Tuggerah Lakes Flood Study Review

Draft Report

Report MHL2929

26 September 2025

Prepared for: Central Coast Council

Department of Climate Change, Energy, the Environment and Water

Cover Photograph: Looking across Geoffrey Road, Chittaway Point over Tuggerah Lake towards The Entrance, 3 March 2022, courtesy of Central Coast Council.

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Foreword

The NSW Government's professional specialist advisor, Manly Hydraulics Laboratory (MHL), was commissioned by Central Coast Council to undertake a review of the Tuggerah Lakes Flood Study, improve understanding of flood behaviour and impacts, and better inform management of flood risk in the study area in consideration of the available information and relevant standards and guidelines.

The report was prepared by Kyle Hasler, Armaghan Severi, Matthew Phillips, Atikul Islam and Matthieu Glatz.

Executive summary

The Tuggerah Lakes Flood Study Review, commissioned by Central Coast Council and prepared by Manly Hydraulics Laboratory (MHL), provides an updated assessment of flood behaviour and risk within the Tuggerah Lakes system. This review builds upon the foundational 1994 Tuggerah Lakes Flood Study by Lawson and Treloar and the 2014 Tuggerah Lakes Floodplain Risk Management Study and Plan (FRMSP) by WMA Water.

A review and update of the 1994 flood study is warranted noting recent advances in rainfall and runoff modelling techniques, significant changes in key guidelines, the availability of an additional 30 years of monitoring data available throughout the catchment, the occurrence of several historical floods including a number of recent events, new interim entrance management procedures (MHL, 2022) and the continued development of the foreshores of Tuggerah Lakes.

Purpose and scope

The primary objective of this study is to improve understanding of lake-based flood behaviour and its consequences, and to provide a technically robust foundation for managing flood risk. The study focuses exclusively on inundation originating from the Tuggerah Lakes system, namely Tuggerah Lake, Budgewoi Lake, and Lake Munmorah, and does not seek to define tributary or overland flooding, which are addressed in separate catchment studies. The study also sought to represent current catchment and entrance conditions, excluding any potential entrance management strategies or modifications, such as training walls, that may or may not be implemented in the future.

Methodology and key components

The key components of this flood study included:

- Review of historical and recent flood studies and data;
- Community consultation including a survey of over 8,800 residents, with 484 responses informing local flood awareness and historical flood impacts;
- Extreme value analysis on Tuggerah Lake level observations;
- Hydrological and hydraulic modelling of events from 20% AEP to 1 in 500 AEP and the Probable Maximum Flood (PMF);
- Hydraulic modelling of various oceanic inundation scenarios under present-day and future climate change scenarios;
- Calibration to the June 2007 and July 2022 flood events, and validation using the March 2021 event;
- Sensitivity testing of key parameters (e.g. rainfall losses, entrance scour, tailwater levels);
- Flood mapping and hazard classification aligned with NSW Flood Risk Management Guidelines;

- Evaluation of climate change impacts for 2040, 2070, and 2120; and
- Evaluation of flood consequences on the community, infrastructure, property and emergency response.

Key findings

Analysis of the results of the hydrologic and hydraulic modelling found that flooding within the Tuggerah Lakes catchment is relatively slow onset in nature, driven by prolonged rainfall events of moderate intensity, with critical durations ranging between 72 and 144 hours. The entrance channel (i.e. the channel connecting the lakes to the ocean at The Entrance) plays a role in flood behaviour, with its dynamic morphology, potentially ranging from fully closed to wide open. During major events, the entrance channel can scour and widen, facilitating increased outflows; in dry periods, it can infill with sand, reducing tidal exchange between the lake system and the ocean.

The model was calibrated and validated using three recent flood events, showing good agreement between modelled and observed lake levels. A comprehensive sensitivity analysis was undertaken to evaluate the influence of key hydrologic and hydraulic parameters on flood behaviour within the Tuggerah Lakes system under the 1% AEP flood event scenario.

Sensitivity testing confirmed that rainfall losses, tailwater levels, and entrance scour duration are the most influential parameters affecting flood peaks. For example:

- Should no rainfall losses occur in the catchment, this may increase peak lake levels by 0.14 m.
- Should the scour take longer or be slower, this may increase peak lake levels by up to 0.15 m.
- High ocean tailwater levels (e.g. 2.35 mAHD) may increase peak lake levels by 0.12 m.

These results were used to inform the uncertainty associated with the model and as such the recommended flood planning levels and freeboard.

A table summarising the results of the present study as determined by hydrologic and hydraulic modelling, and by extreme value analysis is presented below. This table also compares results using similar methodologies as determined by the 1994 study.

Event	Peak Tuggerah Lakes flood level (mAHD)				
	1994 study		Present study		
	Extreme Value Analysis	Hydrologic and hydraulic modelling	Annual Maximum Series Extreme Value Analysis	Peak-Over-Threshold Extreme Value Analysis	Hydrologic and hydraulic modelling
PMF		2.70			3.04
1 in 500 AEP			2.35 – 2.45		2.62
1 in 200 AEP			2.25 – 2.33		2.46
1% AEP	2.20	2.23	2.13 – 2.21		2.24
2% AEP			1.98 – 2.06		2.03
5% AEP	1.90	1.80	1.73 – 1.78		1.73

Event	Peak Tuggerah Lakes flood level (mAHD)				
	1994 study		Present study		
	Extreme Value Analysis	Hydrologic and hydraulic modelling	Annual Maximum Series Extreme Value Analysis	Peak-Over-Threshold Extreme Value Analysis	Hydrologic and hydraulic modelling
10% AEP			1.50 – 1.53	1.34	1.49
20% AEP	1.35	1.36		1.07	1.22
50% AEP	0.90	0.91		0.76	

Climate change impacts

The study adopted the SSP2-4.5 scenario for climate change projections, consistent with Central Coast Council's draft policy. Projected increases in rainfall intensity and sea level could raise lake flood levels by:

- +0.28 m by 2040
- +0.50 m by 2070
- +0.83 m by 2120

These projections are based on ARR 2019 guidance and can be used to inform long-term planning.

Flood prone areas and community impacts

It was found that key areas identified as vulnerable to lake flooding include, but are not limited to:

- Chittaway Point
- Tacoma and Tacoma South
- Tuggerawong
- The Entrance North (behind the Wilfred Barrett Drive levee)

Flood mapping was refined to isolate lake-driven inundation from tributary and overland flooding. Hazard classifications and Flood Emergency Response Classification Categories (FERCCs) were applied in accordance with NSW Flood Risk Management Guidelines.

Flood mapping was prepared for each of the abovementioned scenarios, consisting of peak water level, depth and velocity mapping. A preliminary impact assessment identified the number of affected lots, key infrastructure, and roads under various flood scenarios. The study also defined a new Flood Planning Area (FPA), which will be adopted by Council. A freeboard of 0.5 m above the 1% AEP level was adopted to define the FPA to account for modelling uncertainty, and in accordance with the NSW Flood Risk Management Manual.

Contents

Classification: Public

Classification: Public

TABLES

FIGURES

Classification: Public

1 Introduction

1.1 Background

Under the NSW Flood Prone Land Policy and Flood Risk Management Manual (2023; superseding the 2005 Floodplain Development Manual), the management of flood liable land remains the responsibility of local government.

The original Tuggerah Lakes Flood Study was completed in 1994 by Lawson and Treloar. The study was undertaken to determine the flood behaviour events with Annual Exceedance Probabilities (AEP) of 50%, 20%, 5% and 1% 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.

This study was followed by the Tuggerah Lakes Floodplain Risk Management Study and Plan (FRMSP) published in 2014 (WMA Water, 2014). The Tuggerah Lakes FRMSP provided management recommendations to reduce risk to life, public and private infrastructure associated with flooding. Several recommendations were made to reduce flood risk including adaptation planning for foreshore suburbs, flood emergency management planning, development of public education and awareness, adoption of development controls and formalising an entrance management strategy. The FRMSP was based on modelled flood behaviour from the Tuggerah Lakes Flood Study (Lawson and Treloar, 1994).

A review and update of the original flood study investigations is now warranted for a number of reasons including recent advances in rainfall and runoff modelling techniques, significant changes in key guidelines (Australian Rainfall and Runoff, ARR 2019), additional 29 years of monitoring data available throughout the catchment, several historical floods including a number of recent events, new interim entrance management procedures (MHL, 2022), increased development of the foreshores of Tuggerah Lakes and the benefits associated with making more informed land use planning decisions.

1.2 Study objectives

The objective of this study is to improve understanding of flood behaviour and impacts and better inform management of flood risk in the Tuggerah Lakes study area in consideration of the available information, and relevant standards and guidelines. The aim of this study is to inform:

- Relevant government information systems;
- Government and strategic decision makers on flood risk;
- The community;
- Flood risk management planning for existing and future development;
- Emergency management planning for existing and future development, and strategic and development scale land-use planning to manage growth in flood risk; and
- Other key stakeholders (including utility providers and the insurance industry) on flood risk.

The outputs of the study may be able to assist this by facilitating information sharing on flood risk across government and with the community, and providing a better understanding of:

- The variation in flood behaviour, flood function, flood hazard and flood risk in the study area;
- Impacts and costs for a range of flood events or risks on the existing and future community;
- Impacts of changes in development and climate on flood risk;
- Emergency response situation and limitations; and
- Effectiveness of current management measures.

This study focuses on lake-based flooding within the Tuggerah Lakes system and does not include detailed modelling of tributary or overland flood interactions. Specifically, flooding associated with major contributing creeks and rivers is outside the scope of this study. These catchments are addressed in separate flood risk management studies and plans.

Further, this study does not set out to assess the impacts of a managed trained or permanently open entrance. The modelling reflects current natural entrance dynamics and excludes hypothetical modifications or interventions. These types of interventions are outside the scope of this flood study and may be considered in future Flood Risk Management Studies and Plans (FRMS&P) or Coastal Management Programs (CMPs), where broader strategic and environmental implications can be evaluated.

1.3 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 tidal channel through the barrier dune at The Entrance. 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 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 km^2, 160 km^2 and 14 km^2 respectively to the southern end of Tuggerah Lake, and Wallarah Creek drains a catchment area of around 32 km^2 into Budgewoi Lake.

Prior to European settlement in 1825, Aboriginal peoples occupied the Tuggerah Lakes catchment area (Darkinjung land) 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) around the low-lying foreshore of the lakes. Nowadays, around 80% of the shorelines of the Tuggerah Lakes are urbanised, primarily in the form of residential land use, and is susceptible to flood damages. In 2014, it was estimated that approximately 1,300 buildings would be impacted by the 1% AEP lake flood event and with a long-term annual average damage for the foreshore properties surrounding Tuggerah Lakes of $2.2 million (WMA Water, 2014).

Ocean tides in the region are microtidal with mean spring and neap ranges of 1.3 m and 0.8 m, respectively. The regional wave climate is of moderate to high energy. The tidal range within the lakes is relatively small in the order of centimetres and average lake levels vary between 0.2 to 0.3 m AHD due to the dynamic constriction of the entrance channel and shoals. Over the past 29 years, recorded lake levels at Long Jetty (211418) typically vary between 0.09 and 0.50 m AHD (90% of the time) and have been measured to reach in excess of 1.75 m AHD during flood events.

The study area is presented in **Figure D.1**. Hydrologic modelling for the present study covered the full catchment area presented, while hydraulic modelling and analysis of flood impacts and behaviour in the present study was focussed on flooding of the Tuggerah Lakes system in lower reaches of the catchment, with elevations less than approximately 3 mAHD.

1.4 History of flooding and rainfall

Historical records and observations provide valuable evidence of historic flood behaviour in the Tuggerah Lakes catchment in response to heavy rainfall. Flood events have had a history of resulting in inundation of land and, in some instances, built assets. A summary of historical peak lake water levels for Tuggerah Lakes is shown in **Table 1.1**. It is noted that accurate gauged water levels measurement commenced in Tuggerah Lakes in 1985 after installation of the Toukley and Killarney Vale gauges. Prior lake water levels are based on historical observations.

The largest known flood occurred on the 18 June 1949, reaching a lake level of approximately 2.1 m AHD. Lake flood levels are estimated to have equalled or exceeded 1.5 m AHD at least 14 times over the last 100 years and five times since gauged water level records began in 1985 (February 1990, June 2007, February 2020, March 2021 and July 2022). Recent flooding in July 2022 resulted in lake levels reaching 1.76 m AHD at Toukley and Wallarah Creek Bridge gauges, the highest on record since gauging began in 1985.

Table 1.1 Summary of historical peak lake water levels (adapted from WMA Water, 2014)

Event	Historical recorded peak lake level (m AHD)	Measured gauge peak lake level (m AHD)		
		Toukley	Wallarah Creek Bridge	Long Jetty
18 June 1949	2.10	-	-	-
April 1946	1.88	-	-	-
2 May 1964	1.87	-	-	-
April 1927	1.81	-	-	-
1931	1.81	-	-	-
6 July 2022	-	1.76	1.76	1.72
11 Feb 2020	-	1.66	1.66	1.67
10 June 2007	-	1.68	1.65	1.64
4 February 1990	-	1.61	-	-
4 March 1977	1.59	-	-	-
22 March 2021	-	1.50	1.49	1.52
1963	1.53	-	-	-
1953	1.49	-	-	-
1941	1.48	-	-	-

Notes: Historical records obtained from WMA Water (2014) and Lawson and Treloar (1994). It is likely that several floods prior to 1970 may not have been recorded. Gauged lake levels can be subject to wind and wave setup effects.

Photographs of recent and historical flood events have been provided by community members as part of the community consultation process and from Central Coast Council's Library Service. Selected photos and historical accounts of past flood events (chronologically listed) are shown below (**Figure 1.1** to **Figure 1.17**).

A detailed summary of historical flood information and accounts spanning 1867 to 1992 is provided in *Tuggerah Lakes Flood Study Compendium of Data. New South Wales. Coast and Rivers Branch. October 1992*.

Also associated with past flood events is historical information describing changing entrance conditions and past interventions at the dynamic entrance channel opening to the ocean. This information is summarised in the *Tuggerah Lakes Entrance Management Study, MHL, 2022.*

Additional flood history in various upstream catchments and tributaries feeding into Tuggerah Lakes is documented in previous flood studies (see **Section 2**).

Figure 1.1 Flooding c. 1909 looking south from Wyong through to Tuggerah over the road and train lines. Courtesy of Central Coast Council

Figure 1.2 Damages to the original Long Jetty (built 1914 by William Henry Price) following flooding in Easter 1927. Courtesy of Central Coast Council

Figure 1.3 Northern railway line just north of Tuggerah Station covered by flood waters, Wyong 1927. Courtesy of Central Coast Council

FEARS OF FLOOD

There is considerable apprehension among residents of Tuggerah, Wyong, Gosford and Woy Woy as a result of the flood waters again rising. Early yesterday afternoon the floods showed signs of receding, but towards evening commenced to rise again. Three feet of water washed through some homes at Woy Woy, and although the position was slightly easier this morning grave fears are entertained unless the rain ceases. The Wyong River burst its banks at Wyong this morning, marooning many homes. Road traffic between Peats Ferry and Gosford is suspended owing to washaways.

The rainfall in Sydney for the 24 hours ended 9 a.m. to-day was 780 points, which is the highest since 1883.

Figure 1.4 The Northern Star Newspaper, Page 7, July 8 1931
https://trove.nla.gov.au/newspaper/article/94187368

WYONG

Families sat on the rooftops at Wyong and watched the floodwaters swirl past the houses. Hundreds were rescued by police boats. Several houses outside the town are completely submerged.

The main railway line between Sydney and Newcastle was under water for more than half a mile south of Wyong.

When the Wyong river burst its banks the floodwaters spread over hundreds of acres of low lying country.

The Pacific Highway at places was feet deep in water and traffic ceased.

Sergeant M. D. McAuliffe and Constable R. Wilson, of Wyong, rescued more than 50 people from their marooned houses in two motor launches.

The main road between Wyong and Tuggerah Lakes was flooded to a depth of five feet.

Citrus fruit growers in the Gosford district suffered heavily. More than 2,000 orange trees at one farm were under water, and the owner estimated he would lose £5,000.

Figure 1.5 The Canberra Times, Page 1. 20 June 1949
https://trove.nla.gov.au/newspaper/article/2809821

Figure 1.6 Parry's Jetty under flood c. 1960s. Bailey, Harold. Courtesy of Central Coast Council

Figure 1.7 Payne's boat shed on Tuggerah Lake at Long Jetty during flood 1960s. Bailey, Harold. Courtesy of Central Coast Council

Figure 1.8 Approximately 250 m north along South Tacoma Rd from Kingsland Cl, facing northwest, 5th February 1990. Courtesy of a local resident

Figure 1.9 Marine Rescue Tuggerah Lakes Unit, Peet St, Toukley, 10th February 2020. Courtesy of a local resident

Figure 1.10 Leonard St, The Entrance North, Facing southwest, 11th February 2020. Courtesy of a local resident

Figure 1.11 Lakedge Ave, Berkeley Vale, immediately south of Kingsford Smith Dr, facing east, 4th March 2022. Courtesy of a local resident

Figure 1.12 Lakedge Ave, Berkeley Vale, 100 m south of Kingsford Smith Dr intersection, Facing south, July 2022. Courtesy of a local resident

Figure 1.13 Lakedge Ave, Berkeley Vale, Facing south along Albatross Road at the intersection of Lakedge Avenue and Albatross Road, 8th July 2022. Courtesy of a local resident

Figure 1.14 Tuggerah Pde, Long Jetty, Facing east along Venice Street at the intersection of Tuggerah Pde and Venice Street, July 2022. Courtesy of a local resident

Figure 1.15 Moui Ave, Chittaway Bay, July 2022. Courtesy of a local resident

Figure 1.16 230 Geoffrey Road facing southwest, Chittaway Point. July 2022. Courtesy of a local resident

Figure 1.17 Facing north along Crosby Crescent, Killarney Vale, July 2022. Courtesy of a local resident

1.5 Land use and zoning

Land zoning GIS spatial data was provided by the Council, shown in **Figure D.2**. The land zoning within the floodplain surrounding the lakes is classified under a range of zonings. Land use within the catchment primarily consists of Forestry (RU3), National parks and natural reserves (E1), Environmental management (E3), Primary production (RU1), Recreational waterways (W2), Environmental conservation (E2), Low density residential (R2).

1.6 Demographic overview

Understanding the social characteristics of the study area can help ensure appropriate risk management practices are adopted and shape the methods used for community engagement. House tenure and age distribution data obtained from census data can indicate the community's experience with recent flood events, and hence an indication of community's flood awareness. As per The Bureau of Meteorology Flood Preparedness Manual, using the population census data and other information held by councils and state agencies can help to identify the potential number and location of people in an area with special needs or requiring additional support during floods (Australian Government (Attorney – General's Department), 2009). The relevant information has been extracted from the 2021 Census for Wyong and tabulated in **Table 1.2**.

1.7 Relevant Policies, legislation and guidance

The NSW Floodplain Risk Management Process

The Tuggerah Lakes Flood Study Review has been prepared in accordance with the New South Wales Government's *Flood Risk Management Manual* (NSW Government, 2023). The primary objective of which is to:

> *"reduce the impact of flooding and flood liability on communities and individual owners and occupiers of flood prone property, and to reduce private and public losses resulting from floods, utilising ecologically positive methods wherever possible."*

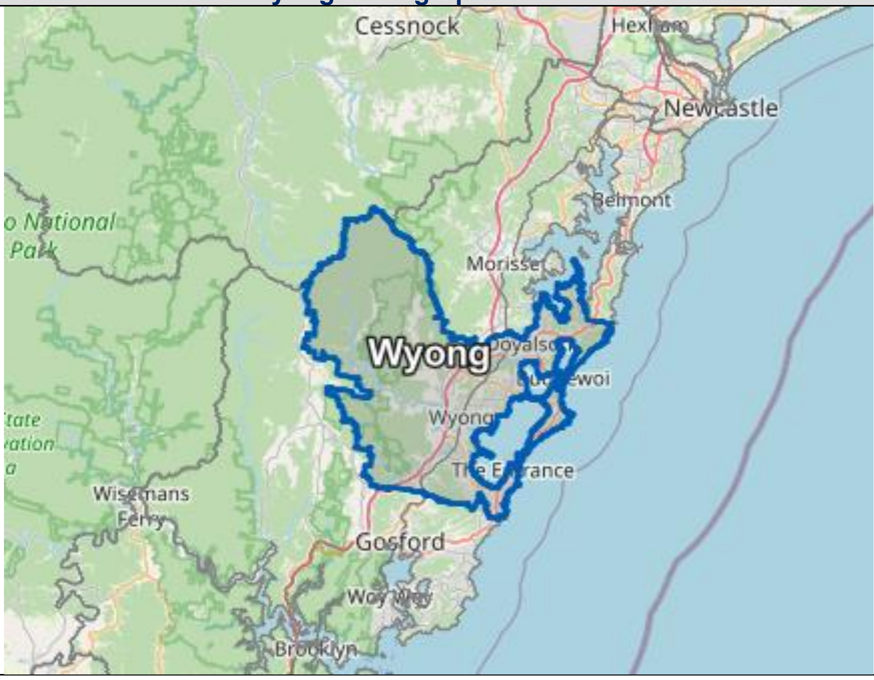
Under the policy, primary responsibility for flood risk management rests with local government. Financial and technical assistance is provided to councils by the NSW Government.

The *Flood Risk Management Manual* defines the following steps in the Flood Risk Management Process:

- Formation of a Project Technical Group
- Data Collection
- Flood Study Preparation
- Floodplain Risk Management Study Preparation
- Floodplain Risk Management Plan Preparation
- Floodplain Risk Management Plan Implementation

By following the NSW Flood Risk Management Process, Central Coast Council is and has been adopting a best practice, State supported pathway for the methodical identification, assessment and implementation of robust and effective flood risk management measures to reduce the impacts of flooding on the community and existing development, and to ensure that future development is compatible with flood risk. Councils following the NSW Flood Risk Management Process demonstrate duty of care with respect to the management of flood liable land and are exempted from liability under Section 733 of the Local Government Act 1993.

Table 1.2 Wyong demographic overview based on the 2021 census.

Wyong demographic overview	
	
Source: https://www.abs.gov.au/census/find-census-data/quickstats/2021/10202	
Population	168,171
Number of private dwellings	69,505 (either occupied or unoccupied)
Number of single-person householders	16,890 (26.8%)
Property tenure	Owned: 42,999 (68.1%, either outright or with a mortgage) Rented: 18,062 (28.6%)
Number of persons over the age of 75	16,874 (9.9%)
Number of single-parent families	9,840 (21.4%)
Language	English only is spoken at home: 149,094 (88.7%) A non-English language spoken at home: 5,095 (8.1%)
Average number of children per families with children	1.8
Average number of children per all households	0.7
Number of educated people aged 15 years and over	120,219 (87.7%)
Employed (including worked full-time, part-time and away from work)	70,958 (94.8%)

Following the NSW Flood Risk Management Process, Central Coast Council have undertaken the Tuggerah Lakes Flood Study (Lawson and Treloar, 1994) to understand flood behaviour and the Tuggerah Lakes Floodplain Risk Management Study and Plan (WMA Water, 2014) to provide management recommendations to reduce risk to life, public and private infrastructure associated with flooding (see **Section 1.1**).

A review and update of the Tuggerah Lakes Flood Study ensures that an understanding and predictions of flood behaviour, a fundamental component of the Flood Risk Management Process, are technically robust and meet contemporary standards and guidelines.

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.

Central Coast Local Environmental Plan 2022

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 Central Coast Local Environmental Plan (LEP) 2022.

The Central Coast LEP 2022 has been developed in accordance with NSW Department of Climate Change, Energy, the Environment and Water (DCCEEW) requirements to control development via land zonings and other relevant planning provisions.

Standard Instrument (Local Environmental Plans) Amendment (Flood Planning) Order 2021 modified previous clauses 5.21 and 5.22 of all LEPs. Clause 5.21 is a compulsory inclusion while Council's can "opt in" to include clause 5.22. Amongst other changes, clause 5.21 explicitly requires that the impact of climate change on flooding be considered. The wording also sharpens the focus on the Flood Planning Area as the principal area in which flood related development controls apply. Clause 5.22 allows for development controls to be applied to land between the flood planning area (FPA) and the Probable Maximum Flood (PMF) for sensitive and hazardous development such as caravan parks, hospitals, seniors housing, etc.

Tuggerah Lakes Coastal Management Program (currently in development).

Coastal Management Programs (CMP's) set the long-term strategy for the management of Council's coastal environments including the various lakes, lagoons, estuaries, beaches and their associated catchments. Central Coast Council has begun preparing the Tuggerah Lakes CMP in accordance with the NSW Government Coastal Management Framework. The CMP will replace existing Estuary & Coastal Zone Management Plans which were prepared under previous legislation.

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. Mapping of the coastal zone under the SEPP is shown in **Figure D.3**. 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.

Tuggerah Lakes Interim Entrance Management Procedure (MHL, 2022)

Under the NSW Flood Risk Management Manual (2023), the management of flood liable land remains the responsibility of local government. The Tuggerah Lakes Floodplain Risk Management Study and Plan (FRMSP) (WMA Water, 2014) provides management recommendations to reduce risk to life, public and private infrastructure associated with flooding. The FRMSP recommended several high priority actions to reduce flood risk including adaptation planning for foreshore suburbs, flood emergency management planning, development of public education and awareness program, adoption of development controls and formalisation of an entrance management strategy.

The Tuggerah Lakes Interim Entrance Management Procedure provides 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 the interim entrance management strategy is 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 utilise real-time quantitative data to facilitate a rational, proactive and informed approach to management actions.

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 protection of Aboriginal cultural heritage in NSW. DCCEEW administers the NPW Act and requires Aboriginal consultation to be undertaken in accordance with statutory requirements.

- *Crown Lands Management Act 2016*: The purpose of this Act is to consolidate statutory provisions dealing with the ownership, use and management of Crown land into one Act. The objects of the Act include facilitating Aboriginal people's use of Crown land, with emphasis on the co-management of Crown land where appropriate.

- *Biodiversity Conservation Act 2017*: Provides legislative requirements for 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.

- *Fisheries Management Act 1994 (FM Act)*: The FM Act 1994 contains provisions that allow for the preparation of threat abatement plans, threatened species recovery plans and habitat protection plans. These tools are enacted by legislation, and they outline actions to protect and rehabilitate aquatic habitats and threatened species, populations and communities.

- *Policy and guidelines for fish habitat conservation and management* (DPI, 2013): policy and guidance for artificial management of ICOLL entrances.

- *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.

- *Water Management Act 2000*: The objects of the Water Management Act 2000 are to provide for the sustainable and integrated management of the water sources of the state for the benefit of both present and future generations and, in particular: Ecologically sustainable development. Protect, enhance and restore water recourses.

- *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.

Tuggerah Lakes and its entrance region 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
- to 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;

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

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

  (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 Tuggerah Lakes Estuary Management Plan (2006) 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): 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.

A preliminary 'matters of national environmental significance' search has identified the following for the Tuggerah Lakes Study area:

- Listed Threatened Ecological Communities: 5
- Listed Threatened Species: 96
- Listed Migratory Species: 76

1.8 Flood behaviour

The Tuggerah Lakes system is susceptible to different modes of flooding, including inundation from both catchment rainfall-runoff and oceanic processes. Flood behaviour exhibited within the study is summarised as follows.

1.8.1 Mainstream flooding

Mainstream flooding is a result of relatively high-water flows which overtop the natural or artificial banks along any part of a watercourse (rivers, creeks, tributaries), lake, dam or lagoon. This study focuses on mainstream flooding of the lake waterbodies (Tuggerah Lake, Budgewoi Lake and Lake Munmorah) in the lower region of the Tuggerah Lakes catchment.

During high catchment rainfall events, there is a significant lag between the water level in the lakes and those in upstream reaches of tributaries (Wyong River, Ourimbah River, etc.), due to the substantial overbank flood storage capacity in the lake's floodplain areas.

Previous flood study investigation found critical flood durations of approximately 48 hours and 24 hours for the 1% Annual Exceedance Probability (AEP) and Probable Maximum Flood (PMF) events respectively (Lawson and Treloar, 1994). Longer duration extreme floods were noted to be critical for Tuggerah Lakes due to the volume of runoff being the principal factor in raising flood levels in the Lake system. The large surface area of the Lake system requires a considerable volume of runoff to raise the water level. The extent, rate and duration of flooding is governed by the volume of catchment runoff, temporal and spatial distributions of rainfall runoff over the catchment, ocean conditions (waves, tides and ocean anomalies) and the dynamic morphology of the entrance region (degree of entrance constriction).

The dynamic morphology of the entrance region is detailed in the Tuggerah Lakes Entrance Management Study (MHL, 2022). Using tidal harmonic analysis of historical lake level records, the study classified entrance dynamics into five characteristic morphological states, namely wide open, moderately open, moderately constricted, heavily constricted and fully closed. In the lead up to a flood event, the entrance may be any of these states depending on antecedent rainfall and ocean conditions in the several months and years prior. During a flood event, the entrance naturally scours and widens with the release of floodwaters from the lake system, with the entrance channel in some cases reaching widths in excess of 100 m. Following a flood and during periods of relatively low rainfall, the entrance naturally infills with marine sand to a more constricted state. Further information on entrance dynamics and modelling approach is provided in **Section 3.9**.

1.8.2 Overland flooding

Overland flooding is caused by heavy rainfall flowing across the ground or overflowing pipes, pits and gutters. It is inundation as a result of local runoff rather than inundation created by overbank flows discharging from a watercourse, lake or dam. Local overland flooding is often characterised by a rapid rise in flood levels, particularly where the local catchment is relatively steep and small. Overland flooding can be important for upstream areas of the Tuggerah Lakes catchment with lower reaches typically dominated by flooding of the lake water body with catchment runoff and coastal inundation.

1.8.3 Coastal inundation

Generally elevated ocean levels occur in combination with increased wave activity (wave setup at the entrance), spring tidal cycles and ocean anomalies (storm surge, coastal trapped waves, etc.). With the entrance channel relatively scoured and open, the water level in Tuggerah Lakes can temporarily increase as a result of elevated ocean water levels. Given the large storage volume of the Lakes system, this rise in water levels is relatively minor (rise of typically less than 1 m) compared to that associated with long duration heavy rainfall events. Lake levels may rise with long duration coastal storm events, occurring over multiple days, which create a pumping effect of ocean inflows over consecutive tidal cycles. The influence of coastal events on lake levels are reduced with more constricted entrance morphology that acts to throttle the amount ocean inflows into the Lake system. Projected sea level rise is likely to increase the impacts of coastal inundation on Tuggerah Lakes foreshores over the coming decades. While coastal inundation is not the focus of this study, the influence of the ocean conditions on lake flooding are assessed and incorporated in this study.

1.8.4 Combination of flood modes

These modes of flooding may occur in isolation or in combination with each other. For example, in May 1974 a significant coastal event with relatively minor rainfall resulted in lake levels increasing to approximately 1.2 m AHD to 1.3 m AHD with an estimated entrance width of around 40 m (Lawson and Treloar, 1994). During this event, the moderately constricted entrance likely provided some degree of restriction to ocean inflows and alleviated potential coastal inundation. On the other hand, in July 2022, lake levels reached a peak of 1.72 m AHD at Long Jetty and 1.76 m AHD at Toukley due to flooding associated with heavy catchment rainfall and subsiding ocean conditions (relatively minor compared with the May 1974 event).

Flooding is worsened during heavy catchment rainfall events that coincide with large coastal events, during which elevated ocean levels acts to reduce the outflows at the Lakes entrance.

Antecedent entrance conditions are noted also to influence flooding in the Lake system, particularly when the entrance is fully closed. Umwelt (2011) estimated 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. Full entrance closure is historically noted during the 1940's and may have exacerbated flood level during the large floods recorded during this period, however this is difficult to confirm due to lack of records.

