account for wave run up and tidal anomaly from storm surge, otherwise, the pilot channel is likely to infill on the incoming high tide. Council is to utilise the MHLFIT decision support tool to inform favourable timing for opening of the pilot channel after this trigger has been met.

5.2.4 Optional non-flood entrance berm management works

Should the entrance enter a moderately constricted, heavily constricted or full closed state, Council may wish to undertake entrance berm management works as required to support entrance social and environmental outcomes. Entrance berm management works are to be undertaken in the designated region shown in **Figure 5.7**. Entrance berm management works may include but are not limited to:

- Entrance berm scraping works to widen the existing entrance throat channel guided by pre-flood procedures for a moderately constricted entrance outlined in **Section 5.2.3.3** (excluding criteria for predicted flood trigger level).
- Entrance berm scraping works to promote a typical entrance channel configuration with the opening against the southern shore and a sand spit berm height that increases from south to north, helping to prevent wave overwash and entrance breakout across the mid and northern sections.
- Entrance berm scraping works to source sand to enhance and support favourable shorebird nesting conditions where prior environmental assessment and approvals allow.
- Entrance berm scraping works to source sand to maintain access path at Hutton Rd carpark and/or nourish North Entrance Beach.
- Pilot channel preparation works if the entrance is in a heavily constricted or fully closed state. These are to be guided by pre-flood procedures for a heavily constricted or fully closed entrances outlined in **Section 5.2.3.3**.
- Other requirements for non-flood entrance works were identified as part of the review and update of this procedure.

Non-flood works are required to be undertaken in accordance with relevant policies.



NSW GOVERNMENT

DESIGNATED REGION FOR OPTIONAL NON-FLOOD ENTRANCE BERM MANAGEMENT WORKS

Manly Hydraulics Laboratory

Report MHL2811
Figure
5.7

Report Figure

5.3 Monitoring and real-time decision support

5.3.1 Rainfall and water level monitoring

The interim entrance management procedure is informed and supported by Central Coast Council's monitoring network which currently includes 12 rainfall stations and 10 water level stations located within the Tuggerah Lakes catchment shown in Figure 3.3 (owned by the NSW Department of Planning and Environment Biodiversity and Conservation Division and Central Coast Council). The network is maintained routinely by Manly Hydraulics Laboratory (MHL) to meet or exceed a target of 95% data capture.

Rainfall stations provide continuous (event-based) sampling with data recorded after every 0.5 mm tip of rainfall with an accuracy of ± 3%. Data is transferred to MHL via Internet Protocol typically within 5 minutes of each 0.5 mm of rainfall. Water level data is sampled typically every 15 minutes with an accuracy of ± 20 mm and transferred via Internet Protocol. Water level stations are located at key catchment locations for flood warning including monitoring of Tuggerah Lakes waterbodies and tributaries. These provide near real-time warning of flood levels when pre-determined thresholds are exceeded. Rainfall and water level stations have automated alarm messaging capabilities should this be required to support entrance management procedures.

The monitoring is supported by MHL's cloud-based database storage which boasts near real-time environmental data retrieval for over 1000 sites across the state sourced from the Bureau of Meteorology (BoM), Water NSW, as well as MHL's own sites. This database also supports the NSW Floods Near Me app developed by MHL. Rainfall and water level data is also transferred and maintained to the Bureau of Meteorology (BoM) to assist in the delivery of NSW non-flash flood riverine forecasting and warning services.

Water level, rainfall and ocean tide monitoring data can be visualised in real-time via Central Coast Councils MHLFIT web portal described in the following section.

5.3.2 MHLFIT decision support

The Central Coast MHL Flood and Coastal Intelligence Tools (MHLFIT) provide important real-time decision support to help inform and support the interim entrance management procedure (see **Figure 5.8**). At present, the MHLFIT system includes the following components to inform entrance management:

- Realtime visualisation of water level and rainfall monitoring data throughout the Tuggerah Lakes Catchment **(Figure 5.9)**
- Realtime M2 tidal harmonic analysis at The Entrance Bridge water level gauge (Station number 561001) to provide an indication of prevalent trends in entrance condition **(Figure 5.10)**.
- Realtime hydrologic, hydraulic and entrance modelling incorporating forecast tides and BoM forecast rainfall (from the Australian Digital Forecast Database - ADFD), to provide advanced flood warning and decision support (**Figure 5.11**).
- Flood level extent visualisation (**Figure 5.12**).

- On-demand user-defined what-if scenario modelling to inform flood level predictions (**Figure 5.13**).

This information is used to provide decision support for Council and emergency services as to the predicted level of flooding that may be experienced.

The accuracy of the MHLFIT flood predictions is subject to rainfall forecast variability, entrance, ocean and catchment conditions. Due to the uncertainty inherent in water level predictions of this nature, real-time water level predictions are run for different rainfall forecast scenarios and supplemented sensitivity testing using what-if scenarios and on-demand lake level predictions.

Council may wish to pursue further additions to the Central Coast MHLFIT decision support tool should these be required to inform entrance management. These may include remote entrance channel and berm monitoring techniques supported by satellite/aerial imagery, drone surveying or lidar applications.

It is important to note that MHLFIT lake level predictions have been developed for the purpose of decision support for the Tuggerah Lakes Interim Entrance Management Procedure. MHLFIT lake level predictions do not include prediction of overland catchment flooding, stormwater flow connectivity, hydraulic structures or wind setup. Flood warning information for Tuggerah Lakes should be obtained from the Bureau of Meteorology (BoM).

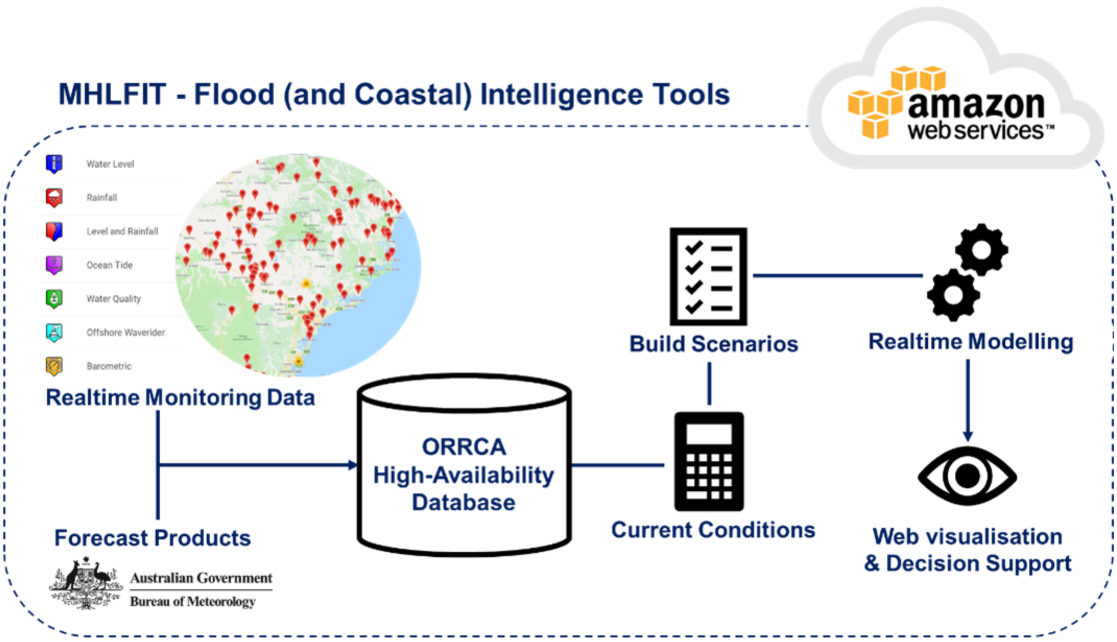
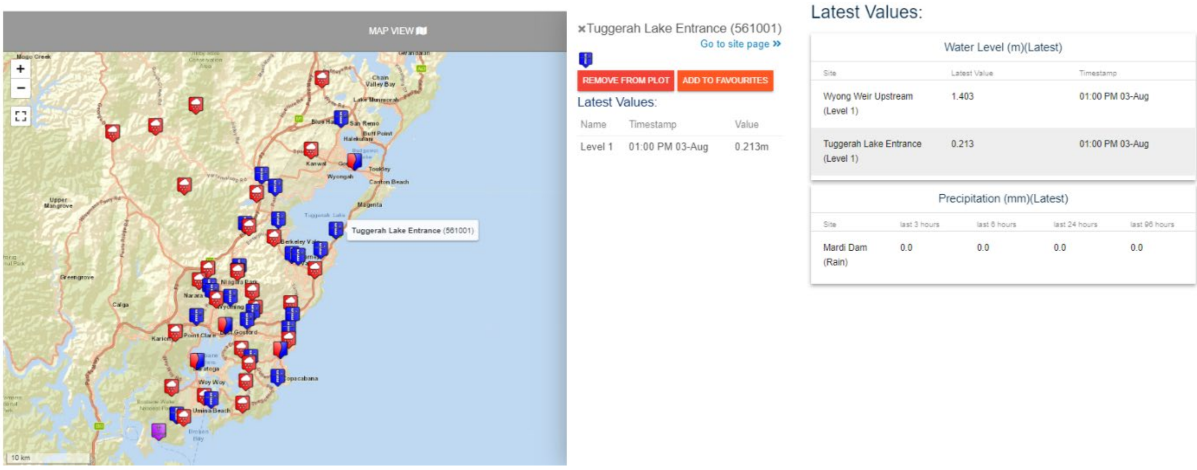


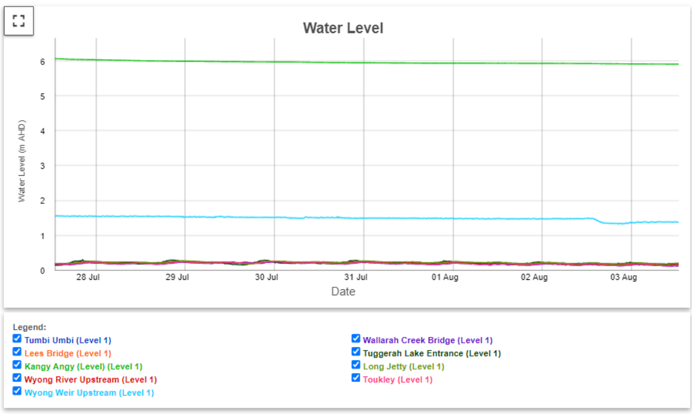
Figure 5.8: Framework for MHLFIT - MHL Flood (and Coastal) Intelligence Tools



Latest Water Levels

Water Level (m)(Latest)

Site	Latest Value	Timestamp
Wyong Weir Upstream (Level 1)	1.390	12:45PM 03/08/2022
Lees Bridge (Level 1)	0.183	12:45PM 03/08/2022
Toukley (Level 1)	0.166	12:45PM 03/08/2022
Long Jetty (Level 1)	0.220	12:45PM 03/08/2022
Tumbi Umbi (Level 1)	0.215	12:45PM 03/08/2022
Wallarah Creek Bridge (Level 1)	0.140	12:45PM 03/08/2022
Tuggerah Lake Entrance (Level 1)	0.217	12:45PM 03/08/2022
Kangy Angy (Level) (Level 1)	5.918	12:45PM 03/08/2022
Wyong River Upstream (Level 1)	0.170	12:45PM 03/08/2022



Latest Catchment Rainfall

Precipitation (mm)(Latest)

Site	last 3 hours	last 6 hours	last 24 hours	last 96 hours
Whitemans Ridge (Rain)	0.0	0.0	0.0	0.0
Yarramalong (Rain)	0.0	0.0	0.0	0.5
Toukley (Rain)	0.0	0.0	0.0	0.0
Berkeley Vale (Rain)	0.0	0.0	0.0	0.0
Hamlyn Terrace (Rain)	0.0	0.0	0.0	0.0
Wyee (Rain)	0.0	0.0	0.0	0.0
Mardi Dam (Rain)	0.0	0.0	0.0	0.0
Kulnura (Rain)	0.0	0.0	0.0	0.0
Bateau Bay (Rain)	0.0	0.0	0.0	0.0
Kangy Angy (Rain)	0.0	0.0	0.0	0.0

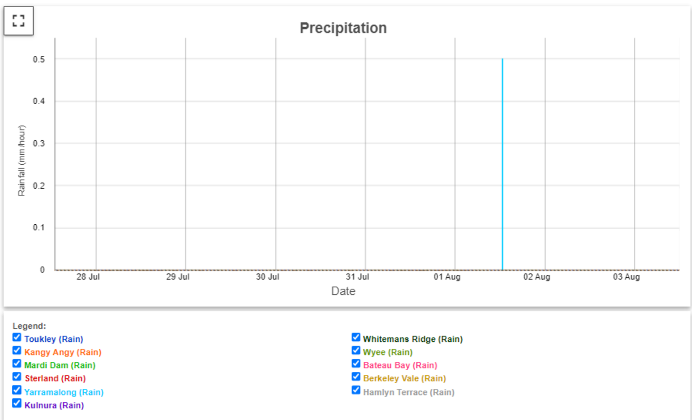


Figure 5.9: Example Tuggerah Lakes MHLFIT realtime monitoring data visualisation

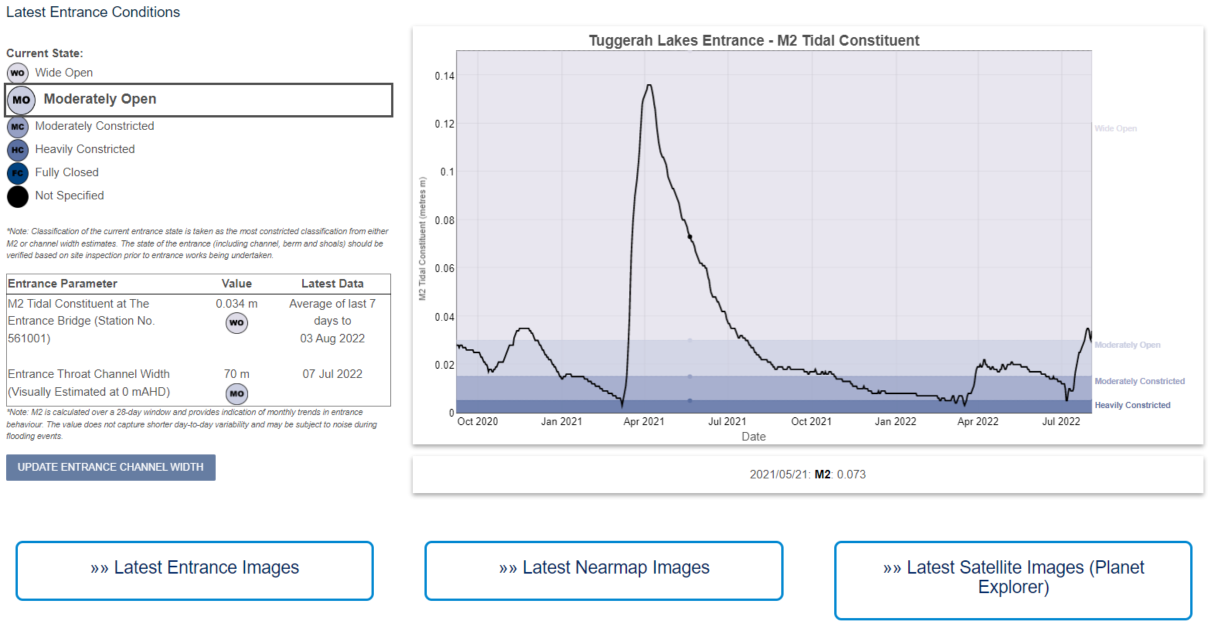


Figure 5.10: Example Tuggerah Lakes MHLFIT realtime analysis and decision support

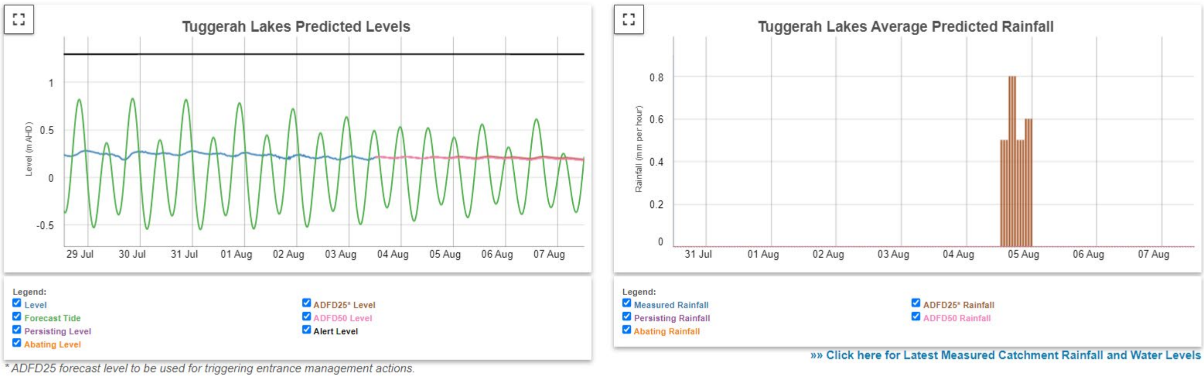


Figure 5.11: Example Tuggerah Lakes MHLFIT realtime lake level predictions

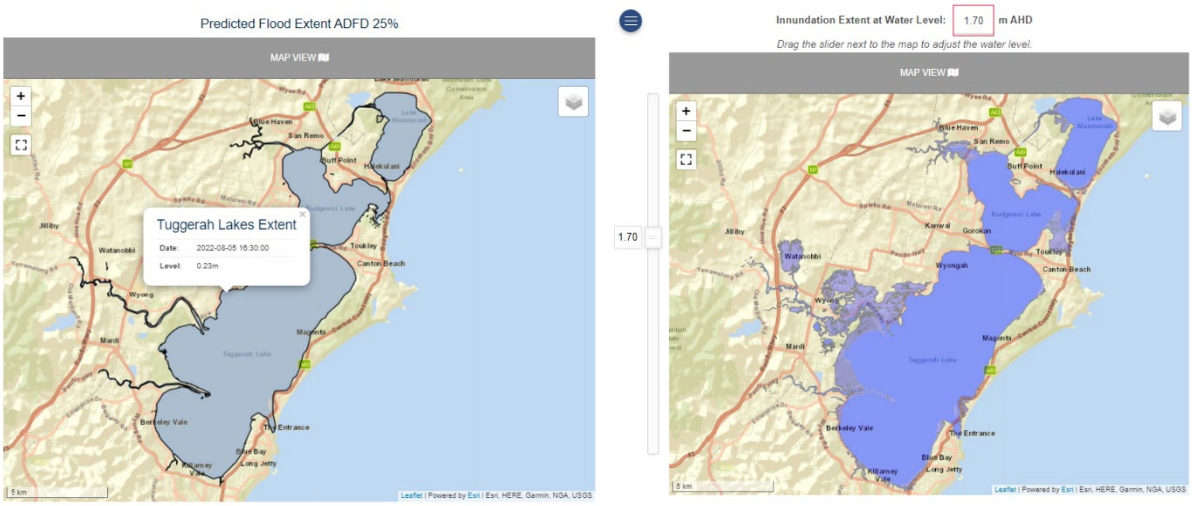


Figure 5.12: Example Tuggerah Lakes MHLFIT inundation extent mapping

Figure 5.13: Example Tuggerah Lakes MHLFIT customised on-demand lake level modelling

5.4 Environmental considerations

This section provides a preliminary overview of potential environmental impacts as a result of the proposed interim management procedure. A more detailed environmental assessment will be undertaken as part of a Review of Environmental Factors (REF) to be completed in accordance with the Environmental Planning and Assessment Act 1979. Relevant environmental policies related to the interim entrance management procedure are listed in **Section 5.8**.

Table 5.2 outlines potential environmental impacts and relevant controls related to the interim procedure.

Table 5.2: Potential environmental impacts

Environmental consideration	Potential Impacts	Environmental Controls
Seagrass and Vegetation	Unlikely to have any impacts given the works are not located in any seagrass beds. The proposed works will have minimal impacts on dry-weather lake level variability affecting seagrass beds and fringing lake habitats.	N/a.
Water Quality and Turbidity	Unlikely to have any adverse impacts on water quality. Assisted entrance opening prior to flood events may temporarily improve ocean discharge during such events. Exposure of buried organic sediment in the entrance berm exposed during scraping/excavation is unlikely and any impacts would be similar to those that occur with natural entrance scour in this region.	N/a.
Aquatic and Wetland Ecology	Unlikely to have any adverse impact on aquatic and wetland ecology. Entrance openings will assist ocean discharge with the onset of flooding.	N/a.
Non-flood lake level characteristics	Unlikely to have adverse impacts on dry-weather lake level variability in Tuggerah Lakes. Management works do not alter dry-weather entrance conditions beyond their natural state.	N/a.
Shorebird breeding and ecology	Potential impacts on the breeding area of the Sternula albifrons - Little Tern, listed endangered under the *Biodiversity Conservation Act 2016*. This migratory shorebird typically breeds on the northern section of the entrance berm, with council erecting temporary fencing to protect the area during breeding months between mid-October to mid-February. The common red-capped Plover *Charadrius ruficapillus* also may nest on the entrance berm during these months.	Entrance berm is to be regularly monitored via onsite inspection for the presence of shorebird nesting sites prior to works being undertaken to determine appropriate environmental controls to mitigate impacts on nesting. This is to be undertaken in consultation with relevant environmental agencies. Entrance works are to be undertaken in the designated region at the southern end of the entrance berm outside and an agreed buffer (TBD) of shorebird nesting (see procedure figures). Designated access routes and operational procedures are to be determined following site inspections to avoid disturbances of machinery access to the berm on the breeding area. Should environmental assessment and approval allow, sand won

Environmental consideration	Potential Impacts	Environmental Controls
		during works may be used to support the establishment of shorebird nesting areas for improved environmental outcomes. Any further impacts on the breeding area would require to be mitigated or offset in accordance with the *Biodiversity Conservation Act 2016.*
Dune and berm ecology	Disturbances to berm ecology associated with machinery access and beach scraping/excavation. The proposed works are unlikely to impact upon dune ecology.	The entrance works are to be located in the southern region of the entrance berm close to the typical location of the throat channel. This location is likely to have the least impact on berm ecology considering the increased natural variability of the berm in this region that occurs with entrance widening, flood scour and throat channel migration. Berm scraping and pilot channel excavation levels are to be within the natural variability of berm scour that would occur during flood events. Designated access routes and operational procedures are to be determined following site inspections to minimise erosion and disturbances to berm ecology. Any further impacts of berm works would be addressed in more detail under a REF as part of the interim procedure.
Terilbah Island	The entrance management works are unlikely have adverse impacts on the Terilbah Island (Wyrrabalong National Park) located further upstream. Minor increases in entrance flows may result due to the works with the onset of flooding with negligible impacts at the upstream location of Terilbah Island.	N/a.
Sediment contamination & acid sulfate soils	Excavation of channel openings and berm management is likely to be clean, marine sand and does not contain any contaminants. The works are unlikely to results in impacts related to acid sulfate soils.	N/a.
Air Quality	Emissions associated with machinery used to open the entrance and transport emissions.	Council may seek avenues to offset these emissions.

Environmental consideration	Potential Impacts	Environmental Controls
Recreational and beach user	Disruption to public and beach users associated with closure of Hutton Rd carpark, restricted access to entrance berm and presence of machinery on beach.	Council to notify public of timing of intended works and any disruptions associated with the works.
Entrance Hydraulics	The entrance works will assist the natural entrance breakout/scour during the onset of flooding. The works will artificially provide earlier entrance breakout and assisted opening to improve ocean discharge with the onset of flooding.	Entrance works are to be undertaken according to the prescribed procedures to avoid migration of the main throat channel outside of its typical opening location which is generally towards the southern region of the entrance berm. Continued monitoring of the entrance region and realtime decision-support tools will help to guide entrance operations to reduce / adverse impacts on entrance hydraulics.
Bank Erosion/bridge footings	The proposed entrance works are unlikely to cause additional bank erosion or undermining of structural footings located within the entrance.	N/a.
Flooding	Refer to Tuggerah Lakes Entrance Management Study (MHL, 2022) for a detailed assessment on flood impacts. The works are likely to result in minor reduction peak flood levels (typically less than 0.2 m) and associated flood damages. The interim procedure does not intend to eliminate risk associated with flooding in Tuggerah Lakes and is to be implemented alongside other floodplain risk management controls identified in the FRMSP (WMAwater, 2014)	Entrance works are considered beneficial.
Coastal processes	Artificial migration of entrance channel to the northern region of the entrance berm may result in adverse impacts on coastal processes associated with shifting the main entrance opening away from its typical location which is generally in the south. Such openings may cause adverse changes to nearshore currents and sediment dynamics along adjacent beaches.	Entrance works are to be undertaken according to the prescribed procedures to avoid migration of the main throat channel outside of its typical opening location which is generally toward the southern region of the entrance berm. Sand won during works may be placed on eroded sections of North Entrance Beach.

Restricted and environmentally sensitive areas

A number of environmentally sensitive habitats line shallow waters and foreshores of Tuggerah Lakes. Estuarine habitats, endangered ecological communities and estuarine vegetation mapping are provided in **Appendix E**

A preliminary summary of environmentally sensitive areas includes:

- Seagrass beds are outlined by estuarine vegetation mapping in **Appendix E** (NSW DPI).

The mapping indicated that meadows of these species cover approximately 17.7 km^2, with mangroves and saltmarsh covering approximately 0.001 km^2 and 0.108 km^2 respectively (Williams et. al., 2006). These are located outside of the proposed entrance channel and berm management works.

- Waterway and Fish Habitat Classification – Class 1 Major Key Fish Habitat containing Type 1 (Highly sensitive key fish habitat) and Type 2 (Moderately Sensitive Key Fish Habitat).

- Terilbah Island, Wyrrabalong National Park

- Matters of environmental significance (EPBC Act Protected Matters Report generated 22 August 2021 **Appendix E**):

- No world heritage properties
- No national heritage places
- Not located within 1 km of wetlands of international importance
- Not located within 1 km of the Great Barrier Reef Marine Park
- The Commonwealth Marine Area is not located within 1 km of the proposed works
- Two threatened ecological communities are within 1 km of the proposed works. These include:
    - Coastal Swamp Oak (Casuarina glauca) Forest of New South Wales and South East Queensland ecological community (Endangered)
    - River-flat eucalypt forest on coastal floodplains of southern New South Wales and eastern Victoria (Critically Endangered)
- 71 listed threatened species
- 74 listed migratory species

Other Matters listed under the EPBC Act 1999 relevant to the proposal include:

- Tuggerah Lakes is a classified as a nationally important wetland
- 94 listed marine species
- 14 whales and other cetaceans
- No critical habitats
- No Commonwealth Reserves (Terrestrial), Commonwealth Land, Commonwealth Heritage Places, nor Australian Marine Parks.

- Closest coastal wetlands under SEPP 14 (Coastal Wetlands) is at Chittaway Point, 3 km from the proposed works.

- Heritage

Indigenous heritage

- A search of the NPWS Aboriginal Heritage Information Management System identified three Aboriginal sites in the immediate vicinity of the entrance region with one in close proximity to the entrance throat channel (AHIMS basic search 22 August 2021). Further investigation is to be undertaken as part of a Review of Environmental Factors (REF) to address any potential impacts associated with the entrance works.

Non-Indigenous heritage

- The EPBC Act Protected Matters Search Tool identified no Commonwealth Heritage Places or National Heritage Places.

A more detailed environmental assessment will be undertaken as part of a REF after the interim entrance management procedure is finalised.

5.5 Safety

All entrance management works will be conducted in accordance with Council's work health and safety and environmental policies and procedures and any relevant state legislation. These are to be undertaken consistent with Councils current safety measures for similar works at Coastal Lagoons entrances. All staff must wear appropriate PPE during entrance management activities.

Prior to the commencement of works, the site will be cordoned off using para webbing or similar and signs will be placed on either side of the work site indicating that this section of beach is closed and that there are dangers associated with strong currents, rough water and unstable, collapsing ground.

If necessary, temporary lighting, sufficient to highlight the location of the work, will be erected.

Council Lifeguards must be on-site prior to pilot channel openings being completed whenever openings are conducted during day light hours. Once the pilot channel opening is affected and the plant has been moved away from the pilot channel opening area, the Council Lifeguards will take control of the site.

5.6 Roles and responsibilities

Roles and responsibilities related to the interim entrance management procedure are outlined in **Table 5.3**.

Council's community engagement team are to be responsible for arranging relevant communication and public messaging to inform the General Public when entrance works are being undertaken.

The advice on impending entrance works is to be given to:

- Local fisheries officer
- Local shorebird environmental consultant and/or National Parks and Wildlife Services
- Department of Planning and Environment - Biodiversity and Conservation – Coastal Representative
- Contractors or in-house staff responsible for undertaking entrance works
- Council Lifeguards and Lifesavers, if they are on duty at the time of the impending
- Council comms and engagement team and customer contact

Table 5.3: Outline of roles and responsibilities

Role / Organisation / Section	Responsibilities
Ongoing as required	
Manly Hydraulics Laboratory	Maintenance and provision of MHLFIT system including water level and rain gauges.
CCC Environmental Infrastructure	Routine site inspections and environmental procedures to support shorebird nesting following existing environmental protocols.
CCC Environmental Infrastructure	Review of interim entrance management procedures as required to minimise impact on shorebird nesting sites when present.
CCC Flood Strategy and Planning (with assistance from Catchments to Coast)	Monitoring of entrance condition via MHLFIT webpage with site inspections as required.
CCC Flood Strategy and Planning (with assistance from Catchments to Coast)	Routine (e.g., fortnightly/monthly during dry-weather and daily during flood events) entrance width estimates to update width classification shown on MHLFIT webpage.
CCC Environmental Infrastructure	Maintenance of access to entrance berm at Hutton Rd carpark.
CCC Catchments to Coast	Prepare and maintain environmental approvals.
CCC Communications and Engagement	Preparation and distribution of public communications pre, during and post event.
Pre-flood	
Bureau of Meteorology	Issue Flood Watch and/or Severe Weather Warning for very heavy rain that may lead to flash flooding
CCC Flood Strategy and Planning	Issue internal flood standby notice.
CCC Flood Strategy and Planning	Undertake pre-flood site inspection of the entrance to determine any procedure details.
CCC Environmental Infrastructure	Undertake pre-flood site inspection to determine environmental controls regarding shorebird nesting.
CCC Environmental Infrastructure	Confirm resources for entrance works and undertake preparations.
CCC Flood Strategy and Planning and LEMO	Continue to monitor BoM forecasts and warnings, and MHLFIT webpage.
CCC Flood Strategy and Planning	Interpretation and use of MHLFIT modelling to inform estimates of peak flood level predictions.
Manly Hydraulics Laboratory/CCC Flood Strategy and Planning/Catchments to Coast/Environmental Infrastructure	Flood and coastal engineering consultation and guidance on entrance works including pilot channel locations and timing of opening.
CCC Unit Manager Environmental Management Unit/CCC Executive Team	Confirmation of entrance works “go-ahead” and mobilisation of resources based on peak flood level predictions.
CCC Environmental Reporting and Emergency Management	Notifying relevant agencies of planned works.
CCC Environmental Infrastructure	Confirmation of timing of pilot channel opening/berm lowering (if undertaken).
CCC Environmental Infrastructure and/or Council supervised subcontractors	Undertake entrance works following safety and environmental protocols.
CCC Lifeguards	Managing public safety after entrance are completed and plant is removed.
Post-flood	
CCC Flood Strategy and Planning, Environmental Infrastructure and Catchments to Coast	Review and evaluate interim procedure as required.

5.7 Land zoning

Land zoning within the Tuggerah lakes catchment and entrance region of the proposed entrance management works is shown in **Figure 5.14** (Royal Haskoning, 2020).

The interim entrance management procedure will be located on land both above and below the Mean High Water Mark (MHWM). Berm scraping and pilot channel works may include Land below the MHWM and will need to be licenced via the Department of Planning and Environment - Crown Lands. Entrance shoal channels are located within the entrance channel on land zoned as Recreational Waterway (W2).

Significant areas of the foreshore are zone Public Recreation (RE1) and are crown reserves under the management of Central Coast Council. These areas include Terilbah Reserve, Karagi Foreshore Park (including the estuary eastern beach), Picnic Point Reserve, and the southern foreshore of the estuary behind the seawall in the vicinity of Marine Parade.

Land above MHWM on which the entrance management works would be undertaken is Crown Land (Lot 7313/-/DP1147369 and Lot 7314/-/DP1147369) under the management of the Council. It is classified Public Recreation (RE1) under the Wyong Local Environmental Plan 2013. Berm preparation and pilot channel fall on Lot 7313/-/DP1147369. Placement of sand won from berm scraping at North Entrance Beach falls on Lot 7314/-/DP1147369.

Figure 5.14: Land use zoning Tuggerah Lakes Entrance from Royal Haskoning (2020)

Terilbah Island is zoned (E1) (National Parks) and is part of the “Protected Area” of Wyrrabalong National Park, gazetted in 1991, and is under the control of the NSW Department of Planning and Environment (DPE).

5.8 Relevant Policies

The interim entrance management procedure will require a Review of Environmental Factors (REF) to be completed in accordance with the Environmental Planning and Assessment Act 1979. Relevant policies related to the interim entrance management procedure are listed below.

Environmental Planning and Assessment Act 1979

The NSW Environmental Planning and Assessment Act 1979 (EP&A Act) creates the mechanism for development assessment and determination by providing a legislative framework for the development and protection of the environment from adverse impacts arising from development. The EP&A Act outlines the level of assessment required under State, regional and local planning legislation and identifies the responsible assessing authority.

Wyong Local Environmental Plan 2013

The EP&A Act is the governing legislation for planning and controlling land uses and development within NSW. Central Coast Council's planning provisions as enabled by this Act include the Wyong Local Environmental Plan 2013.

The Wyong Local Environmental Plan 2013 has been developed in accordance with NSW Planning Industry and Environment (DPE) requirements to control development via land zonings and other relevant planning provisions.

SEPP (Resilience and Hazards) 2021 – Chapter 2 Coastal Management

SEPP (Resilience and Hazards) 2021 Ch. 2 Coastal Management aims to promote an integrated and coordinated approach to land use planning in the coastal zone. For areas mapped as ‘coastal wetland and littoral rainforests’ – including sizeable areas in the study area near the three lakes – development consent is required for the clearing of native vegetation, and for earthworks, construction of a levee, draining the land and environmental protection works, and for any other development. For areas mapped as ‘coastal environment areas’ – covering much of the study area – development consent must not be granted unless the consent authority has considered whether the proposed development is likely to cause an adverse impact on “the integrity and resilience of the biophysical, hydrological (surface and groundwater) and ecological environment” amongst other factors. The development must be designed, sited and managed to either avoid, minimise or mitigate adverse impacts.

SEPP (Infrastructure) 2007

SEPP (Infrastructure) 2007 aims to facilitate the effective delivery of infrastructure within NSW by public authorities. It does this by prescribing the infrastructure related works that may be undertaken without development consent, although the public authority may still be required to obtain an approval, licence or permit under another Act, such as the Fisheries Management Act 1994.

Under Clause 49, Division 7 of State Environmental Planning Policy (SEPP) Infrastructure 2007, flood mitigation work is defined as;

> *"work designed and constructed for the express purpose of mitigating flood impacts. It involves changing the characteristics of flood behaviour to alter the level, location, volume, speed or timing of flood waters to mitigate flood impacts. Types of works may include excavation, construction or enlargement of any fill, wall or levee that will alter riverine flood behaviour, local overland flooding, or tidal action so as to mitigate flood impacts."*

Under Clause 50, Division 7 of SEPP Infrastructure 2007, development for the purpose of flood mitigation may be carried out by or on behalf of a public authority without consent on any land. This includes reference to development for any of the following purposes if the development is in connection with flood mitigation work:

- Construction works
- Routine maintenance works
- Environmental management works

Under Clause 129, Division 25 of SEPP Infrastructure 2007, waterway or foreshore management activities (including instream management or dredging to rehabilitate aquatic habitat or to maintain or restore environmental flows or tidal flows for ecological purposes) undertaken by a public authority are permissible without consent.

Should the works be deemed not to require development consent, a Review of Environmental Factors (REF) is prepared in accordance with the requirements of the Environmental Planning and Assessment Act, 1979.

Permits and licences

For the proposed entrance management works, Central Coast Council is considered to be a determining authority as the activity is to be carried out by Council. The following agencies are also determining authorities as permits and licenses may also be required for the works from:

- NSW Department of Planning and Environment (DPE) – Crown Lands Licence
- Department of Primary Industries (DPI) – Fisheries Permit
- DPE, Environment, Energy and Science (EES) Group, NSW EPA – Environment Protection Licence

NSW Flood Prone Land Policy

The NSW Government Flood Prone Land Policy aims to provide solutions to existing flood problems in developed areas and ensure that new development is compatible with the flood hazard and does not contribute to an increase in flood risk. Under the Policy, the management of flood prone land is the responsibility of the Local Government. The State Government supports the implementation of flood management measures to alleviate existing flooding problems and provides specialist technical advice to assist Councils in the discharge of their floodplain management responsibilities.

The Policy outlines the following floodplain management 'process' for the identification and management of flood risks.

The Tuggerah Lakes Floodplain Risk Management Study and Plan (WMAWater, 2014) forms an important stage in the floodplain risk management process providing proposed floodplain risk management measures. A high priority measure recommended under the Tuggerah Lakes FRMSP, was the formalising of an Entrance Management Strategy to manage flooding.

The proposed works of this study seek to provide an interim entrance management procedure to alleviate flood impacts while a formalised entrance long-term entrance management strategy is being developed.

Other State legislative and policy requirements

- *Protection of the Environment Operations Act 1997* (POEO Act) - Activities should be carried out in a manner which does not result in the pollution of waters.

- *National Parks and Wildlife Act 1974* (NPW Act) and *Amendment* 2010 – Provides for protection of Aboriginal cultural heritage in NSW. DPE administers the NPW Act and requires Aboriginal consultation to be undertaken in accordance with statutory requirements. Harm is permissible under an approved Aboriginal Heritage Impact Permit (AHIP). An AHIP is not required for the works as no potential harm to Aboriginal sites has been identified.

- *Crown Lands Management Act 201*6 – Activities below the MHWM, a licence is required from the NSW Department of Planning and Environment (DPE).

- *Biodiversity Conservation Act 2017* -The works will require environmental assessment for potential impact on threatened species, or ecological communities listed in the *NSW Fisheries Management Act* or *NSW Biodiversity Conservation Act*, or their habitats. Measures to mitigate any potential impacts will require to be developed as part of the proposed management works.

- *Fisheries Management Act 1994 (FM Act)*

If dredging (including excavation) or reclamation is to be undertaken below the highest astronomical tide, ss199, 200, and 201 of the FM Act may apply. These sections apply to any dredging works carried out in water land. For public authorities, other than local councils, the FM Act requires prior referral of dredging works to the Minister for Primary Industries for consultation prior to the issuing of any approvals/authorisations. For local councils or persons, the Act requires a permit from the Minister for Primary Industries (unless the work has already been authorised under the Crown Lands Act 1989 or by a local authority). The maximum penalty for unauthorised dredging is $220,000 for local government authorities or corporations and $110,000 for individuals.

Under the FM Act, NSW DPI has the power to regulate activities that can impact on waterways through the issuing of permits and associated conditions. Where approved, activities such as sediment extraction, dredging and reclamation works, harm to marine vegetation or blockages to fish passage are conditioned to ensure that water quality of receiving waters is protected.

- *Policy and guidelines for fish habitat conservation and management* (DPI, 2013)

The policy states:

> *"In addition to the general policies stated in Chapter 3, the following policies apply to ICOLL management:*

1) Any proposals to artificially open ICOLLs must be authorised by a permit from the Minister or authorised by NSW DPI or other public authority after consultation with the Minister under the FM Act.

2) NSW DPI supports minimal interference with ICOLL barriers and advocates natural processes being allowed to operate to the greatest extent possible.

3) NSW DPI does not support the artificial opening of an ICOLL unless the proponent can demonstrate that the social, environmental and economic benefits greatly outweigh any potential adverse impacts.

4) NSW DPI supports using estuary management plans and environmental assessment processes to analyse the issues relating to opening a particular ICOLL, and to develop an entrance management plan. Proposals for artificial openings which are to be carried out according to a formulated entrance management plan are more likely to be approved.

Guidelines for implementing the above policies include:

a) Illegal openings should be guarded against by the erection and maintenance of signs near the ICOLL entrance warning people that unauthorised opening is illegal and may result in prosecution.

b) The decision to open an ICOLL should be made on the basis of factual data on:

- *verified water levels and the nature and extent of associated flooding impacts - which should be referenced to a standard datum (e.g., Australian Height Datum) obtained from appropriately sited staff gauges, or automatic water level recorders, and*
- *quantitative evidence of changes to relevant water quality parameters (especially nutrient and bacterial levels) produced by monitoring programs designed specifically to assess water quality pre- and post-opening.*

c) In the short-term (i.e., prior to an entrance management plan being put in place), an interim strategy for each problematic ICOLL should be formulated, documented and agreed to. The interim strategy should be made in consultation with all relevant natural resource management agencies, representatives of local community interest groups and affected landholders and provide a clear guide to where, when and under what conditions to open the ICOLL entrance. Criteria to be met may include:

- *a preset water level above which a breach is recommended;*
- *a preset range between which a breach is recommended if heavy rainfall is predicted;*
- *a preset duration of high water level and/or wetland/pasture inundation over which a breach may be recommended;*
- *other environmental parameters (e.g., avoiding the breeding season of threatened birds such as the Little Tern).*

d) The main purpose of the interim strategy should be to account for critical environmental issues and if required, to facilitate a sanctioned opening at very short *notice (e.g., Coila Lake Entrance Management Policy gives the relevant 'approval' bodies 3 days to respond to a breach request).*

e) In the event that the criteria for an artificial opening are met, breaching should be conducted during a falling tide (if possible, around a spring tide) so that the potential for establishing an entrance channel long enough to flush the water body is achieved.

f) In the long-term, local councils and government agencies should aim to reduce the need for artificial manipulation by taking active measures to remove, relocate or otherwise manage items of low-lying infrastructure that currently necessitate breaches below the natural breakout range, and adopting catchment management practices that:

- *reduce the inputs of nutrients and pollutants from point and diffuse sources,*
- *prevent transfer of flood prone and riparian land on the margins of ICOLLs into private ownership,*
- *prevent the future development or subdivision of flood-prone and riparian lands by adopting appropriate zonings and buffers in relevant land use planning instruments,*
- *implement community awareness campaigns to gain broad based understanding and support for the environmentally responsible management of ICOLLs."*

- *Marine Estate Management Act 2014* and *Marine Estate Management Regulation 1999* –

The Act Declares and manages NSW marine parks. The Regulation outlines requirements for protection of various zones within marine parks. As the works are outside any Marine Park, no approvals are required.

- *Water Management Act 2000* – Under the Water Act, approval is required to undertake controlled activities on waterfront land. However, the Water Management Regulation 2011 outlines a number of exemptions for controlled activities. Where a public authority is carrying out the controlled activity on or in waterfront land, approval from the Office of Water is not required.

- *Coastal Management Act 2016* - The Coastal Management Act 2016 replaced the Coastal Protection Act 1979 and establishes a new strategic framework and objectives for managing coastal issues in NSW. The Act defines the coastal zone as comprising four coastal management areas. SEPP (Resilience and Hazards) 2021 Ch. 2 Coastal Management gives effect to the objectives of the Act from a land use planning perspective, by specifying how development proposals are to be assessed if they fall within the coastal zone. The four coastal management areas are:

1. Coastal wetlands and littoral rainforests area — areas which display the characteristics of coastal wetlands or littoral rainforests that were previously protected by SEPP 14 and SEPP 26
2. Coastal vulnerability area — areas subject to coastal hazards such as coastal erosion and tidal inundation
3. Coastal environment area — areas that are characterised by natural coastal features such as beaches, rock platforms, coastal lakes and lagoons and undeveloped

headlands. Marine and estuarine waters are also included

4. Coastal use area — land adjacent to coastal waters, estuaries and coastal lakes and lagoons.

The proposed works fall within the coastal environment area and coastal use area. The objectives of the coastal environment area are:

- to protect and enhance the coastal environmental values and natural processes of coastal waters, estuaries, coastal lakes and coastal lagoons
- enhance natural character, scenic value, biological diversity and ecosystem integrity
- to reduce threats to, and improve the resilience of, coastal waters, estuaries, coastal lakes and coastal lagoons, including in response to climate change to maintain and improve water quality and estuary health
- to support the social and cultural values of coastal waters, estuaries, coastal lakes and coastal lagoons
- to maintain the presence of beaches, dunes and the natural features of foreshores, taking into account the beach system
- to maintain and, where practicable, improve public access, amenity and use of beaches, foreshores, headlands and rock platforms.

The objectives of the coastal use area are:

- to protect and enhance the scenic, social and cultural values of the coast by ensuring that—

  (i) the type, bulk, scale and size of the development are appropriate for the location and natural scenic quality of the coast, and

  (ii) adverse impacts of development on cultural and built environment heritage are avoided or mitigated, and

  (iii) urban design, including water sensitive urban design, is supported and incorporated into development activities, and

  (iv) adequate public open space is provided, including for recreational activities and associated infrastructure, and

  (v) the use of the surf zone is considered,
- to accommodate both urbanised and natural stretches of coastline.

The proposed entrance management works will need to meet the objectives of the coastal use and coastal environment area. They will also need to be consistent with the Tuggerah Lakes Estuary Management Plan (2006) - which is a gazetted document and has the status of a certified Coastal Zone Management Plan (under the transitional provisions outlined in the Coastal Management Act 2016) until such time as it is replaced by a certified Coastal Management Program.

Commonwealth Legislation

- *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) requires that proposals for development or "actions" that have, will have, or are likely to have, a significant impact on any matter of national environmental significance are to be referred to the

Commonwealth Environment Minister for consideration and approval.

The EPBC Act identifies the following matters of national environmental significance:

- World heritage;
- National heritage;
- Wetlands of international importance;
- Listed threatened species and communities;
- Listed migratory species;
- Protection of the environment from nuclear actions; and
- Marine environment.