1.8.5 Observed flood prone areas

Details of specific flood prone areas have been collated from the previous studies outlined in **Section 2** and from new accounts obtained through the community consultation process undertaken for this flood study. The aim is to capture and convey the key areas within the Tuggerah Lakes study area that have been susceptible to known lake flooding issues in the past. Listed flood prone areas include:

- Low-lying foreshore areas of Tuggerah Lake including regions in The Entrance North, The Entrance, Long Jetty, Killarney Vale, Berkeley Vale, Chittaway Bay, Chittaway Point, Tacoma, Tacoma South, Tuggerawong, Gorokan, Toukley and Canton Beach.
- Low-lying foreshore areas of Budgewoi Lake including regions in Gorokan, Toukley, Budgewoi, Buff Point, San Remo and Charmhaven.
- Low-lying foreshore areas of Lake Munmorah including regions in Budgewoi and Halekulani.
- Lower reaches of Wallarah Creek including Blue Haven.
- Lower reaches of the Wyong River including Wyong, Tacoma, Tacoma South and Tuggerah.
- Lower reaches of Ourimbah Creek including Chittaway Bay, Chittaway Point and Kangy Angy.
- Lower reaches of Tumbi Umbi Creek.

2 Previous studies

A review of previous relevant studies was undertaken to provide context and inform the present work as well as identify any critical knowledge gaps. A summary of this review focusing on key relevant studies is presented below.

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

The Flood Study Report for Tuggerah Lakes (Tuggerah, Budgewoi and Munmorah), completed for the former Wyong Shire 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 hydrologic model covering the entire catchment area and a 1D MIKE11 hydraulic model (with representative cross-sections) of the lake systems in the lower catchment east of Wyong. The WBNM hydrologic 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 hydrologic models were calibrated based on the recorded flood levels in February 1990, August 1990, and February 1992 events.

For design analysis the entrance scour behaviour was simulated from a MIKE11 entrance breach model with a combined incised scouring channel (trapezoidal) to represent entrance channel flows and long overflow barrier (or weir) to represent berm overflows. The entrance breach parameters (similar to those of a dambreak) were calibrated based on limited information sources available.

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 - ARR1987 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 contributing factors in the propagation of the elevated ocean level.
- The 1% AEP flood level was modelled with the following parameters:
    - Ocean conditions characterised by spring tides, wave setup of 0.07 m (corresponding with an offshore significant wave height of 4.5 m) and an inverse barometric effect determined from the average of historical flood events (value not specified). Due to the relatively slow response of the lake system, the timing of the peak tide and flood was tested and found to be relatively insensitive by

comparison with other parameters.

- A 20 m wide initial entrance channel which scours to a wider channel during the flood simulated using a MIKE11 entrance breach model.
- An initial lake level of 0.3 m AHD.
- Wind setup effects were determined to be small during flooding and inconclusive such that these were not included in the design flood model runs.

- The results of the Flood Study showed that in 1% AEP event 48 hours was the critical duration; however, it was found that 24 hours was the critical duration for the PMF event.
- The study provides design flood levels within Tuggerah Lake that were prepared based on frequency analysis and hydrologic/hydraulic computer modelling summarised in **Table 2.1**. The design flood levels are based on an entrance breach model that was calibrated against historic floods. However, the outcomes of sensitivity analysis showed that peak 1% AEP water levels could change by up to 0.1 m if alternate breach parameters were adopted. Nevertheless, it is considered that the levels presented in **Table 2.1** provide the best contemporary description of design flood levels within the Tuggerah Lakes system.

Table 2.1 Design flood levels within the lakes system (Lawson & Treloar Pty. Ltd, 1994).

Design event	Flood level (m AHD)
PMF	2.70
1% AEP	2.23
5% AEP	1.80
20% AEP	1.36
50% AEP	0.91

- The Flood Study results found a significant lag time (approx. 24 - 48 hours) 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 is one of the contributing factors controlling the flood behaviour in the lakes.
- The Flood Study results revealed that the water level in Tuggerah Lake rises faster than Lake Munmorah. One reasonable explanation is that most of the catchments drains 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.
- Entrance breach mechanisms were noted to be a key factor influencing lake flood levels. Limited data was available on the scour behaviour of the entrance during floods.

An entrance breach model was developed based on limited entrance information, documented lagoon breakouts at other locations and other flood studies including entrance breakout. Sensitivity to entrance breach parameters was conducted indicating a 1% AEP peak lake level change of between -0.12 m and +0.08 m for ±10% change to entrance breach parameters (particularly side erosion index and head loss factors).

- During model development wave setup was estimated at the entrance for historical flood events using wave refraction computation, surf zone model (Goda, 1985) and MIKE21 simulation of the entrance. Results are shown below.

Table 2.2: Modelled wave setup in the entrance (from Lawson and Treloar, 1994)

Historical flood	Peak H_S (m)	T_Z (s)	Direction (°)	Wave setup for different entrance channel depths (m)			
				0.5 m	1 m	1.5	2.0 m
02-07/02/90	3.7	6.7	62	0.21	0.10	0.05	0.00
01-05/08/90	7.2	7.3	133	0.45	0.34	0.30	0.25
09-10/02/92	4.5	5.9	148	0.25	0.14	0.10	0.05

- The report recommended long-term data collection at the entrance to the Pacific Ocean to better define entrance breach processes and streamflow gauging at the upstream river gauging stations to improve model calibration.

2.2 Tuggerah Lakes Floodplain Risk Management Study and Plan, WMA Water, 2014

Tuggerah Lakes Floodplain Risk Management Study and Plan was prepared by WMA Water on behalf of the former Wyong Shire Council in November 2014. The study was prepared to identify and evaluate a range of measures that could be potentially implemented to reduce the impact of flooding across the floodplain of the Tuggerah Lakes system.

The study was mainly focused on land that is located below 3 m AHD. That is, it did not consider flooding along each of the major tributary inflows to the lake system, including Wallarah Creek. Nevertheless, it does provide useful information regarding flooding mechanisms across the Tuggerah Lakes system. Wallarah Creek catchment drains into Budgewoi Lake. Accordingly, the prevailing water levels in Budgewoi Lake can influence flood behaviour along the downstream reaches of Wallarah and Spring Creek.

The study utilised a calibrated and verified WBNM hydrologic 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.

It was noted that the severity of flooding across the lake system is strongly influenced by the level of the beach berm and whether there are elevated ocean levels at the time of a flood (elevated ocean levels may prevent the egress of floodwaters from the lake system). The report also notes that rainfall over a period of 2 to 5 days is typically required to elevate lake levels significantly.

The study notes that the non-flood water level within the lakes is typically 0.3 m AHD with no apparent tidal fluctuation. However, the water level can vary from 0.1 to 0.5 m AHD depending on the volumes of inflow from the contributing catchments and the prevailing entrance conditions.

This report recommended several options to manage flooding in Tuggerah Lakes, which led to a short-list of 14 actions, tabulated in **Table 2.3**. 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.

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 oceanic residual and swell events, which may produce higher levels in the lakes.

Table 2.3 Proposed floodplain risk management options (WMA Water, 2014).

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.

Priority	Measure	Description
	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.

2.3 Tuggerah Lakes Entrance Management Study, MHL, 2022

MHL was commissioned by Central Coast Council to undertake Tuggerah Lakes Entrance Management Study which was completed in August 2022. The study was prepared 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.

The condition of the entrance was found to be a 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 intervention to maintain open conditions.

Modelling of interim management options for the Tuggerah Lakes entrance was 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 interim procedure aimed to reduce the risk to life, public and private infrastructure associated with flooding in accordance with the FRMSP (WMA Water, 2014). Flood level reductions associated with the procedure were expected to be small (typically less than 0.2 m), however, were considered beneficial in assisting to reduce flood damages. These reductions were reported likely to diminish for floods coinciding with extreme coastal anomalies and/or with projected sea level rise over the next 50 - 100 years.

It was noted that the 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 along the Tuggerah Lakes foreshores.

It was 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 (WMA Water, 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 was 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.

2.4 Wyong River Catchment Flood Study, BMT, 2014

The Wyong River Catchment Flood Study was prepared by BMT WBM Pty Ltd on behalf of the former Wyong Shire Council in October 2014. The study was prepared to define the existing flood behaviour in the Wyong River catchment and establish the basis for subsequent floodplain management activities. The Wyong River acts as the primary tributary to the Tuggerah Lakes system, draining approximately 60% of the total catchment area of the lakes.

The Wyong River Catchment Flood Study involved the development of hydrologic and hydraulic models to simulated flood conditions in the catchment. The hydrologic model was developed using XP-RAFTS software to simulate the rainfall-runoff process. The hydraulic model comprised a two-dimensional TUFLOW model with a uniform 8 m grid.

Calibration was undertaken by means of comparison to recorded water levels at streamflow gauge locations, with the WaterNSW derived rating curves at each of these locations deemed inappropriate for use in model calibration and accordingly adjusted to hydraulic model results. The hydrologic and hydraulic models were calibrated principally against the June 2007, and additionally against the February 1990, March 1977, June 1964, and June 1949 events.

The model calibration parameters adopted for all calibration events included an IL of 35 mm, which was justified as being '*larger*' as it was '*found to give a better representation of the initial catchment response to the input rainfall conditions.'* However, it is noted that the June 2007 modelled calibration event commences at 9am on 7 June 2007, *after* a burst of rainfall averaging approximately 30 mm across the catchment had already fallen over the preceding nine hours, and therefore the effective initial loss of the modelling approach is higher. A CL of 2.5 mm is adopted as it was similar to the '*design continuing loss rate as recommended in ARR (2001).*'

The calibration of the February 1990 event at the streamflow gauge locations on the Wyong River at Yarramalong and Gracemere suggested that actual effective rainfall (rainfall - losses) was much less than that derived with standard IL/CL method. As such, the Runoff Curve Number (RCN) loss method was found to provide a better match when events had a higher initial rainfall, whereas events with lower initial rainfall intensity, such as the June 2007 event, were found to be less sensitive to the adopted loss model.

In terms of the aptitude of the final calibrated model, results saw a tendency towards underestimation of peak flood levels, and a comparatively early rise and fall of flood levels across both calibration events with continuous flood level data to which to compare. In the June 2007 event, peak flood levels were approximately 500mm lower than recorded at Yarramalong, and 300 mm lower than recorded at Gracemere and the Fishway.

When progressing to design events, preliminary design simulations adopted standard IL and CL values of 15 mm and 2.5 mm/h, respectively. For impervious areas, adopted IL and CL values were taken as 2 mm and 0 mm/h. This approach was found to result in '*significant over-estimations of peak flood levels for the more frequent events*' as compared to observed annual maxima at the gauging sites and as such a Runoff Curve Number method was adopted for rainfall loss representation, with a curve number of 70. Critical durations of 36 hr and 9 hr were determined for the Wyong River and Mardi Creek catchments. Relevant to the present study, the adopted design events also saw flood levels in Tuggerah Lake increasing from a fixed IWL of 0.25 m AHD to peak flood levels ranging between 1.36 mAHD for the 20% AEP event and 2.7 mAHD for the PMF.

2.5 Other studies

Several flood studies have been undertaken for the catchments draining to Tuggerah Lakes. **Table 2.4** summarises the hydrologic and hydraulics modelling parameters for a potential consideration in the present study.

Table 2.4 Summary of relevant studies

Study	Year	Client	Author	Hydrologic model		Hydraulic model			ARR	Adopted critical duration	Calibration events	Comment
				Type	Design event parameters	Type	Cell Size	Downstream boundary conditions				
Tuggerah Lakes Flood Study	September 1994	former Wyong Shire Council	Lawson & Treloar Pty. Ltd	WBNM	● Initial loss (IL): 15 mm ● Continuing loss (CL): 2.5 mm/hr ● Non-linearity parameter (n): 0.23 ● Lag parameter (C): 1.15	MIKE11	-	Water level at the ocean: a realistic astronomic tide level of 0.8 m AHD with a storm surge of 0.4 m leading to an ocean level of 1.2 m AHD plus 0.2 m shoreline wave set-up	1987	Design events: 48 hr PMF: 24 hr	February 1992, August 1990, February 1990 May 1974	-
Tumbi Umbi Creek Flood Study Review	December 1994	former Wyong Shire Council	Paterson Consultants	WBNM	-Not specified	MIKE11	-	-	-	-	January 1978, February 1981, April 1990, February 1992	-
Porters Creek Flood Study	July 2009	former Wyong Shire Council	Cardno	XP-RAFTS	● Impervious surfaces: IL: 1.5 mm CL: 0.0 mm/hr ● Partially developed areas: IL: 10 mm CL: 2.5 mm/hr ● Forested areas: IL :15 mm CL: 4 mm/hr	TUFLOW	● Floodplain: 15 m ● Urban areas: a nested 4 m	Constant water level at the confluence with Wyong River ranging from 5.03 to 6.53 m AHD for 10%AEP to PMF events.	1987	Design events: 9 hr PMF: 1 hr	June 2007, October 2004	-
Ourimbah Creek Catchment Flood Study	October 2013	former Wyong Shire Council	Catchment Simulation Solutions	XP-RAFTS	● Pervious areas: IL: 15 mm CL: 4 mm/hr ● Impervious areas:	TUFLOW	● Rural area: 8 m ● Urban area: 4 m	Tuggerah Lake level increasing from “normal” level to peak	1987	Critical storm duration varies from 2 hr to 48 hr	June 2011, June 2007, February 1992	Study stated sandy nature of catchment.

Study	Year	Client	Author	Hydrologic model		Hydraulic model			ARR	Adopted critical duration	Calibration events	Comment
				Type	Design event parameters	Type	Cell Size	Downstream boundary conditions				
					IL: 1.5 mm CL: 0 mm/hr			Tuggerah Lake flood level ranging between 1.36 m AHD for 20% AEP and 2.7 m AHD for PMF and considering Tuggerah Lakes peaks 20 hour after rainfall onset.		throughout the catchment.		
Killarney Vale / Long Jetty Catchments Overland Flood Study	May 2014	former Wyong Shire Council	Catchment Simulation Solutions	XP-RAFTS	● Pervious areas: IL: 10 mm CL: 2.5 mm/hr ● Impervious areas: IL: 1 mm CL: 0 mm/hr	TUFLOW	2 m	Tuggerah Lake level increasing from “normal” level to peak Tuggerah Lake flood level ranging between 1.36 m AHD for 20% AEP and 2.7 m AHD for PMF and considering Tuggerah Lakes peaks 20 hour after rainfall onset.	1987	Peak catchment outflow occurs approximately 1.5 hr after the initial onset of the design rainfall, while the peak lake stage occurs about 20 hr after the onset of rainfall	December 2010, June 2007, February 1981	30-minute, 2-hour and 3-hour storms produced worst case flooding in upstream sections, along major waterways and within major detention basins, respectively.
Wyong River Catchment Flood Study	October 2014	former Wyong Shire Council	BMT WBM Pty Ltd	XP-RAFTS	● Pervious areas: IL: 15 mm CL: 2.5 mm/hr ● Impervious areas: IL: 2 mm	TUFLOW	8 m	Tuggerah Lake level increasing from 0.25 m AHD to peak Tuggerah Lake	1987	Design events: Critical duration of 36 hr and 9 hr for Wyong River and	June 2007, February 1990, March 1977, June 1964,	-

Study	Year	Client	Author	Hydrologic model		Hydraulic model			ARR	Adopted critical duration	Calibration events	Comment
				Type	Design event parameters	Type	Cell Size	Downstream boundary conditions				
					CL: 0 mm/hr			flood level ranging between 1.36m AHD for 20% AEP and 2.7 m AHD for PMF.		Mardi Creek catchment. PMF: Critical duration of 24 hr and 2 hr for Wyong River and Mardi Creek catchment.	June 1949	
Tuggerah Lakes Floodplain Risk Management Study and Plan	November 2014	former Wyong Shire Council	WMA Water	WBNM	The study adopted the model developed as part of 1994 study and no updates were made to the model. ● IL: 15 mm ● CL: 2.5 mm/hr ● Non-linearity parameter (n): 0.23 ● Lag parameter (C): 1.15	MIKE11	-	Water level at the ocean: a realistic astronomic tide level of 0.8 m AHD with a storm surge of 0.4 m leading to an ocean level of 1.2 m AHD plus 0.2 m shoreline wave set-up	1987	Design events: 48 hr PMF: 24 hr	February 1992, August 1990, February 1990, May 1974	● A completely new entrance breach mechanism was applied due to the superseded entrance mechanism adopted in MIKE11. ● The study was mainly focused on land that is located below 3 m AHD.
Northern Lakes Flood Study	October 2015	former Wyong Shire Council	Cardno	No hydrologic modelling was undertaken.	Direct rainfall approach has been used. ● Pervious areas: IL: 15 mm CL: 1.5 mm/hr	TUFLOW (Direct Rainfall)	2 m	Lake level of 0.5 m AHD was adopted for the 20% and 5% AEP events and 0.6 m AHD was	1987	1% AEP: 1.5 hr PMF: 15 min and 30 min	-	

Study	Year	Client	Author	Hydrologic model		Hydraulic model			ARR	Adopted critical duration	Calibration events	Comment
				Type	Design event parameters	Type	Cell Size	Downstream boundary conditions				
					● Impervious areas: IL: 5 mm CL: 0.5 mm/hr			adopted for the 1% AEP and PMF events				
Wallarah Creek Catchment Flood Study	April 2016	former Wyong Shire Council	Catchment Simulation Solutions	XP-RAFTS	● Pervious areas: IL: 10 mm CL: 2.5 mm/hr ● Impervious areas: IL: 1 mm CL: 0 mm/hr	TUFLOW	● Floodplain: 4 m ● Urban areas: 2 m	A constant water level of 0.67 and 0.92 m AHD in Budgewoi Lake for the 5% and 1% AEP events, respectively.	1987	The following storm duration were simulated for each design event: 1.5, 2, 6 and 9 hr. The 1.5-hour storm generally dominates in areas of shallow flow while the 2-hour storm duration dominates along the upstream sections of major creek as well as major overland flow paths.	April 2015, June 2007	
Tuggerah Lakes Southern Catchments Flood Study	February 2018	Central Coast Council	WMA Water	WBNM	● Lag parameter (C): 0.7 to 2.8. ● Pervious areas: IL: 20 mm CL: 4 mm/hr ● Impervious areas: IL: 1.5 mm CL: 0 mm/hr	TUFLOW	Urban areas: 2 m	Constant level of 0.6 m AHD for design events	1987	Design events: 2 hr and 9 hr PMF: 1 hr or 2 hr depending on the location	April 2015, June 2007	-

Study	Year	Client	Author	Hydrologic model		Hydraulic model			ARR	Adopted critical duration	Calibration events	Comment
				Type	Design event parameters	Type	Cell Size	Downstream boundary conditions				
Tuggerah Lakes Entrance Management Study	August 2022	Central Coast Council	MHL	WBNM	● Pervious areas: IL: 0-60 mm CL: 3.5 mm/hr ● Lag parameter (C): 2.5	MHLFIT tool	-	Ocean water level	2019	-	-	-

Classification: Public

2.6 Summary

This section provides an overview of previous flood-related investigations in the Tuggerah Lakes catchment. Over the past 30 years, numerous studies have been conducted to better understand the flooding issues in the area. These investigations offer valuable insights for the current study, including survey data (such as creek cross-sections and bridge/culvert details), historical flood damage areas, and flood marks from past events.

The review highlighted variability in the modelling approaches and parameters used in these studies, making it challenging to accurately replicate historical flood behaviour, especially during initial flood responses. It was also noted that flood levels in the Tuggerah Lakes are influenced by various factors, including catchment inflows, entrance conditions, and ocean dynamics.

Specifically, the existing Flood Study and Floodplain Risk Management Study and Plan (FRMSP) for Tuggerah Lakes, completed in 1994 and 2014 respectively, require updates to incorporate advancements in flood modelling capabilities, new data collected since then, and the latest best practices outlined in ARR 2019. Additionally, the completion of an evidence-based interim entrance management procedure in 2022 has enhanced understanding of the complex interactions between catchment flooding, entrance conditions, and ocean dynamics, particularly during various flow events, providing valuable insights for the current study.

3 Data collection and review

This section summarises the collation and review of available and relevant data in the study area.

3.1 Water level and rainfall data

MHL manages a network of water level (15-minute recording frequency) and near-real-time rainfall recording stations within or in the vicinity of the study area. The Bureau of Meteorology (BoM) also operate a network of near-real-time rainfall recording stations within or in the vicinity of the study area. WaterNSW manages a network of water level (15-minute recording frequency) recording stations within or in the vicinity of the study area, a subset of which possess derived stage-discharge rating curves and associated rated discharge time series.

These relevant gauge networks are detailed in **Table 3.1** and their location is illustrated in **Figure D.4**.

3.2 Topographic data

Light Detection and Ranging (LiDAR) data is aerial survey data that provides a detailed topographic representation of the ground. 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 steeply varying terrain, the vicinity of buildings and/or the presence of water.

LiDAR survey of the study area and its immediate surroundings was obtained for the study from ELVIS (https://elevation.fsdf.org.au/). 1-metre resolution LiDAR data from the 'Gosford' dataset (NSW Spatial Services 2011-2020) was used. 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 D.5**.

Also, a consolidated 1 m resolution LAS data was provided by CCC and utilised in the present study.

As part of the data review, a comparison was made between the 2011 - 2020 LiDAR dataset and elevation of reference marks obtained from Sixmaps. Under the S&SI Reg 2017, only marks that have a vertical class of L2A, LA, LB, LC, LD, 2A, A or B should be used for the adoption of AHD. Therefore, marks classified as "E" (marks with approximate positions), and "U" (marks with an unknown position or height) were excluded from the assessment. The difference between the 2011-2020 LiDAR dataset and the elevation of the reference marks were calculated and presented in **Figure D.5** and **Figure 3.1**. It was observed that this difference ranges from -1.0 to 1.0 m with most elevation differences falling between -0.1 to 0.3 m which is consistent with the vertical accuracy of the dataset. Marks with differences exceeding ± 0.3 m were inspected; many were near vegetation, fences, road signs, or resurfaced areas, contributing to observed discrepancies.

Table 3.1 Summary of relevant rainfall and water level stations

Type	Ownership	Number	Name	GDA 94/MGA Zone 56		Data period	Used?	Purpose
				Easting	Northing			
Near-real-time rainfall	DCCEEW BC	211401	Toukley	362599	6318531	Feb 1985-ongoing	✓	Hydrologic model input
	DCCEEW BC	211417	Wyong Weir Upstream	351596	6316778	Jan 1986-Apr 2008	✓	
	DCCEEW BC	561026	Dooralong (Whitemans Ridge)	343653	6324899	Apr 1989-ongoing	✓	
	DCCEEW BC	561078	Kulnura (Pioneer Park)	333796	6321517	June 1989-ongoing	✓	
	DCCEEW BC	561133	Hamlyn Terrace	357399	6319854	Mar 2010-ongoing	✓	
	DCCEEW BC	561082	Mardi Dam	351038	6314555	Oct 1988-ongoing	✓	
	DCCEEW BC	561132	Kangy Angy	350168	6310609	Aug 2010-ongoing	✓	
	DCCEEW BC	561134	Berkeley Vale	353191	6309376	Jun 1988-ongoing	✓	
	DCCEEW BC	561069	Bateau Bay	358098	6305653	Jan 1980-ongoing	✓	
	DCCEEW BC	561079	Lisarow	348900	6305317	Apr 1989-ongoing	✓	
	DCCEEW BC	561137	Yarramalong	338869	6322377	Nov 1988-ongoing	✓	
	DCCEEW BC	567138	Sterland	342433	6315335	Apr 1989-ongoing	✓	

Type	Ownership	Number	Name	GDA 94/MGA Zone 56		Data period	Used?	Purpose
				Easting	Northing			
	SRA	5SRA05	Warnervale	356155	6320015	Jan 1986-Apr 2010		Alternative nearby sites
	DCCEEW BC	561072	Chittaway	350336	6310109	Dec 1989-Aug 2010		Alternative nearby sites
	BoM	61381	Mount Elliot	350641	6302971	Dec 2000-Jul 2022		Alternative nearby sites
	DCCEEW BC	561084		350646	6302980	Dec 1987-ongoing	✓	Hydrologic model input
	DCCEEW BC	561085	Narara	344310	6304220	Apr 1989-ongoing	✓	
	DCCEEW BC	561136	Strickland	345377	6305541	Dec 1985-ongoing	✓	
	WaterNSW	211010	Jilliby	350148	6320358	May 2016-ongoing	✓	
	DCCEEW BC	561081	Mandalong	351103	6335474	Dec 1988-ongoing	✓	
	BoM	61201	Watagan Central	330768	6344394	May 1959-Jun 2022	✓	
	DCCEEW BC	561097	Wyee	358855	6327981	May 1992-ongoing	✓	
	DCCEEW BC	561067	Martinsville	351277	6341500	Mar 1988-ongoing	✓	
	BoM	61385	Wyong (Olney Forest)	345215	6338888	Dec 2000-Nov 2023	✓	
	BoM	61382	Kulnara (Jeavons)	333848	6328663	Dec 2000-ongoing	✓	

Type	Ownership	Number	Name	GDA 94/MGA Zone 56		Data period	Used?	Purpose
				Easting	Northing			
	BoM	61432	Palm Grove (Lyrebird Lane)	341906	6314401	Nov 2018-May 2023		Sterland (567138) nearby
AWS	BoM	61375	Mangrove Mountain AWS	333388	6315201	Jul 1994-ongoing		Alternative nearby sites
	BoM	61366	Norah Head AWS	367450	6316613	Feb 1995-ongoing	✓	Hydraulic model calibration (wind data)
Water level	DCCEEW BC	211420	Wallarah Creek Bridge	360913	6323587	May 1994-ongoing	✓	Hydraulic / hydrologic model calibration
	DCCEEW BC	211401	Toukley	362599	6318531	Feb 1985-ongoing	✓	
	DCCEEW BC	211417	Wyong Weir Upstream	351596	6316778	Jul 1990-ongoing	✓	
	DCCEEW BC	211425	Lees Bridge	353684	6311538	May 1993-ongoing	✓	
	DCCEEW BC	211418	Long Jetty	358757	6308079	Sep 1991-ongoing	✓	
	DCCEEW BC	211419	Tumbi Umbi	355321	6307480	Apr 1994-ongoing	✓	
	CCC	61384	Kangy Angy	350168	6310609	Dec 2000-Feb 2017		No data available for key events
	CCC	212464	Lisarow (Cutrock Creek)	348883	6305388	Jul 2009-ongoing		
	CCC	2124127	Lisarow (Tall Timbers)	349098.6	6305933	Mar 2014-ongoing		
	CCC	61386	Wyong River upstream Bridge	353247	6315353	Jun 2020-ongoing	✓	Hydraulic / hydrologic model calibration

Type	Ownership	Number	Name	GDA 94/MGA Zone 56		Data period	Used?	Purpose
				Easting	Northing			
	CCC	561001	Tuggerah Lake Entrance	360059	6309209	Jan 1996-Aug 2016	✓	
	DCCEEW BC	211416	Wyong River downstream Bridge	353402	6315330	Sep 1993-Jun 2003	✓	
	MHL	2114111	Wyong River at Gears	343031	6319600	Nov 2005-ongoing	✓	Hydraulic / hydrologic model calibration
	DCCEEW BC	213470	Sydney	338842	6255833	Sep 1987-ongoing	✓	Downstream boundary condition
	DCCEEW BC	212440	Patonga	339821	6286294	Jun 1992-ongoing		
Water level (with flow rating curve)	WaterNSW	211009	Wyong River at Gracemere	347220	6317541	Dec 1972-ongoing	✓	Hydrologic model calibration
	WaterNSW	211014	Wyong River at Yarramlong	339346	6323343	Nov 1976-ongoing	✓	
	WaterNSW	211017	Wyong River at Fishway	351563	6316778	Sep 2011-ongoing	✓	
	WaterNSW	211010	Jilliby Creek upstream Wyong River (Durren Lane)	350148	6320358	Dec 1972-ongoing	✓	
	WaterNSW	211013	Ourimbah Creek upstream Weir	345841	6308872	Nov 1976-ongoing	✓	
	WaterNSW	211015	Ourimbah Creek downstream Bangalow Creek	350107	6311190	Oct 2003-ongoing	✓	

Notes:

- DCCEEW BC: Department of Climate Change, Energy the Environment and Water - Biodiversity and Conservation Group
- CCC: Central Coast Council
- SRA: former State Rail Authority
- AWS: Automated Weather Station

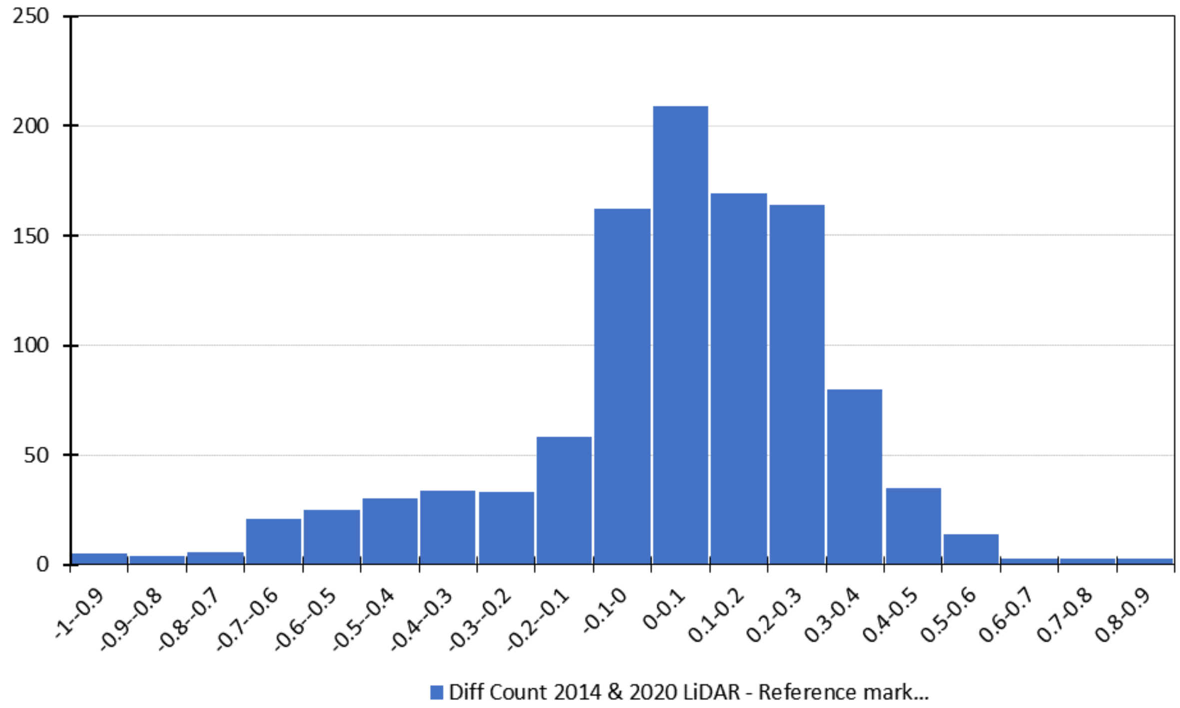


Figure 3.1 Distribution of the difference between 2011-2020 Gosford LiDAR data and the reference marks.

3.3 Lake bathymetry and entrance channel survey data

A bathymetric survey is the study of underwater beds and banks of the lakes. As the LiDAR data does not accurately represent lake profiles when water is present, bathymetric survey is necessary to reliably define the stage-storage curve of lakes.

There were existing bathymetric survey datasets covering lake bathymetry and entrance channel including:

- The survey datasets collected in 1975 covering the entire lakes area, by the then NSW Office of Environment and Heritage.
- The survey datasets collected in 1979 covering the entrance channel and parts of the lakes, by the then NSW Office of Environment and Heritage.
- Entrance and nearshore bathymetry survey datasets collected in 2008 and 2011, provided by Council.
- The survey datasets of the entrance channel and marina collected in 2018 - 2021 by Central Coast Council.
- The Marine LiDAR dataset DCCEEW in 2018 by DCCEEW.

The lake bathymetry for this study was created incorporating the survey points collected in 1975 covering the entire area of the lakes and bathymetry survey data collected between 2011 and 2022 covering the entrance channel. The extents of the available bathymetry datasets are displayed in **Figure D.6**.

3.4 Aerial photography

The most recent available aerial imagery was obtained from Google Earth (www.googleearth.com), captured in 2022 to observe current features within the study area.

Moreover, Council provided Web Map Services (WMS) URLs connecting to the aerial photography tabulated in **Table 3.2**.

Table 3.2 Aerial photography details provided by the Council.