An assessment of the significance of the proposed works shall be undertaken in accordance with the EPBC Act, to determine any significant impacts requiring referral to the Federal Minister for approval.

A permit may be required for activities in or on a Commonwealth area that may affect a member of a listed threatened species or ecological community, a member of a listed migratory species, whales and other cetaceans, or a member of a listed marine species.

5.9 Adaption for climate change impacts

The Tuggerah Lakes Floodplain Risk Management Plan (2014) carried out a sensitivity analysis for sea level rise using estimates from the *NSW Coastal Planning Guideline: Adapting to Sea Level Rise* (2010). These consisted of:

- 0.4 m sea level rise by 2050
- 0.9 m sea level rise by 2100

Estimates for sea level rise under different emissions scenarios for the NSW coast were examined in *Sea Level Rise Science and Synthesis for NSW* (Glamore et al., 2016). The study estimated sea level rise for a high-end emissions scenario (RCP8.5) (central value with 66% confidence limit shown in brackets):

- 0.27 [0.19 - 0.36] by 2050
- 0.78 [0.54 - 1.06] by 2100

More recent sea level rise predictions are also provided for Sydney, Fort Denison as part of the Inter Intergovernmental Panel on Climate Change (IPCC) 6th Assessment report (Fox-Kemper et al., 2021). The IPCC report (subject to final editing) found that for a for a high-end emissions scenario (SSP5-8.5) (central value with 66% confidence limit shown in brackets):

- 0.23 [0.17 - 0.31] by 2050
- 0.78 [0.59 - 1.06] by 2100

Under sea level rise projections, Bruun rule approximations assume that the beach profile and entrance berm level will shift landward and upward. The Wyong Coastal Hazard Study (SMEC, 2010) indicated a Bruun rule recession factor of 29.5 for the North Entrance beach region near the Tuggerah Lakes entrance channel (Block A), such that for every 1 m of sea level rise the entrance berm retreats by 29.5 m.

Under a high-end emissions scenario of SSP5-8.5 (central value), berm levels at the entrance are estimated to shift upward by approximately 0.8 m and retreat landward by approximately 23.6 m by 2100. Design berm scraping and pilot channel levels could be incrementally raised to adapt to this increase. Long-term period berm monitoring would provide a useful dataset to confirm any trends in entrance berm elevations with sea level rise and adapt berm management procedures accordingly.

It is important to note that the expected benefit of the interim entrance management works in alleviating flood damages are expected to diminish as sea level rise continues over the next 50 - 100 years. As such, the impacts of flooding will continue to be experienced even under the implementation of the proposed works and will likely worsen with sea level rise as time progresses. It is important that the community in the Tuggerah Lakes Floodplain understand their level of flood risk as well as adapt and prepare to live with the impacts of flooding.

5.10 Conclusion and further recommendations

The Tuggerah Lakes Interim Entrance Management Procedure provides a rational decision-making framework for Central Coast Council to undertake entrance management works to the entrance throat channel and berm at the Tuggerah Lakes entrance. The procedure is supported by MHLFIT decision support tools that utilising real-time quantitative data and predictive lake level modelling to facilitate a rational, proactive and informed approach to management actions. It provides an interim entrance management approach until an Entrance Management Strategy is formalised through the CMP process.

The interim procedure aims to reduce the risk to life, public and private infrastructure associated with flooding in accordance with the FRMSP (WMAwater, 2014). Flood level reductions associated with the procedure are expected to be small (typically less than 0.2 m), however, are considered beneficial in assisting to reduce flood damages. These reductions are likely to diminish for floods coinciding with extreme coastal anomalies and/or with projected sea level rise over the next 50 - 100 years.

It is important to note that flooding in Tuggerah Lakes cannot be eliminated. The impacts of flooding will continue to be experienced even under the implementation of the proposed interim management procedure and will likely worsen with sea level rise. It is important that the community in the Tuggerah Lakes Floodplain understand their level of flood risk as well as adapt and prepare to live with the impacts of flooding. The interim procedure is to be implemented alongside of other floodplain risk management controls identified in the FRMSP to reduce flood risk. Reviewing and updating planning controls will be vital for future flood risk management in Tuggerah Lakes given the significant low-lying development situated in the Tuggerah Lakes foreshores.

The interim procedure recognises the ecological importance of the dynamic variability of the Tuggerah Lakes entrance and has developed procedures to provide tailored works for different entrance conditions. The interim procedure does not seek to maintain a permanently open entrance and the entrance channel will naturally constrict with sand, particularly during dryer periods with low rainfall and scour to a wider entrance during wetter periods with increased rainfall. The interim procedure seeks to allow natural entrance processes to operate with minimal disturbances in accordance with the *Policy and guidelines for fish habitat conservation and management* (DPI, 2013).

Entrance works are to be undertaken immediately prior to flooding to assist in providing flood risk reduction. Regular ongoing entrance berm works to continuously maintain flood-ready berm conditions were not considered to be feasible given the highly dynamic nature of the entrance including berm rebuilding and channel infilling processes. The interim entrance management procedure is to be reviewed following flood events as required.

It is recommended that further work as part of the Floodplain Risk Management process and Coastal Management Program include review/provision of priority floodplain risk management controls identified in the FRMSP (WMAwater, 2014), review of sea level rise impacts on flooding and coastal inundation in Tuggerah Lakes, and investigation of entrance shoal dredging to support entrance management including recreational, environmental, and social outcomes. It is also recommended that Council continue to investigate potential new technologies and methods that may improve entrance condition monitoring and support management works as they become available in the future.

The next steps are likely to involve developing public messaging and protocols to inform the community of interim entrance procedures and when works are being undertaken. Council may wish to consider developing a public MHLFIT web interface with live rainfall, lake level and entrance monitoring data. Ongoing community engagement is to form a key component in formalising an Entrance Management Strategy as part of the CMP process.

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Appendix A Glossary of terms & abbreviations

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 an 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 streamflow, 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.
CMP	Coastal Management Program
Cross-shore sediment transport	Movement of sand onshore and offshore between the subaerial beach and surfzone driven by waves and currents.
CZMP	Coastal Zone Management Plan
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.
FFS	Flood Forecasting System
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.
FRMSP	Floodplain Risk Management Study and Plan
Harmonic analysis	Process of measuring or calculating the relative amplitudes and frequencies of all the significant harmonic components present in a given wave form.
Intermittently Closed and Open Lakes and Lagoons. (ICOLL)	A coastal lagoon or lake that alternates form being open or closed to the ocean by a dynamic natural sand body at its entrance. There are about 70 ICOLL's on the NSW coastline.
Indian Spring Low Water (ISLW)	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).
LiDAR	Light Detection and Ranging. Remote sensing instrument used to measure distances.
Littoral Zone	An area of the coastline in which sediment movement by wave, current and wind action is prevalent.
M2 tidal constituent	One of the harmonic elements, or constituents, that can be used to derive astronomical tides in mathematical terms. Each constituent represents a periodic change of relative position of the Earth, Sun and Moon. The M2 constituent represents the principal lunar semi-diurnal constituent and is often the largest of constituents. Its period is half a tidal lunar day.
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).
MHLFIT	Manly Hydraulics Laboratory Flood (and Coastal) Intelligence Tools

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.
PPE	Personal protective equipment
PMF	Probable Maximum Flood.
REF	Review of Environmental Factors
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).

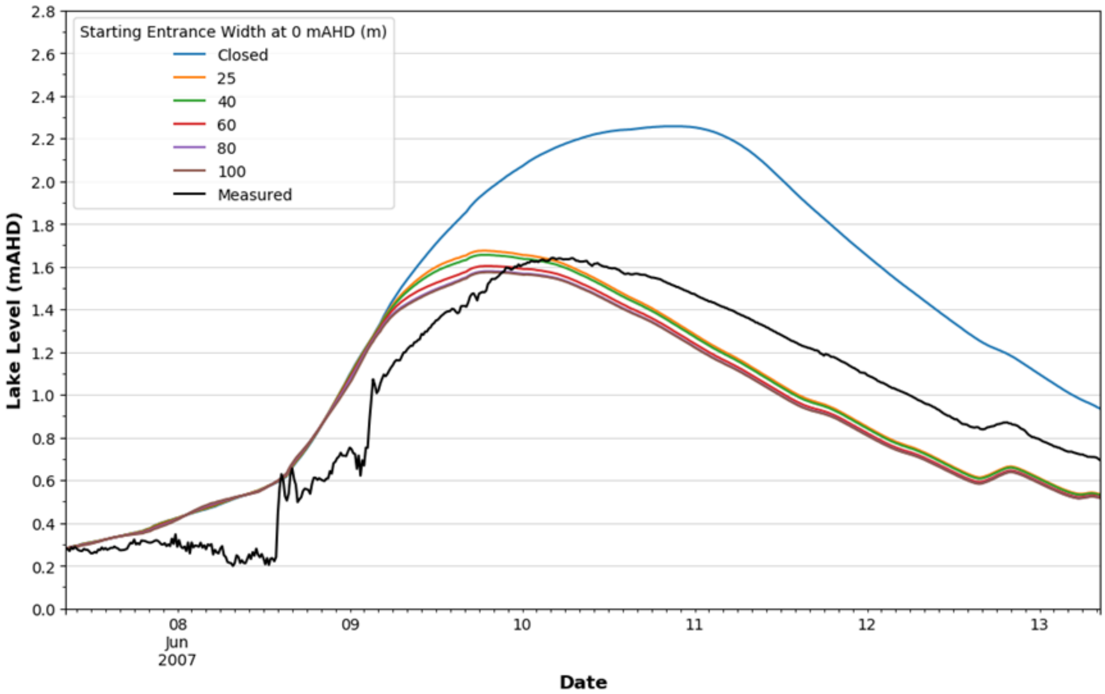
Storm Surge	The local change in the elevation of the ocean along a shore due to a storm. The storm surge is measured by subtracting the astronomic tidal elevation from the total elevation. It typically has a duration of a few hours. Since wind generated waves ride on top of the storm surge (and are not 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.
Throat Channel	The region of the entrance channel that cuts through the entrance beach berm prior to its confluence with the ocean. The width and depth of the throat channel constantly changes with entrance flows that varying during droughts and floods, tidal currents and ocean processes.
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

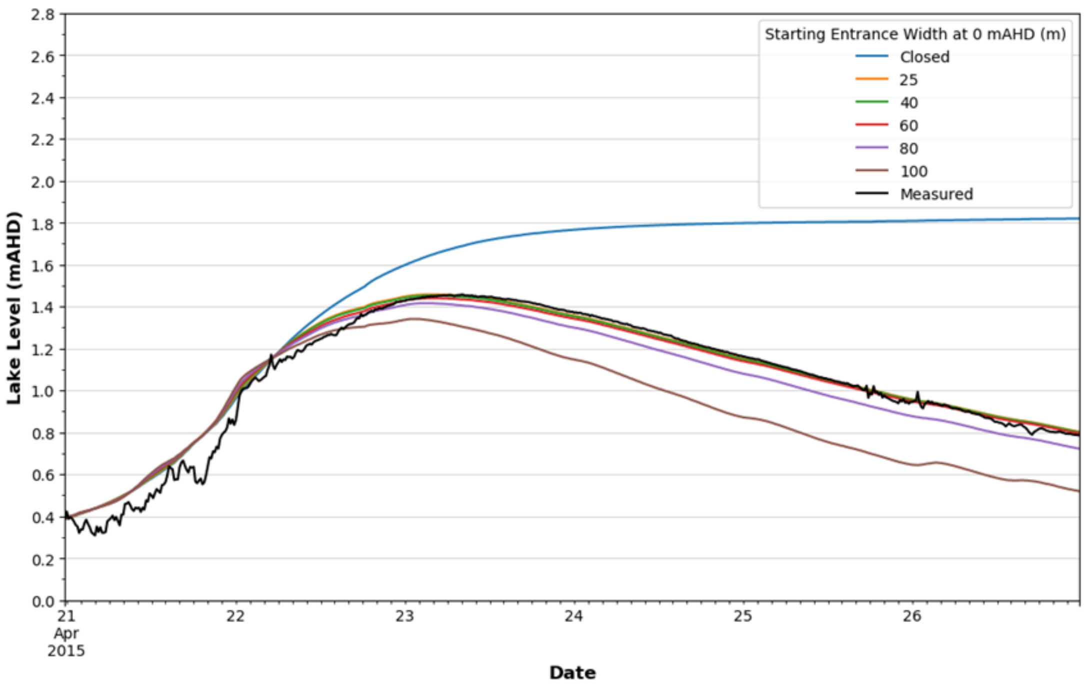
Appendix B Model outputs of varying entrance conditions during flood events

Simulated flood level plots for varying entrance channel width

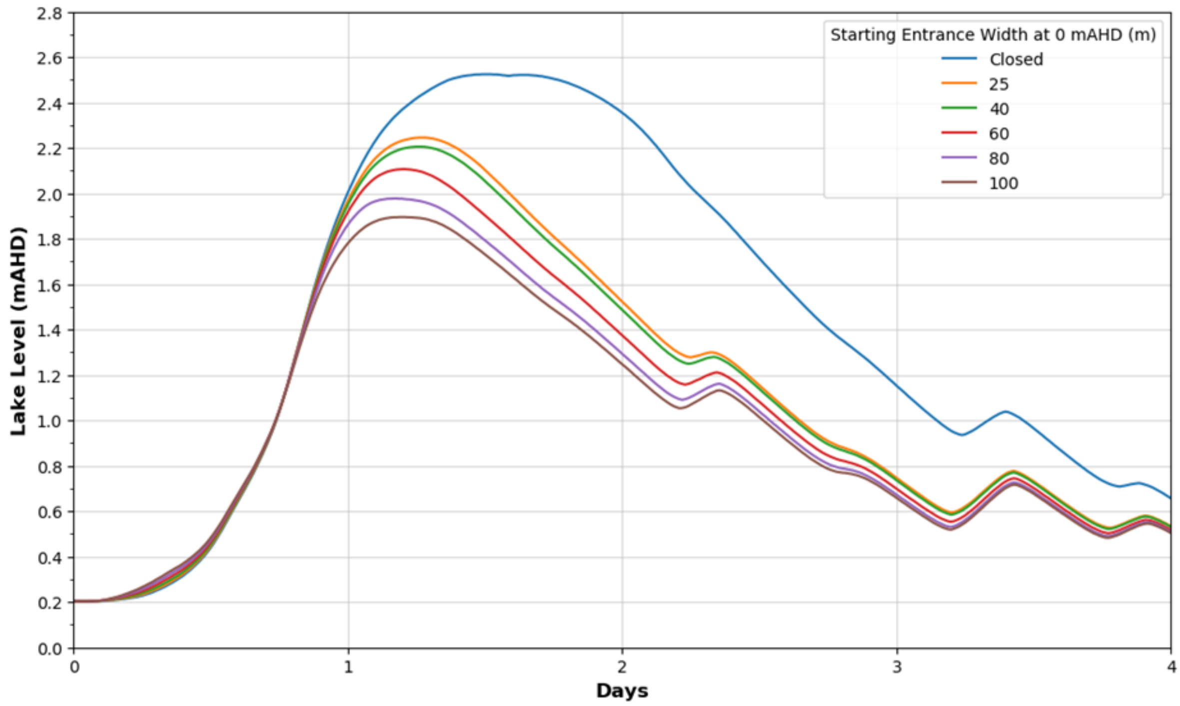
June 2007 - Modelled with calibrated starting bed level at -1 m AHD



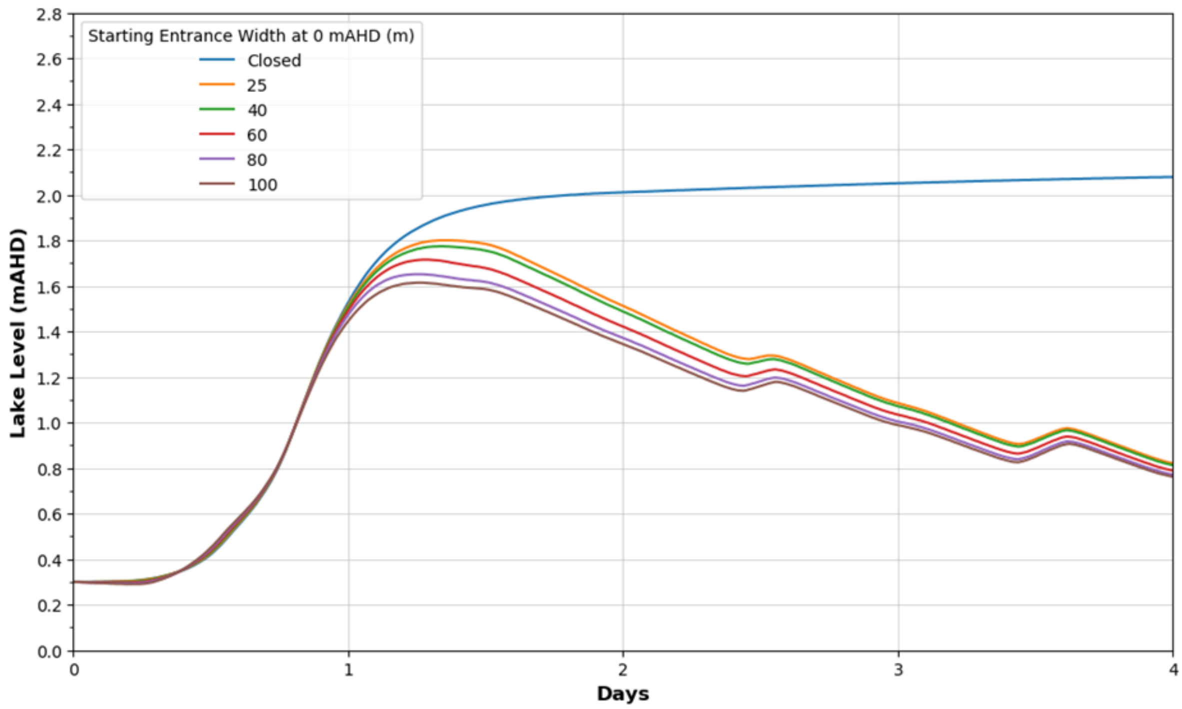
April 2015 - Modelled with calibrated starting bed level at -1 m AHD

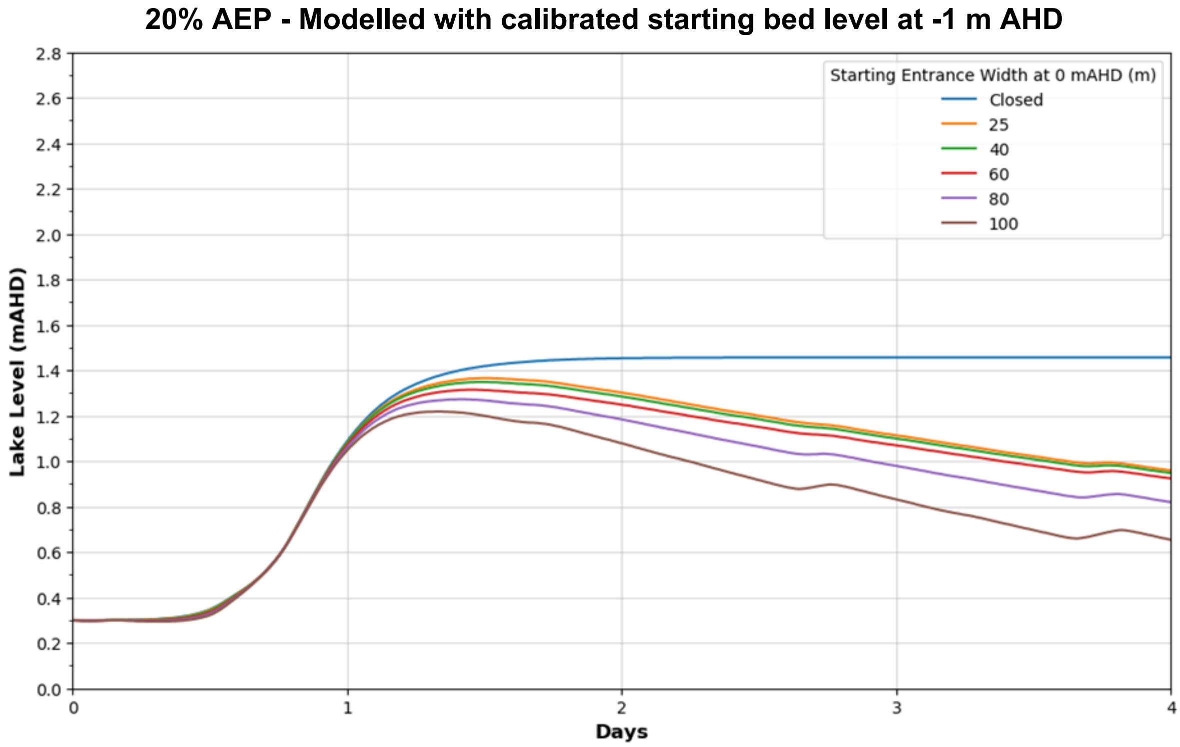


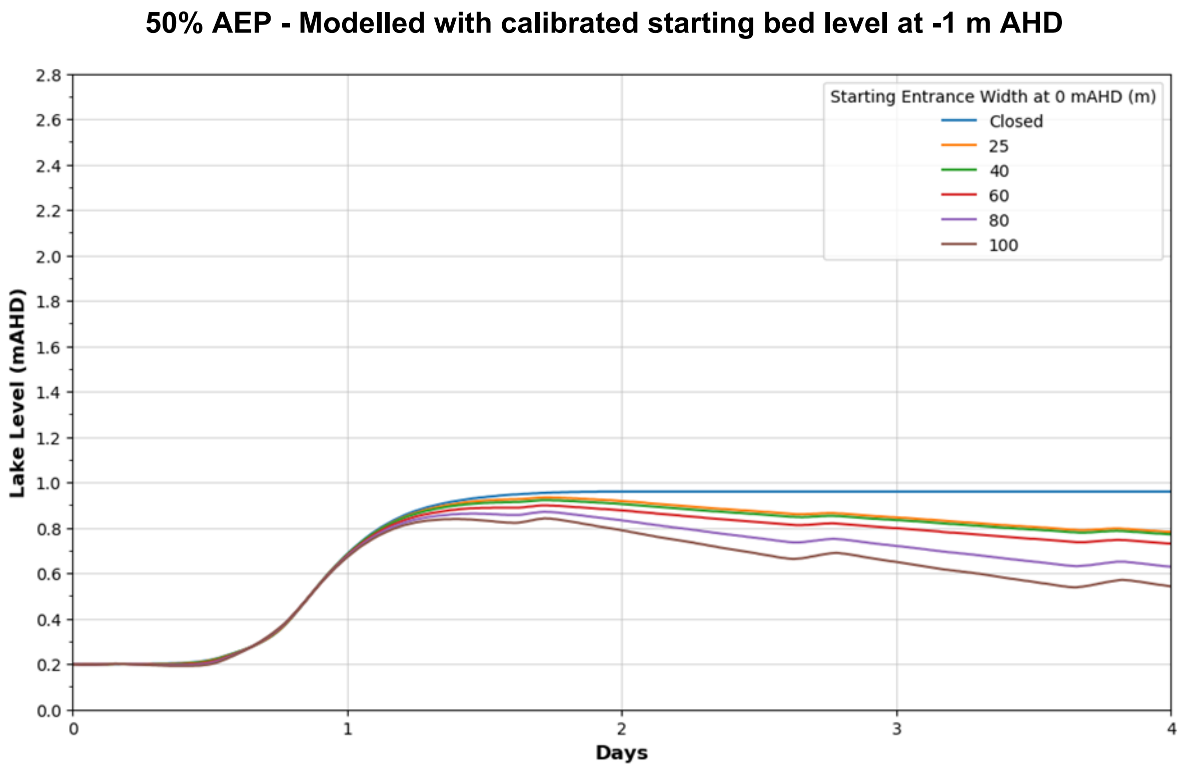
1% AEP - Modelled with calibrated starting bed level at -1 m AHD



5% AEP - Modelled with calibrated starting bed level at -1 m AHD

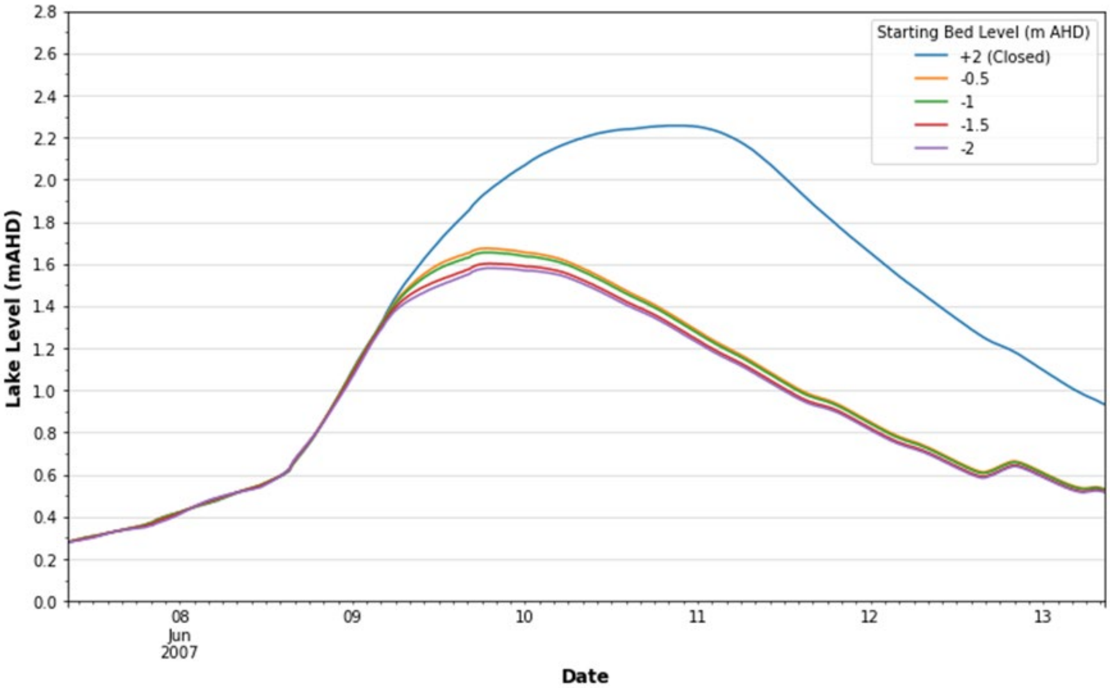



20% AEP - Modelled with calibrated starting bed level at -1 m AHD
Starting Entrance Width at 0 mAHD (m)
Closed
25
40
60
80
100
Lake Level (mAHD)
Days
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
0
1
2
3
4

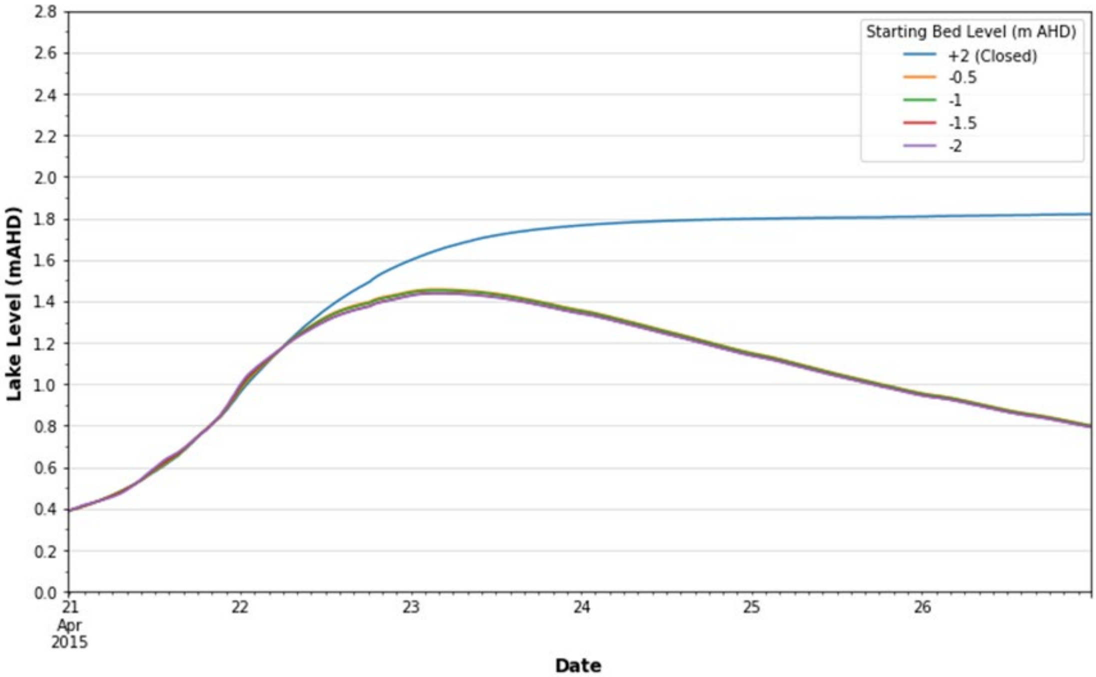

50% AEP - Modelled with calibrated starting bed level at -1 m AHD
Starting Entrance Width at 0 mAHD (m)
Closed
25
40
60
80
100
Lake Level (mAHD)
Days
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
0
1
2
3
4

Simulated flood level plots for varying entrance channel bed level

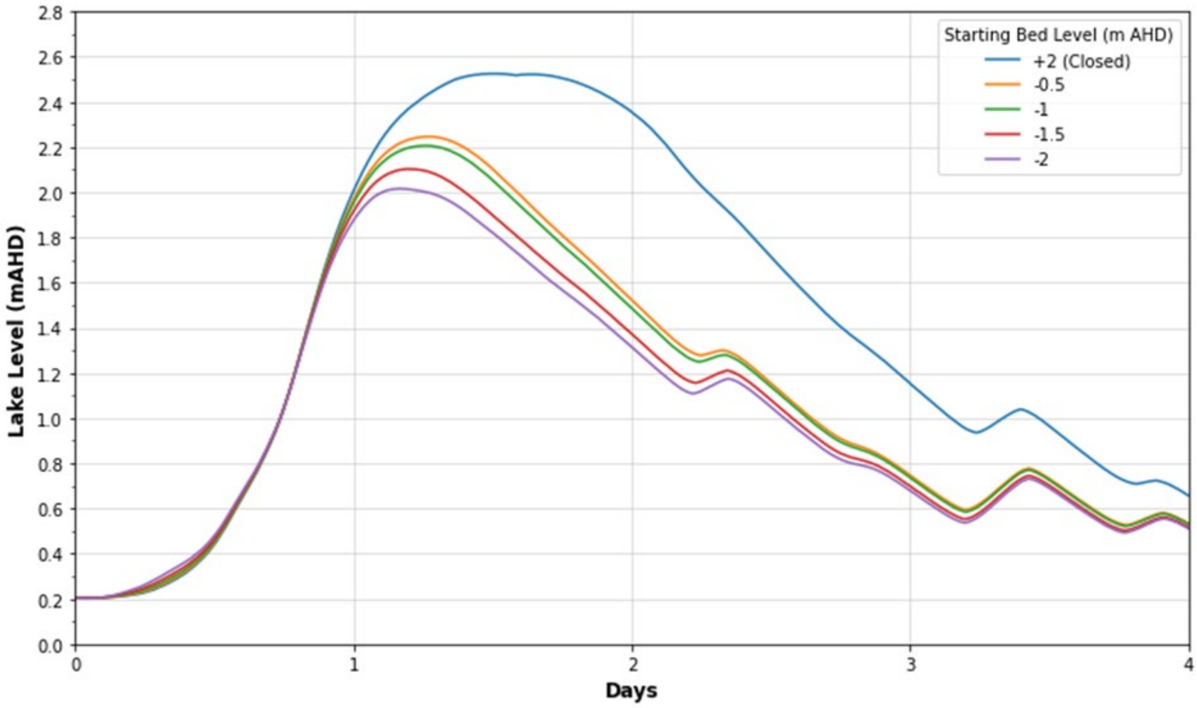
June 2007 - Modelled with a calibrated entrance starting width of 40 m



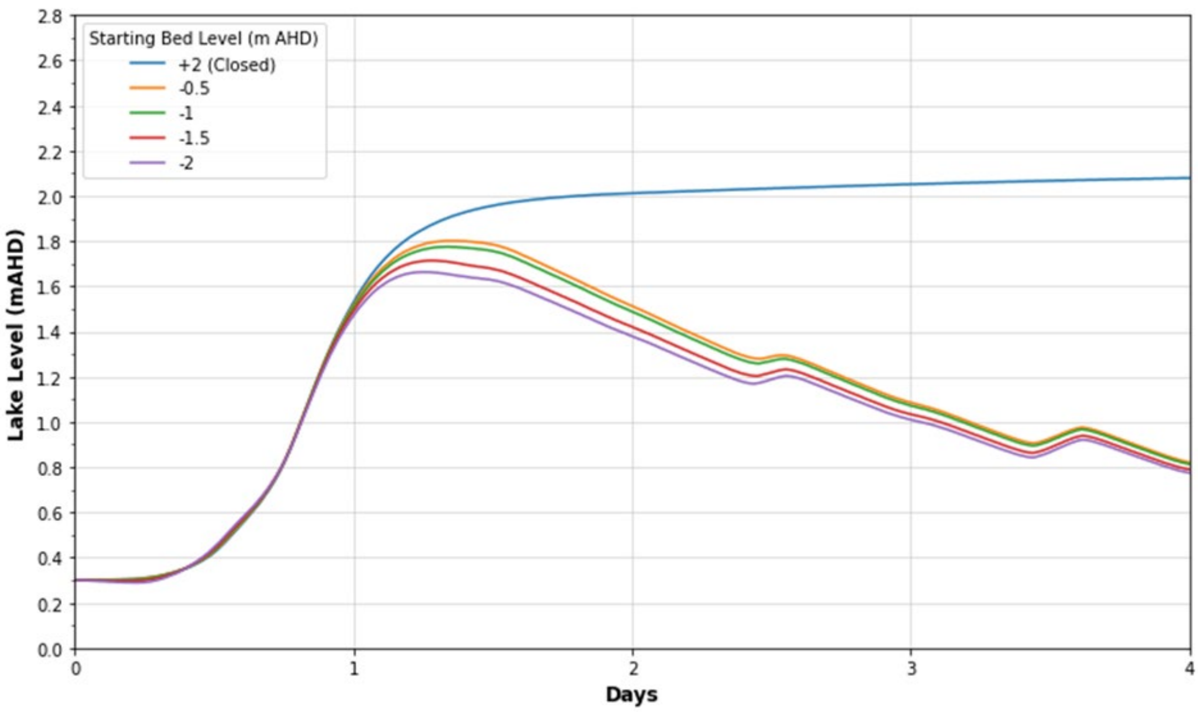
April 2015 - Modelled with a calibrated entrance starting width of 40 m



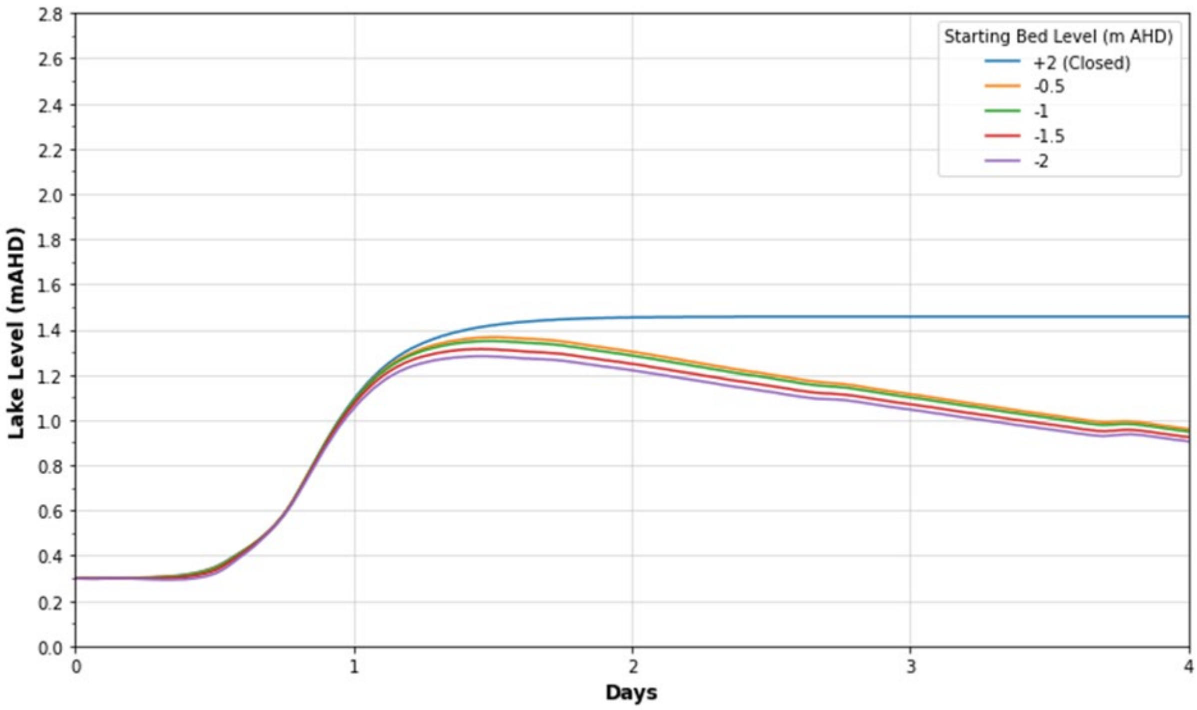
1% AEP - Modelled with a calibrated entrance starting width of 40 m



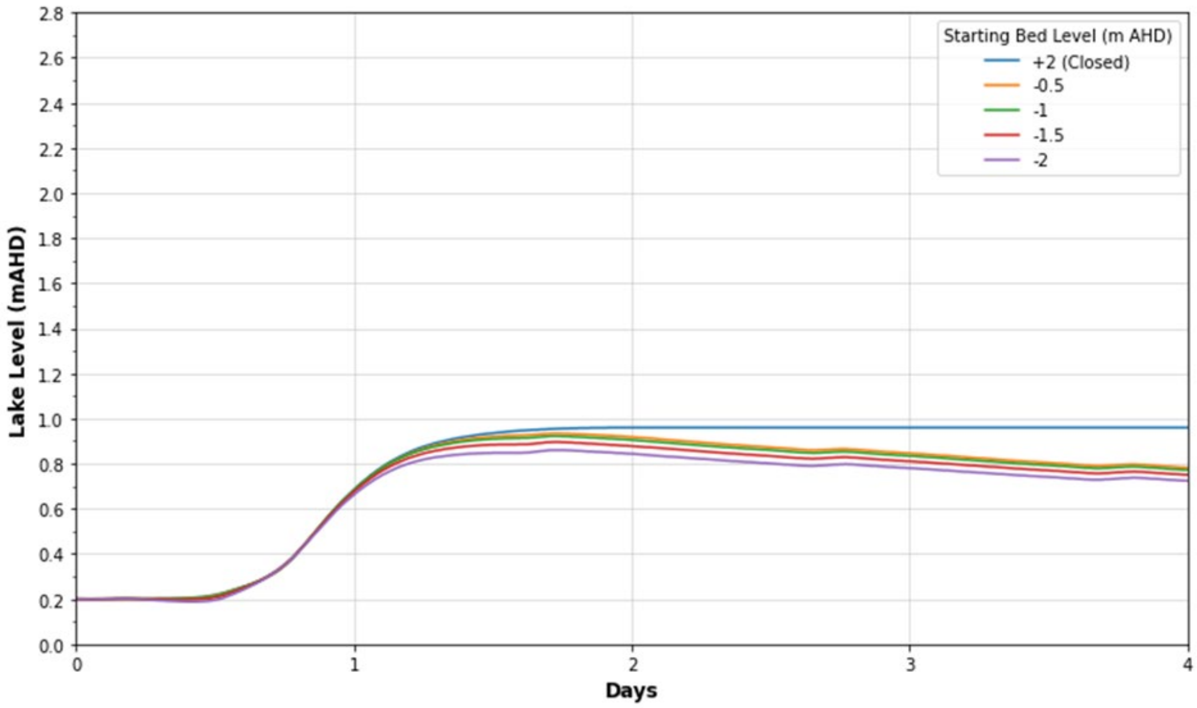
5% AEP- Modelled with a calibrated entrance starting width of 40m



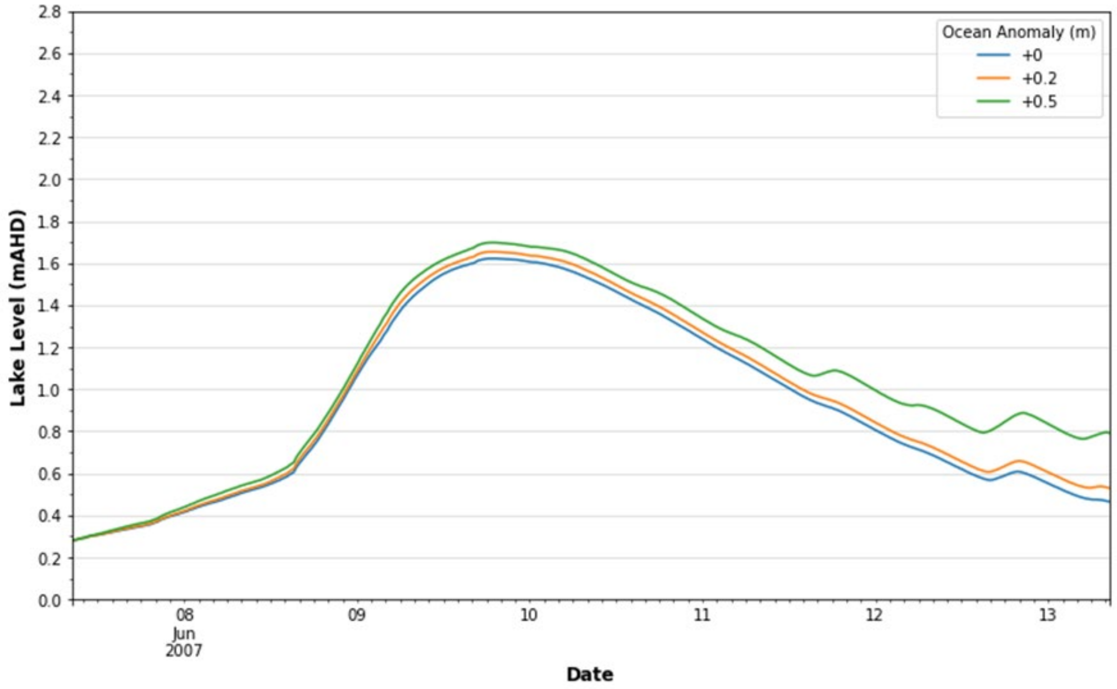
20% AEP - Modelled with a calibrated entrance starting width of 40 m



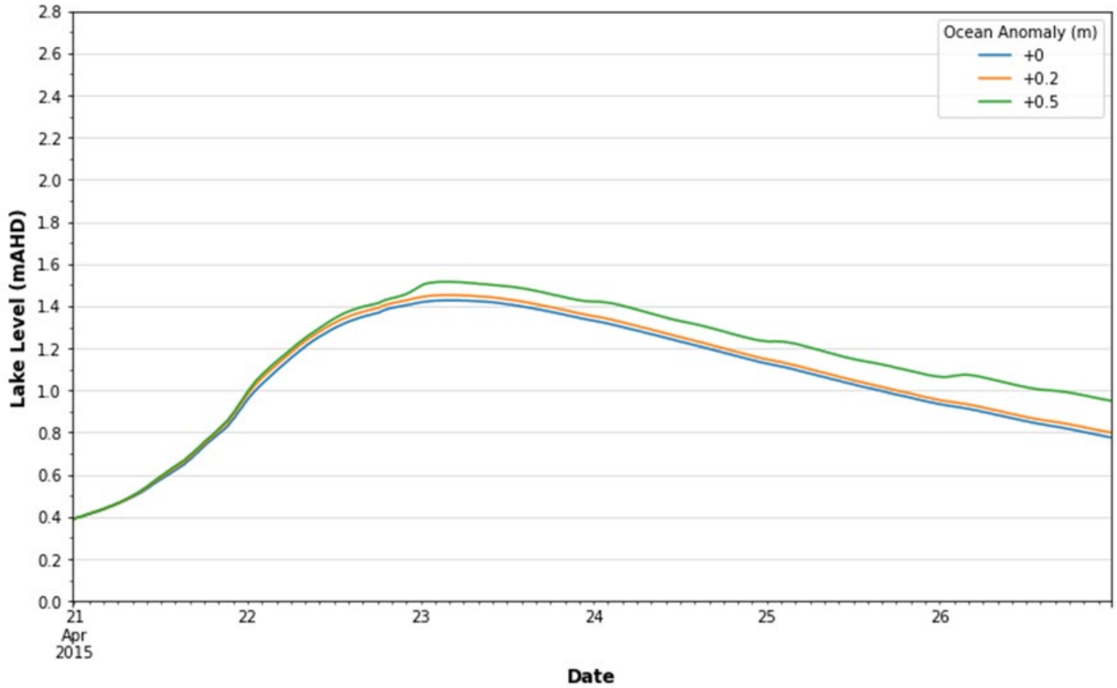
50% AEP - Modelled with a calibrated entrance starting width of 40 m