Date	Extent	Resolution (cm)
2019	Central Coast LGA	5
2018	Central Coast LGA	5
2016	Central Coast LGA	10
2016	Wyong LGA	10
December 2015	Gosford LGA	5
April 2015	Gosford LGA	5
2014	Wyong LGA	10
2014	Gosford urban and partial rural	10
2012	Gosford urban coverage only	5
2012	Central Coast LGA	10
2010	Gosford LGA	10 cm Urban / 20 cm Rural
2010	Wyong LGA	10
2007	Gosford urban coverage only	10
2006	Wyong LGA	10
2005	Gosford LGA	15

3.5 Drainage network

Council provided several GIS layers to represent the drainage system surrounding the Tuggerah Lakes. The layers included pits, pipes, culverts, headwall, gross pollutant traps (GPT), drainage channel, flood gates as well as levees.

The various layers were compared with the information existing in previous models as part of the hydraulic model development. The review identified some missing data required for modelling of the stormwater network as follows:

- Pipe data including approximate locations and pipe sizing were available across the catchment, except for some small areas with missing pipe network details (e.g., pipe size).
- A minimum pipe size of 0.3 m was included in the hydraulic model.
- Locations of pits were mostly available; however, invert level and pit sizes were not always present in the data provided.

In the absence of these data, a minimum cover depth of 0.3 m for all provided pits using standard pipe grading as a guide to ensure hydraulic continuity has been assumed. Furthermore, all kerb-type pits will be assumed to be 1800 mm wide and 200 mm high.

It is noted that inclusion of these drainage network structures will exclusively focus on areas in lower reaches of the catchment that may be directly subject to inundation because of backwater from the lakes (e.g., with elevations less than approximately 3 m AHD) and/or considered to be significantly influential on lake inundation levels. Noting this intent, the assumptions discussed above are not expected to be consequential.

This drainage network is shown in **Figure D.7**.

3.6 Bridges

Bridges located within the lower reaches of the catchment (with elevations less than approximately 3 m AHD) shown in **Figure D.8**, include:

- Wyong Road Bridge over Tumbi Umbi Creek
- A foot bridge over Tumbi Umbi Creek
- Wyong Road Bridge over Ourimbah Creek
- A coupled Pacific Hwy Bridge and railway bridge over Wyong River
- Pacific Motorway Bridge over Wyong River
- Yarramalong Road Bridge over Wyong River
- Alison Road Bridge over Porters Creek
- Pacific Motorway Bridge over Deep Creek
- Mardi Road Bridge over Deep Creek
- Collie Lane Bridge over Deep Creek
- Pacific Highway Bridge over Wallarah Creek
- A railway bridge over Wallarah Creek
- Motorway Link Bridge over Spring Creek
- Central Coast Highway over Budgewoi Creek
- Budgewoi Footbridge over Budgewoi Creek
- Main Road Bridge
- The Entrance Bridge over the Tuggerah Lake Entrance Channel

3.7 Weirs

The Wyong River Weir is located on the Wyong River on the western side of Tuggerah Lake approximately 230 m downstream of Pacific Motorway, shown in **Figure D.8**. The Wyong River Weir was originally a sheet-pile and concrete weir that formed the tidal barrier, limiting upstream intrusion of estuarine waters to provide local landholders and Wyong Shire Council with a more reliable fresh water source. In September 1993, a rock ramp fishway was constructed using sandstone blocks. As of 2023, the weir has a rock ramp and a trapezoidal fishway as shown in **Figure 3.2**. The rock ramp fishway is a traditional lateral ridge design and is only engaged during higher flows. The trapezoid fishway has a central chute for high flows and vertical slots on each side for fish to link the tidal reaches of the Wyong River with the upper reaches of the river. The crest of the weir is at approximately 1.2 m AHD and is visible in the LiDAR data.

Figure 3.2 Wyong River Weir and fishway (reprinted from Newcastle Herald published on 17 October 2016)

Ourimbah Creek Weir is located on Ourimbah Creek on the western side of Tuggerah Lake approximately 1.6 km upstream of Pacific Highway and Motorway bridges over Ourimbah Creek, shown in **Figure D.8**. The structure includes a fishway and is presented in **Figure 3.3**.

Figure 3.3 Ourimbah Creek Weir and fishway (obtained from NearMap: captured on 18 August 2022)

Mardi Dam is located 4 km south-west of Wyong, shown in **Figure D.8**. Mardi Dam was built in 1962. Mardi Dam is an off-stream storage facility, meaning it is not fed directly by a stream and must be filled by pumping water from Wyong River and Ourimbah Creek. Water is pumped to Mardi Treatment Plant and then to residents.

3.8 Flood level classifications

The Bureau of Meteorology (BoM) flood level classifications for the Tuggerah Lakes at Long Jetty water level station are currently defined as (BoM, 2024):

- **Major:** 1.6 m AHD
- **Moderate:** 1.3 m AHD
- **Minor:** 0.9 m AHD

It is noted that these flood level classifications were recently updated to better reflect the impacts that have been experienced in recent flooding events. Prior to this update, the BoM flood level classifications for Tuggerah Lakes at Long Jetty water level station were defined as (BoM, 2013):

- **Major:** 2.2 m AHD
- **Moderate:** 1.8 m AHD
- **Minor:** 0.9 m AHD

3.9 Entrance behaviour

MHL recently undertook the Tuggerah Lakes Entrance Management Study (MHL2811, 2022). As part of this project and to support the development of the Tuggerah Lakes Interim Entrance Management Procedure, MHL undertook the following investigations:

- 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.

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

(MHL2811, 2022) classified the condition of the Tuggerah Lakes entrance into characteristic states shown in **Figure 3.4**:

- ***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 **Figure 3.4** show the entrance in each of the above conditions and historical trends in classification over the last 29 years using lake level tidal harmonic analysis are shown in **Figure 3.5** (from MHL2811, 2022).

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

Information and datasets of entrance behaviour at the ocean boundary will be used in the present study to inform entrance behaviour modelling at the downstream ocean boundary of the model.

It is also noted that a rock groyne that has been constructed by the NSW State Government in 2017 to maintain sand on the South Entrance beach appears to generate erosion on its northern side. This appears to guide the primary entrance channel further south than in the past.

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 3.4 Characteristic entrance conditions (MHL2811, 2022)

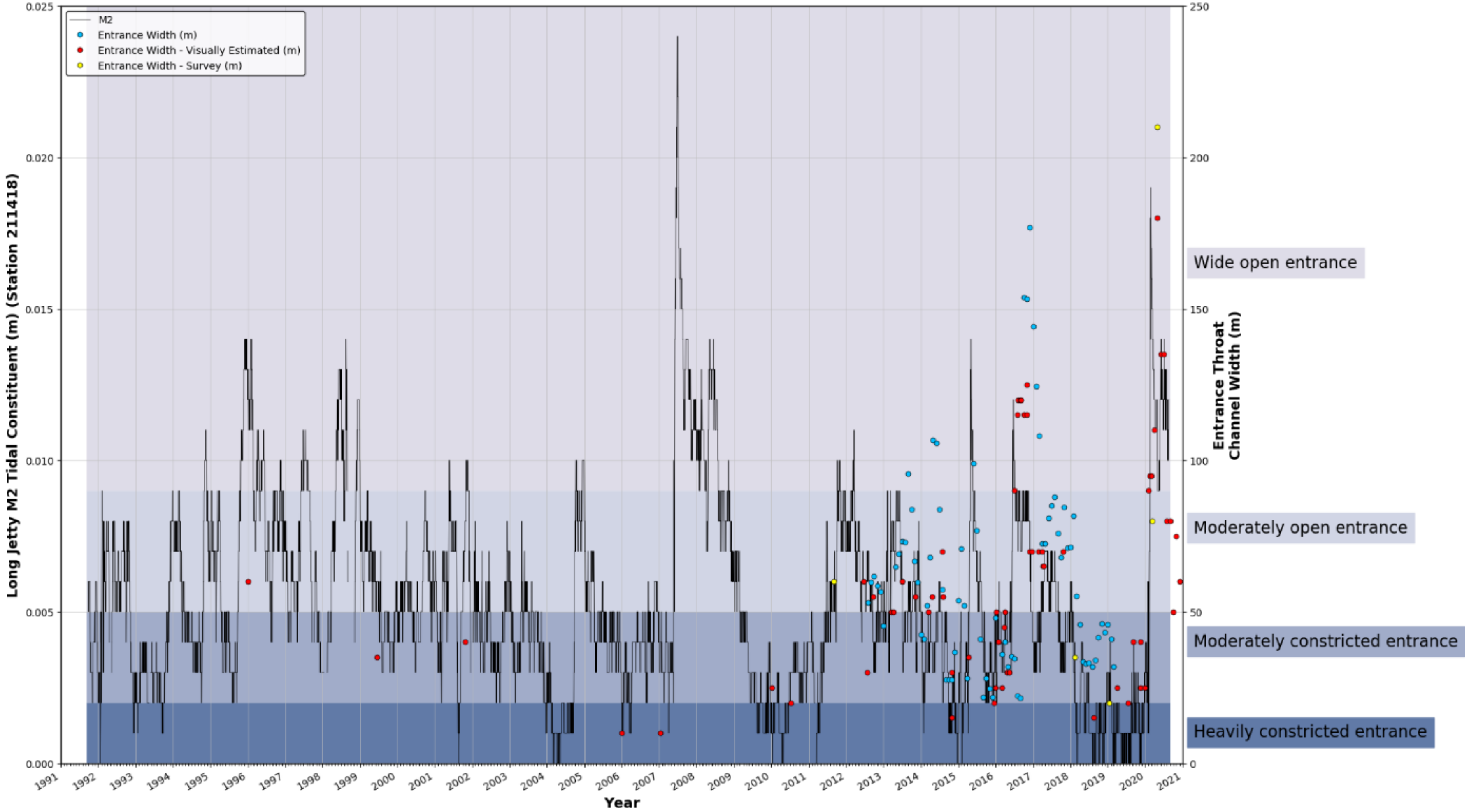


Figure 3.5 Trends in characteristic entrance conditions 1991 - 2020 using tidal harmonics and entrance width (MHL2811, 2022)

3.10 Other relevant GIS information

Several GIS layers were provided by Council including:

- Cadastral information representing the lot boundaries of all properties located within the entire Central Coast Council Local Government Area (LGA). This will be utilised to assess the number of properties impacted by flooding.
- The footprints of all buildings located within the Central Coast Council LGA. This layer will inform the number of buildings that may become affected by flooding.

4 Community consultation

4.1 Consultation process

Consultation provides an opportunity for various stakeholders, including the community, to collaborate in developing the Tuggerah Lakes Flood Study Review. Engaging the community throughout the process provides opportunities to both garner useful feedback and increase community acceptance of the floodplain risk management process.

The consultation program for the flood study review has included the following activities:

- Inception and progress meetings between MHL and Council's Catchment and Coast Advisory Committee;
- Consultation with agencies and stakeholders; and
- Letter and questionnaire for property owners and residents.

These activities are described at greater length below.

4.2 Catchment and Coast Advisory Committee

The Catchment and Coast Advisory Committee (the Committee) was formed by Council to provide a forum that brings together the diverse expertise and community knowledge that is needed to address technical, social, economic and ecological issues concerning floodplain risk management in the study area. The committee fulfills the functions of a Flood Risk Management Committee as described in the *Flood Risk Management Manual (DCCEEW, 2023)*.

The committee comprises representatives from:

- Central Coast Council, including planners and engineers;
- NSW Department of Climate Change, Energy, the Environment and Water, Biodiversity Conservation Division (BCD); and
- the community.

Meetings with the Committee occurred at key stages of the project. Following the reintroduction of Councillors on 8 October 2024 however, all existing advisory committees were dissolved.

At the time of writing, Council's Floodplain Management team were required to temporarily report to the newly established Environment and Planning Committee. In saying this, a new Coastal, Estuary and Floodplain Risk Management Sub-Committee has since been formed which assumes the role of the old Catchments to Coast Advisory Committee.

4.3 Website

A 'Your Voice Our Coast" webpage was developed by Council to provide information to residents about the study, general flooding information, and a link to an online questionnaire as described in the following section.

4.4 Letter and questionnaire

4.4.1 General approach

In November 2022, 8852 letters were distributed to all owners and renters that may be at risk of flooding within the study area. The community letter introduced the flood study review and alerted the residents and businesses of an online questionnaire that was available to complete. A copy of the letter is included in **Appendix A**.

The online questionnaire was developed using the SurveyMonkey platform and was made available until end of December 2022 seeking community input about historic flooding and general information to understand the level of flood awareness of and gather information from the community. The questionnaire is also included in **Appendix A**.

4.4.2 Questionnaire results

A total of 484 responses were received. This represents a response rate in the order of 5.5%. Results of the questionnaire are provided in **Appendix A**.

The following key observation were made based on the community questionnaire respondents:

- Most respondents have a residential property (97.7%). A few properties are commercial and farming/rural.
- 83.7% of respondents are owner occupied.
- Many residents have been living in the catchment for a long time (22.3% lived there between 10 and 20 years, 27.9% have lived there for over 20 years and 28.5% lived there for less than 5 years).
- About 78.5% of the respondent mentioned that their property was affected by flooding. It is important to note the personal interpretation of flood affectation (i.e., flooding of property vs. flooding of building) and to note that the questionnaire was sent to residents in the Tuggerah Lakes floodplain as highlighted by the previous study. A map showing the location of the respondents and whether that reported being flood-affected or not is provided in **Figure D.9**.
- Nearly half (48.5%) of the respondents provided one or multiple examples of flood events. The most commonly impacted part of the property included the ground (~50%) and the garage/shed (~33%). However, approximately 20% of the respondent mentioned that their building was affected.
- Observed flood depths were typically described as being over 0.3 m (~61% over 0.3 m, ~40% over 0.5 m and ~20% over 1 m).
- Flooding durations are typically long and range between a few hours to several weeks with the majority of respondent (~76%) describing flooding as lasting for more than 24 hours.
- The main events mentioned by respondents in the questionnaire include July 2022, February-March 2022, March 2021, February 2020 and June 2007.
- Several residents provided photographs as well as other flood information. Examples of photographs are provided in **Section 1.4**.

5 Extreme value analysis for Tuggerah Lake

As was the case in the previous *Tuggerah Lakes Flood Study (1994)*, an extreme value analysis (EVA) on recorded annual peak water levels in the Tuggerah Lakes was performed and is described below.

5.1 Preamble

An EVA is a statistical technique used to examine the extreme deviations from the median of probability distributions. Its purpose is to assess the likelihood of events that are equal to or more extreme than those previously observed. An EVA typically uses historical data, such as peak water levels, to estimate the probability of future extreme events, which is particularly valuable for floodplain risk assessment and management.

One of the key outputs of the EVA is the return period, which indicates the average time interval expected between occurrences of specific extreme water levels. This concept aligns with the foundations of floodplain planning, such as policy development and decisions related to expansion. The EVA approach provides a relatively simple method for understanding the flooding behaviour of the Tuggerah Lakes.

Flood peaks are influenced by a complex joint probability process that involves multiple random variables associated with rainfall events, antecedent conditions, entrance conditions and rainfall-runoff dynamics. It is noted that a key assumption of any EVA is data homogeneity over the record period, which necessitates the assumption that the previously mentioned processes that can influence the manifestation of peak lake levels are consistent over time.

To ensure statistically significant results, EVA relies on the collection of historical data over an extended period. This data is typically segmented into unbiased periods, such as an annual maximum (AM) series, or a series of independent flood peaks over a given threshold (POT) can be extracted. These series are then able to be utilised to identify trends and fit an appropriate statistical model to estimate extreme values among and beyond the recurrence intervals of the observations.

Common statistical models used to fit AM and POT series include the Generalised Pareto (GP), or Generalized Extreme Value (GEV) distributions, which are formulated to capture the upper-tail behaviour of extreme events.

Section 2.2.2.3 of ARR 2019 provides guidance on when practitioners should prefer either the AM or POT approach. It recommends using the AM series for recurrence intervals with an AEP of less than 10% (i.e., the most extreme floods), as it is easier to extract and define over long, discontinuous data periods with the allowance of censored events, and therefore offers more reliable estimates for low AEP floods. On the other hand, for events with an annual exceedance probability greater than approximately 20% (i.e., events more frequent than 0.2 exceedances per year), the POT approach is generally preferred, as it captures all flood events in this range. This is because the AM series may overlook many events that are of a similar magnitude to these more frequent floods, as they are often not the largest event each year. Therefore, based on the rationale outlined above, both approaches are used for defining events, with each applied as recommended.

The next section summarises the available data taken forth for both analysis approaches.

5.2 Data review

As described and presented in the *Tuggerah Lakes Flood Study (1994)*, partial historical peak flood level data for the period from 1927 to 1985 is available. Between 1927 and 1960 this data is highly partial, with only major peaks available, however these peaks are some of the highest on record, so their inclusion for the AM series analysis is considered essential. The remaining annual maximum series from 1961 to 1985 was mostly captured, with six years of data unavailable. From 1986 to 2024, water level monitoring stations have been in place on Tuggerah Lake (see **Table 3.1**), from which complete AM and POT series were able to be derived.

It is therefore noted that a complete annual maximum series could not be established prior to 1986, and therefore an assumption would have to be made about the data gaps during the residual data period to perform the AM series analysis. Furthermore, it is noted that the POT approach could only be performed on the period of continuous water level monitoring available from 1986.

Table 5.1 Annual maximum series data summary for Tuggerah Lake (1927-2024)

Start	End	Period (yr)	Data (yr)	Missing (yr)	Type
1927	1960	34	6	28	Major peaks
1961	1985	25	19	6	Most peaks
1986	2024	39	39	0	Continuous
	TOTAL	98	64	34	

5.3 Annual maximum series analysis

5.3.1 Plotting position

As is discussed in the *Tuggerah Lakes Flood Study (1994)*, the water level record for the Tuggerah Lakes is largely partial, and an assumption would have to be made regarding the plotting position approach for the missing years. The 1994 study posits two approaches to deal with the period of partial data from 1921 to 1985:

1. Assume the 32 available records from the partial data period to be a continuous record with an effective length of 32 years.

   This approach is expected to overestimate the frequency of larger events, since there is an effective decrease of the length of the record, and since the partial data is likely biased towards the capture of larger events.

2. Assume the 32 available records from the partial data period to be the largest events occurring during the 59-year partial data period.

   This approach is expected to much more reliably predict the frequency of larger events, since the full length of the record is preserved, but may underestimate the frequency of small events not captured in the missing years of data.

   The concern regarding the low-end fit is also slightly offset by the practice of adding the 34 missing years as censored data, assuming all these years had a peak lake level below the smallest observation during the partial data period (0.42 mAHD, 1972). This technique was not available at the time of the 1994 study.

Since the focus of the present study is towards the events of a larger scale, the second approach was adopted, noting that the missing data years of the partial data period could be included as censored data.

5.3.2 Fitting

FLIKE is an extreme value analysis package that calculates the probability of flood events based on historical records. FLIKE is fully compliant with Book 3 of ARR 2019 and although it has been developed specifically for discharge estimation, it can be applied to any extreme value analysis.

It supports five probability distributions, namely:

- Log-Normal,
- Log-Pearson 3 (LP3),
- Gumbel,
- Generalised Extreme Value (GEV), and
- Generalised Pareto.

FLIKE uses an advanced Bayesian methodology for the estimation of distribution parameters, which enables the inclusion of historic partial series data. The data discussed previously was used to fit all five available probability models using the software, with the result of each approach exhibited in **Figure 5.1**.

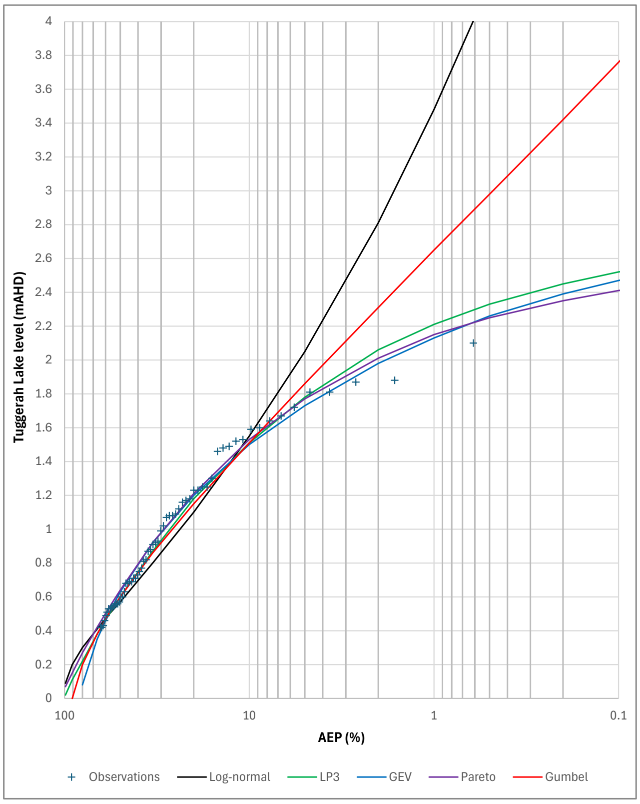


Figure 5.1 Tuggerah Lakes AM series EVA (1927-2024)

The Log-Normal and Gumbel models, with their inability to asymptote to a reasonable upper bound, are poor fits and further consideration of these models was excluded.

The remaining models, namely the LP3, GEV and Pareto models offered a reasonable match to the observed data. These models generally behaved similarly, matching the less frequent observations closely, slightly underestimating the moderate events, and generally slightly overstating the observations at the upper tail of the curve, making them inherently conservative for events rarer than approximately 3% AEP. The fit quality demonstrated is typical of statistical models of these types applied to data series of this length, exemplified by the broadly similar results of those fits with stable upper tails.

5.4 Peak over threshold analysis

To maximise the use of all recorded extremes, peak-over-threshold methods include all events over a suitably chosen threshold generally set at two standard deviations above the mean (refer **Section 5.4.1**) which are at least some days apart (refer **Section 5.4.2**). This is then fitted to the Generalised Pareto (GP) distribution.

5.4.1 Threshold selection

POT models focus on flood peaks exceeding a specified threshold. As a result, the choice of threshold is a critical aspect of the POT methodology and has a significant influence on both the magnitude and the shape of the confidence intervals. The threshold should be set to capture the maximum number of extreme events without being unduly influenced by the central tendency of the data. According to ARR 2019, several studies offer guidance on threshold selection, with recommendations suggesting that the threshold should be chosen so that the number of events exceeding it is at least greater than the number of years represented in the data. In totality, the studies advise that the ratio should fall within a range of one to five. Sensitivity analyses which assessed the quality of fit, determined that the optimal peak-over-threshold level was two standard deviations above the mean, specifically at a value of 0.54 mAHD. This resulted in the inclusion of approximately 64 events (after the declustering process discussed below) for a given 39 years of data, which lies within the acceptable ratio.

5.4.2 Declustering

When performing an EVA, it is a key assumption that all peaks selected are independent. As discussed in ARR 2019, when analysing a flood record, the selection of independent peaks can be subjective as the interval recorded between flood peaks may be quite short. If left unaddressed, extreme water levels associated with the same flooding event may be sampled over numerous consecutive samples within the record. To mitigate this phenomenon, an approach called declustering is performed. Noting that a typical flooding event in the Tuggerah Lakes can last in the order of weeks, declustering was applied using a block length of 14 days. This meant no two values could occur in the peak-over-threshold dataset if they were within 14 days of each other. The sampled extreme values considering the aforementioned threshold selection and declustering considerations are presented in **Figure 5.2**.

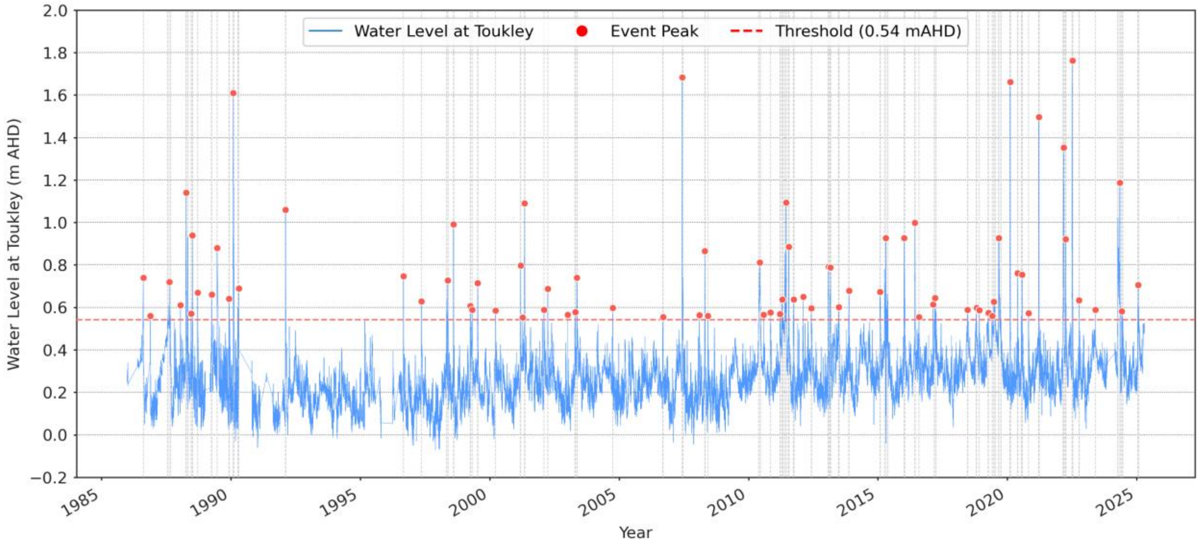


Figure 5.2 Data points selected for Tuggerah Lakes POT EVA (1986-2024)

5.4.3 Fitting

The data discussed above was used to fit the Generalised Pareto probability model using the *pyextremes* Python library, with the result exhibited in **Figure 5.3**.

The model offered a reasonable match to the observed data, closely aligning with the less frequent observations, slightly underestimating the moderate events, and overestimating the upper tail. A result of this quality is typical of statistical fits applied to relatively short to moderate-length time series, where data sparsity and statistical heterogeneity can lead to overfitting or instability in the tail estimates. It is also noted that this fit is broadly not applicable above the approximate 10% AEP result, as per the limitations outlined in ARR 2019.

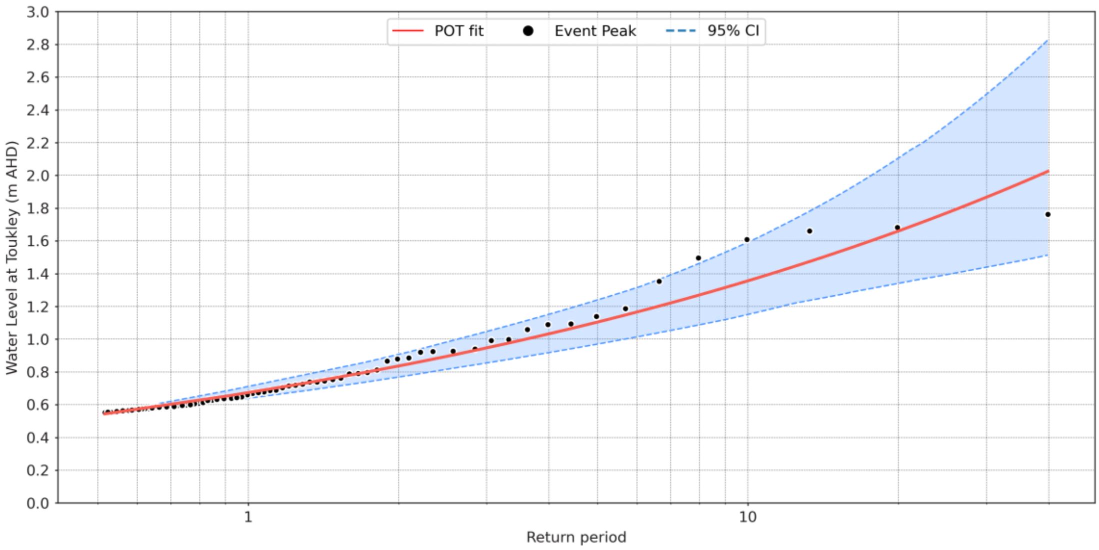


Figure 5.3 Tuggerah Lakes POT EVA (1986-2024)

5.5 Results and discussion

Table 5.2 presents a comparison of flood level estimates derived from various Extreme Value Analysis (EVA) approaches, including Annual Maximum (AM) series and Peak Over Threshold (POT) methods using LP3, GEV, and Generalised Pareto distributions. These are compared against the 1994 study estimates for key AEP events.
The central estimate for each approach is presented in the larger text, while the 95th percentile confidence interval is shown in smaller surrounding text.

Table 5.2 EVA-based design flood level estimates for Tuggerah Lakes

Event	Peak Tuggerah Lakes flood level (mAHD)				
	1994 study	AM series			POT
		LP3	GEV	Pareto	Pareto
Upper bound*		2.76	2.89	2.60	
1 in 500 AEP		2.17 - 2.45 - 3.20	2.08 - 2.39 - 3.30	2.10 - 2.35 - 3.00	
1 in 200 AEP		2.08 - 2.33 - 2.90	2.00 - 2.26 - 2.90	2.02 - 2.25 - 2.70	
1% AEP	2.20	1.97 - 2.21 - 2.70	1.91 - 2.13 - 2.60	1.94 - 2.15 - 2.50	
2% AEP		1.83 - 2.06 - 2.40	1.80 - 1.98 - 2.40	1.83 - 2.01 - 2.30	
5% AEP	1.90	1.60 - 1.78 - 2.00	1.58 - 1.73 - 2.00	1.60 - 1.77 - 2.00	
10% AEP		1.35 - 1.51 - 1.70	1.36 - 1.50 - 1.70	1.37 - 1.53 - 1.70	1.11 - 1.34 - 1.67
20% AEP	1.35				0.94 - 1.07 - 1.23
50% AEP	0.90				0.71 - 0.76 - 0.86

* represents the asymptote of the fitted probability distribution, which is purely a statistical characteristic that may not be meaningful in situations where a physical upper limit does not exist or is not applicable.

Notably, the 1994 study estimates for the 1% AEP of 2.20 mAHD is on the upper end of the values estimated from the current EVA results ranging between 2.13 and 2.21 m AHD. The updated results also show a marked reduction in flood level estimates for more frequent events. For instance, the 20% AEP level has decreased from 1.35 mAHD in the 1994 study to approximately 1.07 mAHD in the current analysis, while the 50% AEP estimate has dropped from 0.90 mAHD to around 0.76 mAHD. These differences are primarily driven by two key factors. First, the current study benefits from an additional 30 years of observed data, which includes a greater number of moderate and frequent flood events but no additional extreme events. The inclusion of this data has steepened the upper tail of the AM series distributions and provided a more statistically representative sample for frequent events. Second, the present study follows the updated guidance of ARR 2019, which recommends more rigorous uncertainty treatments, and the use of differing approaches tailored to different recurrence interval ranges. Unlike the more manual graphical approach used in the 1994 study, the current analysis applies statistical fitting techniques, allowing for more robust estimation and clearer quantification of uncertainty. In particular, the availability of continuous water level data collected since the 1994 study, capturing both minor and moderate flood events that were previously underrepresented, enabled the use of the POT approach. This significantly enhanced the reliability of estimates for more frequent events. The inclusion of these lower-magnitude events has shifted the statistical distribution, resulting in lower central estimates for frequent recurrences as noted above.

6 Hydrologic analysis

Hydrologic modelling consists of determining the volume of water and the flows generated in a catchment based on various parameters including rainfall, catchment area, percentage of the ground that is pervious (such as grass or bare earth for example) or impervious (such as concrete or roads) and typical lag coefficient (which defines the time the flood water takes to travel through the catchment).

6.1 Model selection

A Watershed Bounded Network Model (WBNM 2017_004) was adopted for hydrologic modelling of the Tuggerah Lakes catchment. It is an event-based hydrologic 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 (WMA Water, 2018).

The WBNM software is one of the few modelling packages that currently incorporates Australian Rainfall and Runoff 2019 (ARR 2019) design rainfalls and procedures. 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, a WBNM model (version 2017) was considered appropriate for this study. This version of the model has been developed to include the 2016 Intensity-Frequency-Duration (IFD) diagrams that are at the basis of the ARR 2019 guideline requirements.