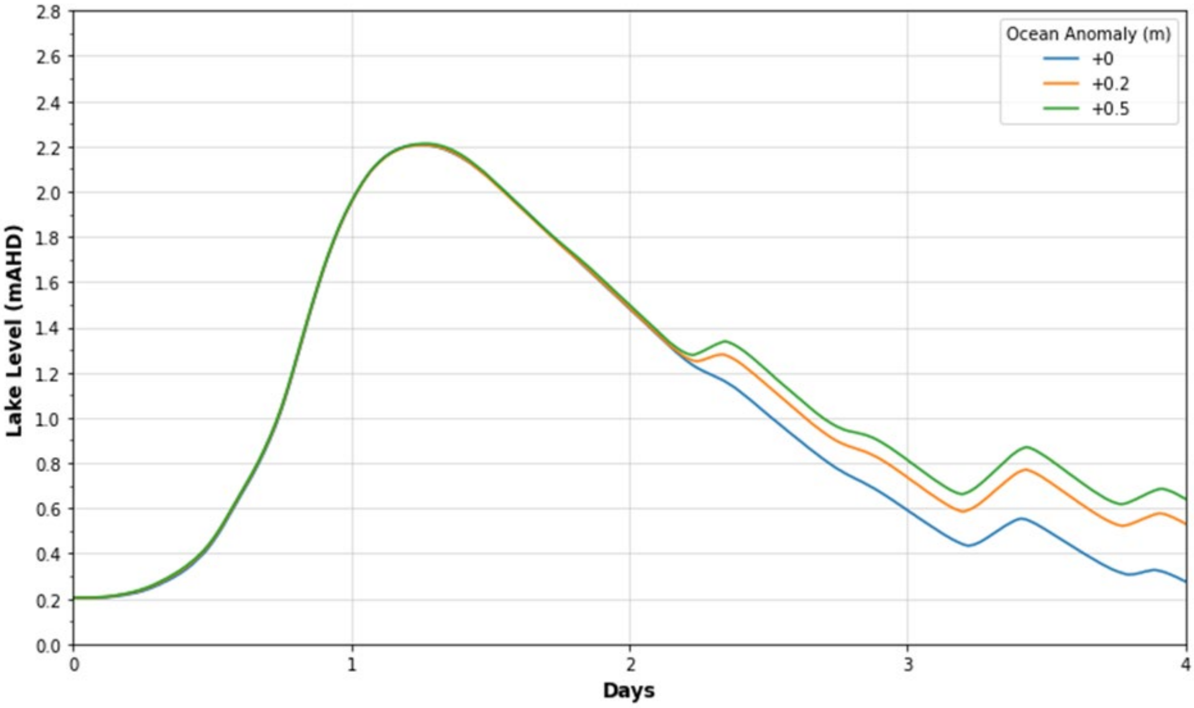
Simulated flood level plots for varying ocean water level anomalies
June 2007 Flood



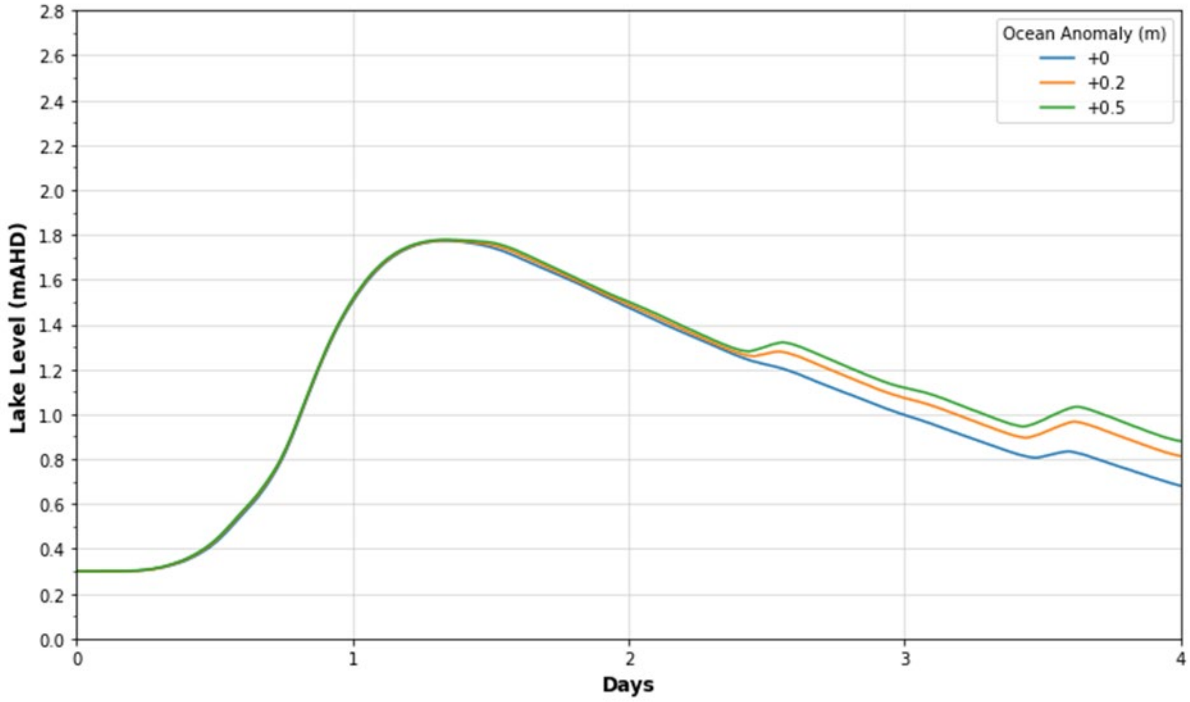
April 2015 Flood



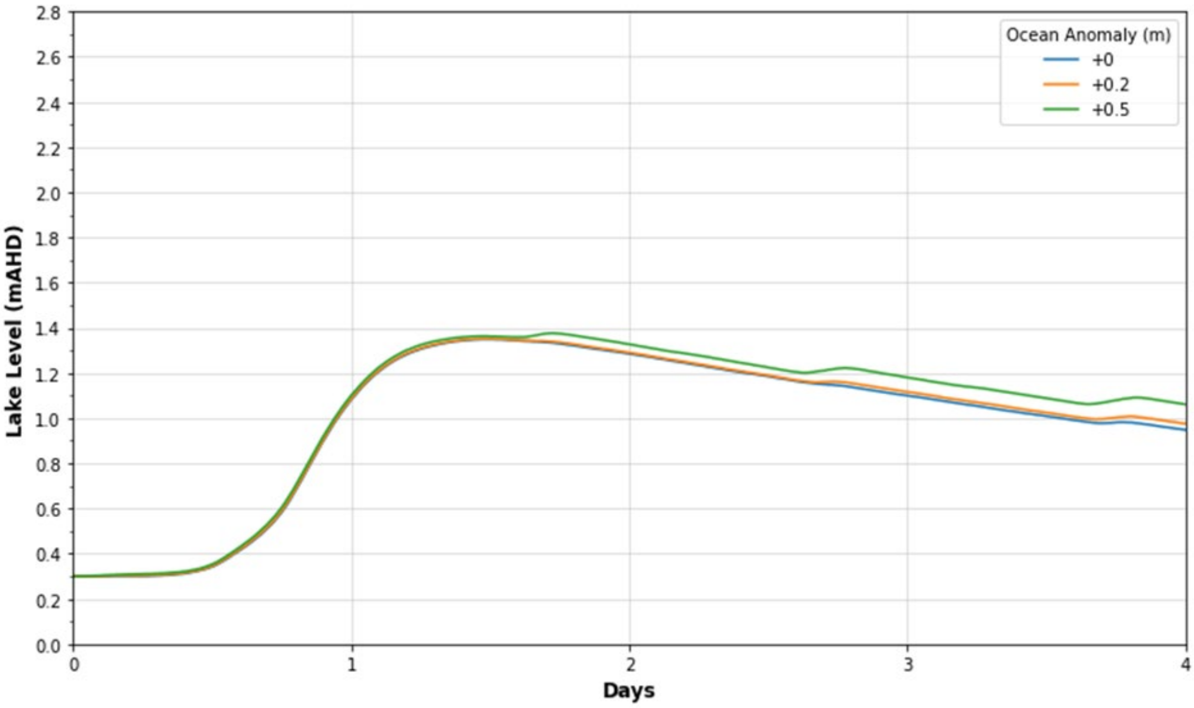
1% AEP


Ocean Anomaly (m)
+0
+0.2
+0.5
Lake Level (mAHD)
Days
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
0
1
2
3
4

5% AEP

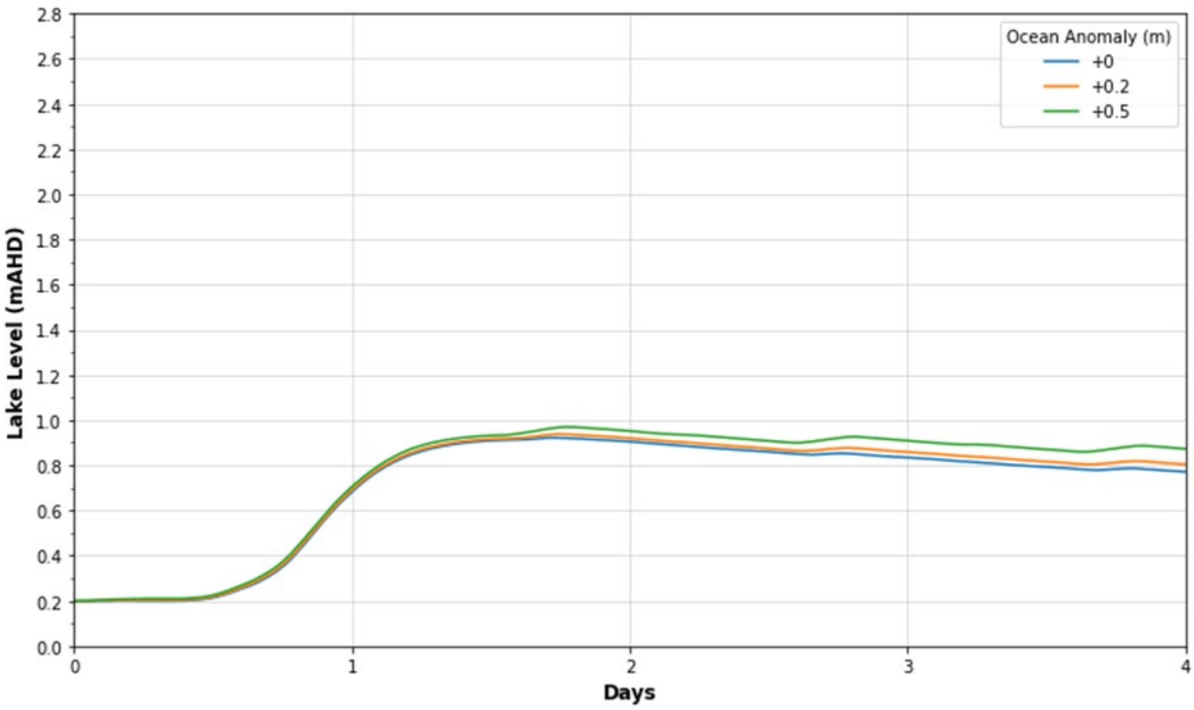

Ocean Anomaly (m)
+0
+0.2
+0.5
Lake Level (mAHD)
Days
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
0
1
2
3
4

20% AEP



Ocean Anomaly (m)
+0
+0.2
+0.5
Lake Level (mAHD)
Days

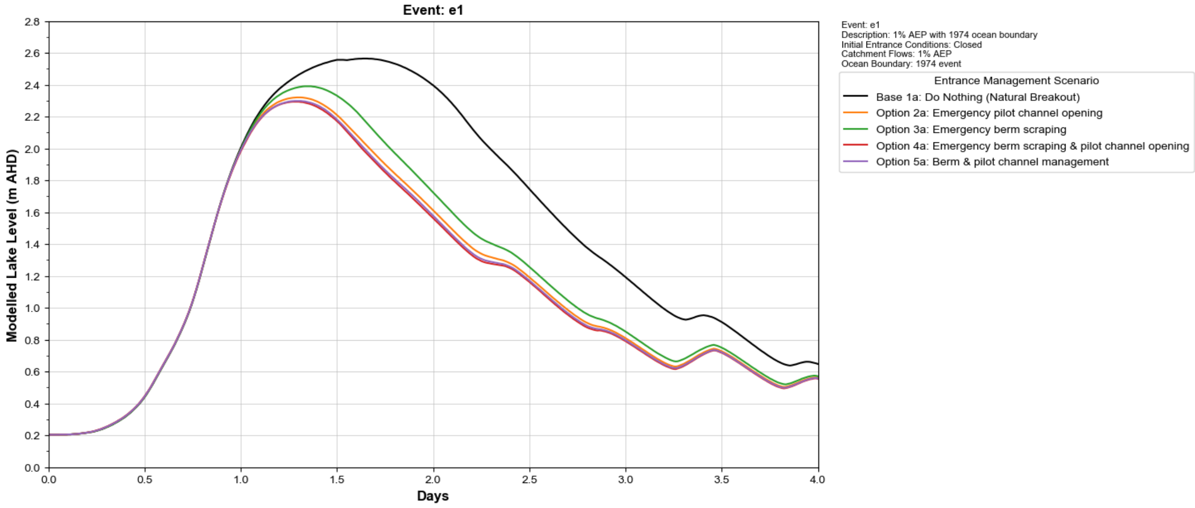
50% AEP

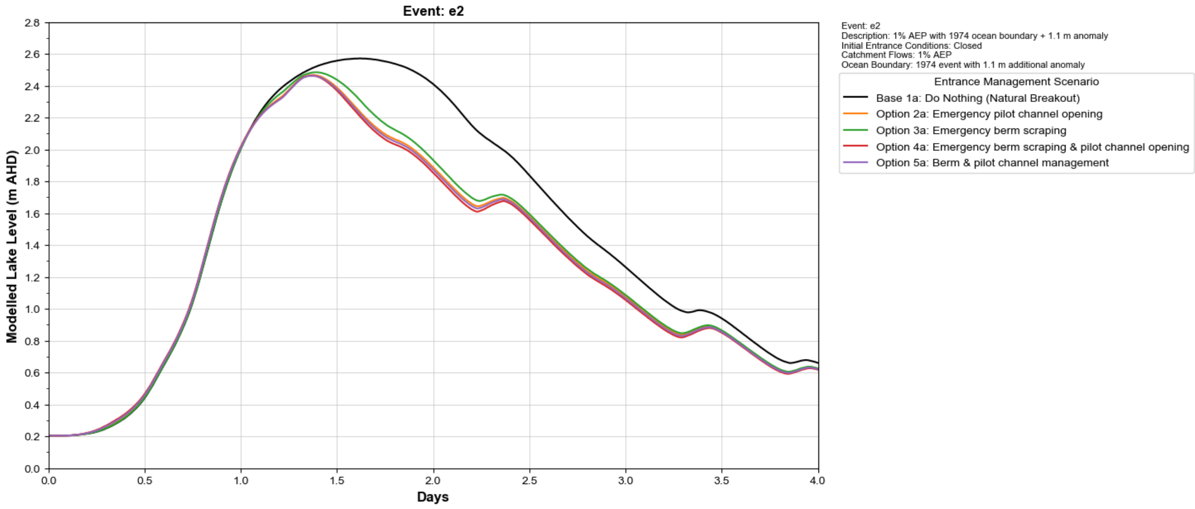


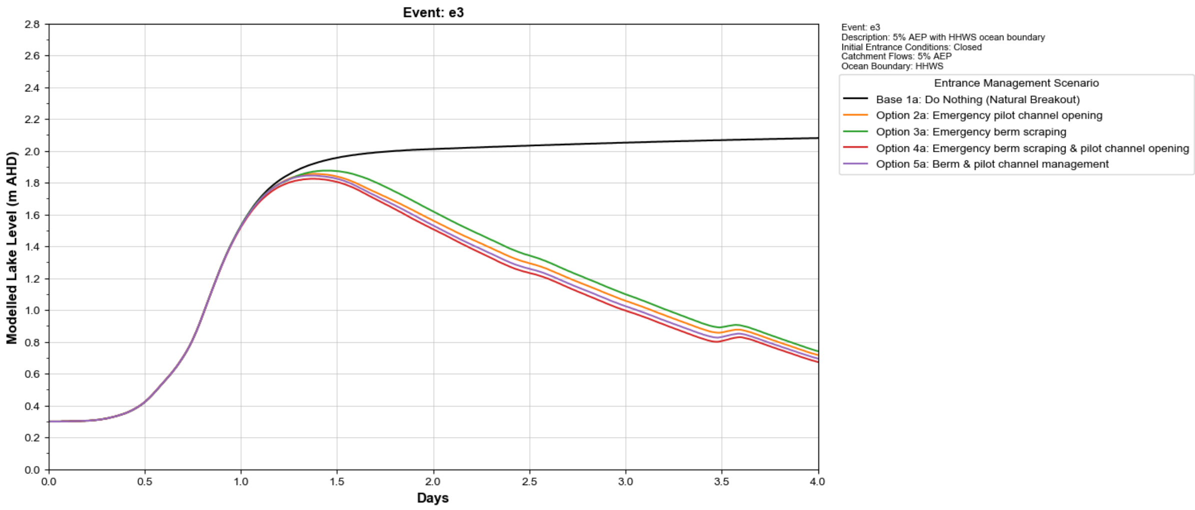
Ocean Anomaly (m)
+0
+0.2
+0.5
Lake Level (mAHD)
Days

Appendix C Management options model results

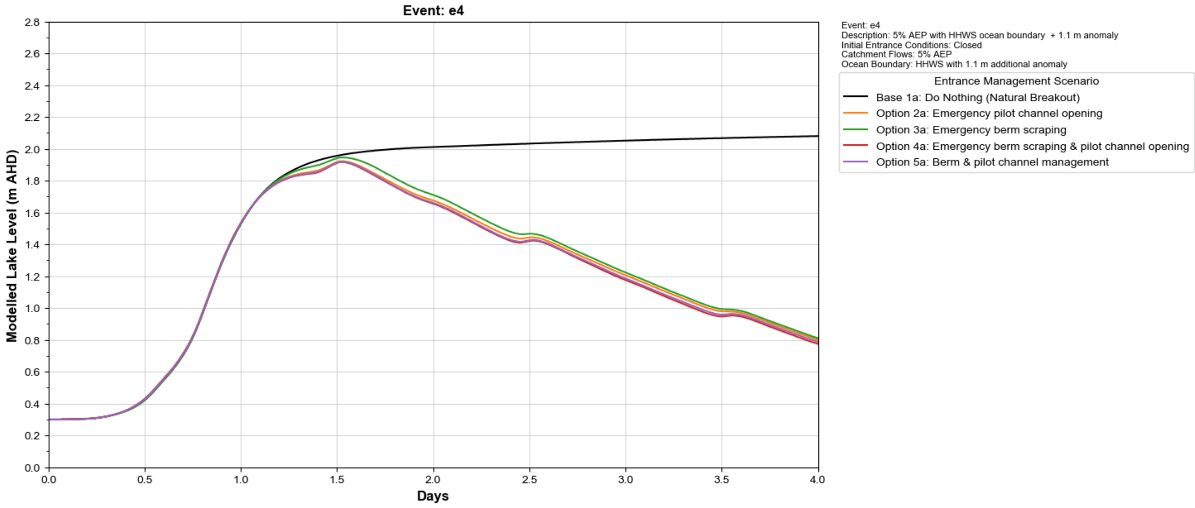
Model results for initially closed entrance