6.2 Model setup

6.2.1 Catchment delineation

A GIS-based terrain analysis tool called CatchmentSIM (version 3.6) was used to delineate the overall Tuggerah Lakes catchment into 71 individual sub-catchments using the available 1m LiDAR data (**Section 3.2**). The delineation considered the location of hydraulic constraints, gauging stations and topographic features. CatchmentSIM also allows for the determination of the surface characteristics of each sub-catchment such as area and percentage imperviousness.

The investigation showed that the total catchment area at the outlet of Tuggerah Lakes is approximately 797 km^2. Wyong River contributes 55% of the catchment area, Ourimbah Creek comprises 21%, the lakes themselves contribute 14%, and the remaining 10% covers other catchment areas such as Wallarah Creek and Tumbi Creek, as illustrated in **Figure D.10**.

6.2.2 Model parameters

Parameters required by the WBNM model include sub-catchment area and linkage, pervious and impervious percentage, runoff lag factor, stream routing lag factor, rainfall input, initial losses and continuing losses.

6.2.2.1 Impervious areas

Impervious areas were derived by adopting impervious percentages for various land uses obtained from the NSW Department of Climate Change, Energy, the Environment and Water. A land use map is presented in **Figure D.2**. Based on land use areas, a weighted average was calculated for each sub-catchment using CatchmentSIM. The urbanised/residential areas were assumed to be 60% impervious, roadway corridors and water bodies/basins 100% impervious while the rest was assumed as pervious surface. **Table 6.1** summarises the percentage imperviousness used for each sub-catchment as per **Figure D.10**.

Table 6.1 Adopted percentage impervious for each sub-catchment

Sub-catchment ID	% Impervious	Sub-catchment ID	% Impervious	Sub-catchment ID	% Impervious
1	78.28	25	3.45	49	4.99
2	71.98	26	2.88	50	3.43
3	48.96	27	3.76	51	9.73
4	3.53	28	2.20	52	0.23
5	33.01	29	3.92	53	0.00
6	3.11	30	1.40	54	13.54
7	0.66	31	2.48	55	12.2
8	1.32	32	2.27	56	23.63
9	46.43	33	4.56	57	12.47
10	2.76	34	3.63	58	21.63
11	1.94	35	1.44	59	3.51
12	1.96	36	1.66	60	4.57
13	5.50	37	0.00	61	19.76
14	17.32	38	0.33	62	39.47
15	62.8	39	0.98	63	13.73
16	16.19	40	0.00	64	8.05
17	4.27	41	0.00	65	28.17
18	3.14	42	0.00	66	8.43
19	3.79	43	0.00	67	5.22

Sub-catchment ID	% Impervious	Sub-catchment ID	% Impervious	Sub-catchment ID	% Impervious
20	0.12	44	0.00	68	2.81
21	11.58	45	12.34	69	2.35
22	2.46	46	29.07	70	51.81
23	5.12	47	3.60	71	14.03
24	4.63	48	21.33	-	-

6.2.2.2 Rainfall losses

Rainfall losses including initial loss (IL) and continuing loss (CL), can be widely variable from storm to storm and catchment to catchment. The amount of loss is dependent on several factors such as catchment topography, soil, vegetation, and the antecedent soil moisture (M. El-Kafagee, 2011). It is recommended in ARR 2019 that practitioners undertaking flood investigations in New South Wales should use a hierarchical approach to design loss estimation. A summary of this recommended hierarchy is provided in **Table 6.2**, ranked from the most preferred to the least preferred approach.

Table 6.2 ARR 2019 hierarchical approach to design rainfall loss estimation

Preference	Approach
1	Average of calibration losses from the actual study on the catchment, if available
2	Average of calibration losses from other studies in the catchment, if available and appropriate for the study
3	Average calibration losses from other studies in the similar adjacent catchments, if available and appropriate for the study
4	NSW FFA-reconciled losses available through the ARR Data Hub
5	Default ARR data hub losses

It is noted that the most preferred approach, being the use of the average of calibration losses from the actual study on the catchment, inherently relies on the accurate and appropriate determination of losses as part of the calibration of the hydrologic model. To give further confidence to the validity of these parameters and for the purposes of comparison, losses determined through each approach from across the hierarchy have been determined.

At the bottom of the hierarchy, the default ARR data hub losses were extracted for a representative area of the Tuggerah Lakes catchment region, yielding an IL value of 49.0 mm and a CL of 1.2 mm/h (3.0 mm/h * 0.4 NSW factor).

Next, it was found that the NSW FFA-reconciled losses were available for the upper and lower Wyong River, Jilliby Jilliby Creek and Ourimbah Creek catchments. A summary of the key parameters from this repository is shown in **Table 6.3**.

Table 6.3 NSW FFA-reconciled losses summary for Tuggerah Lakes catchments

Source: https://data.arr-software.org/static/pdf/appendix.pdf

Station	Station Name	Fit Quality	IL (mm)	CL (mm/h)
H25	Wyong River at Yarramalong	Good	18.2	5.00
H28	Wyong River at Gracemere	Good	50.0	3.92
H27	Jilliby Creek upstream Wyong River	Poor	14.3*	1.50*
H26	Ourimbah Creek upstream Weir	Good	64.3	4.81

**Initial and continuing loss values appear inconsistent with other neighbouring gauges values, and this is likely the result of the poor FFA fit quality.*

As outlined in the **Chapter 2**, several studies have been conducted within the Tuggerah Lakes catchment. Unfortunately, there was no consistency among these studies in relation to IL and CL values for pervious areas, underscoring the highly variable and complex hydrology of the Tuggerah Lake catchment. Previously calibrated continuing losses for pervious surfaces have ranged between 1.5 and 4.0 mm/h, while impervious surfaces have consistently been 0 mm/h. Due to the variable nature of historically adopted initial losses, their values were investigated once again. Optimal calibration results were achieved by adopting a CL of 1.0 mm/h and IL of 58-80 mm (depending on the historic event). While these values appear larger than the initial loss values described in **Table 2.4**, it is noted that this table summarises the parameters that have been adopted for the design events and calibration initial loss values often exceed the design value. These values were considered reasonable given the IL and CL losses derived from the ARR Datahub are 49 mm and 1.2 mm/h respectively. Detailed calibration and validation results are further detailed in **Section 6.3**.

6.2.2.3 Lag parameter

A lag parameter (C) is used for the conversion of rainfall to runoff on pervious surfaces. WBNM developers recommend lag parameter values ranging between 1.3 and 1.8 (Boyd and Bodhinayake, 2006). The value of the lag factor can vary based on the characteristics of the watershed, including soil type, land use, slope, and vegetation. Generally, a lag parameter value down to 1.3 is recommended for catchments with steep slopes and fast drainage and thus a peakier flow profile, while a value of up to 1.8 is suggested for catchments with a flatter flow profile (i.e., flow with a longer duration and lower peak).

Investigation of gauging data and the topography of the Tuggerah Lakes catchment indicates that Tuggerah Lakes tributaries are largely expected to demonstrate a faster response in flow, featuring a peaky rising limb and a flatter tailing limb.

Calibration outcomes, as described in **Section 6.3**, revealed that a C parameter value of 1.3 adequately replicates the flow across gauging locations. The upper catchments of the model consist of steep topography leading to a quick response in flow and therefore justifying a lower lag factor. Lower in the catchment, flows then fill floodplain fringe and storage areas, which acts to attenuate flows reaching the lakes. It is noted that the latter effect sometimes cannot be accounted for by the lag parameter alone.

The impervious lag factor is used to reduce the C lag parameter to a value appropriate for impervious surfaces. An impervious lag factor of 0.1 was adopted based on calibration results against measured flow data during flood events for sub-catchments upstream of the Wyong Weir. 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. Refer to **Table 6.7** for the values of the lag parameter.

6.3 Model calibration and validation

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. The model calibration process also demands a high degree of confidence in the recorded data to which the model is to be calibrated to converge towards.

Event selection for model calibration and validation was performed through consideration of several factors, including the magnitude, recency, data availability, significance and complexity of the event. Through consideration of these factors and reference to the historical flood record presented in **Table 1.1**, it was determined that the July 2022 and June 2007 events be selected for model calibration, with the March 2021 event selected for model validation. The July 2022 and March 2021 events were selected as they are the most recent significant flood events that occurred in the Tuggerah Lakes, whereas the June 2007 event was selected as a result of its comparably large peak flood level, notoriety and availability of supplementary data through other previously adopted flood studies covering the Tuggerah Lakes catchment area (e.g., the Wyong River Catchment Flood Study). It is noted that the February 2020 event was considered as it is another large event in recent times. However, this event was not selected because of the artificial intervention of multiple channels being dredged at the entrance during the event, making this event too complex to accurately represent in the hydraulic model.

Having decided on relevant events, an important first step in the model calibration process is the acquisition and confirmation of relevant calibration data quality. Being a hydrologic model, the most essential parameter to calibrate against is flow discharge. As outlined in **Section 3.1**, a number of water level gauge locations exist across the Tuggerah basin, with a subset of these sites possessing a stage-discharge rating curve derived from observed flow gaugings. However, the reliability of these rating curves is critical in determining an accurate discharge, particularly during larger flow events which are presently of interest. As a result, the calibration gauges are introduced in the following section and their rating curve confidence assessed.

6.3.1 Rating curve analysis

The Tuggerah Lakes catchment is made up of several distinct tributaries. The two largest are the Wyong River and Ourimbah Creek, which account for nearly 60% and 20% of the catchment area, respectively. The remaining approximately 20% of the Tuggerah Lakes catchment consists largely of the lakes themselves, and a handful of smaller creeks and overland catchments, on which rating curve analyses cannot be performed.

6.3.1.1 *Wyong River at Yarramalong (211014)*

The gauge located highest within the catchment is on the Wyong River at Yarramalong (211014). The rating curve and measured flow gauging points at this gauge location are presented in **Figure 6.1**.

As can be seen in this diagram, the rating curve exhibits a fair relationship with the data, where available. However, only one flow gauging point is available for flows in excess of ~30 m^3/s (~2,500 ML/d), and with extrapolation relied upon to derive a rating relationship for flows above ~100 m^3/s (~8,500 ML/d), at the time coinciding with a measured stage of 25.110 m AHD. It is noted that the peak water levels in all three of the calibration events significantly exceed this rating extrapolation threshold.

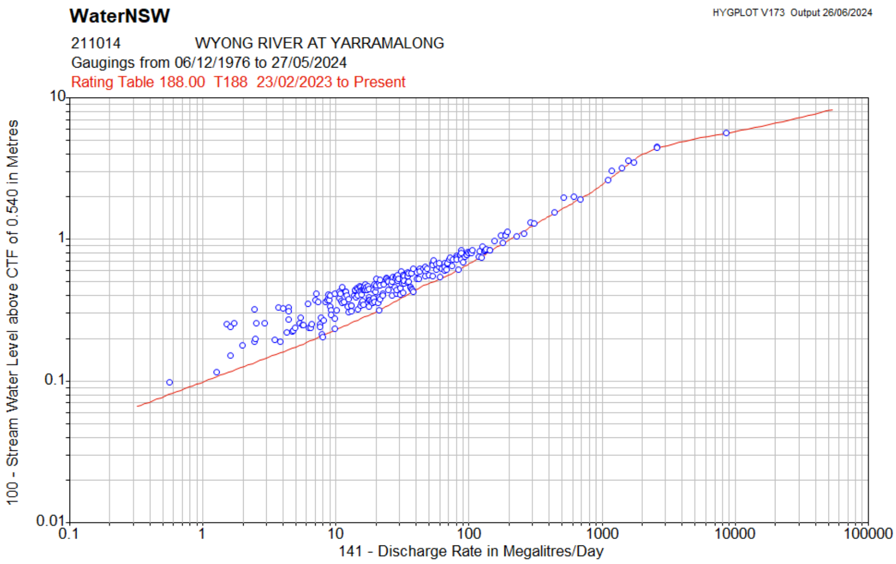


Figure 6.1 Comparison plot of gaugings and latest ratings for Wyong River at Yarramalong (211014) (WaterNSW)

This conclusion was similarly reached by the Wyong River Catchment Flood Study (2014), which noted that *"[the] bank-full level at the gauge is around 24 m AHD, equivalent to almost 40 m^3/s flow"* and that there was *"a close match between the [modelled and site] rating curves until around 100 m^3/s [(8640 ML/day)] when the two curves begin to deviate*". The modelled and existing rating curve at the time of the 2014 study are presented in **Figure 6.2**.

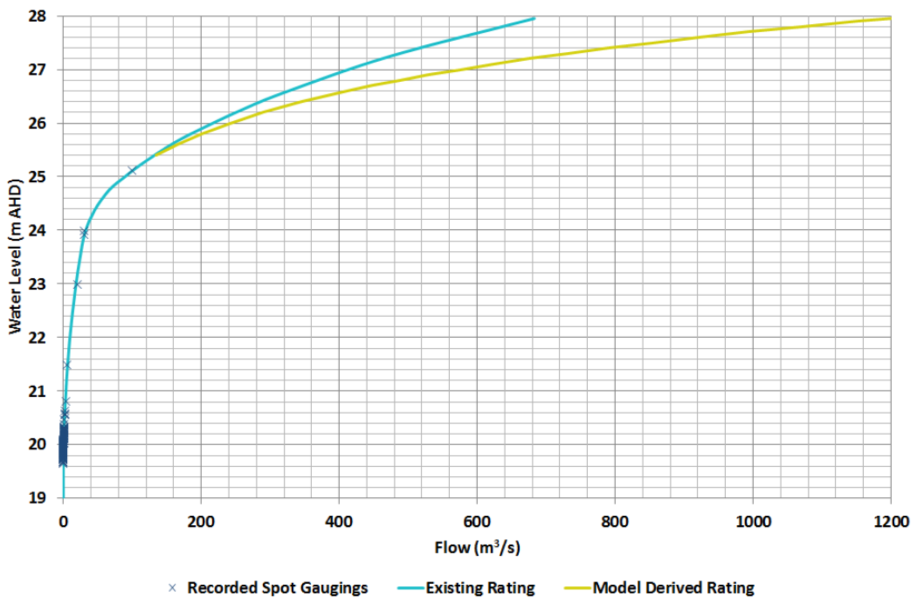


Figure 6.2 Comparison plot of modelled and WaterNSW-derived ratings, as extracted from the Wyong River Catchment Flood Study (2014), for the Wyong River at Yarramalong (211014)

It was therefore determined that flows derived from the WaterNSW derived stage-discharge rating at this location be considered unreliable for the purpose of the calibration of the hydrologic model.

6.3.1.2 Wyong River at Gracemere (211009)

The next gauge progressing down the Wyong River is located at Gracemere (211009). The rating curve and measured flow gauging points at this gauge location are presented in **Figure 6.3**.

As can be seen in this diagram, the rating curve exhibits a fair relationship with the data, where available. However, extrapolation of the rating curve is relied upon to derive a rating relationship for flows above ~80 m^3/s (~7,000 ML/d), at the time coinciding with a measured stage of 11.235 m AHD. It is noted that the peak water levels in all three of the calibration events significantly exceed this rating extrapolation threshold.

A similar conclusion was again reached by the Wyong River Catchment Flood Study (2014), which noted that *"[the] bank-full level at the gauge is around 10.5m AHD, equivalent to around 60 m^3/s flow*" and that there was "*a close match between the [modelled and site] rating curves until around 80 m^3/s when the two curves begin to deviate*".

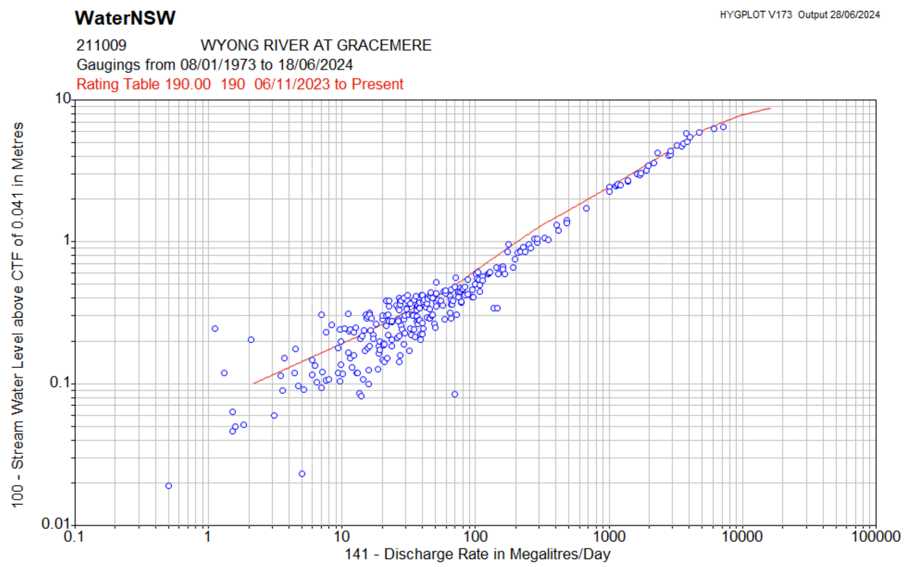


Figure 6.3 Comparison plot of gaugings and latest ratings for Wyong River at Gracemere (211009) (WaterNSW)

Further concerns regarding the reliability of the stage-discharge rating curve are raised through an inspection of the rating curve history plot for the Wyong River at Gracemere gauge, which shows that over the period of operation of the gauge, the shape of the adopted stage-flow rating curve has undergone significant and regular modifications, indicating the high uncertainty surrounding the relationship, particularly at higher stages. The modelled and existing rating curve at the time of the 2014 study are presented in **Figure 6.4**.

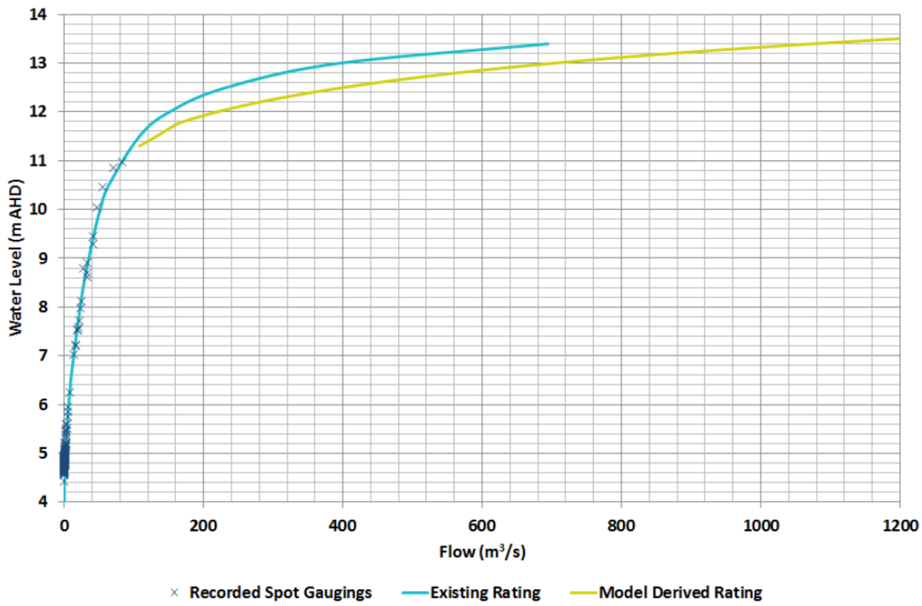


Figure 6.4 Comparison plot of modelled and WaterNSW-derived ratings, as extracted from the Wyong River Catchment Flood Study (2014), for the Wyong River at Gracemere (211009)

It was therefore determined that flows rated from the WaterNSW derived stage-discharge relationship at this location be considered unreliable for the purpose of the calibration of the hydrologic model.

6.3.1.3 *Wyong River at Wyong Fishway (211017)*

The final gauge with an adopted stage-discharge rating progressing downstream the Wyong River is located at the Wyong Fishway (211017). The rating curve and measured flow gauging points at this gauge location are presented in **Figure 6.5**.

As can be seen in this diagram, minimal flow gauging data exists at this location, with WaterNSW tending to censor flow values above 70 m^3/s likely because of this significant uncertainty.

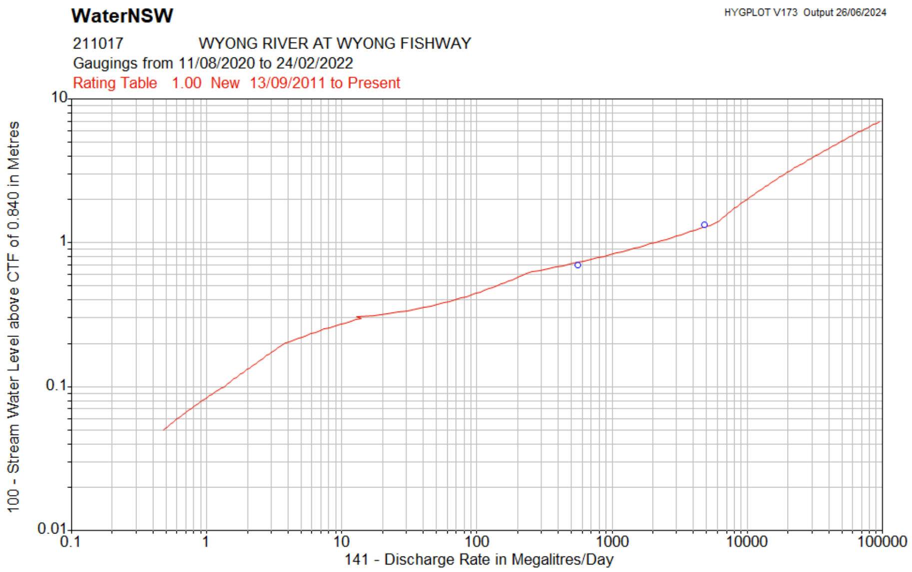


Figure 6.5 Comparison plot of gaugings and latest ratings for Wyong River at Wyong Fishway (211017) (WaterNSW)

It was therefore determined that flows derived from the WaterNSW derived stage-discharge rating curve at this location be considered unreliable for the purpose of the calibration of the hydrologic model.

6.3.1.4 *Jilliby Creek upstream Wyong River (211010)*

Jilliby Jilliby Creek is a tributary of the Wyong River, joining downstream of Gracemere. The Jilliby Creek upstream Wyong River (211010) gauge is located on this tributary near Durren Lane. The rating curve and measured flow gauging points at this gauge location are presented in **Figure 6.6**.

As can be seen in this diagram, the rating curve exhibits a fair relationship with a portion of the flow gauging data, with a secondary alignment of points seen above the adopted curve. However, extrapolation of the rating curve is relied upon to derive a rating relationship for flows above ~20 m^3/s (~1,700 ML/d), at the time coinciding with a measured stage of 10.058 mAHD. It is noted that the peak water levels in all three of the calibration events significantly exceed this rating extrapolation threshold.

A similar conclusion was again reached by the Wyong River Catchment Flood Study (2014), which noted that *"[the] site was known to be unreliable for estimating flood flows due to the nature of the floodplain topography and this is still the case, even with a modelled rating*" and that "*[the] modelled rating is extremely flat above the bank-full level of 11m AHD… making it difficult to establish a reliable rating curve.*"

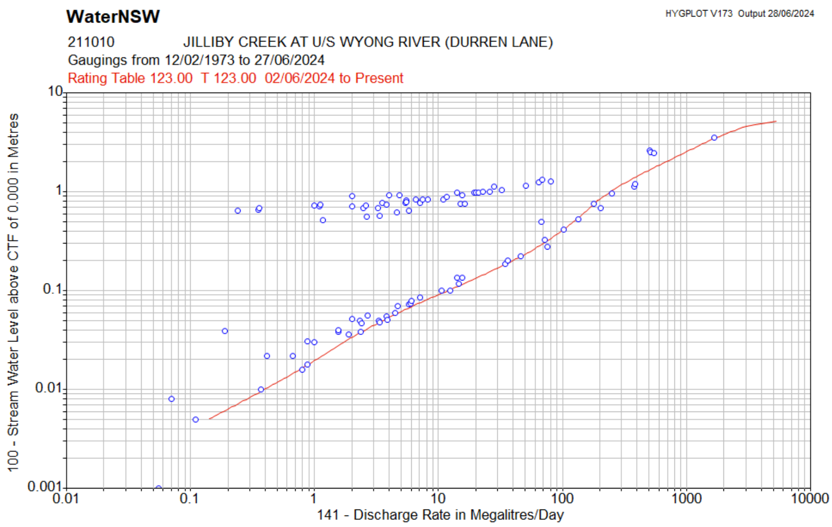


Figure 6.6 Comparison plot of gaugings and latest ratings for Jilliby Creek upstream Wyong River (211010) (WaterNSW)

The modelled and existing rating curve at the time of the 2014 study are presented in **Figure 6.9.**

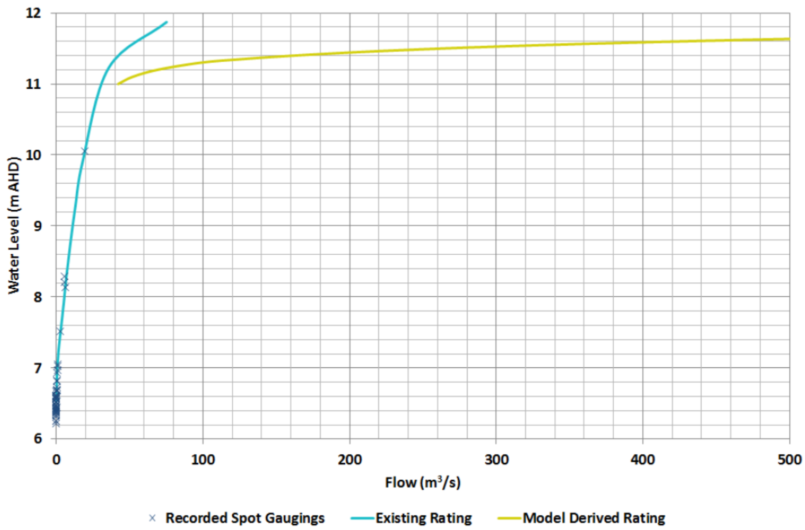


Figure 6.7 Comparison plot of modelled and WaterNSW-derived ratings, as extracted from the Wyong River Catchment Flood Study (2014), for Jilliby Creek upstream Wyong River (211010)

It was therefore determined that flows derived from the stage-discharge rating curve at this location be considered unreliable for the purpose of the calibration of the hydrologic model.

6.3.1.5 Ourimbah Creek upstream Weir (211013)

The gauge located highest within the Ourimbah Creek catchment is located at Ourimbah Creek upstream Weir (211013). The rating curve and measured flow gauging points at this gauge location are presented in **Figure 6.8**.

As can be seen in this diagram, the rating curve exhibits a good relationship with the flow gauging data. However, extrapolation of the rating curve is relied upon to derive a rating relationship for flows above ~40 m^3/s (~3,500 ML/d), at the time coinciding with a measured stage of 17.249 m AHD. It is noted that the peak water levels in all three of the calibration events exceed this rating extrapolation threshold.

On the matter, the Ourimbah Creek Catchment Flood Study (2013) concluded that *“the rating curve and the associated discharge estimates are likely to be reliable although discharge estimates at very high stages … will be prone to some uncertainty.*”

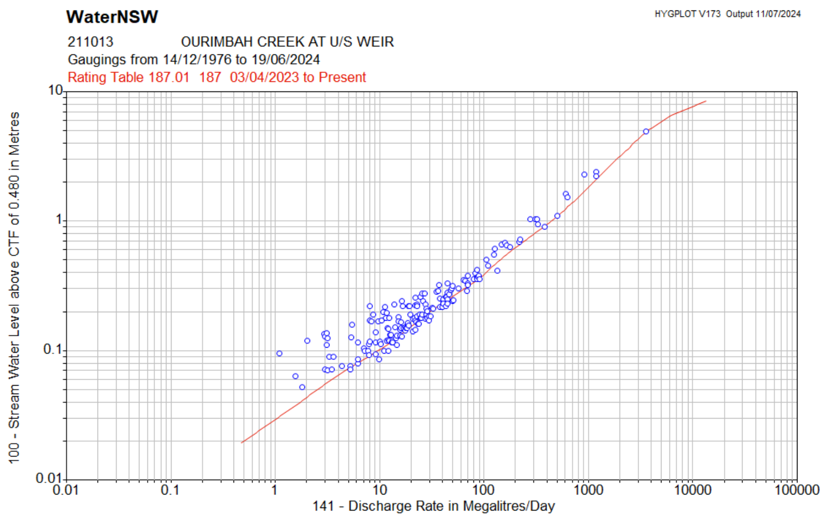


Figure 6.8 Comparison plot of gaugings and latest ratings for Ourimbah Creek upstream Weir (211013) (WaterNSW)

It was therefore determined that flows derived from the stage-discharge rating curve at this location be considered reliable for the purpose of the calibration of the hydrologic model.

6.3.1.6 Rating curve analysis summary

Noting the lack of reliable flow gauge locations along the entirety of the significant Wyong River catchment, and to adequately calibrate the hydrologic model, an alternative calibration approach was required.

As such, it was determined that the TUFLOW model developed as part of the Wyong River Catchment Flood Study could be modified to accept the outputs of the calibrated hydrologic model. This would allow for the hydraulic model to be utilised to translate flows as determined by the new hydrologic model into water levels at key gauge locations. This has the effect of removing the reliance on unsuitable flow time series derived from the abovementioned extrapolated rating curves and instead allows direct comparison of modelled flood levels to gauged water level time series of much higher reliability.

While this approach was adopted with the aim of translating the outputs of the hydrologic model into a form that can be reliably calibrated, the use of a secondary hydraulic model to achieve this inherently introduces the effect of any underlying deficiencies that may exist in the hydraulic model of the Wyong River Catchment Flood Study. However, this model was also calibrated against a variety of events and was adopted as such and is therefore considered to be appropriate for this purpose and the results of the calibration for the three selected calibration/validation events are described in **Sections 6.3.2** to **6.3.4**.

6.3.2 July 2022 calibration

6.3.2.1 Rainfall data and event summary

The July 2022 flooding event saw intense rainfall which broke numerous longstanding records across much of the NSW east coast. The event was associated with an East Coast Low that formed off the Hunter coast of NSW on 2 July. The East Coast Low moved offshore on 3 July, but onshore flow continued to bring persistent rain to the Central Coast and Greater Sydney. Rainfall intensified on the June 4 and 5 when a trough extending from the East Coast Low passed over the Central Coast and Greater Sydney. The event sustained heavy rainfall and caused widespread damage across the Central Coast, Greater Sydney and Illawarra regions (BoM, 2022). A high-level review of the rainfall records indicates that an average of over 400 mm of rain fell over a ten-day period between 2 and 12 July 2022.

The distribution of rainfall gauge locations within the Tuggerah Lakes catchment are exhibited in **Figure D.4**, with their respective periods of record shown in **Table 3.1**. A comprehensive coverage of continuous rainfall data was available across the catchment in the July 2022 event from both the BoM and MHL.

First, a comparison was performed between these continuous gauges in terms of the rainfall depth and temporal pattern across the event. A summary of cumulative precipitation at all relevant continuous gauges in the region plot is shown in **Figure 6.9**.

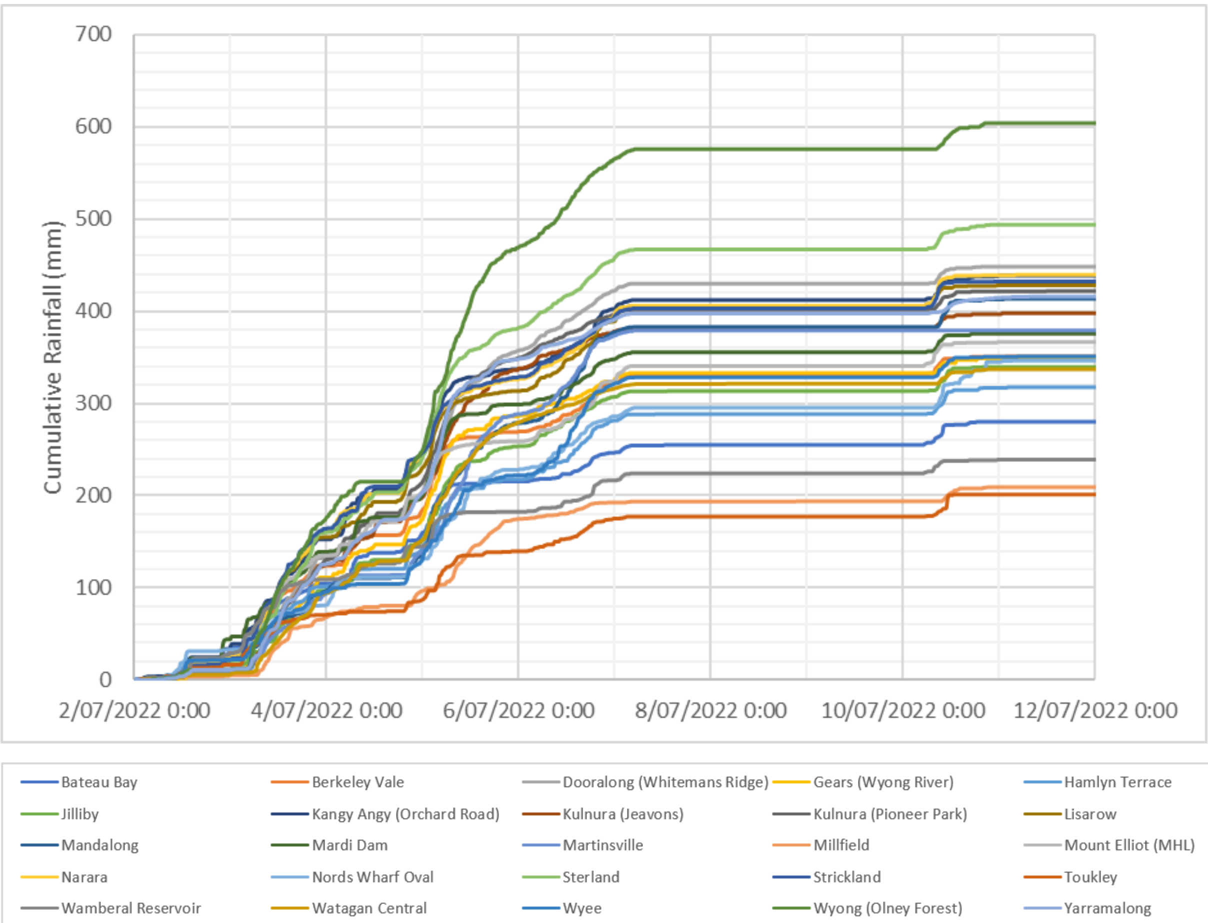


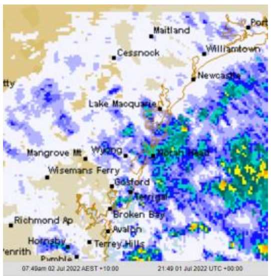
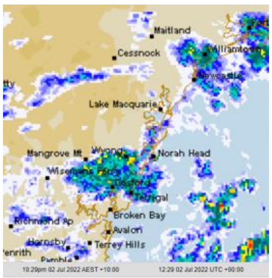
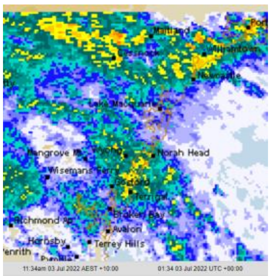
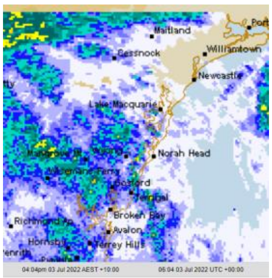
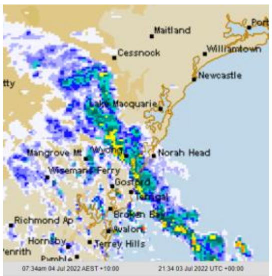
Figure 6.9 Cumulative recorded rainfall depths during the July 2022 calibration event

As can be seen, a wide variability in rainfall depth and modest variability in temporal pattern was observed across the catchment during this event. This is typical of catchments which see the effects of orographic variability and may additionally be because of the complex meteorological lifecycle of the July 2022 event. **Figure D.11** presents the spatial coverage of the available continuous rainfall data across the catchment and is overlaid with recorded rainfall isohyets derived from the observed data at these points. It is noted that rainfall depths and temporal patterns from each gauge location are applied according to the WBNM Theissen polygon approach. The zones of influence of each gauge under this approach are also shown in **Figure D.12**.

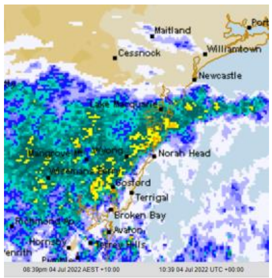
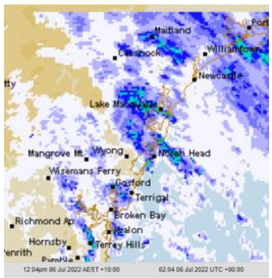
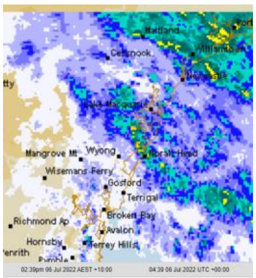
Data from the Martinsville gauge location were excluded because of missing or erroneous data on 10 July 2022, verified by means of comparison with a nearby gauge location at Mandalong. The exclusion of this site does not significantly compromise the spatial coverage of rainfall data across the catchment, and the data for the rest of the event is closely represented by that at Mandalong.

To further validate the observed depths and temporal patterns recorded at the remaining continuous rainfall gauge locations, radar data available from the Sydney (Terry Hills) radar station, located approximately 50 km to the south, was acquired for interrogation from *theweatherchaser.com*. A selection of these radar images is presented and discussed in **Table 6.4**.

Table 6.4 Selected Sydney (Terry Hills) radar imagery during the July 2022 calibration event

Description	Radar image	Description	Radar image
7:49am 2 July 2022 The event begins on the morning of the 2 July with some patchy, low intensity rainfall, with some more intense cells nearer the coast		10:20pm 2 July 2022 By evening, these patchy showers form heavier large cell near the coast, which clears to the west	
3:24am 3 July 2022 By early morning, an intense band of storms crosses the catchment from east to west		8:19am 3 July 2022 Across the morning band grows to cover the entire catchment in moderate to intense rainfall	
11:34am 3 July 2022 Consistent and intense rainfall, as described above, continues into the afternoon		4:04pm 3 July 2022 Consistent rainfall, as described above, continues into the evening, becoming more moderate	
1:24am 4 July 2022 By early morning, the widespread rain has localized into a band of rain, linearly streaming from south-east to north-west		7:34am 4 July 2022 A train of rain continues to progress from south-east to north-west, causing isolated intense rainfall along its length	

Classification: Public

Description	Radar image	Description	Radar image
6:19pm 4 July 2022 After a period of relative calm during the day on 4 July, another thick band of intense rainfall approaches the catchment from the south		8:39pm 4 July 2022 The abovementioned band crosses the catchment during the evening	
12:54am 5 July 2022 Moderate to intense falls are ongoing into the morning of 5 July, now crossing the catchment from east to west		4:29am 5 July 2022 As above	
8:39am 5 July 2022 As above, with falls becoming more moderate and banded on the afternoon of 5 July		12:04pm 6 July 2022 Falls become patchy and less intense throughout the morning of 6 July	
2:39pm 6 July 2022 By the afternoon, a final group of moderate intensity rainfall bands approaches the catchment, now from the north-east		Significant rainfall abates early on the morning of 7 July	

6.3.2.2 Antecedent conditions

The antecedent catchment condition in respect to its degree of wetness prior to a major rainfall event can significantly influence the runoff and loss behaviour of the catchment.

Inspection of the rainfall data preceding the July 2022 event at a representative gauge location as shown in **Figure 6.10** revealed that the early months of 2022 saw some significant rainfall events, with the first five months of the year seeing above average rainfall. Conversely, the month of June immediately preceding the event saw a total rainfall of only 14.6 mm, far below the long-term average for June of 94.6 mm.

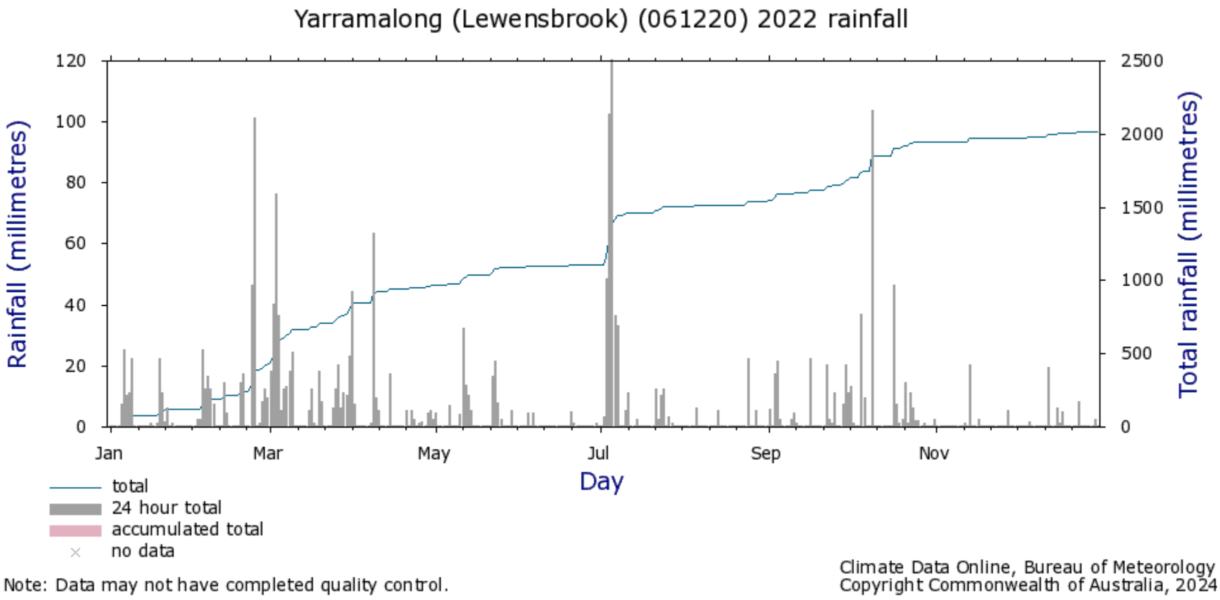


Figure 6.10 2022 daily rainfall at Yarramalong (61220)

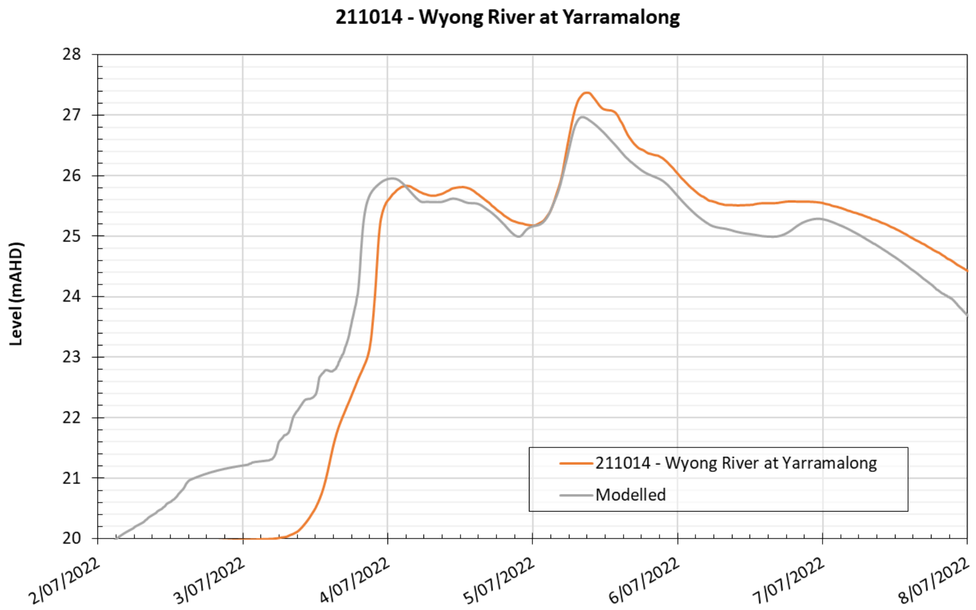
It is anticipated that the significant rainfall amounts seen in the early months of 2022 likely resulted in the deep saturation of soils in the Tuggerah Lakes catchment, with high soil moistures likely. However, the period of below-average rainfall immediately prior to the event may have had the result of moderating soil moisture, particularly at the soil surface. These antecedent moisture and soil conditions were considered further throughout the model calibration process.

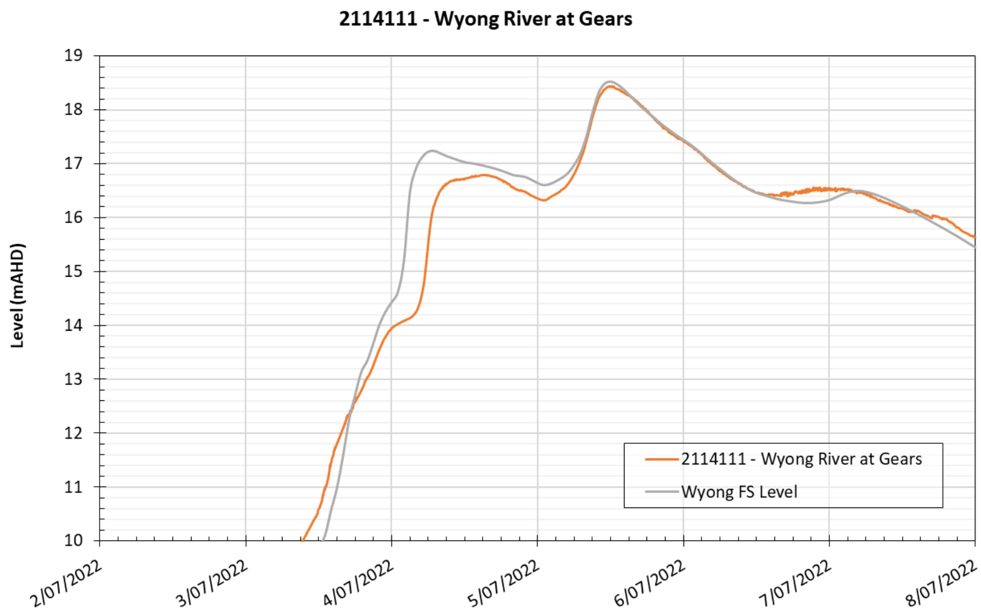
6.3.2.3 Model parameter adjustment

The initial adopted model parameters for this calibration run consisted of those recommended by ARR, namely a CL of 1.2 mm/h, and an IL of 49 mm. These values were adjusted to obtain a CL value of 1.0 mm/hr and an IL value of 58 mm, with the increase in IL value potentially being necessary because of the relatively dry period immediately prior to the event. A routing factor of 1.3 was adopted initially as it was thought that the relevant catchments would display a 'peakier' behaviour owing to their steep upstream topography and geometry, with no further adjustments found to be required.

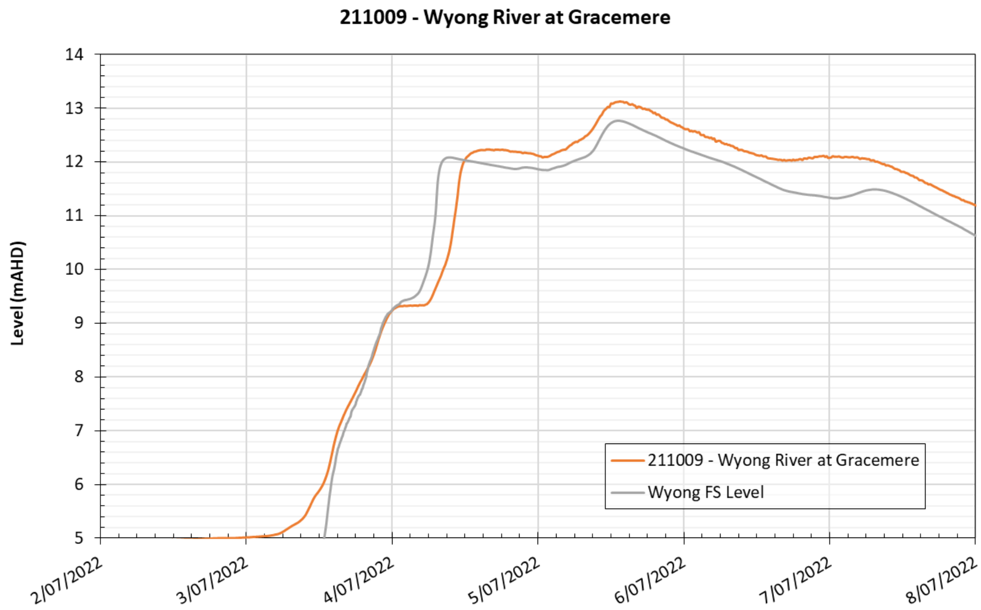
6.3.2.4 Observed and simulated flood behaviour

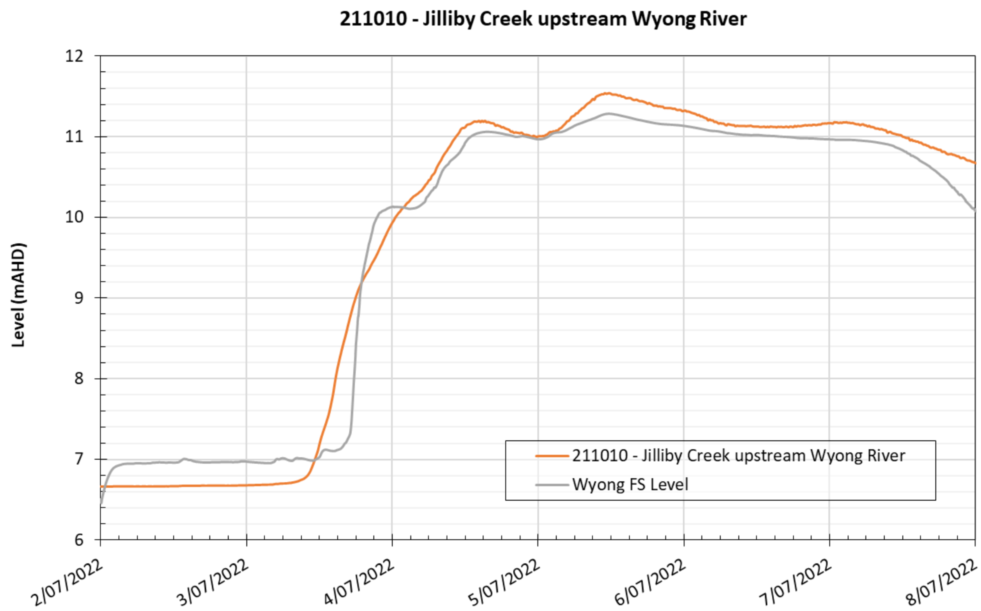
Comparison of the hydrologic model results to available measured level and flow data, where appropriate, for the July 2022 calibration event are presented in **Figure 6.11** and **Figure 6.12.**



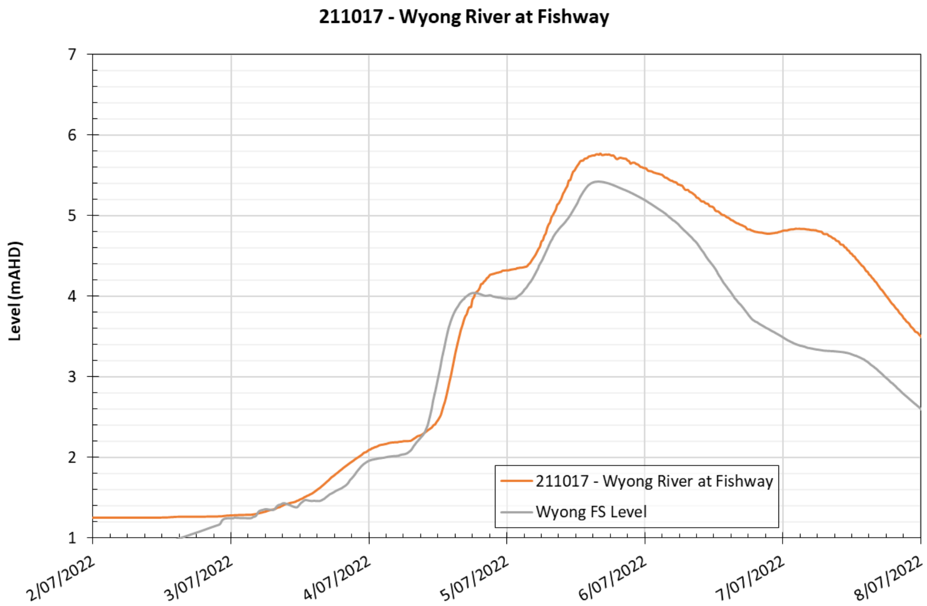


Classification: Public





Classification: Public



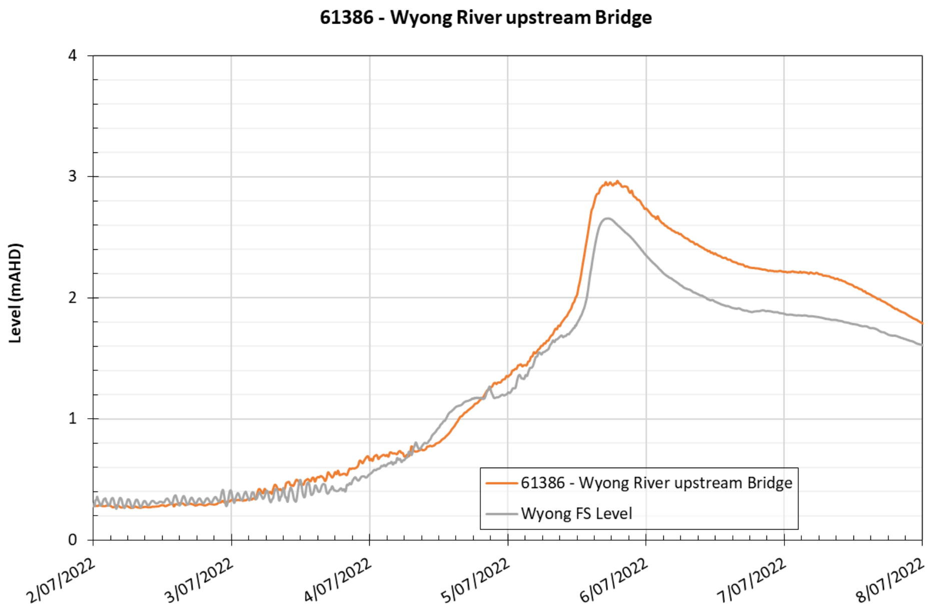


Figure 6.11 Comparison of simulated and observed water level data on the Wyong River for the July 2022 calibration event

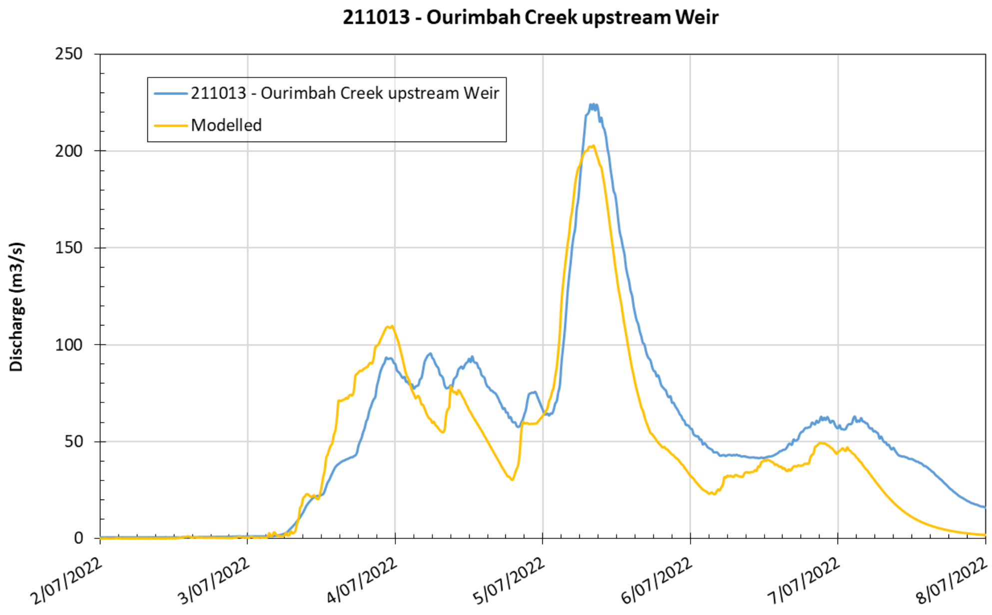


Figure 6.12 Comparison of simulated and flow-rated level data at Ourimbah Creek upstream Weir (211013) for the July 2022 calibration event

For the July 2022 calibration event on the Wyong River, the modelled results provide a reasonable representation of the recorded water levels at all locations.

Being the highest gauge in the catchment, it is reasoned that the Wyong River at Yarramalong gauge was expected to be subject to less hydraulic effects such as storage, losses, structures obstructions, backwater effects from the downstream lake levels and other complex interactions. The result of the model at this location is therefore considered to be closely reflective of the aptitude of the hydrologic model. Noting this, it is observed that the result at this location shows close agreement with that recorded in terms of both timing and magnitude.

Modelled water levels at Gears can be seen to also be in close accordance with those recorded.

Results at Gracemere are also good in the rising limb and peak flood phases, however, do tend to be underestimated in the falling limb.

Close agreement is also demonstrated on Jilliby Jilliby Creek at the Jilliby Creek upstream Wyong River gauge.

In the lower reaches of the Wyong River at Wyong Fishway and Wyong Bridge, the model can be seen to provide a good match between simulated and recorded hydrographs at these locations, accurately capturing the timing and general shape of the event. Key features such as the rising limb, flood peak, and recession phase are well represented in terms of their relative timing and magnitude. Minor discrepancies are noted, including a slight underestimation in peak level and a tendency towards underestimation of level falling limb of the hydrograph. These effects are suspected to be due to a range of factors, including the fact that bathymetry at these locations is estimated, the relatively course grid size of the hydraulic model acting to reduce modelled conveyance, backwater effects from the nearby lake, and potential floodplain and storage losses within the hydraulic model upstream of these locations.

Storage losses can occur when inundated areas are not able to drain fully within the model due to limitations in the representation of small drainage features and groundwater flow.

It is considered that the model reliably reproduces the key flood dynamics observed in this calibration event for the Wyong River, particularly in terms of volume and timing, which are of direct relevance to the present study.

On Ourimbah Creek, a good representation of the timing and shape of the recorded flow-rated levels at the Ourimbah Creek upstream Weir site is demonstrated. However, it is reiterated that these rated flow data are converted from recorded water levels, and the conversion may be unreliable at high stages.

Flood depths as modelled for the July 2022 calibration event are presented in **Figure E.1**.

6.3.3 June 2007 calibration

6.3.3.1 Rainfall data and event summary

The June 2007 flooding event was associated with an East Coast Low that formed off the coast of NSW, just north of Newcastle. The storm produced strong winds, elevated ocean levels and sustained heavy rainfall and caused widespread damage across the Central Coast and Hunter regions. This storm event is often associated with the grounding of the *Pasha Bulker* on 8 June at Nobbys Beach (AIDR, 2024).

A high-level review of the rainfall records indicates that an average of over 300 mm of rain fell over a three-day period between 8 and 10 June 2007.

The distribution of rainfall gauge locations within the Tuggerah Lakes catchment are exhibited in **Figure D.4**, with their respective periods of record shown in **Table 3.1**.

A comprehensive coverage of continuous rainfall data was available across the catchment in the June 2007 event from both the BoM and MHL.

First, a comparison was performed between these continuous gauges in terms of the rainfall depth and temporal pattern across the event. A summary of cumulative precipitation at all relevant continuous gauges in the region plot is shown in **Figure 6.13**. As can be seen, a wide variability in rainfall depth and modest variability in temporal pattern was observed across the catchment during this event. Consistent, widespread rainfall is observed across all sites in the afternoon of 7 June and morning hours of 8 June, with a significant burst of rainfall falling across the catchment in the early afternoon of 8 June. This burst is followed by ongoing steady rainfall at some sites, while other sites see much lower totals. Another burst of rainfall is seen across most sites on the morning of 9 June.

Figure D.13 presents the spatial coverage of the available continuous rainfall data across the catchment and is overlaid with recorded rainfall isohyets derived from the observed data at these points. It is noted that rainfall depths and temporal patterns from each gauge location are applied according to the WBNM Theissen polygon approach. The zones of influence of each gauge under this approach are also shown in **Figure D.14**.