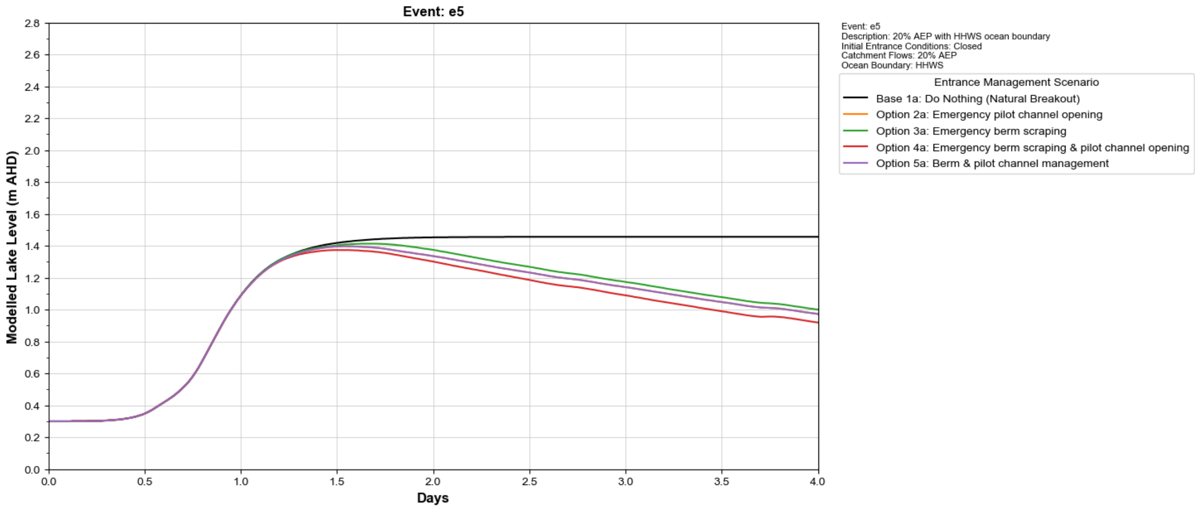


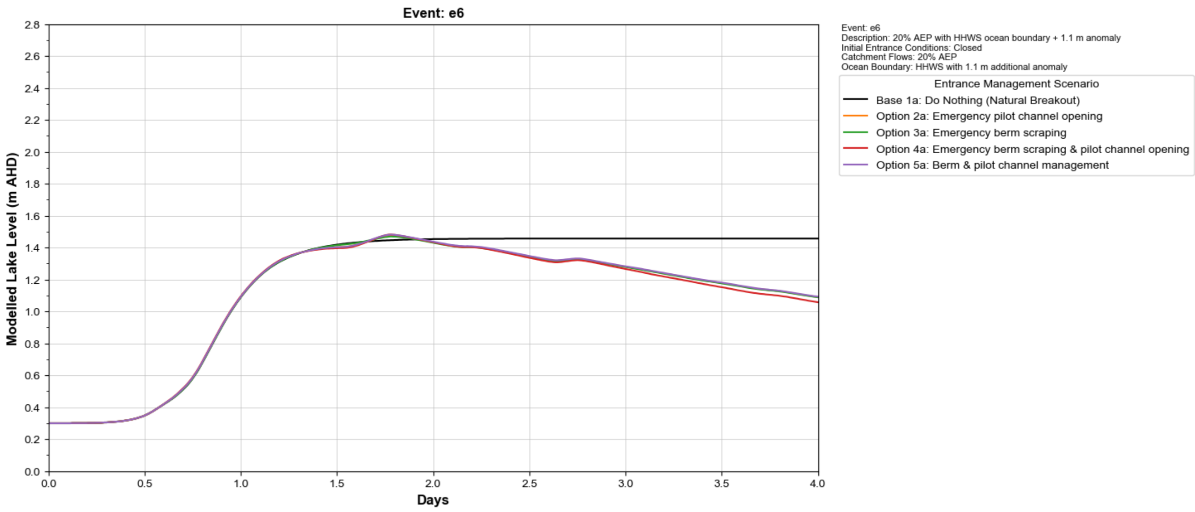


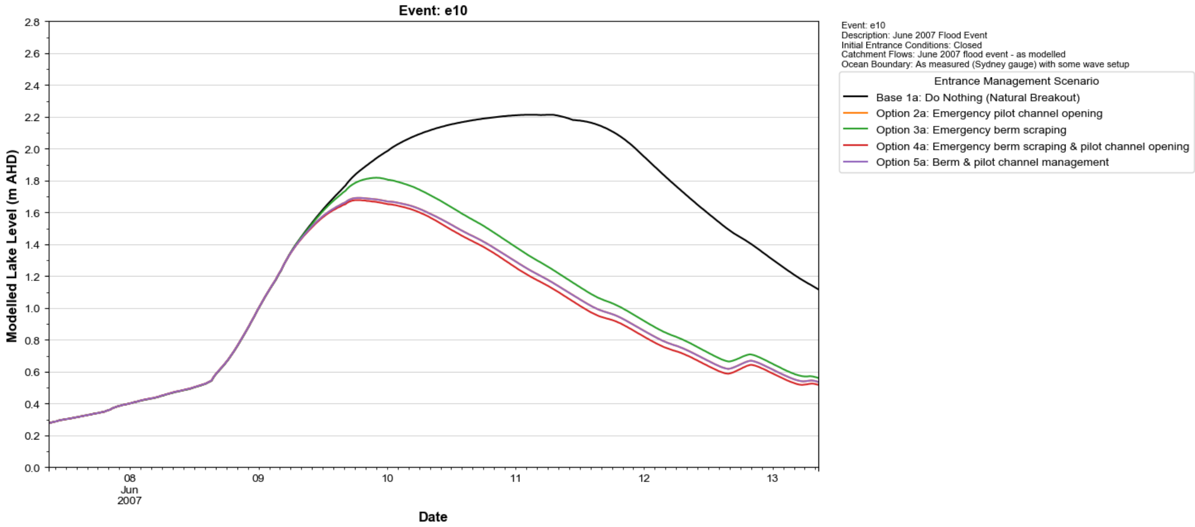


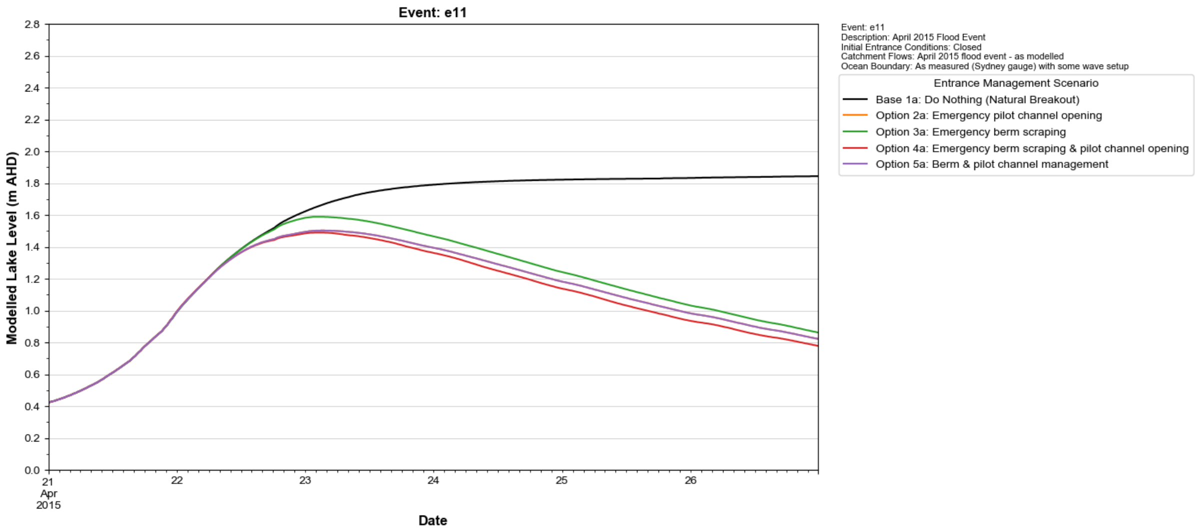
 Classification: Public


Event: e4
Modelled Lake Level (m AHD)
Days
Event: e4
Description: 5% AEP with HHWS ocean boundary + 1.1 m anomaly
Initial Entrance Conditions: Closed
Catchment Flows: 5% AEP
Ocean Boundary: HHWS with 1.1 m additional anomaly
Entrance Management Scenario
Base 1a: Do Nothing (Natural Breakout)
Option 2a: Emergency pilot channel opening
Option 3a: Emergency berm scraping
Option 4a: Emergency berm scraping & pilot channel opening
Option 5a: Berm & pilot channel management

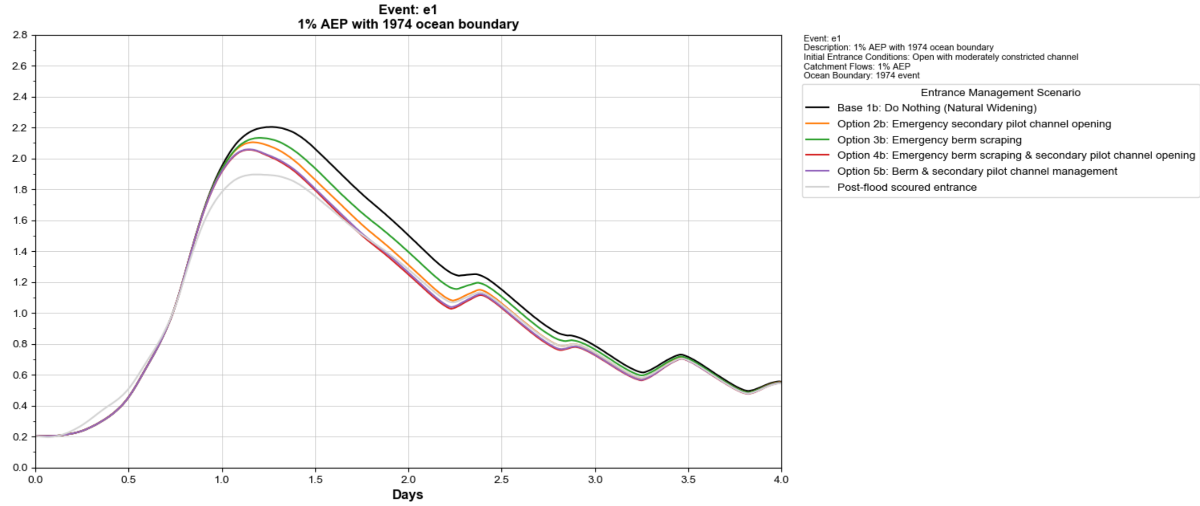

Event: e5
Modelled Lake Level (m AHD)
Days
Event: e5
Description: 20% AEP with HHWS ocean boundary
Initial Entrance Conditions: Closed
Catchment Flows: 20% AEP
Ocean Boundary: HHWS
Entrance Management Scenario
Base 1a: Do Nothing (Natural Breakout)
Option 2a: Emergency pilot channel opening
Option 3a: Emergency berm scraping
Option 4a: Emergency berm scraping & pilot channel opening
Option 5a: Berm & pilot channel management

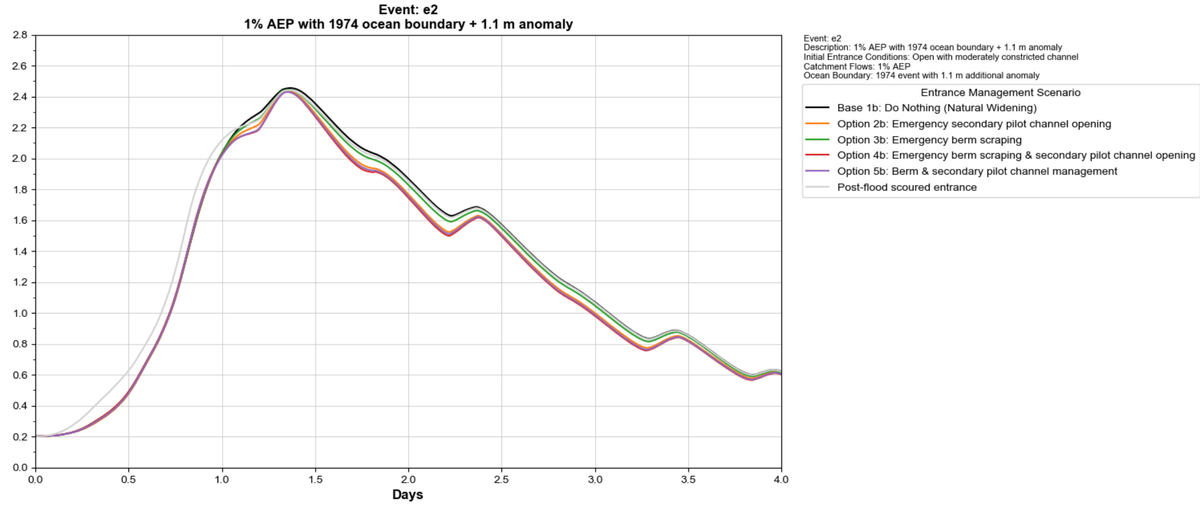

Event: e6
Modelled Lake Level (m AHD)
Days
Event: e6
Description: 20% AEP with HHWS ocean boundary + 1.1 m anomaly
Initial Entrance Conditions: Closed
Catchment Flows: 20% AEP
Ocean Boundary: HHWS with 1.1 m additional anomaly
Entrance Management Scenario
Base 1a: Do Nothing (Natural Breakout)
Option 2a: Emergency pilot channel opening
Option 3a: Emergency berm scraping
Option 4a: Emergency berm scraping & pilot channel opening
Option 5a: Berm & pilot channel management

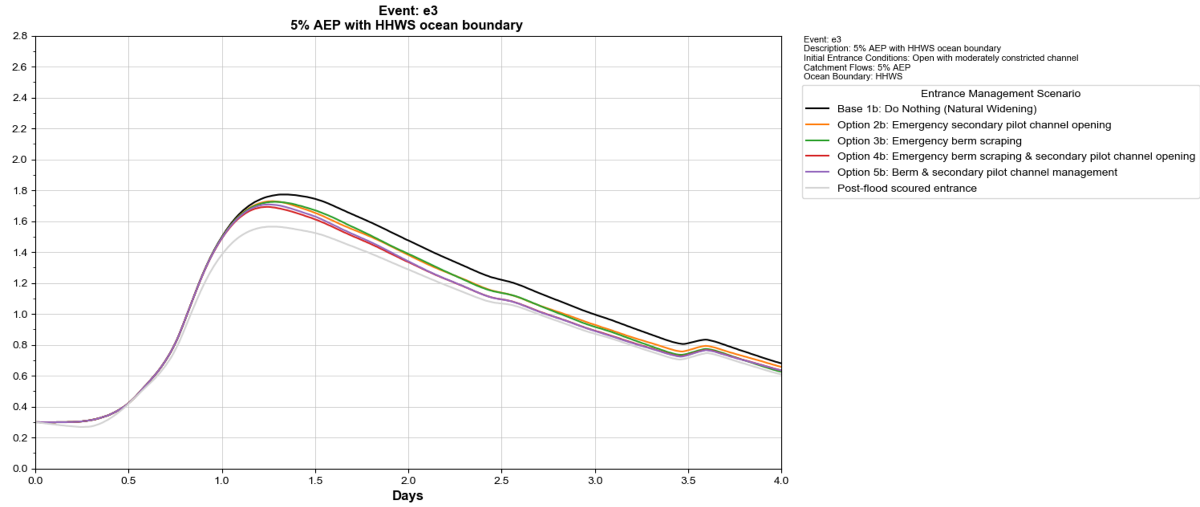

Event: e10
Modelled Lake Level (m AHD)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
08
Jun
2007
09
10
11
12
13
Date
Event: e10
Description: June 2007 Flood Event
Initial Entrance Conditions: Closed
Catchment Flows: June 2007 flood event - as modelled
Ocean Boundary: As measured (Sydney gauge) with some wave setup
Entrance Management Scenario
Base 1a: Do Nothing (Natural Breakout)
Option 2a: Emergency pilot channel opening
Option 3a: Emergency berm scraping
Option 4a: Emergency berm scraping & pilot channel opening
Option 5a: Berm & pilot channel management

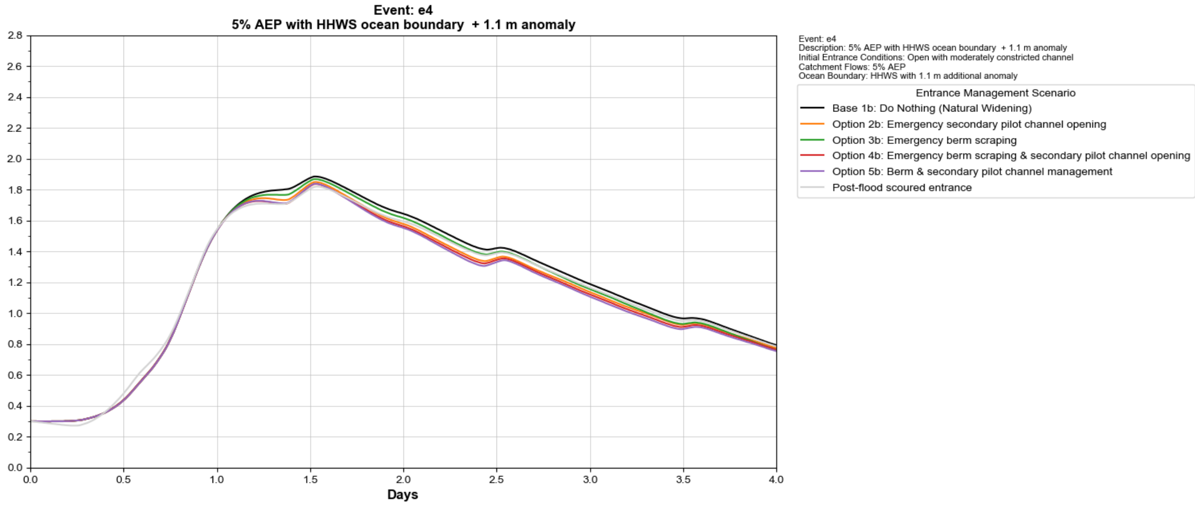

Event: e11
Modelled Lake Level (m AHD)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
21
Apr
2015
22
23
24
25
26
Date
Event: e11
Description: April 2015 Flood Event
Initial Entrance Conditions: Closed
Catchment Flows: April 2015 flood event - as modelled
Ocean Boundary: As measured (Sydney gauge) with some wave setup
Entrance Management Scenario
Base 1a: Do Nothing (Natural Breakout)
Option 2a: Emergency pilot channel opening
Option 3a: Emergency berm scraping
Option 4a: Emergency berm scraping & pilot channel opening
Option 5a: Berm & pilot channel management

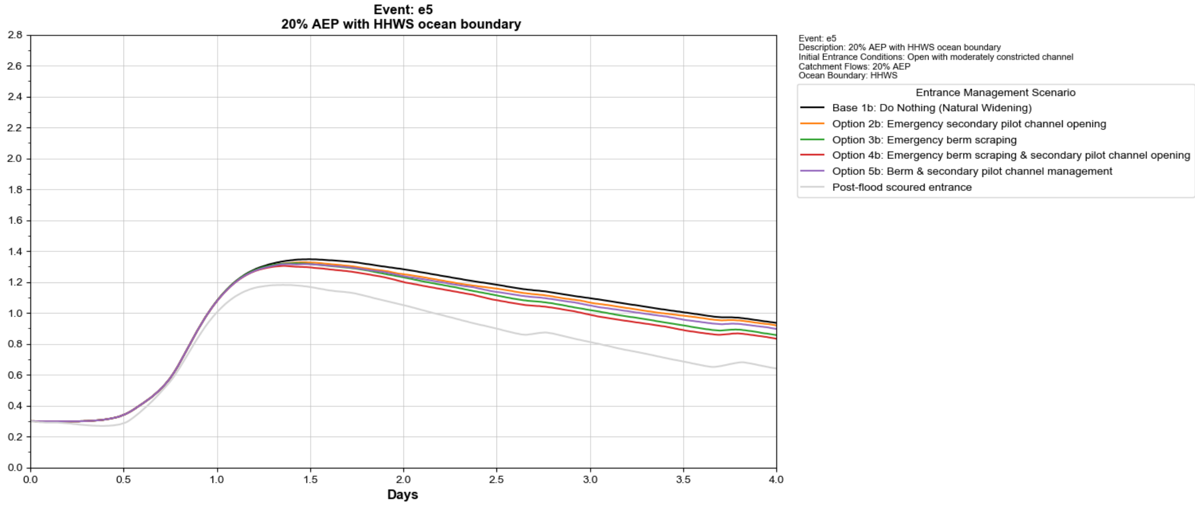
Model results for initially open entrance: moderately constricted

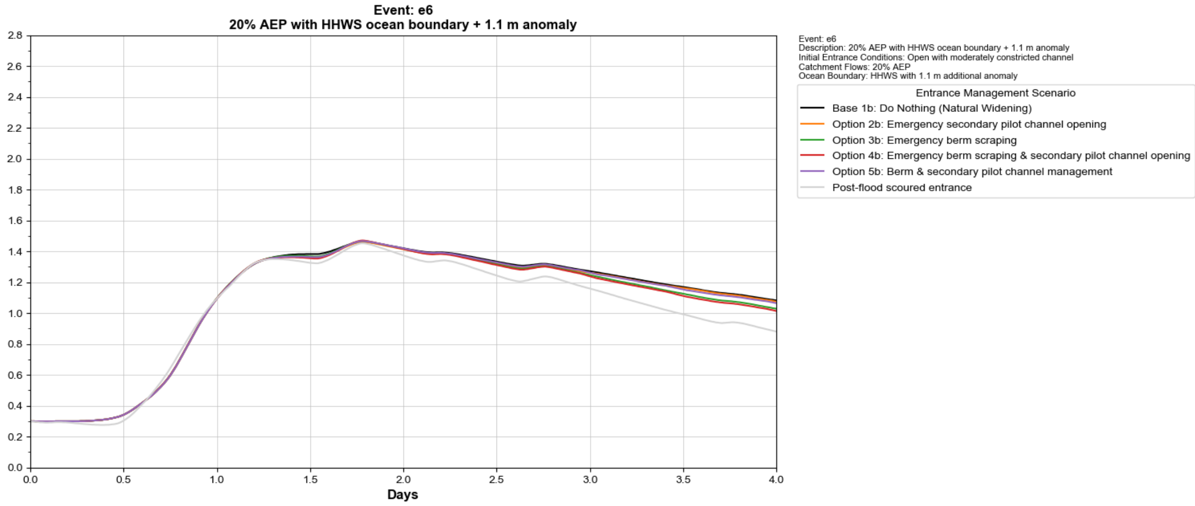


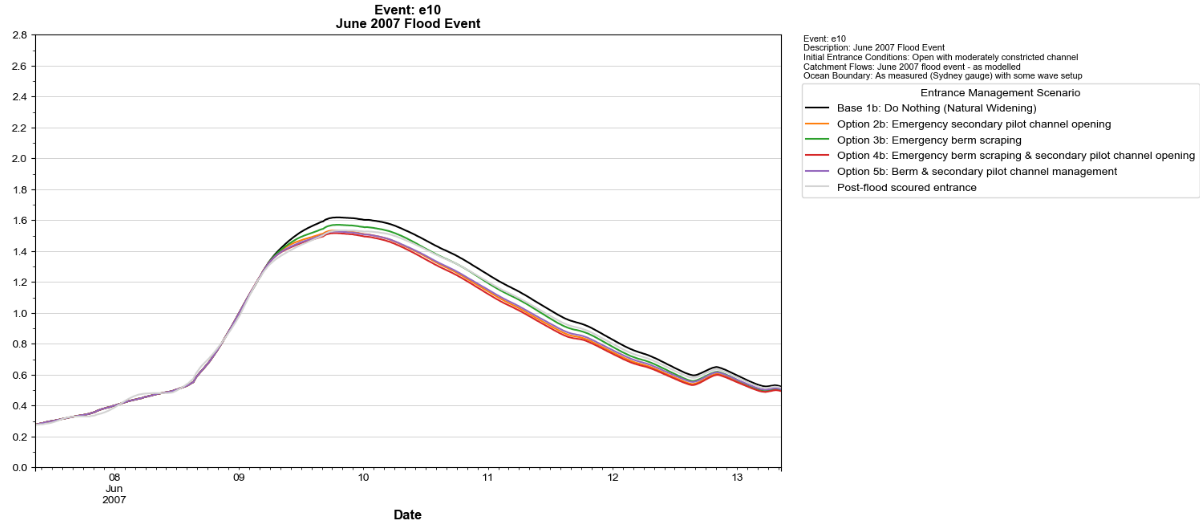


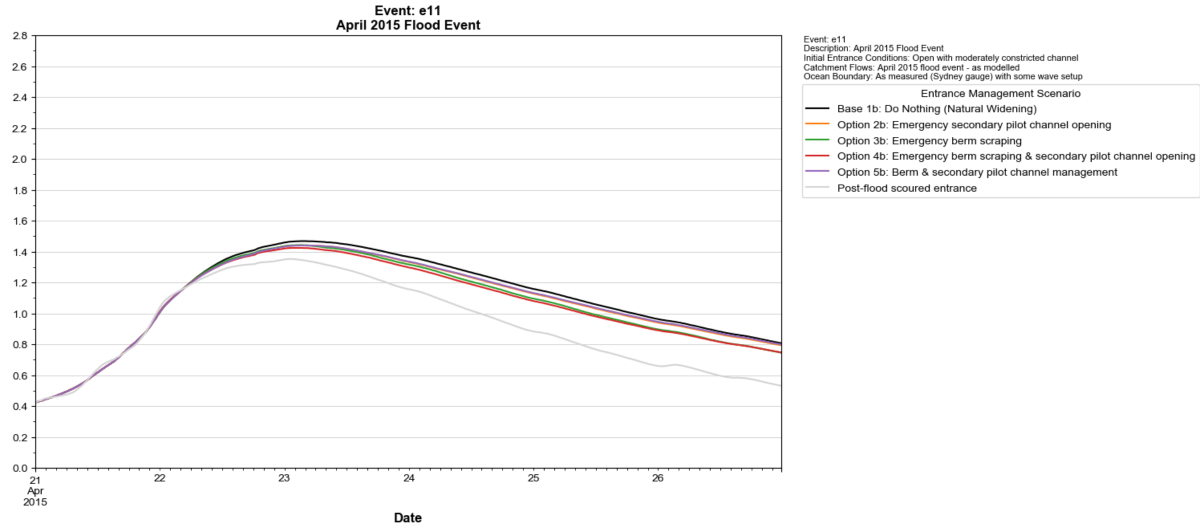



Event: e4
5% AEP with HHWS ocean boundary + 1.1 m anomaly
Days
Event: e4
Description: 5% AEP with HHWS ocean boundary + 1.1 m anomaly
Initial Entrance Conditions: Open with moderately constricted channel
Catchment Flows: 5% AEP
Ocean Boundary: HHWS with 1.1 m additional anomaly
Entrance Management Scenario
Base 1b: Do Nothing (Natural Widening)
Option 2b: Emergency secondary pilot channel opening
Option 3b: Emergency berm scraping
Option 4b: Emergency berm scraping & secondary pilot channel opening
Option 5b: Berm & secondary pilot channel management
Post-flood scoured entrance


Event: e5
20% AEP with HHWS ocean boundary
Days
Event: e5
Description: 20% AEP with HHWS ocean boundary
Initial Entrance Conditions: Open with moderately constricted channel
Catchment Flows: 20% AEP
Ocean Boundary: HHWS
Entrance Management Scenario
Base 1b: Do Nothing (Natural Widening)
Option 2b: Emergency secondary pilot channel opening
Option 3b: Emergency berm scraping
Option 4b: Emergency berm scraping & secondary pilot channel opening
Option 5b: Berm & secondary pilot channel management
Post-flood scoured entrance


Event: e6
20% AEP with HHWS ocean boundary + 1.1 m anomaly
Days
Event: e6
Description: 20% AEP with HHWS ocean boundary + 1.1 m anomaly
Initial Entrance Conditions: Open with moderately constricted channel
Catchment Flows: 20% AEP
Ocean Boundary: HHWS with 1.1 m additional anomaly
Entrance Management Scenario
Base 1b: Do Nothing (Natural Widening)
Option 2b: Emergency secondary pilot channel opening
Option 3b: Emergency berm scraping
Option 4b: Emergency berm scraping & secondary pilot channel opening
Option 5b: Berm & secondary pilot channel management
Post-flood scoured entrance


Event: e10
June 2007 Flood Event
Date
Event: e10
Description: June 2007 Flood Event
Initial Entrance Conditions: Open with moderately constricted channel
Catchment Flows: June 2007 flood event - as modelled
Ocean Boundary: As measured (Sydney gauge) with some wave setup
Entrance Management Scenario
Base 1b: Do Nothing (Natural Widening)
Option 2b: Emergency secondary pilot channel opening
Option 3b: Emergency berm scraping
Option 4b: Emergency berm scraping & secondary pilot channel opening
Option 5b: Berm & secondary pilot channel management
Post-flood scoured entrance

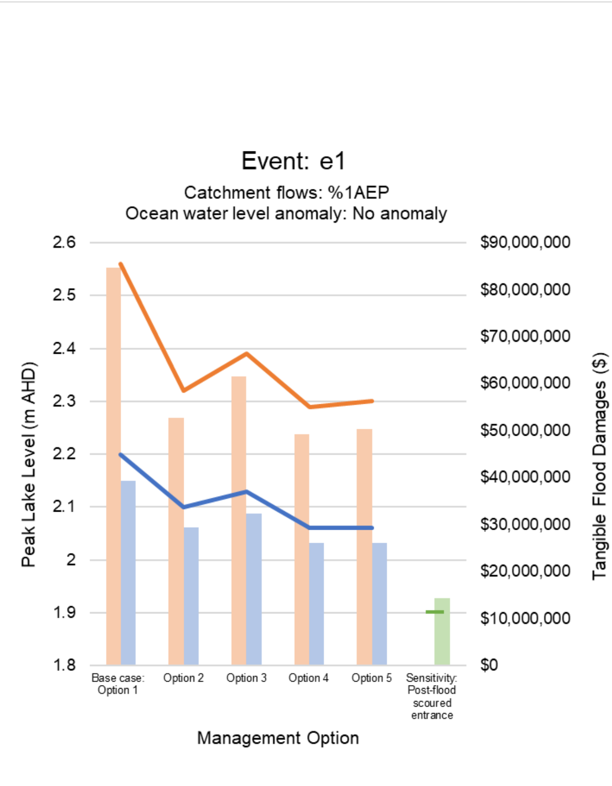

Event: e11
April 2015 Flood Event
Date
Event: e11
Description: April 2015 Flood Event
Initial Entrance Conditions: Open with moderately constricted channel
Catchment Flows: April 2015 flood event - as modelled
Ocean Boundary: As measured (Sydney gauge) with some wave setup
Entrance Management Scenario
Base 1b: Do Nothing (Natural Widening)
Option 2b: Emergency secondary pilot channel opening
Option 3b: Emergency berm scraping
Option 4b: Emergency berm scraping & secondary pilot channel opening
Option 5b: Berm & secondary pilot channel management
Post-flood scoured entrance

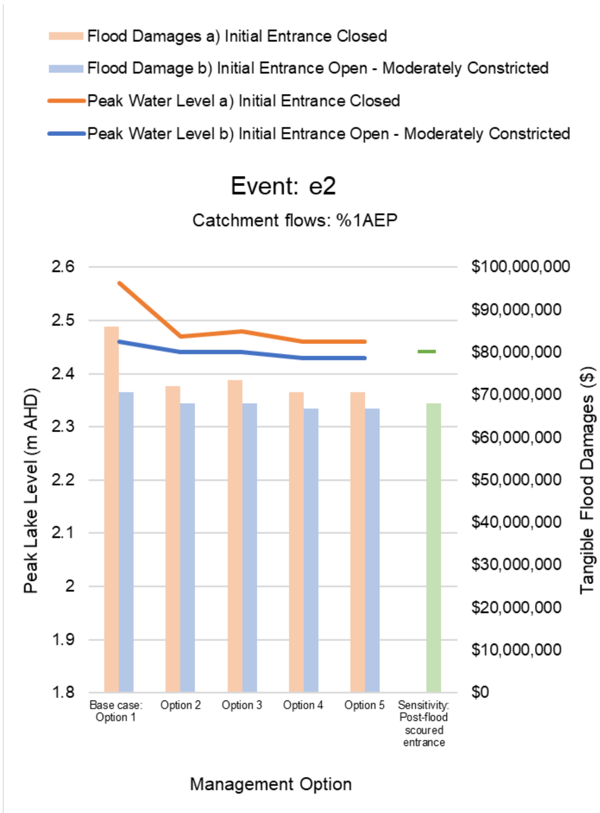
Peak Flood Levels and Flood Duration

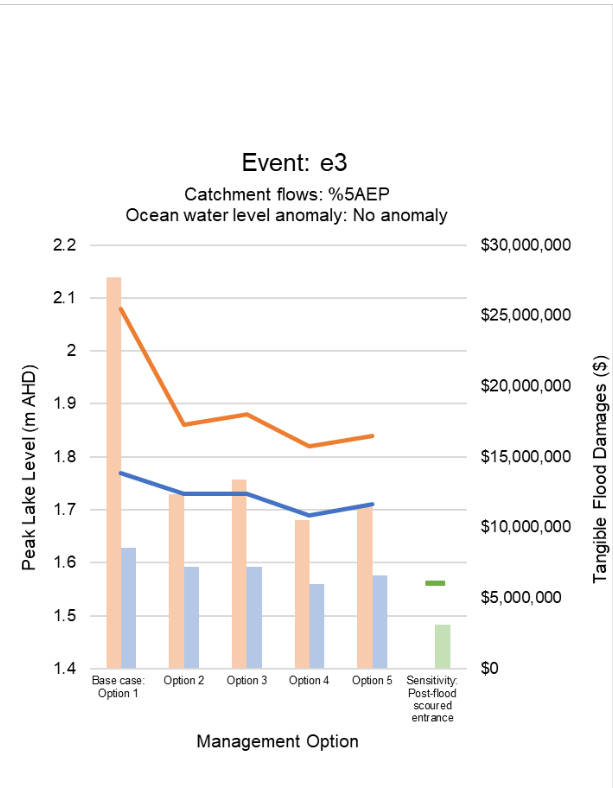
Event	Catchment Flows	Ocean Water Levels	Initial Entrance Condition	Management Option	Peak Lake Level (m AHD)	Rate of rise (m/h)	Flood duration above 1.3 m AHD (h)
e1	1% AEP	1974 Event	Closed	Base Case: Option 1	2.56	0.127	50
				Option 2	2.32	0.129	37
				Option 3	2.39	0.127	39
				Option 4	2.29	0.128	34
				Option 5	2.3	0.129	35
			Open: Moderately Constricted	Base Case: Option 1	2.2	0.125	33
				Option 2	2.1	0.125	28
				Option 3	2.13	0.123	30
				Option 4	2.06	0.125	27
				Option 5	2.06	0.125	27
			Post-Flood Scoured Entrance	Sensitivity	1.9	0.115	28
e2	1% AEP	1974 Event + 1.1 m Anomaly	Closed	Base Case: Option 1	2.57	0.127	51
				Option 2	2.47	0.128	46
				Option 3	2.48	0.128	46
				Option 4	2.46	0.128	45
				Option 5	2.46	0.129	46
			Open: Moderately Constricted	Base Case: Option 1	2.46	0.129	46
				Option 2	2.44	0.129	45
				Option 3	2.44	0.131	46
				Option 4	2.43	0.127	44
				Option 5	2.43	0.126	44
			Post-Flood Scoured Entrance	Sensitivity	2.44	0.137	47
e3	5% AEP	HHWS	Closed	Base Case: Option 1	2.08	0.112	closed
				Option 2	1.86	0.111	37
				Option 3	1.88	0.112	40
				Option 4	1.82	0.112	34
				Option 5	1.84	0.111	35
			Open: Moderately Constricted	Base Case: Option 1	1.77	0.11	33
				Option 2	1.73	0.111	29
				Option 3	1.73	0.111	29
				Option 4	1.69	0.111	27
				Option 5	1.71	0.112	27
			Post-Flood Scoured Entrance	Sensitivity	1.56	0.108	24
e4	5% AEP	HHWS + 1.1 m Anomaly	Closed	Base Case: Option 1	2.08	0.112	closed
				Option 2	1.92	0.113	46
				Option 3	1.95	0.112	46
				Option 4	1.92	0.114	45
				Option 5	1.92	0.113	45
			Open: Moderately Constricted	Base Case: Option 1	1.89	0.115	45
				Option 2	1.85	0.115	42
				Option 3	1.87	0.115	44
				Option 4	1.84	0.115	42
				Option 5	1.84	0.116	41
			Post-Flood Scoured Entrance	Sensitivity	1.82	0.116	44
e5	20% AEP	HHWS	Closed	Base Case: Option 1	1.46	0.09	closed
				Option 2	1.4	0.089	23
				Option 3	1.41	0.09	27
				Option 4	1.37	0.089	19
				Option 5	1.4	0.089	23
			Open: Moderately Constricted	Base Case: Option 1	1.35	0.089	15
				Option 2	1.33	0.09	11
				Option 3	1.32	0.089	9
				Option 4	1.3	0.089	2
				Option 5	1.32	0.089	9
			Post-Flood Scoured Entrance	Sensitivity	1.18	0.083	0
e6	20% AEP	HHWS + 1.1 m Anomaly	Closed	Base Case: Option 1	1.46	0.09	closed
				Option 2	1.48	0.09	41
				Option 3	1.47	0.09	41
				Option 4	1.48	0.09	40
				Option 5	1.48	0.09	41

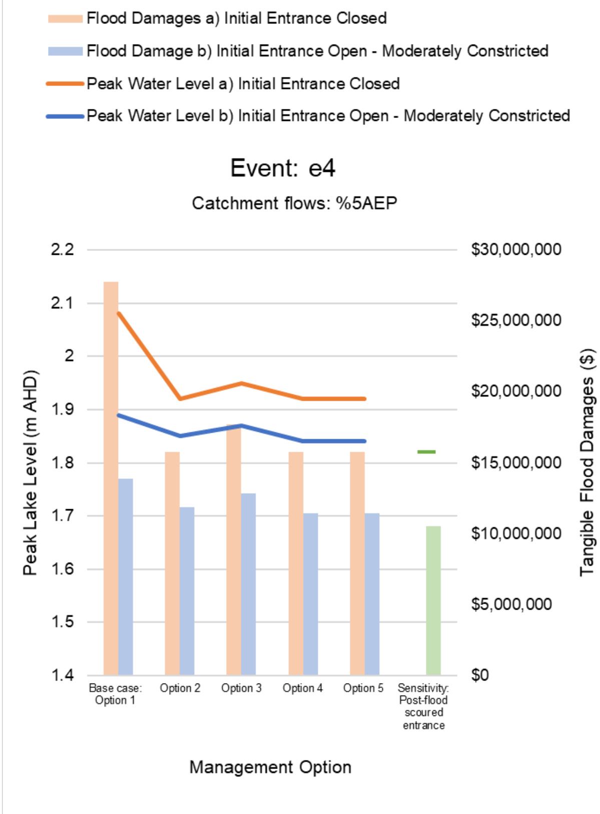
Event	Catchment Flows	Ocean Water Levels	Initial Entrance Condition	Management Option	Peak Lake Level (m AHD)	Rate of rise (m/h)	Flood duration above 1.3 m AHD (h)
			Open: Moderately Constricted	Base Case: Option 1	1.46	0.089	40
				Option 2	1.46	0.088	36
				Option 3	1.47	0.089	35
				Option 4	1.47	0.089	33
				Option 5	1.47	0.088	40
			Post-Flood Scoured Entrance	Sensitivity	1.45	0.083	28
e10	June 2007 Flood Event	As measured (Sydney gauge) with minor wave setup	Closed	Base Case: Option 1	2.21	0	91
				Option 2	1.69	0	42
				Option 3	1.82	0	46
				Option 4	1.68	0	40
				Option 5	1.69	0	42
			Open: Moderately Constricted	Base Case: Option 1	1.62	0	40
				Option 2	1.53	0	34
				Option 3	1.57	0	37
				Option 4	1.52	0	33
				Option 5	1.53	0	34
			Post-Flood Scoured Entrance	Sensitivity	1.53	0	37
e11	April 2015 Flood Event	As measured (Sydney gauge) with minor wave setup	Closed	Base Case: Option 1	1.84	0	closed
				Option 2	1.5	0	49
				Option 3	1.59	0	57
				Option 4	1.49	0	45
				Option 5	1.5	0	49
			Open: Moderately Constricted	Base Case: Option 1	1.47	0	46
				Option 2	1.44	0	41
				Option 3	1.44	0	39
				Option 4	1.42	0	36
				Option 5	1.44	0	41
			Post-Flood Scoured Entrance	Sensitivity	1.35	0	20

Tangible Flood Damages



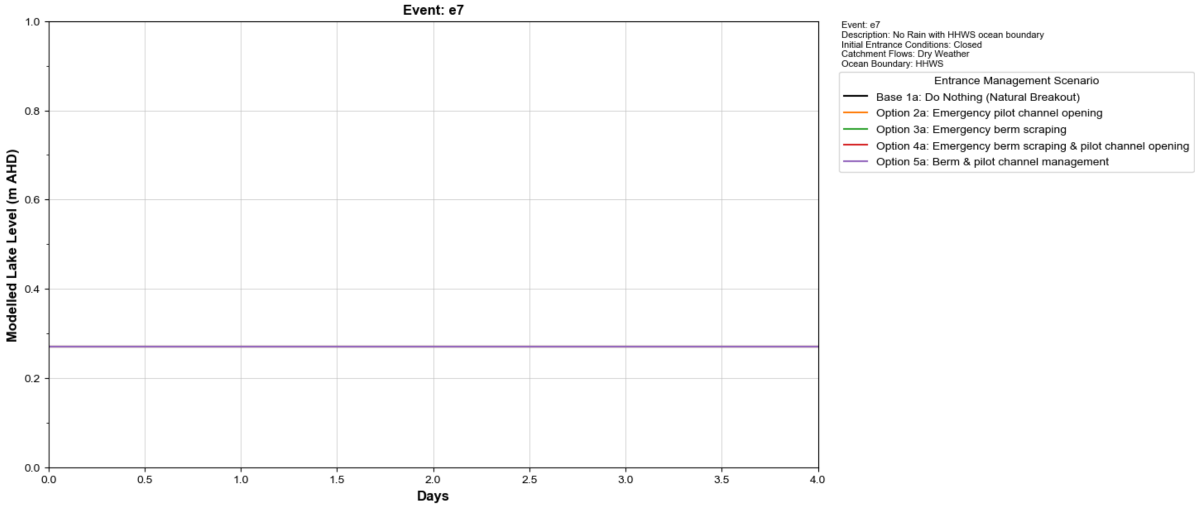


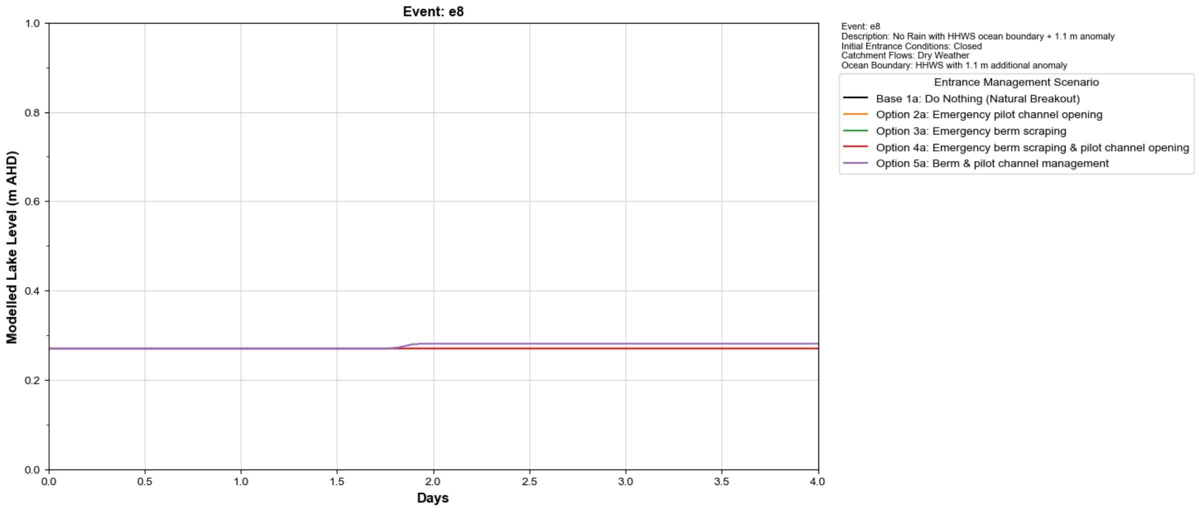


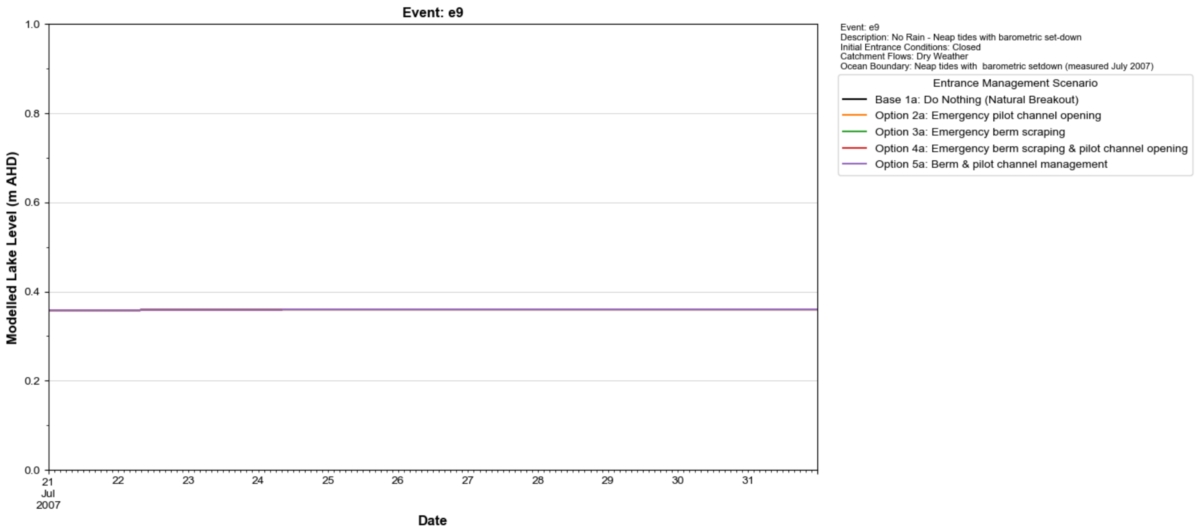


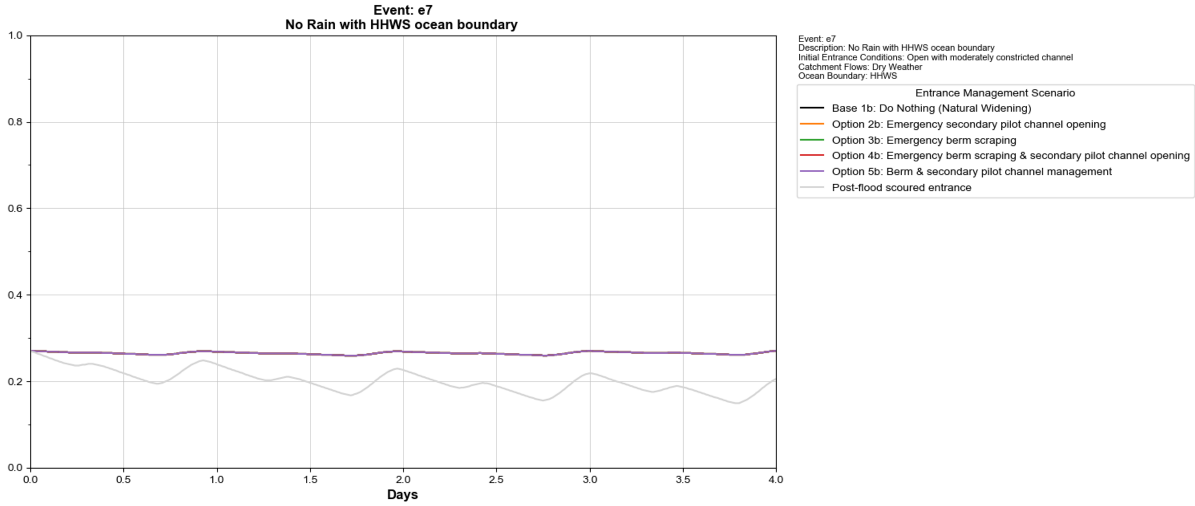

Flood Damages a) Initial Entrance Closed
Flood Damage b) Initial Entrance Open - Moderately Constricted
Peak Water Level a) Initial Entrance Closed
Peak Water Level b) Initial Entrance Open - Moderately Constricted
Event: e5
Catchment flows: %20AEP
Ocean water level anomaly: No anomaly
Peak Lake Level (m AHD)
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
$1,800,000
$1,600,000
$1,400,000
$1,200,000
$1,000,000
$800,000
$600,000
$400,000
$200,000
$0
Tangible Flood Damages ($)
Base case: Option 1
Option 3
Option 5
Management Option
Event: e6
Catchment flows: %20AEP
Peak Lake Level (m AHD)
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
$2,000,000
$1,800,000
$1,600,000
$1,400,000
$1,200,000
$1,000,000
$800,000
$600,000
$400,000
$200,000
$0
Tangible Flood Damages ($)
Base case: Option 1
Option 3
Option 5
Management Option