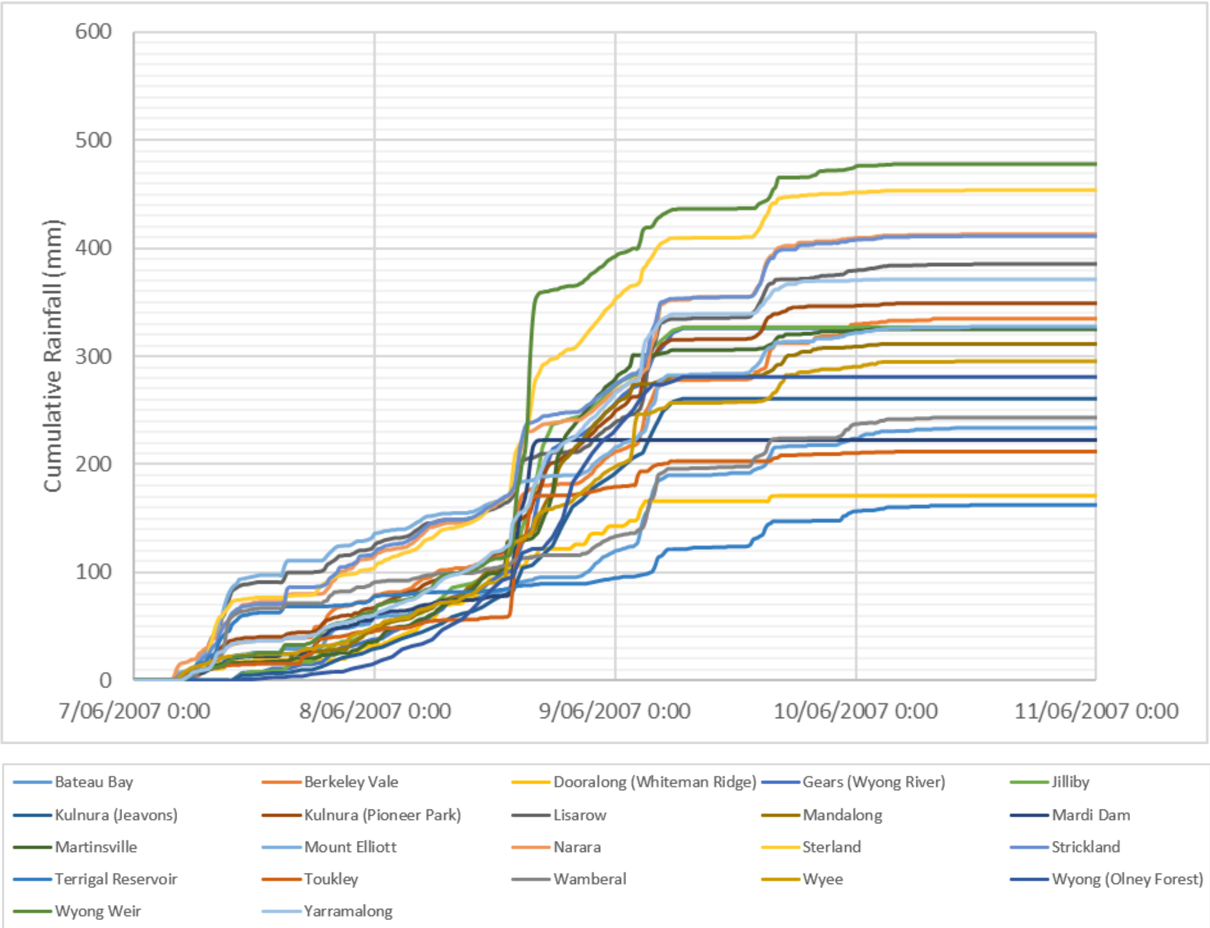
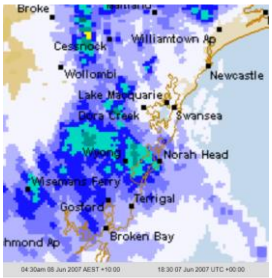
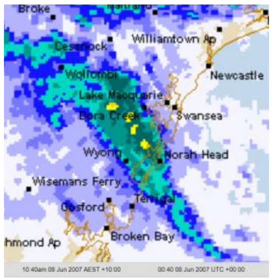
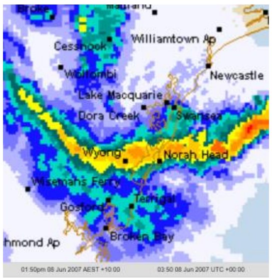
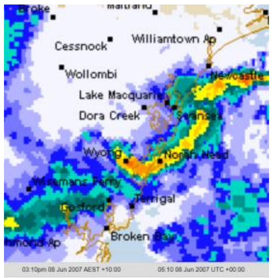
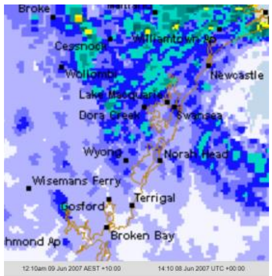
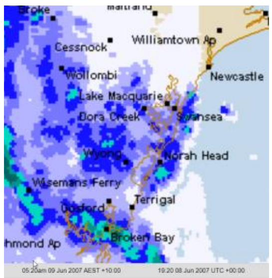


Figure 6.13 Cumulative recorded rainfall depths during the June 2007 calibration event

To further validate the observed depths and temporal patterns recorded at the remaining continuous rainfall gauge locations, radar data available from the Newcastle radar station, located approximately 80 km to the north-east, was acquired for interrogation. A selection of these radar images is presented and discussed in **Table 6.5.**

Table 6.5 Selected Newcastle radar imagery during the June 2007 calibration event

Description	Radar image	Description	Radar image
4:30am 8 June 2007 Widespread rainfall across catchment		10:40am 8 June 2007: Band of moderate intensity rainfall crosses the catchment from north-east to south-west	
1:50pm 8 June 2007: Band of high intensity rainfall crosses the catchment from north to south		3:10pm 8 June 2007: Band of high intensity rainfall continues to impact catchment, with an extended period of intensity focused around the Wyong area	
5:40pm 8 June 2007: Band of high intensity rainfall degenerates into a wider band of moderate intensity and slowly migrating to the west and north		12:10am 9 June 2007: Widespread, moderate intensity rainfall spreads across the entire catchment, growing from north to south	
2:10am 9 June 2007: An intense band of rainfall passes through the catchment from east to west. The centre of the 'East Coast Low' pressure system can be observed passing inland, and is centred on Cessnock at this time		5:20am 9 June 2007: A cluster of moderate intensity rainfall rolls through the catchment from east to west, followed by clear conditions	

Classification: Public

Description	Radar image	Description	Radar image
3:00pm 9 June 2007: After a few dry hours, a final pulse of moderate intensity rainfall rolls through the catchment from south-east to north-west			

6.3.3.2 Antecedent conditions

Inspection of the rainfall data preceding the June 2007 event at a representative gauge location as shown in **Figure 6.14** revealed that the early months of 2007 saw average to below-average rainfall. In particular, the month of May immediately preceding the event saw a total rainfall of only 49.0 mm (37.0mm of which fell on 10 May 2007) and below the long-term average for May of 82.9 mm. The three weeks preceding the event saw a total of only approximately 10 mm.

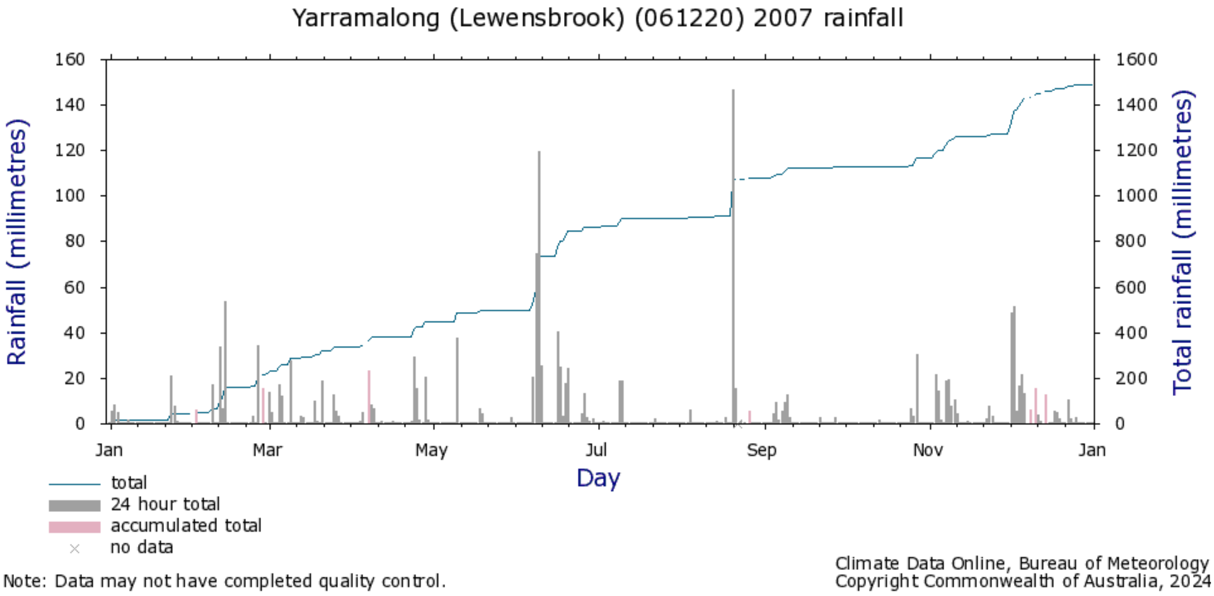


Figure 6.14 2007 daily rainfall at Yarramalong (61220)

It is anticipated that the consistent rainfall amounts seen in the early months of 2007 would bring about typical soil moistures Tuggerah Lakes catchment. Although, the period of below-average rainfall immediately prior to the event may have had the result of reducing soil moisture, particularly at the soil surface. These antecedent moisture and soil conditions were considered further throughout the model calibration process.

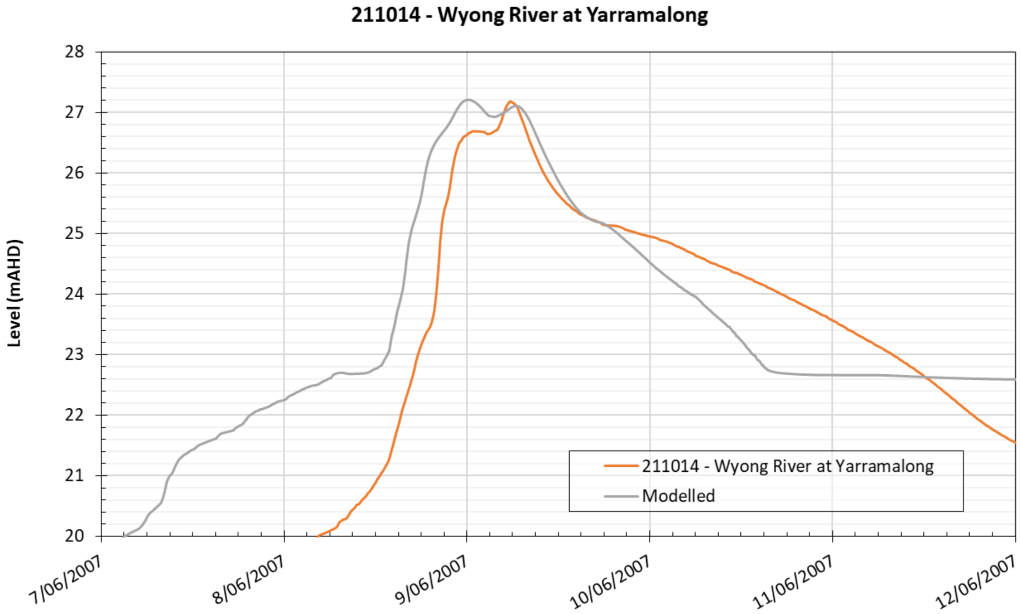
6.3.3.3 Model parameter adjustment

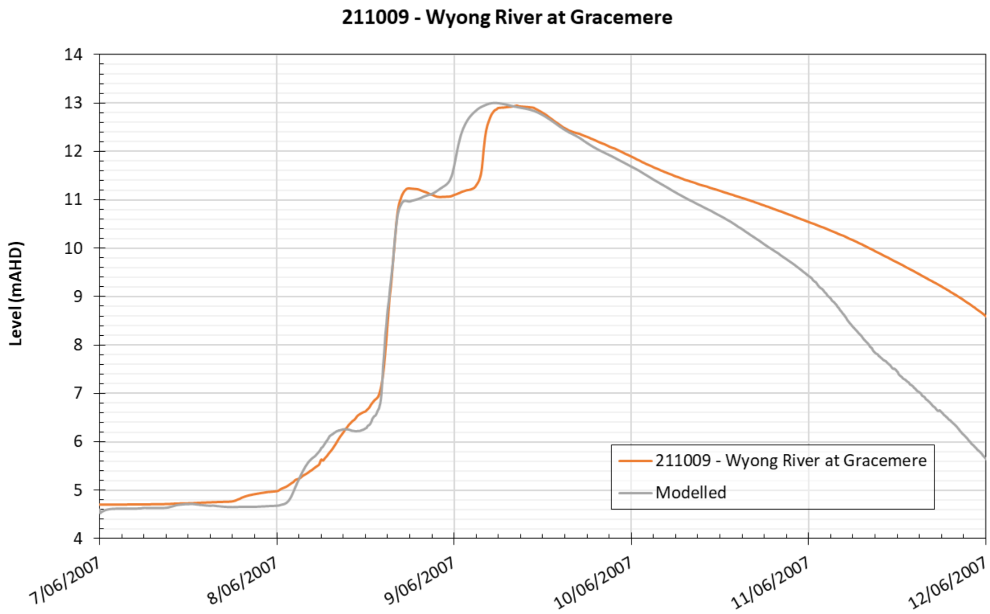
Model parameters adopted for the July 2022 event were initially retained for the June 2007 validation event without modification. However, further testing of the effect of initial loss, considering the drier antecedent conditions prior to this event, necessitated an increase in IL to 80 mm to achieve optimal results. As was discussed in **Section 2.4**, while the Wyong Flood

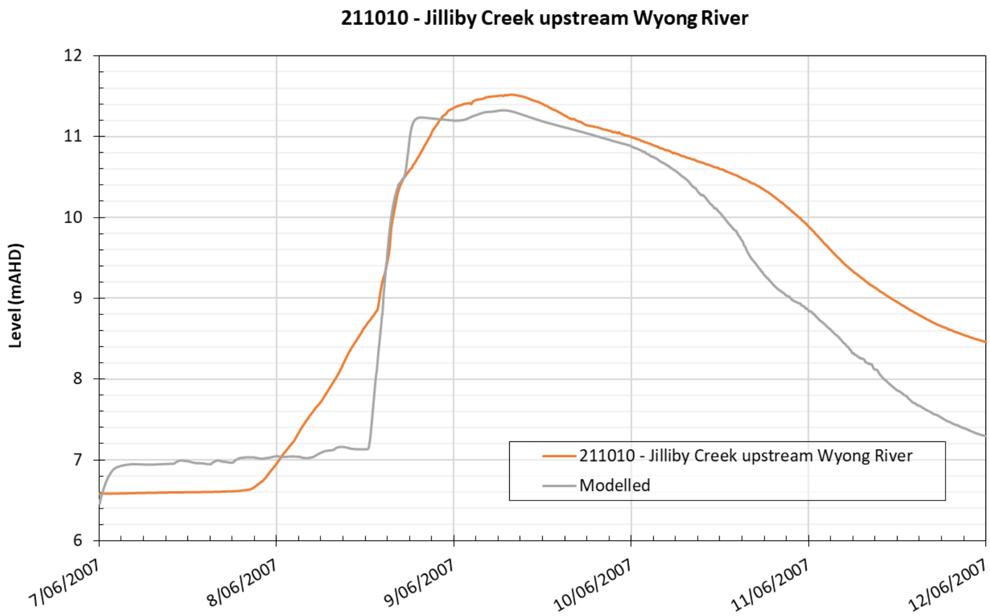
Study adopted an initial loss of 35 mm for all events, this study commences the event at 9am on 7 June 2007, after a burst of rainfall averaging approximately 30 mm across the catchment had already fallen over the preceding nine hours, and therefore the effective initial loss was higher. Furthermore, this study adopted a higher rate of continuous loss of 2.5 mm/h as was recommended by the current version of ARR at the time, which also acted to increase effective losses. Therefore, in the light of the consideration of this extra preceding rainfall and a lower CL value, a higher IL parameter was considered in alignment with the findings of the previous study.

6.3.3.4 Observed and simulated flood behaviour

Comparison of the hydrologic model results to available measured level and flow data, where appropriate, for the June 2007 calibration event are presented in **Figure 6.15** and **Figure 6.16**.




211009 - Wyong River at Gracemere
Level (mAHD)
14
13
12
11
10
9
8
7
6
5
4
7/06/2007
8/06/2007
9/06/2007
10/06/2007
11/06/2007
12/06/2007
211009 - Wyong River at Gracemere
Modelled


211010 - Jilliby Creek upstream Wyong River
Level (mAHD)
12
11
10
9
8
7
6
7/06/2007
8/06/2007
9/06/2007
10/06/2007
11/06/2007
12/06/2007
211010 - Jilliby Creek upstream Wyong River
Modelled

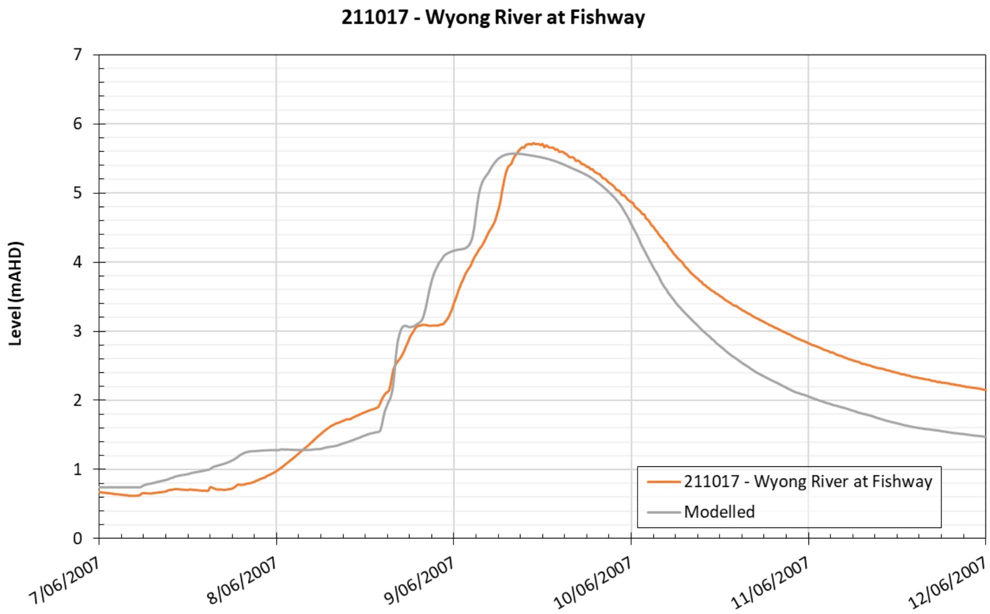


Figure 6.15 Comparison of simulated and observed water level data on the Wyong River for the June 2007 calibration event

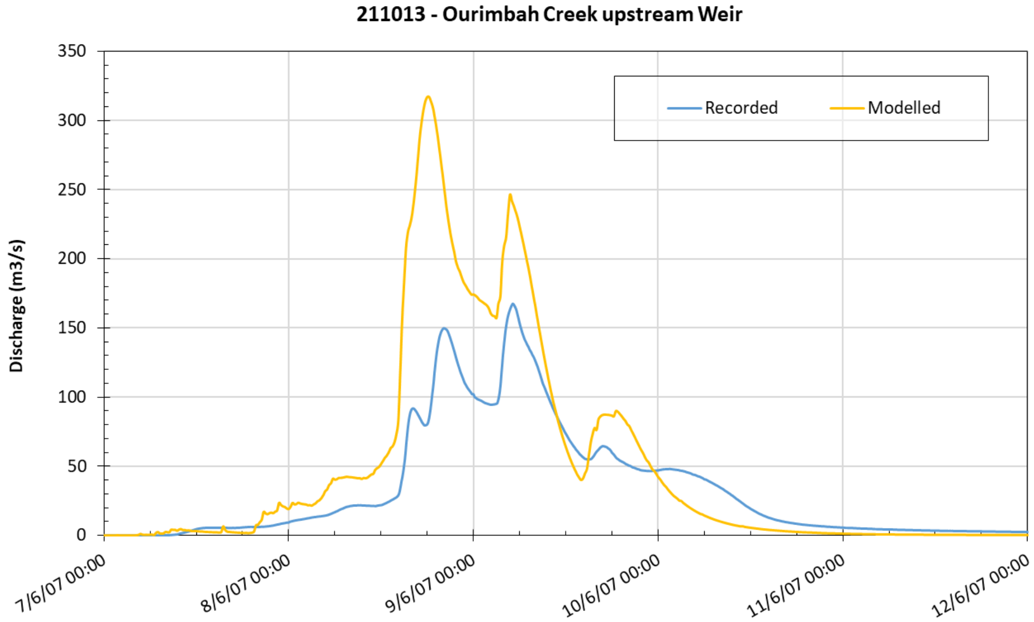


Figure 6.16 Comparison of simulated and observed flow data at Ourimbah Creek upstream Weir (211013) for the June 2007 calibration event

For the June 2007 calibration event on the Wyong River, the modelled results provide a reasonable representation of the recorded hydrographs at all locations.

As discussed for the July 2022 calibration event, the Wyong River at Yarramalong gauge is the least susceptible to hydraulic effects. Noting this, it is observed that the result at this location shows fair agreement with that recorded in terms of both timing and magnitude, particularly at the flood peak. While the discrepancy between modelled and observed water level present across 7 June and the early hours of 8 June appear significant, it is noted that actual flows modelled at this location during this phase of the event are exceedingly small. Quantitatively, modelled flows at Yarramalong before noon on 8 June are no higher than 10 m^3/s and are in fact less than 1 m^3/s prior to 6:30am on 8 June. Furthermore, it is suspected that a causeway or structure not properly represented in the model immediately downstream of this gauge location is causing pooling at lows flows which causes the steady increase in levels despite the low modelled flow. It is recommended that the Wyong Flood Study model be reviewed to ensure that this causeway does not significantly impact flood levels.

Results at Gracemere are well-represented in the rising limb and peak flood phases, however, do tend to be underestimated in the falling limb and lack some resolution in distinguishing the initial and peak rises in flood level. On Jilliby Jilliby Creek, the Jilliby Creek upstream Wyong River gauge result is reasonably replicated, however but the arrival of flows tends to be slightly late and sharp. This is considered to be due to flood waters being held behind features at low levels higher on this reach.

In the lower reaches of the Wyong River at Wyong Fishway, the model can be seen to provide a good match between simulated and recorded hydrographs at these locations, accurately capturing the timing and general shape of the event. Key features such as the rising limb, flood peak, and recession phase are well represented in terms of their relative timing and magnitude. Minor discrepancies are noted, including a very slight underestimation in peak level and a tendency towards underestimation of the falling limb of the level hydrograph. These effects are suspected to be due to a range of factors, including the fact that bathymetry at these locations is estimated, the relatively coarse grid size of the hydraulic model acting to reduce modelled conveyance, backwater effects from the nearby lake, and potential floodplain and storage losses within the hydraulic model upstream of these locations.

It is considered that the model reliably reproduces the key flood dynamics observed in this calibration event for the Wyong River, particularly in terms of volume and timing, which are of direct relevance to the present study.

On Ourimbah Creek, a poor relationship is observed between recorded and modelled flows at the Ourimbah Creek upstream Weir (211013) gauge. While rated flows are subject to significant uncertainties, they can nevertheless be used to evaluate the timing of the discharge hydrograph, which is seen to be well replicated by the hydrologic model.

Flood depths as modelled for the June 2007 calibration event are presented in **Figure E.2**.

6.3.4 March 2021 validation

6.3.4.1 Rainfall data and event summary

The March 2021 flooding event was associated with persistent, heavy rain which fell from March 16 to March 23 across central and northern NSW. The event was caused by a blocking high in the Tasman Sea that directed a strong, low-pressure trough towards the NSW coast. The trough caused life-threatening flooding, hazardous surf, gusty conditions, and widespread damage across the Greater Sydney, Central Coast and north coast regions.

A high-level review of the rainfall records indicates that an average of over 400 mm of rain fell over an eight-day period between 16 and 24 March 2021.

The distribution of rainfall gauge locations within the Tuggerah Lakes catchment are exhibited in **Figure D.4**, with their respective periods of record shown in **Table 3.1**. A comprehensive coverage of continuous rainfall data was available across the catchment in the March 2021 event from both the BoM and MHL.

First, a comparison was performed between these continuous gauges in terms of the rainfall depth and temporal pattern across the event. A summary of cumulative precipitation at all relevant continuous gauges in the region plot is shown in **Figure 6.17**.

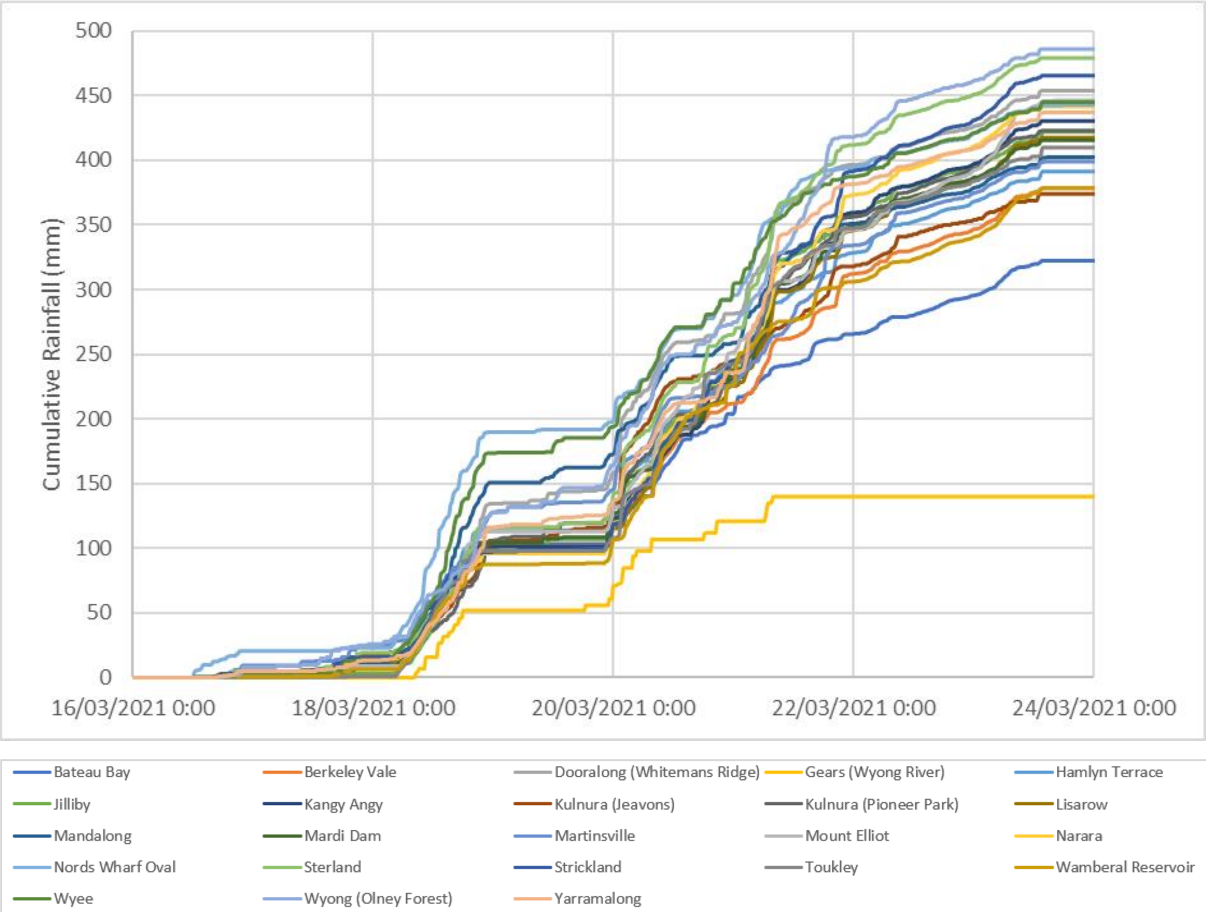
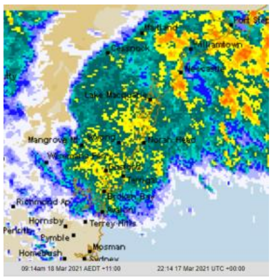
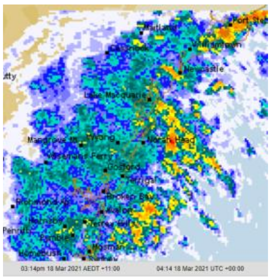
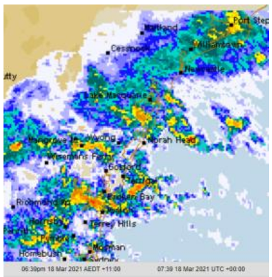


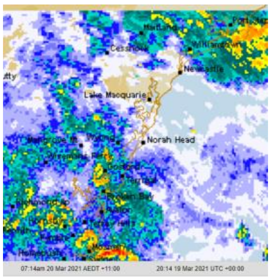
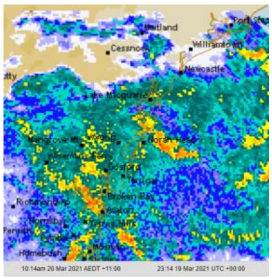
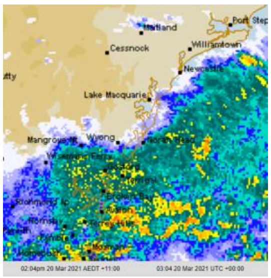
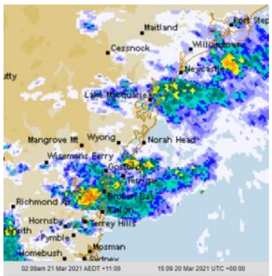
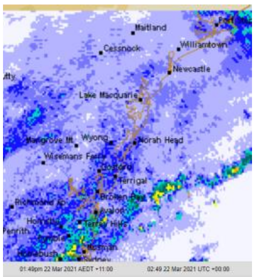
Figure 6.17 Cumulative recorded rainfall depths during the March 2021 calibration event

The site at Gears appears as a distinct lower outlier. It is suspected that the data at Gears was subjected to losses either in transmission or recording, with dropouts also apparent in the accompanying water level data from this site giving further confirmation to this. Subsequently, data from this site was excluded. As can be seen, little variability in rainfall depth and temporal pattern was observed across the catchment during this event. **Figure D.15** presents the spatial coverage of the available continuous rainfall data across the catchment and is overlaid with recorded rainfall isohyets derived from the observed data at these points. The relative uniformity of total rainfall across the catchment area spatially is again apparent. It is noted that rainfall depths and temporal patterns from each gauge location are applied according to the WBNM Theissen polygon approach. The zones of influence of each gauge under this approach are also shown in **Figure D.16**.

To further validate the observed depths and temporal patterns recorded at the remaining continuous rainfall gauge locations, radar data available from the Sydney (Terry Hills) radar station, located approximately 50 km to the south, was acquired for interrogation. A selection of these radar images is presented and discussed in **Table 6.6**.

Table 6.6 Selected Sydney (Terry Hills) radar imagery during the March 2021 validation event

Description	Radar image	Description	Radar image
5:19am 18 March 2021 The event begins in the early morning of 18 March with a broad band of moderate intensity rainfall crossing the catchment from north to south		9:14am 18 March 2021 Later that morning, a broad area of consistent, intense rainfall moves over the entire catchment from the north-east	
3:14pm 18 March 2021 By mid-afternoon, these conditions have not abated, and are still widespread across the catchment		6:39pm 18 March 2021 Later in the evening, conditions become more cellular, with cores of intense rainfall moving across the catchment from the north-east	
11:24pm 18 March 2021 Cellular conditions persist well into the night, eventually retracting inland from the coast by midnight		11:04pm 19 March 2021 On the night of the 19th, and after 24 hours of relative calm, another broad swathe of moderate intensity rainfall covers the catchment from the north-east	
12:44am 20 March 2021 Soon after, within this broad area of moderate intensity rainfall, three bands of embedded high intensity rainfall pass across the catchment from the north-east		2:54am 20 March 2021 The third band of intense rainfall passes through the catchment	

Description	Radar image	Description	Radar image
7:14am 20 March 2021 A gap in rainfall conditions passes over the catchment from the north-east		10:14am 20 March 2021 Broad, moderate to high intensity rainfall falls across the catchment	
2:04pm 20 March 2021 Rainfall clears across the catchment from the north-west		2:09am 20 March 2021 A series of large cells cross the catchment from the north-east	
1:49pm 20 March 2021 These cells become progressively larger, forming a large area of low to moderate intensity rainfall across the catchment, which eventually clears to the east by the morning of 23 March			

6.3.4.2 Antecedent conditions

Inspection of the rainfall data preceding the March 2021 event at a representative gauge location as shown in **Figure 6.18** revealed that the early months of 2021 saw average rainfall conditions.

It is anticipated that the consistent rainfall amounts seen in the late months of 2020 and into early-2021 would bring about moderate soil moistures to Tuggerah Lakes catchment. However, the period of below-average rainfall immediately prior to the event may have had the result of moderating soil moisture, particularly at the soil surface. These antecedent moisture and soil conditions were considered further throughout the model calibration process.