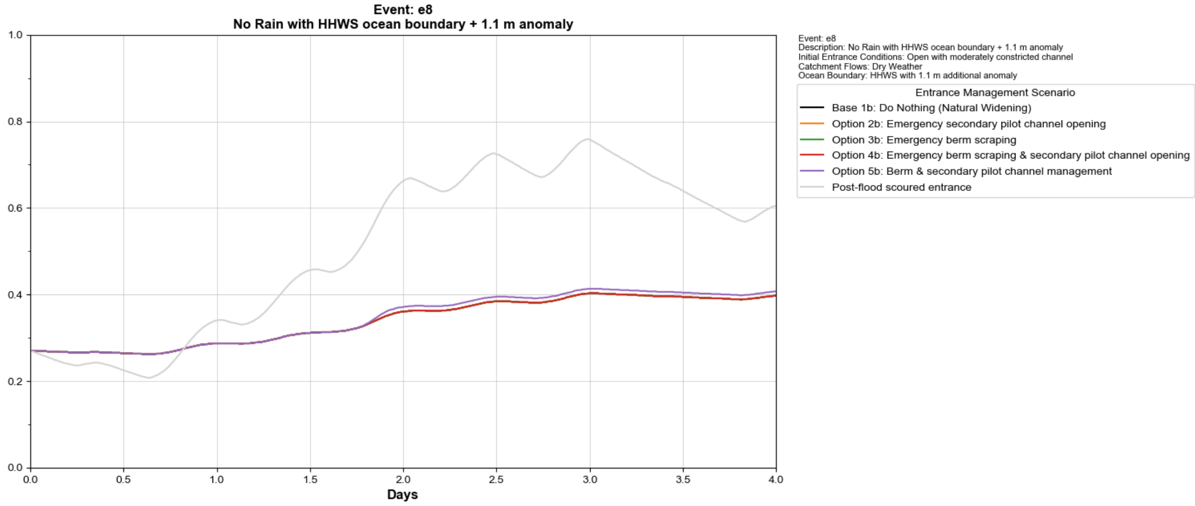
Dry Weather Events Lakes Level

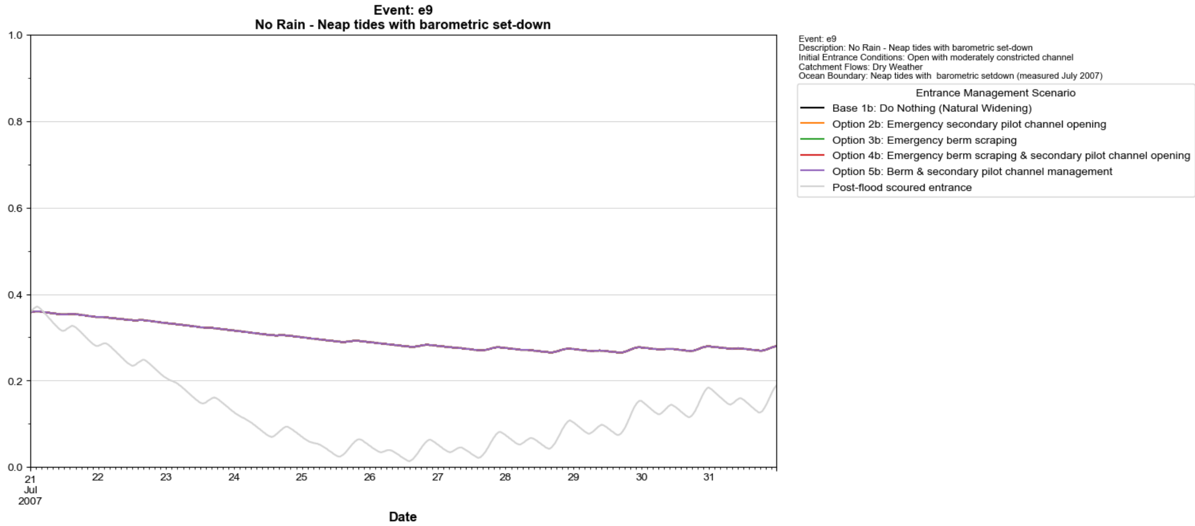







Event: e7
No Rain with HHWS ocean boundary
Event: e7
Description: No Rain with HHWS ocean boundary
Initial Entrance Conditions: Open with moderately constricted channel
Catchment Flows: Dry Weather
Ocean Boundary: HHWS
Entrance Management Scenario
Base 1b: Do Nothing (Natural Widening)
Option 2b: Emergency secondary pilot channel opening
Option 3b: Emergency berm scraping
Option 4b: Emergency berm scraping & secondary pilot channel opening
Option 5b: Berm & secondary pilot channel management
Post-flood scoured entrance
Days

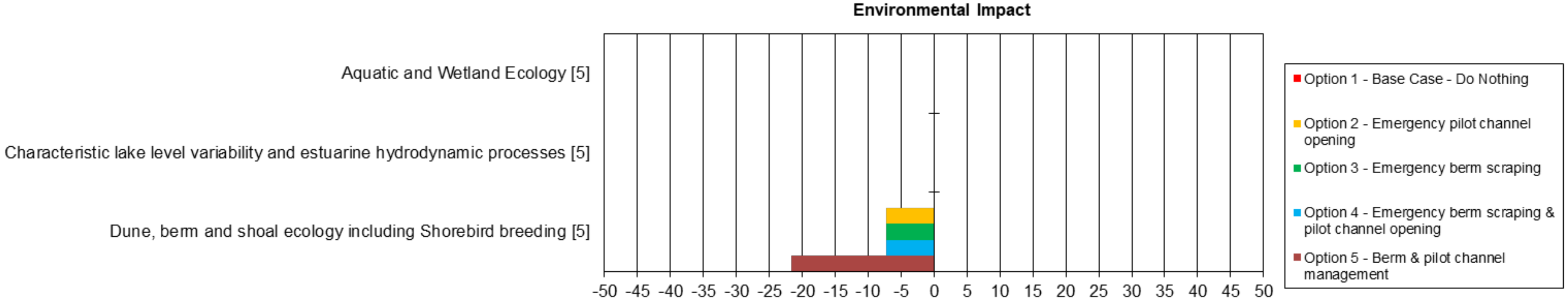

Event: e8
No Rain with HHWS ocean boundary + 1.1 m anomaly
Event: e8
Description: No Rain with HHWS ocean boundary + 1.1 m anomaly
Initial Entrance Conditions: Open with moderately constricted channel
Catchment Flows: Dry Weather
Ocean Boundary: HHWS with 1.1 m additional anomaly
Entrance Management Scenario
Base 1b: Do Nothing (Natural Widening)
Option 2b: Emergency secondary pilot channel opening
Option 3b: Emergency berm scraping
Option 4b: Emergency berm scraping & secondary pilot channel opening
Option 5b: Berm & secondary pilot channel management
Post-flood scoured entrance
Days

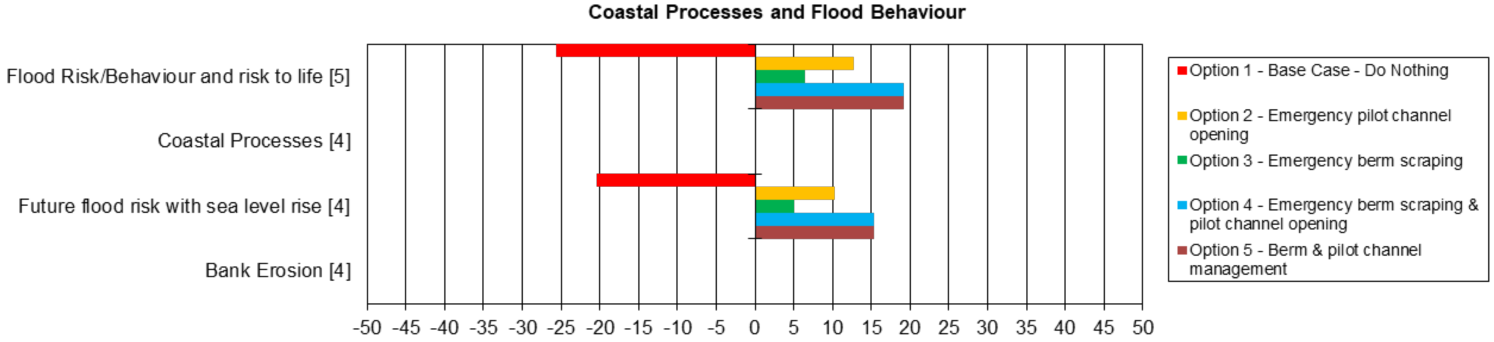

Event: e9
No Rain - Neap tides with barometric set-down
Event: e9
Description: No Rain - Neap tides with barometric set-down
Initial Entrance Conditions: Open with moderately constricted channel
Catchment Flows: Dry Weather
Ocean Boundary: Neap tides with barometric setdown (measured July 2007)
Entrance Management Scenario
Base 1b: Do Nothing (Natural Widening)
Option 2b: Emergency secondary pilot channel opening
Option 3b: Emergency berm scraping
Option 4b: Emergency berm scraping & secondary pilot channel opening
Option 5b: Berm & secondary pilot channel management
Post-flood scoured entrance
21 Jul 2007
Date

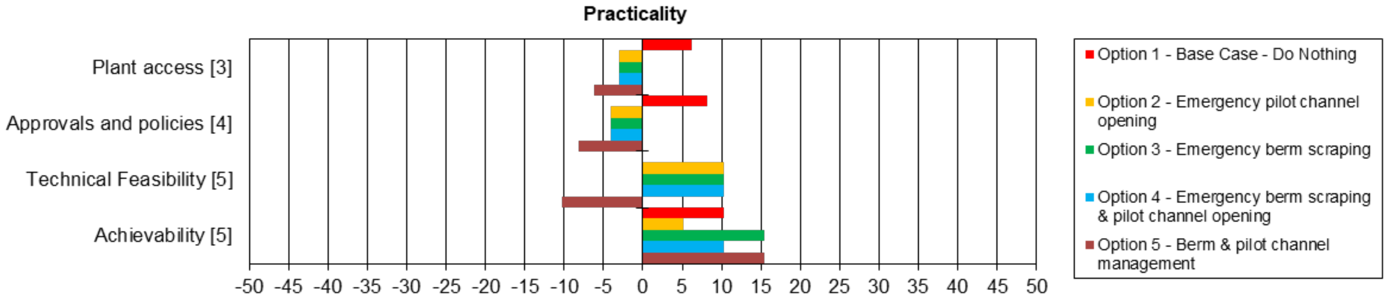
Event	Catchment Flows	Ocean Water Levels	Starting Entrance Condition	Management Option	Peak Lake Level (m AHD)	Duration above 0.5 m AHD (h)
e7	Dry-Weather	HHWS	Closed	Base Case: Option 1	0.27	0
				Option 2	0.27	0
				Option 3	0.27	0
				Option 4	0.27	0
				Option 5	0.27	0
			Open: Moderately Constricted	Base Case: Option 1	0.27	0
				Option 2	0.27	0
				Option 3	0.27	0
				Option 4	0.27	0
				Option 5	0.27	0
			Post-Flood Scoured Entrance	Sensitivity	0.27	0
e8	Dry-Weather	HHWS + 1.1 m Anomaly	Closed	Base Case: Option 1	0.27	0
				Option 2	0.27	0
				Option 3	0.27	0
				Option 4	0.27	0
				Option 5	0.28	0
			Open: Moderately Constricted	Base Case: Option 1	0.4	0
				Option 2	0.4	0
				Option 3	0.4	0
				Option 4	0.4	0
				Option 5	0.41	0
			Post-Flood Scoured Entrance	Sensitivity	0.76	67

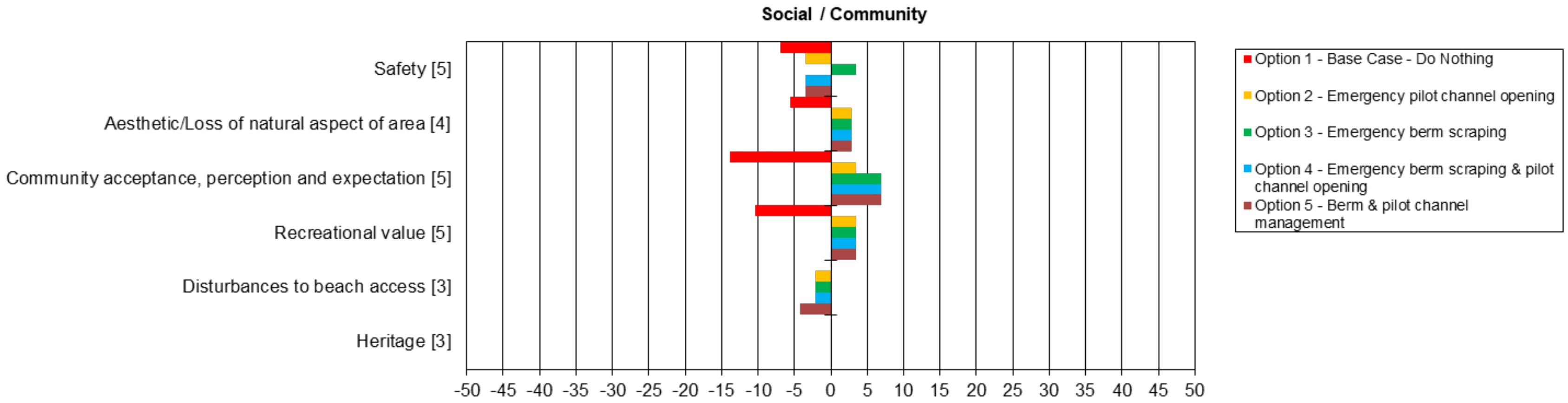
Event	Catchment Flows	Ocean Water Levels	Starting Entrance Condition	Management Option	Minimum Lake Level (m AHD)	Duration below 0.1 m AHD (h)
e9	Dry-Weather	Neap tides with barometric setdown	Closed	Base Case: Option 1	0.36	0
				Option 2	0.36	0
				Option 3	0.36	0
				Option 4	0.36	0
				Option 5	0.36	0
			Open: Moderately Constricted	Base Case: Option 1	0.27	0
				Option 2	0.27	0
				Option 3	0.27	0
				Option 4	0.27	0
				Option 5	0.27	0
			Post-Flood Scoured Entrance	Sensitivity	0.01	129

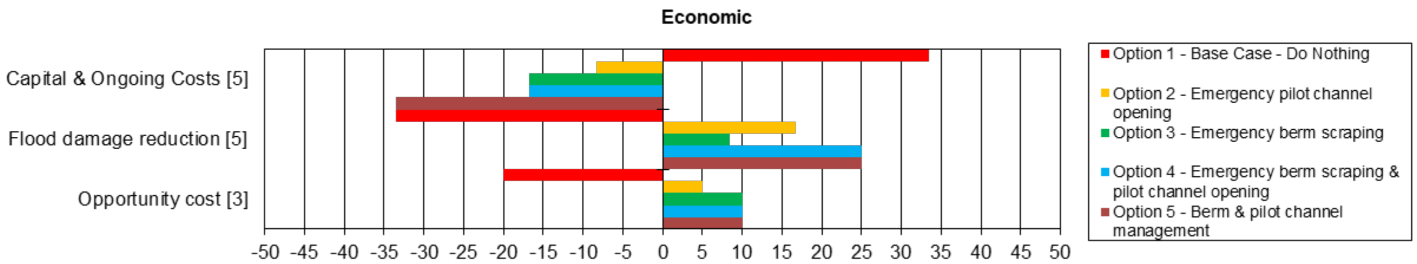
Appendix D Multi-criteria scoring breakdown





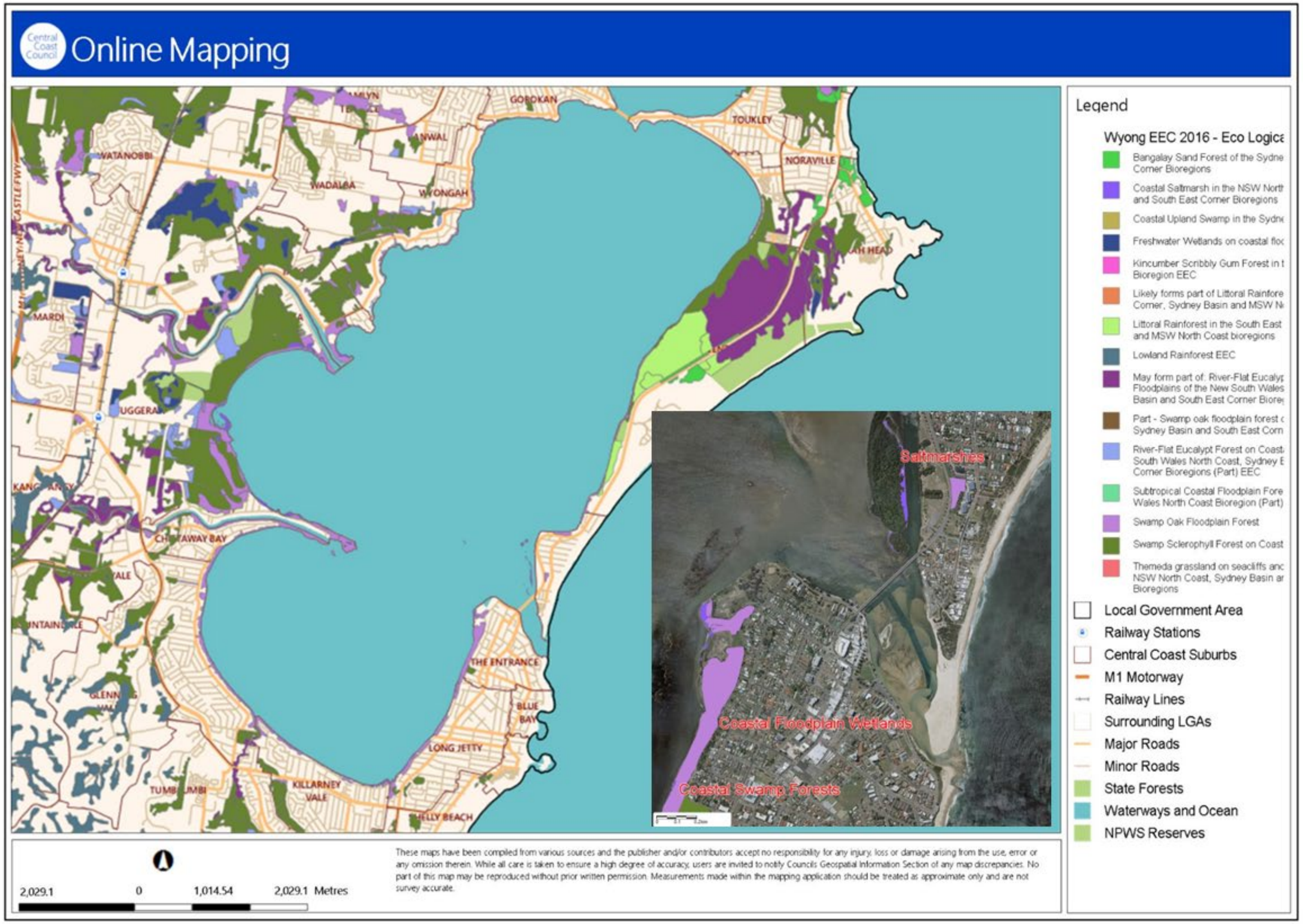



Social / Community
Safety [5]
Aesthetic/Loss of natural aspect of area [4]
Community acceptance, perception and expectation [5]
Recreational value [5]
Disturbances to beach access [3]
Heritage [3]
-50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50
Option 1 - Base Case - Do Nothing
Option 2 - Emergency pilot channel opening
Option 3 - Emergency berm scraping
Option 4 - Emergency berm scraping & pilot channel opening
Option 5 - Berm & pilot channel management

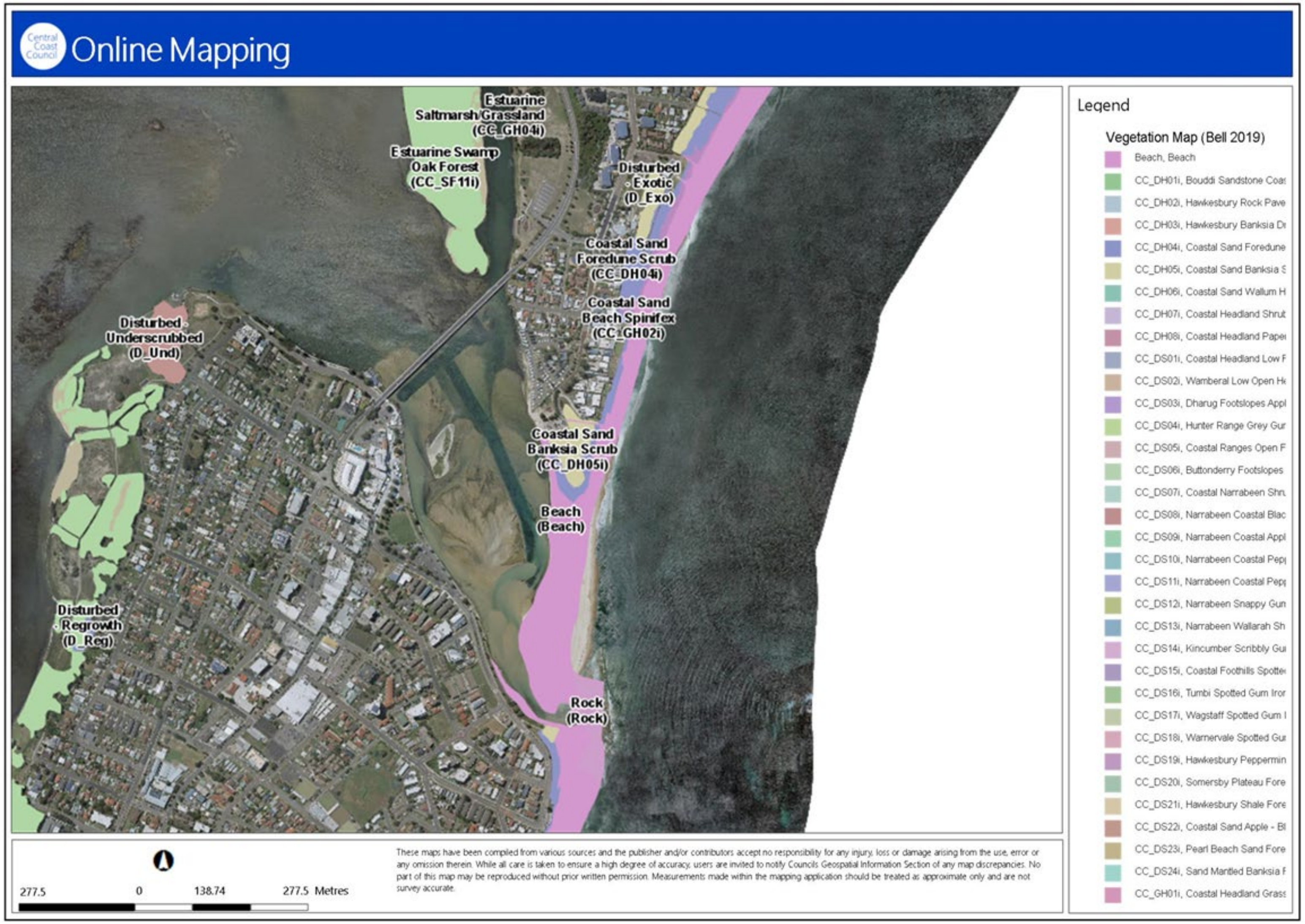

Economic
Capital & Ongoing Costs [5]
Flood damage reduction [5]
Opportunity cost [3]
-50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50
Option 1 - Base Case - Do Nothing
Option 2 - Emergency pilot channel opening
Option 3 - Emergency berm scraping
Option 4 - Emergency berm scraping & pilot channel opening
Option 5 - Berm & pilot channel management

Appendix E Preliminary environmental mapping

Estuarine habitats of Tuggerah Lakes (Creese et al., 2009)



Ecological Endangered Communities (Wyong EEC, 2016)



Vegetation mapping (Bell, 2019)