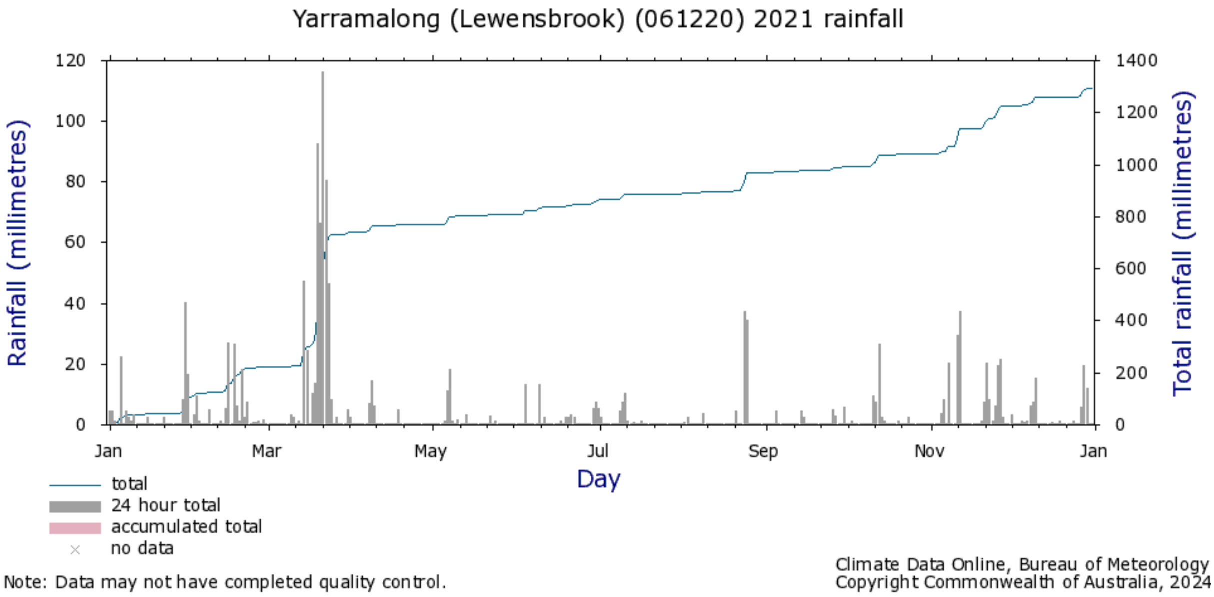


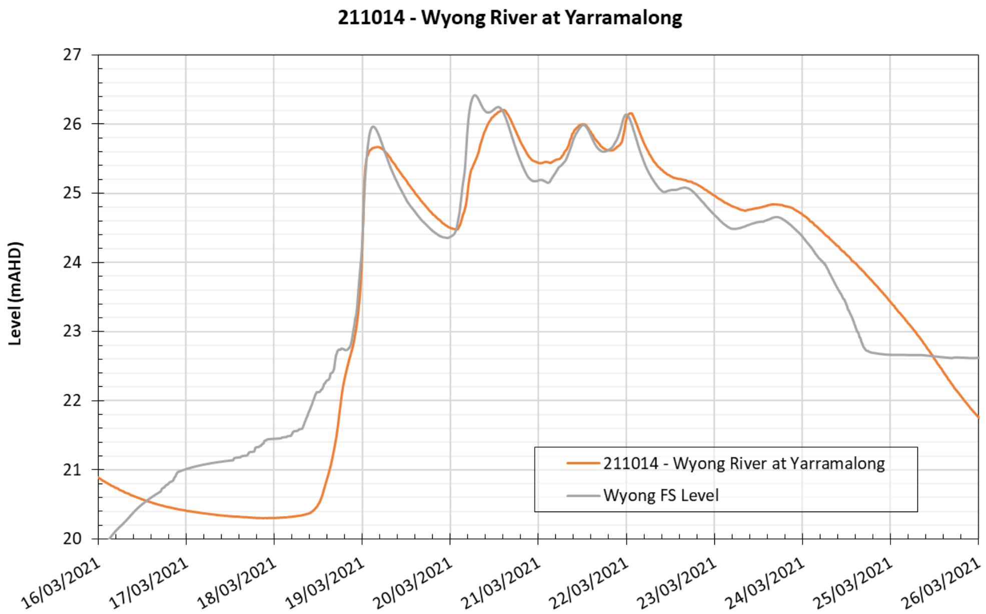
Figure 6.18 2021 daily rainfall at Yarramalong (61220)

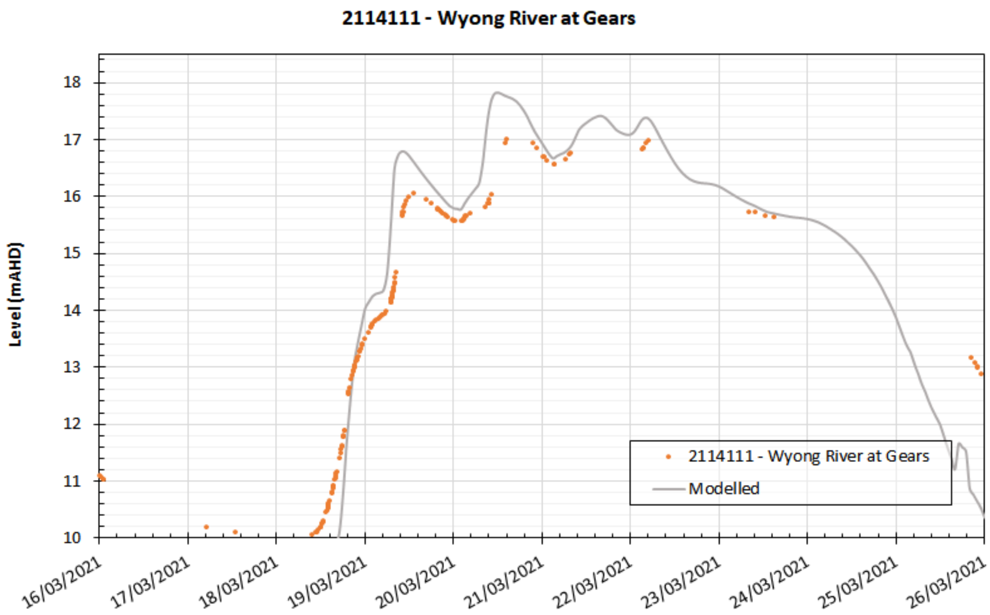
6.3.4.3 Model parameter adjustment

Model parameters adopted for the 2022 calibration event were retained for the March 2021 validation event without modification.

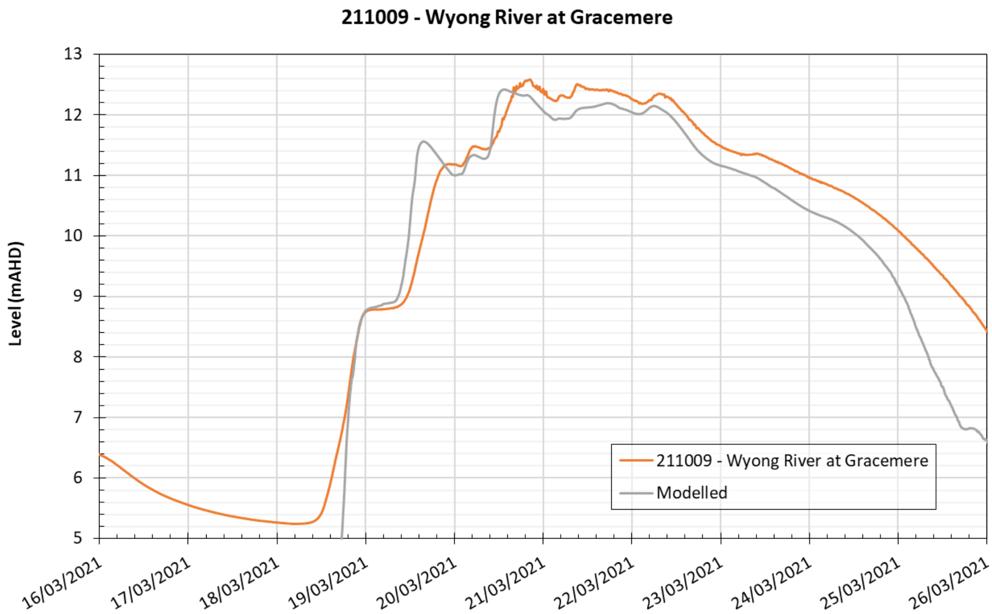
6.3.4.4 Observed and simulated flood behaviour

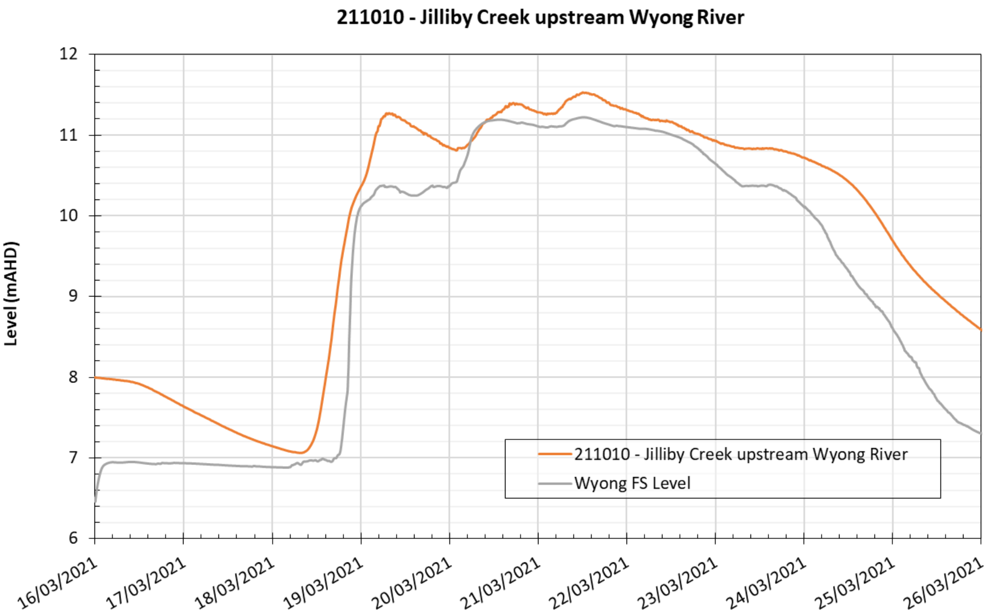
Comparison of hydrologic model results to available measured level and flow data, where appropriate, for the March 2021 validation event are presented in **Figure 6.19** and **Figure 6.20.**

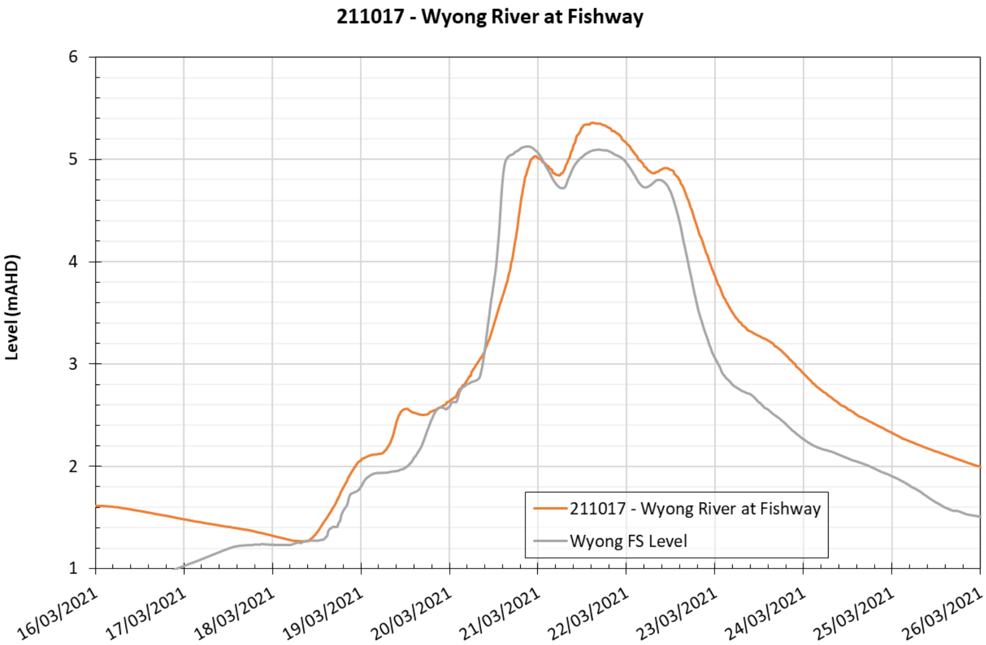




Note: point data have been used for that figure to highlight extensive gaps in available recorded data




211010 - Jilliby Creek upstream Wyong River
Level (mAHD)
12
11
10
9
8
7
6
16/03/2021
17/03/2021
18/03/2021
19/03/2021
20/03/2021
21/03/2021
22/03/2021
23/03/2021
24/03/2021
25/03/2021
26/03/2021
211010 - Jilliby Creek upstream Wyong River
Wyong FS Level


211017 - Wyong River at Fishway
Level (mAHD)
6
5
4
3
2
1
16/03/2021
17/03/2021
18/03/2021
19/03/2021
20/03/2021
21/03/2021
22/03/2021
23/03/2021
24/03/2021
25/03/2021
26/03/2021
211017 - Wyong River at Fishway
Wyong FS Level

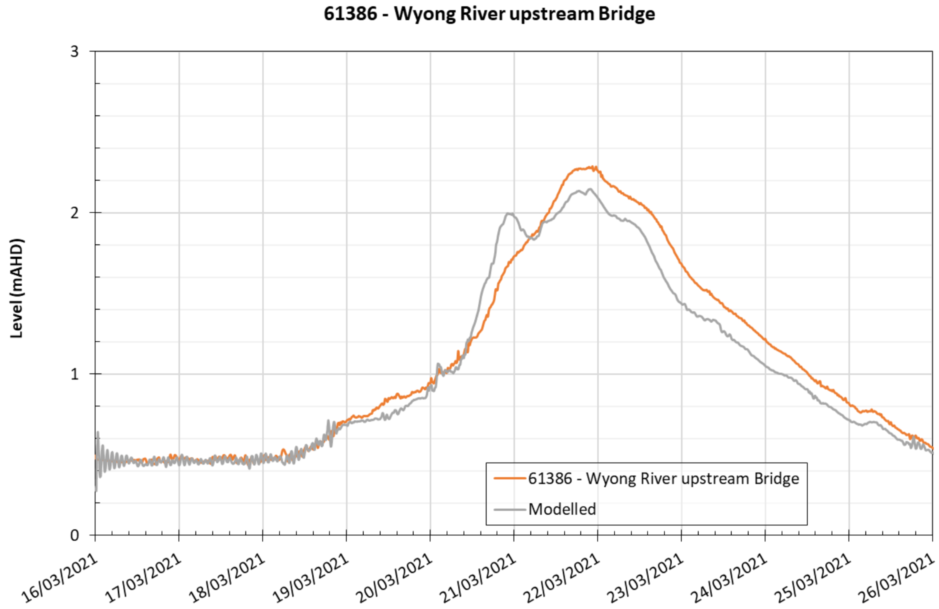


Figure 6.19 Comparison of simulated and observed water level data on the Wyong River for the March 2021 validation event

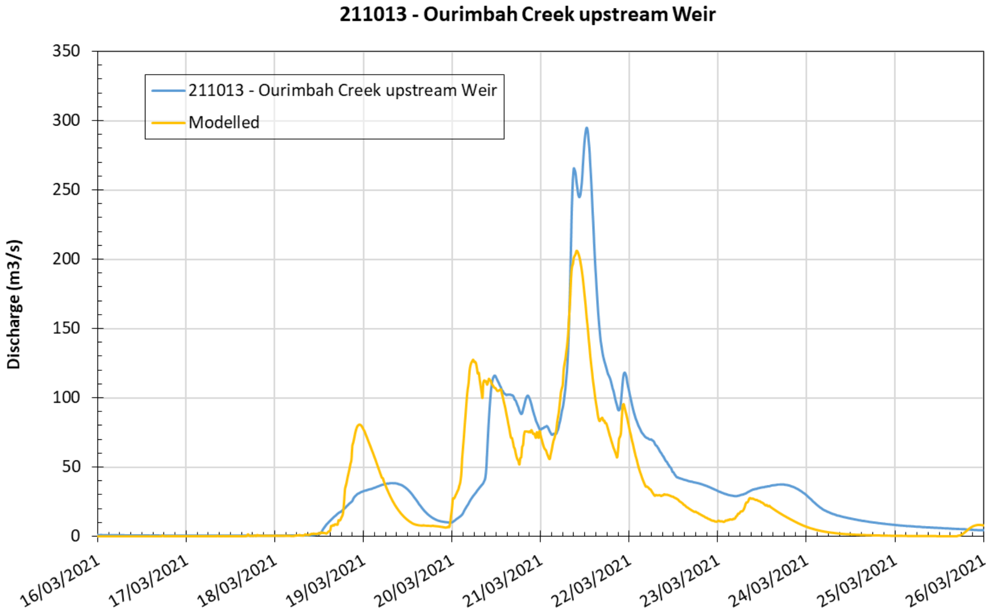


Figure 6.20 Comparison of simulated and observed flow data at Ourimbah Creek upstream Weir (211013) for the March 2021 validation event

For the March 2021 validation event on the Wyong River, the modelled results provide a reasonable representation of the recorded hydrographs at all locations.

The Wyong River at Yarramalong gauge results show close agreement with that recorded in terms of both timing and magnitude.

Results at Gears can be seen to be in general accordance with those recorded, however it is noted that the record at this location is intermittent as a result of data losses during communication. Results at Gracemere are also good in the rising limb and peak flood phases, however, do tend to be underestimated in the falling limb.

On Jilliby Jilliby Creek, some discrepancy is noted at the Jilliby Creek upstream Wyong River gauge, with an underestimated representation of the initial peak at this location in the early hours of 19 March 2021. The rainfall record indicates that this discrepancy is likely caused by a lower amount of rainfall being recorded by the gauges with influence over the sub-catchments upstream of this location. This results in a higher effective initial loss in these sub-catchments, which acts to significantly moderate the initial peak on Jilliby Creek. The explanation of this discrepancy being driven by the granularity in rainfall data capture is validated by the fact that the underestimation of this peak is contrasted with an overestimation of the equivalent peak on the Wyong River at Gracemere at a similar time. The replication of flood behaviour at this location is otherwise reasonable.

In the lower reaches of the Wyong River at Wyong Fishway, the model can be seen to provide a fair match between simulated and recorded hydrographs at these locations, accurately capturing the timing and general shape of the event. Key features such as the rising limb, flood peak, and recession phase are well represented in terms of their relative timing and magnitude. Minor discrepancies are noted, including a very slight underestimation in peak level and a tendency towards underestimation of level falling limb of the hydrograph. These effects are suspected to be due to a range of factors, including the fact that bathymetry at these locations is estimated, the relatively coarse grid size of the hydraulic model acting to locally reduce/increase modelled conveyance, backwater effects from the nearby lake, and potential floodplain and storage losses within the hydraulic model upstream of these locations.

It is considered that the model reliably reproduces the key flood dynamics observed in this calibration event for the Wyong River, particularly in terms of volume and timing, which are of most relevance to the present study.

On Ourimbah Creek, a fair representation of the timing and magnitude of recorded flows at the Ourimbah Creek upstream Weir (211013) is demonstrated. The flood peak is underestimated; however, it is noted that flows derived from this portion of the rating relationship are highly unreliable.

Flood depths as modelled for the July 2022 calibration event are presented in **Figure E.3**.

6.3.5 Summary

The hydrologic model generally provided a good match with the recorded information for the calibration and validation events across the Wyong River and Ourimbah Creek catchments which contribute about 80% of the flow into the Tuggerah Lakes system. Levels of accuracy obtained as part of this study are consistent with the results obtained in the Wyong River Catchment Flood Study. The model was therefore considered appropriately calibrated for the definition of input hydrographs for the hydraulic model. **Table 6.7** summarises the key model parameters used for the calibration/validation events.

Table 6.7 Summary of the model parameters for flood calibration/validation events.

Event	July 2022	June 2007	March 2021
Initial loss (mm)	58	80	58
Impervious initial loss (mm)	0.0	0.0	0.0
Continuing loss (mm/hr)	1.0	1.0	1.0
Lag parameter	1.3	1.3	1.3
Impervious lag parameter	0.1	0.1	0.1
Stream lag factor	1.0	1.0	1.0

7 Hydraulic analysis

Hydraulic modelling consists of understanding the physical properties of the flood water such as depth and velocity. This can be completed in various ways including:

- One-dimensional (1D) modelling, which consists of representing a creek or river with flood information provided at regular interval cross-sections along a stream as well as pipe systems and drainage networks.
- Two-dimensional (2D) modelling, which consists of representing a floodplain as a grid with flood information provided at each cell of the grid allowing the model to define flow paths.
- 1D/2D modelling that consists of a combination of the above.

7.1 Model selection

A 1D/2D TUFLOW Heavily Parallelised Compute (HPC) model with Quadtree features was used to simulate flood behaviour across the study area. TUFLOW is a robust and widely accepted unsteady-state flood simulation software with combined 1D and 2D capabilities. The use of a TUFLOW model allows integrated investigation of local overland flow flooding, mainstream creek flooding, foreshore flooding and tidal influences, and the inclusion of storm-water drainage infrastructure.

Furthermore, TUFLOW HPC offers faster run times using parallel processing capabilities, which are advantageous for large-scale or detailed models. The use of a Quadtree mesh also allows for variable grid resolution, concentrating detail in areas of interest (e.g., around structures or channels, etc.) while keeping computational costs low in less critical or topographically variable areas. This feature is especially useful in regions with complex topography or variable land uses, where different levels of detail are needed, as is the case in the Tuggerah Lakes area.

The GIS data layers, and control files utilised to drive the model can be easily modified for use in any future options assessment, including modelling the impact of mitigation measures, or assessment of development applications. MHL flood modelling processes follow guidance provided in ARR 2019.

The dynamically linked 1D/2D model requires several GIS data to represent the study area. These include:

- 1D Domain
  - Pits and headwalls GIS layer;
  - Pipe network GIS layer;
  - Culvert GIS layer;
- 2D Domain
  - 2D grid / digital elevation model (DEM);
  - Topographic modifications and break lines (e.g., to incorporate embankments);
  - Materials layer (specifies surface roughness and infiltration);

- Layered flow constrictions layer for 2D bridges; and
- Initial water level polygons.

The latest version of TUFLOW at the time of the model construction has been used for modelling (TUFLOW 2023-03-AE).

7.2 Model setup

The following considerations were required to set up the TUFLOW model.

7.2.1 Model extent and grid size

To reduce model run time without compromising the quality of model outputs, a grid resolution of 96 m × 96 m was adopted to represent the waterbodies of the Tuggerah Lakes. A finer resolution grid of 6 m × 6 m was used to define the entrance channel, and around structures, the shoreline of the lakes and areas outside of the lake waterbodies. The sub-grid sampling (SGS) capability of the TUFLOW model was also targeted to a size of 1 m (i.e., the resolution of the available DEM). The SGS capability allows for the use of sub-grid-scale elevation data to enhance the hydraulic accuracy of the model by providing an improved representation of flows in and out of each cell and the definition of the volume within each cell, while keeping reasonable run times.

7.2.2 Modelling approach

The following modelling approach was applied to the development of a detailed and reliable 1D/2D TUFLOW hydraulic model for the study area:

- Extent of the study area and 2D hydraulic model was determined based on the available elevation data;
- Boundary conditions consist of rainfall runoff inflows from the previously discussed hydrologic modelling, and the tidal water levels of the Tasman Sea quantified using recorded water levels at Sydney (213470). Further discussion of these elements is made in **Section 7.2.5**;
- Information from previous studies were incorporated using 2D topographic modifications and 1D elements as appropriate;
- Hydraulic roughness: a materials layer was delineated based on consideration of the NSW Environmental Planning Instrument (EPI) - Land Zoning data set, LiDAR point cloud classifications and Council's building footprint, cadastre, zoning and aerial photography data, supplemented with site observations where necessary. Initial material categories and associated depth-varying Manning's roughness coefficients were adopted from similar studies;
- Buildings: a layer of the building footprints was delineated from LiDAR point cloud classifications and Council's building footprint, cadastre, zoning and aerial photography data, and this was applied as a layer with an appropriately higher roughness;
- Undertake thorough model calibration, validation and verification using alternative methods, and quality assurance checks.

7.2.3 Hydraulic roughness

Hydraulic roughness coefficients (Manning's n) are used to represent the resistance to flow of different surface materials. Hydraulic roughness has a major influence on flow behaviour and is one of the primary parameters in hydraulic model calibration.

Spatial variation in hydraulic roughness was represented in TUFLOW by delineating the catchment into zones of similar hydraulic properties. The hydraulic roughness zones adopted in this study have been delineated based on consideration of the NSW Environmental Planning Instrument (EPI) - Land Zoning data set, LiDAR point cloud classifications and Council's building footprint, cadastre, zoning and aerial photography data, supplemented with site observations where necessary. Factors affecting resistance to flow were of primary importance including surface material, vegetation type and density, and the presence and density of flow obstructions such as buildings, fences and gross pollutant traps (GPTs). Manning's 'n' values assigned to each zone were determined based on land type with reference to standard values recommended by Chow (1959). Land areas with light vegetation were assigned a Manning's value of 0.04, while those areas with thick vegetation assigned a value of 0.1.

A significant portion of the hydraulic model extent consists of lake and other water bodies, whereby vegetation coverage is limited, and water velocities are low, reducing the influence of the Manning's value. In these areas, a relatively smooth value of 0.013 was deemed appropriate. As for the dynamic portion of the entrance, the Manning's value becomes highly influential owing to the higher velocities and shallower depths experienced in this zone. As such, several values for Manning's roughness were trialled for the region downstream of The Entrance bridge to the ocean, which consists of a mix of bare beach sand and rocky outcrops. Roughness values adopted for TUFLOW models of ICOLL entrance zones elsewhere on the NSW coast, for example at Lake Conjola and Burrill Lake, ranged between 0.025-0.030. Various roughness values of this order were trialled, with a value of 0.035 being found to provide the best match to the data across the historical flood events. This slightly elevated value when compared to similar studies can be justified because of the exposure of the rock shelf at the southern end of the beach during flooding events likely yielding a rougher overall surface in this zone.

Figure D.17 and **Table 7.1** further summarise the detailed Manning's n values used in the hydraulic model.

Table 7.1 Adopted Manning's n hydraulic roughness coefficients

Material	Manning's n
Water (i.e., watercourses, rivers, creeks, lakes, reservoirs, dams, pools)	0.013
Pipes and culverts	0.015
Roadways, railways and pavement	0.025
Bare earth / entrance channel	0.035
Low density vegetation (i.e., cropping, pasture and grassland)	0.040
Medium density vegetation (i.e., shrubs)	0.070

Material	Manning’s n
High density vegetation (i.e., nature conservation, plantation forests, woody cover, incl. shadowed areas due to canopy cover)	0.100
Built-up area	0.100
Building footprint	0.300

7.2.4 Structures

Most structures were adopted from previous TUFLOW models to ensure consistency with the adjoining overland studies. A total of 53 culverts and pipes were included as 1D elements to maintain flood connectivity and storage, where appropriate. The following structures were modelled as 2D elements within the hydraulic model, as shown in **Figure D.18**:

- Wyong Road Bridge over Tumbi Umbi Creek
- A footbridge over Tumbi Umbi Creek
- Wyong Road Bridge over Ourimbah Creek
- Pacific Highway Bridge over Wallarah Creek
- Motorway Link Bridge over Spring Creek
- Central Coast Highway over Budgewoi Creek
- Budgewoi Foot Bridge over Budgewoi Creek
- Main Road Bridge
- The Entrance Bridge over the Tuggerah Lake entrance channel

Other structures, such as road embankments and levees, are expected to be adequately represented by the grid of the model or have been incorporated using breaklines where required. In the case of the Wilfred Barrett Drive flood levee in The Entrance North, the operation of flood gates was considered in the hydraulic modelling, with the assumption that the inverted floodgates along Wilfred Barret Drive to prevent backflow through the drainage network remain closed and effective during design events.

There are no weirs within the hydraulic model.

7.2.5 Boundary conditions

7.2.5.1 Inflow

The inflow hydrographs for each calibration and validation event were produced using the calibrated and validated WBNM model and were integrated into the hydraulic model at relative locations (**Figure D.19**), downstream of or at an appropriate location within the catchment.

The inflows incorporated into the hydraulic model include:

- Runoff generated by the Wyong River catchment, assigned at the edge of the model extent downstream of the railway bridge at Wyong as a flow-time (QT) boundary.
- Runoff generated by the Ourimbah Creek catchment, assigned at the edge of the model extent upstream of Wyong Road and downstream of the railway bridge as a flow-time (QT) boundary.
- Runoff generated by the Tumbi Umbi Creek catchment, assigned upstream of Wyong Road as a source area (SA) boundary.
- Runoff generated by the Wallarah Creek catchment, assigned downstream of the railway bridge source area (SA) boundary.
- Runoff generated by local catchments within the bounds of the TUFLOW hydraulic model domain were assigned at relative locations source area (SA) boundary. These local catchments included Glenning Valley, Long Jetty, Northern Lakes, Colongra Wetland, the Tuggerah Lakes themselves, and others.

7.2.5.2 *Outflow*

The sole outflow location within the model is defined by the oceanic water levels of the Tasman Sea. The Tasman Sea is represented within the model as a stage-time (HT) boundary offshore and surrounding the entrance opening, as shown in **Figure D.19**. This boundary is positioned an appropriate distance offshore within the model to enhance the stability of the boundary condition. The data interrogated and ultimately adopted to define the behaviour of this boundary condition are described in the following sections.

Patonga

Data from the ocean tide gauge nearest to the Tuggerah Lakes entrance approximately 30 km to the south at Patonga (212440) was assessed for its suitability for use as the downstream boundary condition baseline. However, this gauge is known to be subject to high tidal anomaly associated with the riverine flooding of the Hawkesbury River. This location has also been known to see the effects of seiche during certain wave conditions because of the geometry of Broken Bay.

The observed and predicted ocean level at Patonga, and the associated tidal anomalies during the two calibration and the validation events are presented in **Figure 7.1**, **Figure 7.2**, and **Figure 7.3**, respectively.

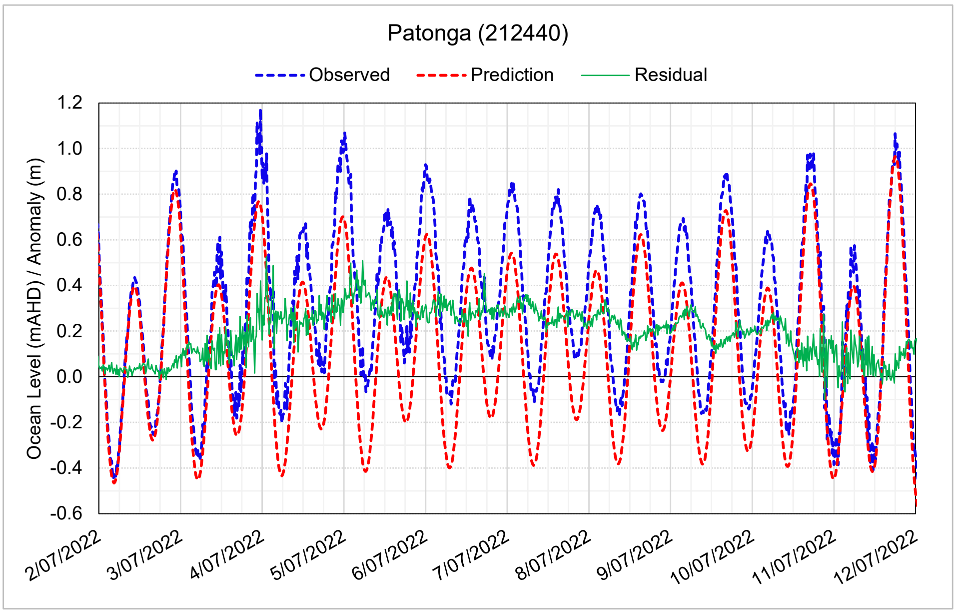


Figure 7.1 July 2022 calibration event – observed water level and anomaly at Patonga

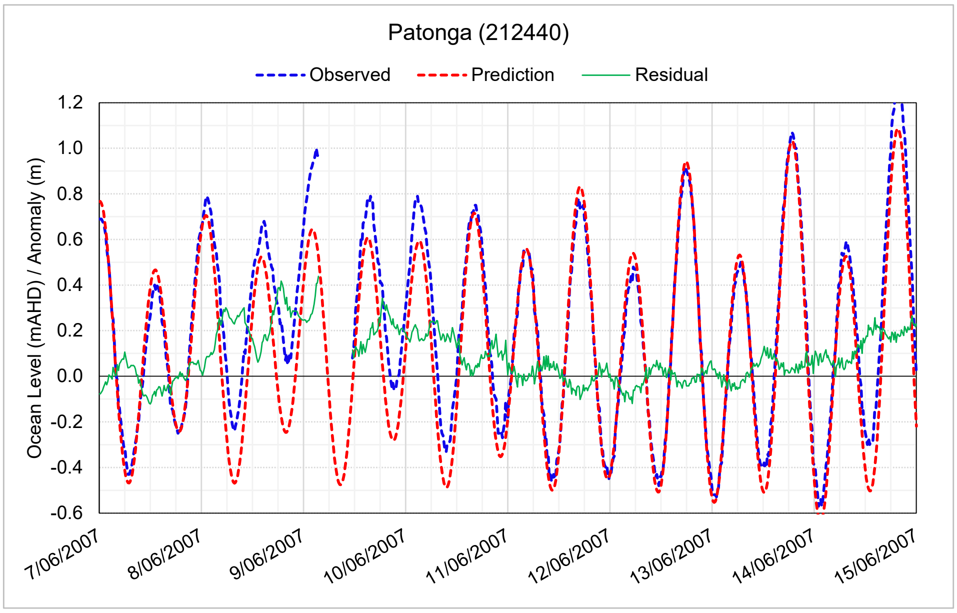


Figure 7.2 June 2007 calibration event – observed water level and anomaly at Patonga

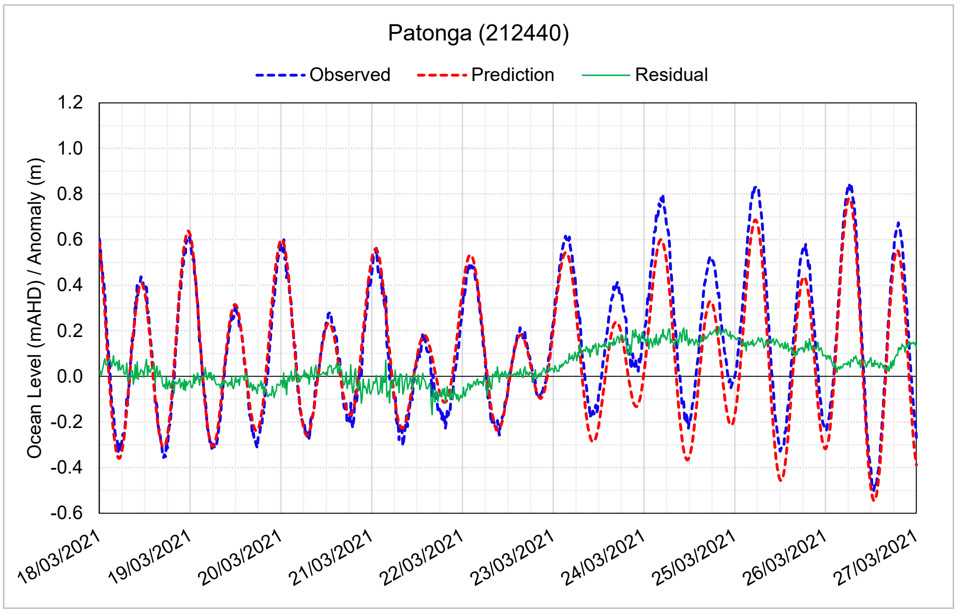


Figure 7.3 March 2021 validation event – observed water level and anomaly at Patonga

The tidal anomaly, being the difference between the predicted and the observed tidal levels, ranged between approximately 0.0 and +0.5 m during the July 2022 calibration event, with the largest anomaly observed on 5 July. Similarly for the June 2007 calibration event, anomalies ranged between approximately -0.1 and +0.5 m, with the largest anomaly observed on 9 June, immediately prior to a period of data loss lasting about eight hours. These anomalies are high and are considered to stem from a combination of complex factors, including widespread barometric forcing, as well as more localised effects such as high runoff from the Hawkesbury system and possible seiche in Broken Bay. Contrastingly, anomalies observed during the March 2021 validation event are near zero until 23 March, when a consistent anomaly of approximately +0.2 m emerges. This anomaly is likely driven by high volumes of runoff from the Hawkesbury system, and less so because of barometric forcing.

It was determined that the measured tidal anomalies at Patonga for each event were either generally unacceptably high or unrepresentative of the anomalies likely to be present near the Tuggerah Lakes entrance during the respective calibration and validation events. Furthermore, data at Patonga during a portion of the June 2007 calibration event was not available.

Consequently, recorded ocean levels at Sydney (213470) were instead assessed for their suitability for use as the baseline downstream boundary condition.

Sydney

Figure 7.4, **Figure 7.5**, and **Figure 7.6** depict the observed and predicted ocean level at Sydney, as well as the associated tidal anomaly, during each of the two calibration and the validation events.

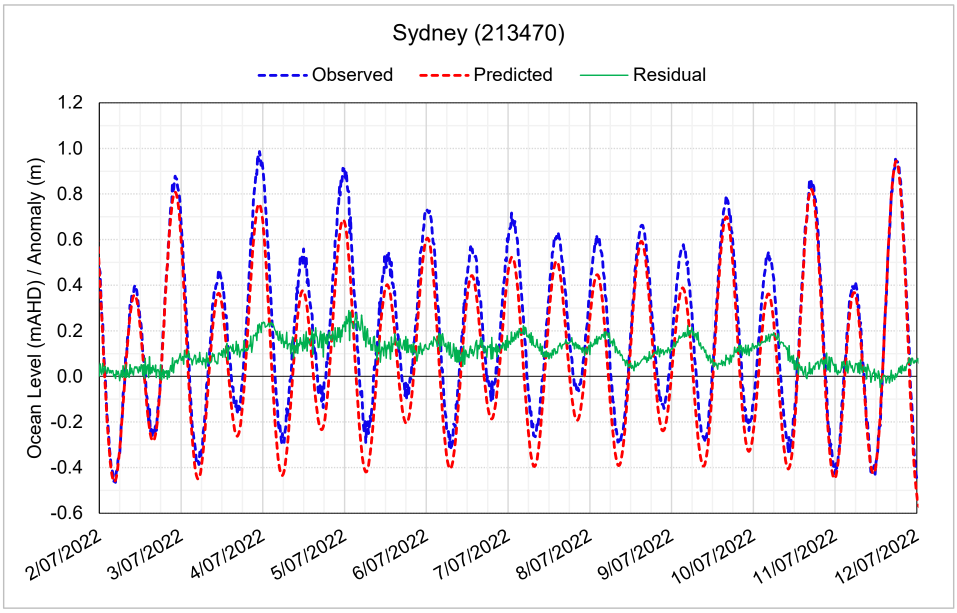


Figure 7.4 July 2022 calibration event – observed water level and anomaly at Sydney

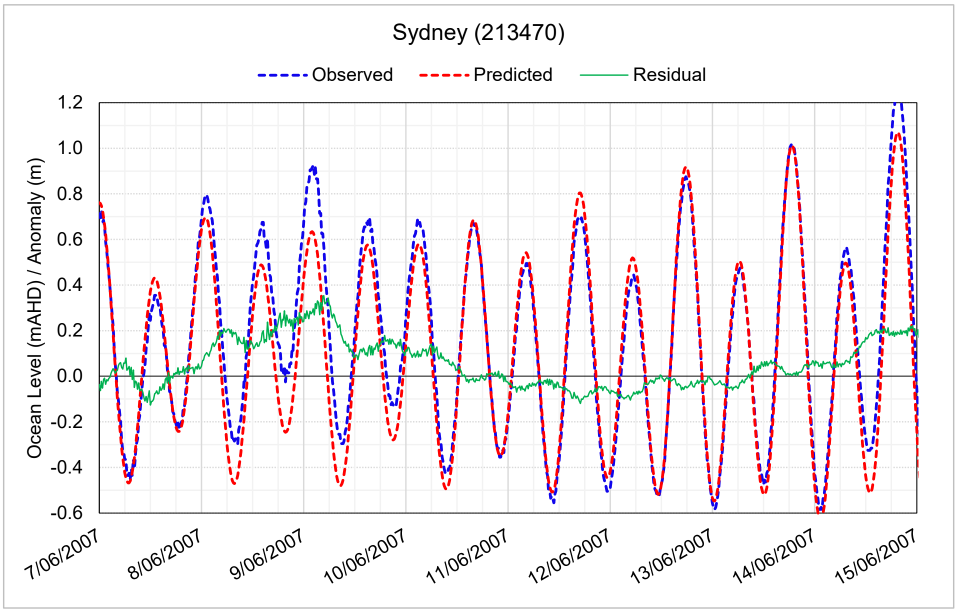


Figure 7.5 June 2007 calibration event – observed water level and anomaly at Sydney

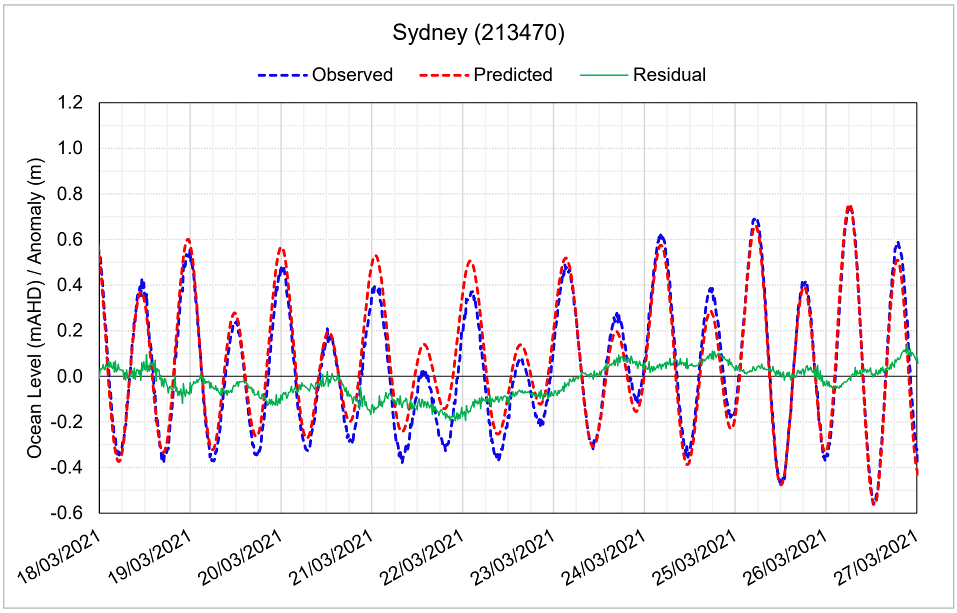


Figure 7.6 March 2021 validation event – observed water level and anomaly at Sydney

The tidal anomaly ranged between approximately 0.0 m and +0.3 m during the July 2022 calibration event, with the largest anomaly observed on 5 July. Similarly for the June 2007 calibration event, anomalies ranged between approximately -0.1 m and +0.3 m, with the largest anomaly observed on 9 June. These anomalies are likely driven by widespread barometric forcing associated with the strong low-pressure systems driving these events. Contrastingly, anomalies observed during the March 2021 validation event lie within an approximate range between -0.2 mAHD and +0.1 mAHD.

It was determined that these anomalies were likely to be more representative of tidal anomalies near the Tuggerah Lakes entrance during the respective calibration and validation events, being primarily driven by widespread barometric effects.

Inspection of these data also reveals variations in tidal behaviour across the selected calibration and validation events. For instance, during the calibration event in July 2022, high tidal levels ranged from 0.5 mAHD to 0.9 mAHD. For the June 2007 event, the high end of this range was similarly around 0.9 mAHD, but had more diurnal variation, with the smaller daily high tide reaching around 0.3-0.4 mAHD.

Wave setup

Wave conditions can have an influence on the dynamics of the berm and channel scour, as well as on lake levels through wave setup. Wave setup comprises the increase in mean water level due to the presence of breaking waves. When a wave breaks, significant energy dissipation occurs. As such, and to conserve momentum, the still water level increases in the shoreward direction. Prevailing oceanic wave parameters, such as wave height, period and spectral character, as well as the bathymetry and shape of a coastline, can influence the degree to which wave setup is able to emerge.

The Tuggerah Lakes Flood Study (Lawson & Treloar, 1994) noted that the wave setup effect *"[at] river and lagoon entrances… becomes more complicated because waves often have not broken completely by the time they propagate to the entrance*" and that "*the waves themselves are affected by flood flows against the direction of wave propagation*". As a result of the large volume of storage in the Tuggerah Lakes and since a significant volume of water would need to flow into the lake system in order to develop the full wave setup level, the 1994 study concluded that "*wave setup impacts will be relatively small at The Entrance under normal opening conditions*". Furthermore, sensitivity testing undertaken as part of the model calibration process indicated that the imposition of a wave setup effect on the tailwater condition negatively impacted modelled results, even in the pre-flood condition. As such, wave setup effects were not considered as part of the model calibration process. This is likely due to the wide-open final entrance configurations seen for each of the historical events and the reasoning outlined in the 1994 study, being that for a wide-open entrance elevated outflows and channel deepening reduce the breaking of waves in the vicinity of the entrance, which in turn minimises wave setup. Despite their exclusion from consideration at this stage, wave setup effects will nevertheless be considered in subsequent sections in terms of sensitivity and design scenarios to account for the uncertainties of the entrance configuration and nearshore wave dynamics in synthetic events.

Wave conditions

Observed offshore wave conditions for each calibration event are documented below, for completeness.

Deepwater wave conditions along the NSW coastline are continuously recorded by a network of seven Waverider buoys managed by MHL. Within this network, the buoys located nearest to the Tuggerah Lakes entrance are located at Sydney, approximately 50 km to the south and Crowdy Head, approximately 200 km to the north. Significant wave heights (mean wave height of the highest third of waves measured) recorded at both locations are presented during the two calibration and the validation periods in **Figure 7.7**, **Figure 7.8** and **Figure 7.9**, respectively.

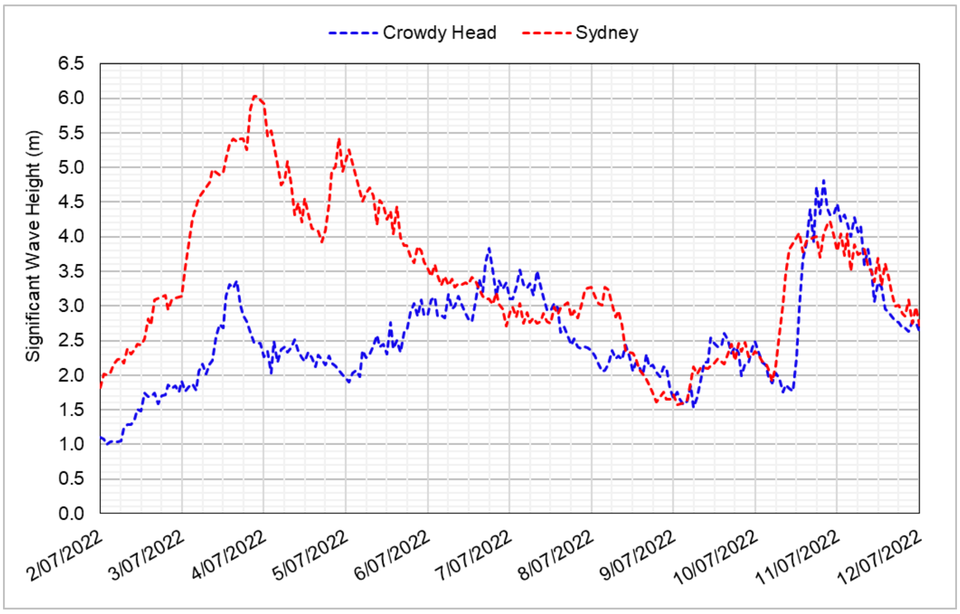


Figure 7.7 July 2022 calibration event – observed significant wave height

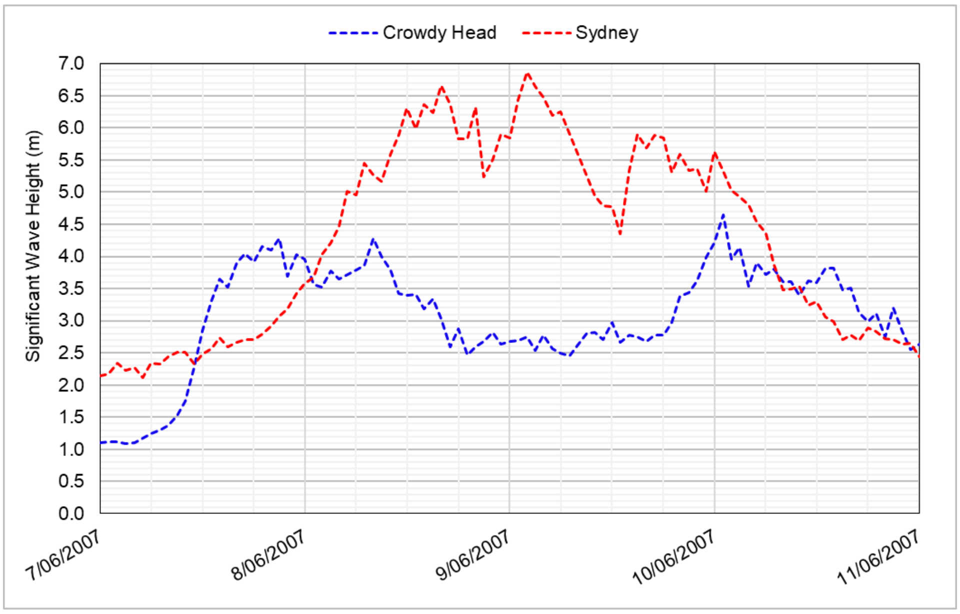


Figure 7.8 June 2007 calibration event – observed significant wave height

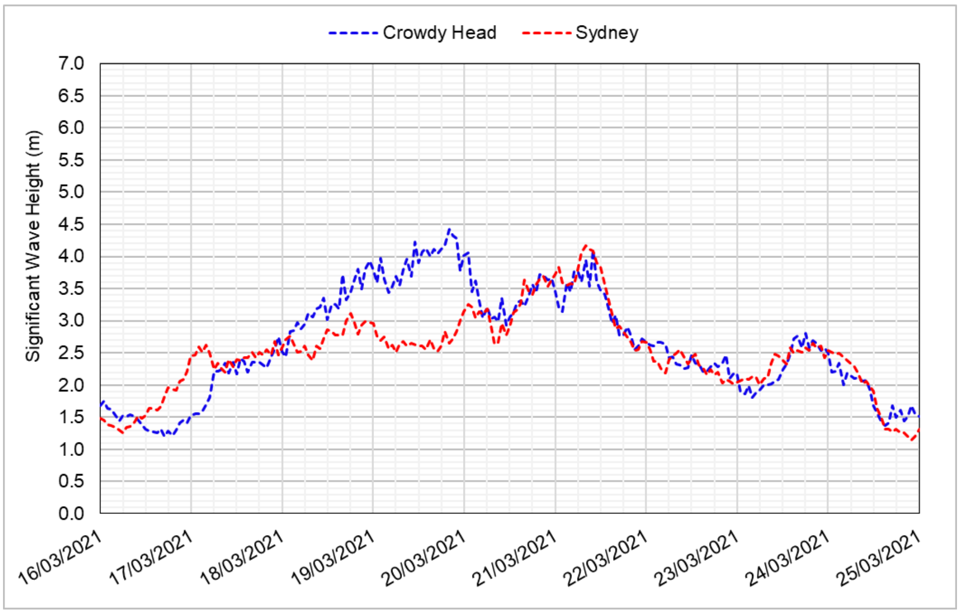


Figure 7.9 March 2021 calibration event – observed significant wave height

Summary statistics of the significant wave height, peak wave periods and wave directions were also produced from these data and are presented in **Table 7.2**.

Table 7.2 Calibration and validation events recorded peak ocean wave conditions at Sydney

Event	Time of Peak	H_S (m)	Period (s)	Direction (°)
July 2022	3/7/2022 21:00	6.02	11.5	120 (SE)
June 2007	9/6/2007 2:00	6.87	10.8	135 (SE)
March 2021	21/3/2021 8:00	4.18	10.8	85 (E)

The following observations were noted:

- Sydney is the buoy closest to the Tuggerah Lakes entrance and is expected to be the most representative of the local conditions,
- Conditions at Crowdy Head were more moderate during the majority of all three events, indicating conditions at the Tuggerah lakes entrance would likely be more moderate than those recorded at Sydney,
- The July 2022 and June 2007 events saw large, powerful seas of a similar scale and character predominantly from a south-easterly direction at both Crowdy Head and Sydney during the time in which the entrance was scouring,
- The March 2021 event saw smaller seas, more predominantly from the east.

7.2.6 Entrance configuration and behaviour

The Tuggerah Lakes system is connected to the ocean via a single tidal channel through the barrier dune at the southern end of North Entrance Beach. The condition of the entrance, where flows exchange to and from the ocean, is highly dynamic and subject to cyclical sediment infilling and scour processes. The lakes system is classified as an Intermittently Closed and Open Lake and Lagoon (ICOLL). As such, the entrance configuration preceding and during flooding events can influence lake flood levels.

Historically, evidence shows that the estuary entrance typically develops near the southern end of North Entrance Beach, partially in response to an underlying bedrock formation and broader sediment transport processes. During more severe flood events, and depending on the berm elevation, flows have been observed to break over the sand barrier to the north of the typical channel. Inspection of historical imagery also indicates that the entrance comprises a dynamic braided shoal system which extends upstream to the vicinity of The Entrance Bridge, approximately 500 m from the ocean.

As a result of the identified influence of the entrance configuration preceding and during lake flooding events, a broad variety of information sources were used to characterise the behaviour of the entrance during the calibration and validation events. This characterisation of entrance behaviour included locating and sizing the entrance outlet and channel throughout the event in terms of width, shape and depth, as well as quantifying the timing and rate of scouring throughout the events.

The sections below detail the key pieces of information utilised.

7.2.6.1 Theory and previous experience

The behaviour of the Tuggerah Lakes entrance 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, and
- Insight from the scour behaviour at other NSW ICOLL entrances (e.g., Gordon, 1990; AWACS, 1994). Entrance scour behaviour was considered in the context of other neighbouring lagoons (e.g., Wamberal, Terrigal, Cockrone and Avoca), though a number of key differences exist in comparison, including longer critical durations in the

order of 20 h (Lawson & Treloar, 1994), a larger catchment size, a long entrance with extensive shoaling and prolonged flood discharges.

Theoretically, Gordon (1990) discusses the fact that a typical coastal lagoon entrance opens in three stages. These three stages are illustrated in **Figure 7.10** and include:

- Stage 1 – Initiation channel stage: this stage represents the original breakout stage during which berm overtopping commences as thin sheet of water. The scour is low, and a pilot channel slowly develops. At the end of this stage, depths of 0.20-0.25 m are typically observed.
- Stage 2 – Weir/hydraulic jump stage: this stage develops rapidly, and flows become supercritical on the crest of the berm and accelerate generating significant scour and widening of the berm.
- Stage 3 – River flow stage: this stage occurs once the berm has been scoured sufficiently wide to reduce flows and allow supercritical flows to stop. Scour then reduces rate and entrance stabilises.

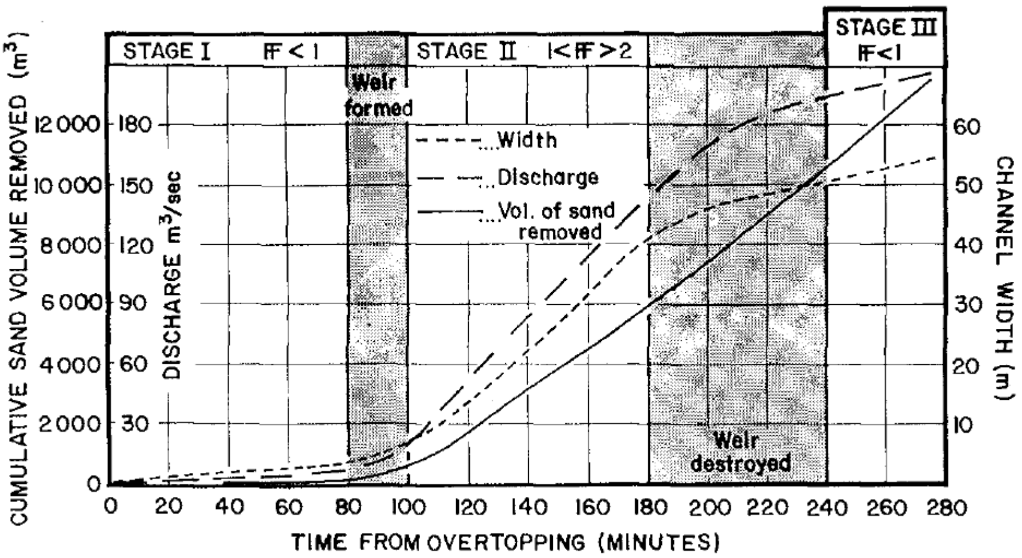


Figure 7.10 Three stages of breakout (Gordon, 1990)

In the case of the Tuggerah Lakes entrance, its configuration rarely allows for a complete progression through these stages as it is rarely fully closed. Furthermore, it is unlikely that the supercritical flow element of the second stage occurs in this entrance, due to the difference in water level between the Tuggerah Lakes system and the ocean not being large enough and the length of the entrance channel (Lawson & Treloar, 1994). An implication of this is that ocean conditions are likely to have some impact on lake flood levels, even during flood events (Lawson & Treloar, 1994).

7.2.6.2 Water levels

The ocean level can have a significant impact on the configuration and amount of scour at the entrance channel. Water level data is available from a network of gauges along the NSW coast, and in the Tuggerah Lakes catchment, with the gauge closest to the entrance itself being located at Tuggerah Lakes Entrance at The Entrance Bridge (ERTS561001). A full discussion on the estimation of ocean water levels at this location is provided in **Section 7.2.5.2**.

7.2.6.3 Berm elevation

Entrance berm levels have been recorded sporadically from the 1940s, and are publicly available as part of the NSW Beach Profile Database (developed by the UNSW Water Research Laboratory on behalf of the NSW Department of Climate Change, Energy, the Environment and Water - www.nswbpd.wrl.unsw.edu.au). These berm elevation data are based on direct survey, photogrammetry and LiDAR measurements of the entrance region. The available beach profile locations at the entrance are shown in **Figure 7.11**.

Figure 7.12 Beach profile locations of berm entrance

These beach profiles were able to be interpolated into 2D elevation grids, which were able to be incorporated into the hydraulic model, where deemed appropriate. These data also provided an insight to the berm characteristics over time, as detailed further in Tuggerah Lakes Entrance Management Study (MHL, 2022). A summary of the relevant pre- and post-event berm elevation surveys available from this source are summarised in **Table 7.3**.

Table 7.3 Relevant berm surveys for calibration and validation events

	June 2007	March 2021	July 2022
Pre-event	N/A	N/A	4 April 2022
Post-event	N/A	13 April 2021	28 September 2022

7.2.6.4 Entrance bathymetry

A comprehensive bathymetric survey of the entire entrance, between the lake body and the ocean, was completed in September 2011 and provided by Central Coast Council.

Inspection of NearMap imagery captured in in August 2011 revealed that the entrance was in a very typical configuration prior to many large events, with a moderately constricted opening to the ocean positioned at the southern end of the beach and developed shoals upstream of this. This imagery also showed that the large rock shelf defining the southern edge of the entrance alignment at the time was likely exposed at the time of the survey, and it was therefore noted that levels observed in this area should not be lowered throughout any scouring process. As a result of these factors, the 2011 entrance survey formed the bulk of the underlying bathymetry as a base on which more event-specific features were added. A range of entrance surveys were also collected in the period 2018 - 2021 by Central Coast Council of the entrance channel and marina. These survey data were interrogated with respect to their time of collection and the corresponding configuration status of the entrance at that time. This informed a general understanding of the entrance channel, berm and shoal development and evolution throughout the dynamic and cyclical processes of scouring and rebuilding prior to, during and after the flood events captured within these data. The surveys with direct relevance to the simulated historical events are tabulated in **Table 7.4**.

Table 7.4 Relevant entrance surveys for calibration and validation events

	June 2007	March 2021	July 2022
Pre-event	Nil	N/A	March 2022
Post-event	Nil	May 2021	July 2022

From these data, the post-event entrance survey of July 2022 offered the greatest insight into the typical scoured configuration of the entrance. This data was particularly useful with respect to detailing the shoals further back from the entrance throat itself, which become more influential after the initial berm scour has occurred during the peak and falling limb flood phase as the cross-sectional area where the shoals are located becomes more constrictive than the cross-sectional area at the scoured entrance berm.

The representative pre- and post-scour entrance surveys were captured using a mix of survey data. The following general observations were made from these surveys:

Pre-event (Figure D.20)

- The entrance opening is typically in the south, with a berm level of up to 3.0 mAHD stretching across the entrance compartment and possible lower berm extensions in the extreme south as the entrance becomes more constrained
- Exposed bedrock at the time of the survey lies along the southern shore of the opening, sitting at levels ranging between -0.0 and -1.0 mAHD
- A remnant channel of varying depth may exist, with chains of pools with a level down to around -1.0 mAHD, interspersed by raised areas up to -0.5 mAHD
- A broad area of shoals between the opening and The Entrance Bridge typically forms an undulating and relatively elevated platform, ranging in level between -0.5 mAHD and 0.3 mAHD

Post-event (Figure D.21)

- The entrance opening could not be surveyed due to swash; however, it can be inferred that, the exposed bedrock on the southern side of the entrance does not scour beyond the levels mentioned above (-0.0 mAHD to -1.0 mAHD)
- The bed level to the north of the bedrock is in sand and can scour to -2.0 mAHD and beyond. This deeper channel can extend from the ocean upstream through the dynamic shoal zone until joining the more stable channels near The Entrance Bridge.
- There appears to be more stable shoals against the western shore of the entrance with a smooth transition to the deeper channel.

7.2.6.5 Satellite imagery

Satellite images were used to estimate the pre- and post-event entrance channel configuration and scour rates, where available. Relevant satellite imagery was also collected on dates as close as possible to the collection date of the bathymetric and berm surveys discussed above. For these purposes, images were collated from all publicly available sources, including Nearmap, GoogleEarth, Landsat, Sentinel, and PlanetLab.

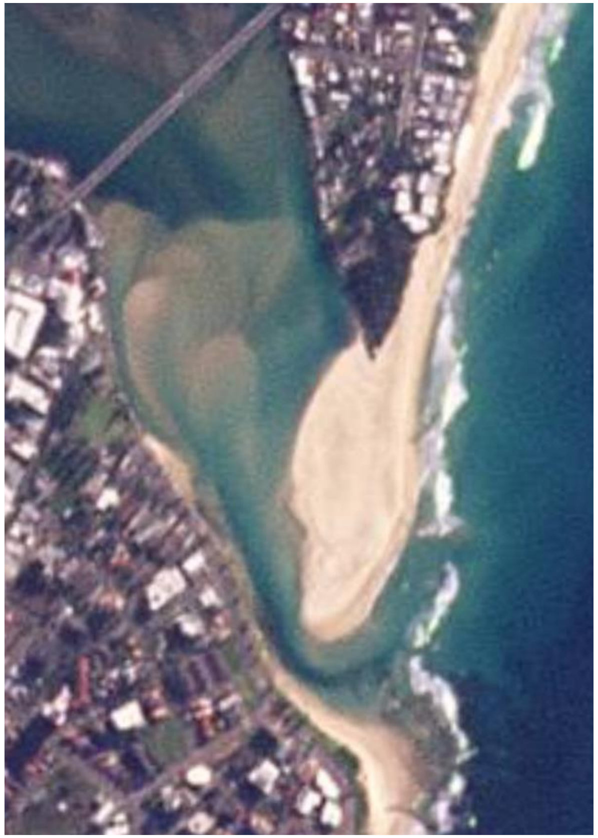
A summary of key satellite images captured prior to, during and after the selected historical flooding events is presented in **Table 7.5**.

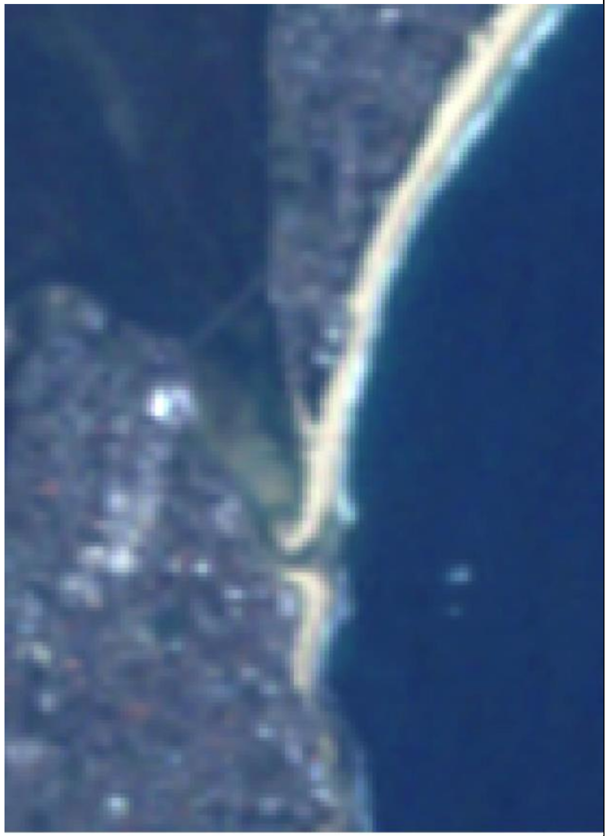
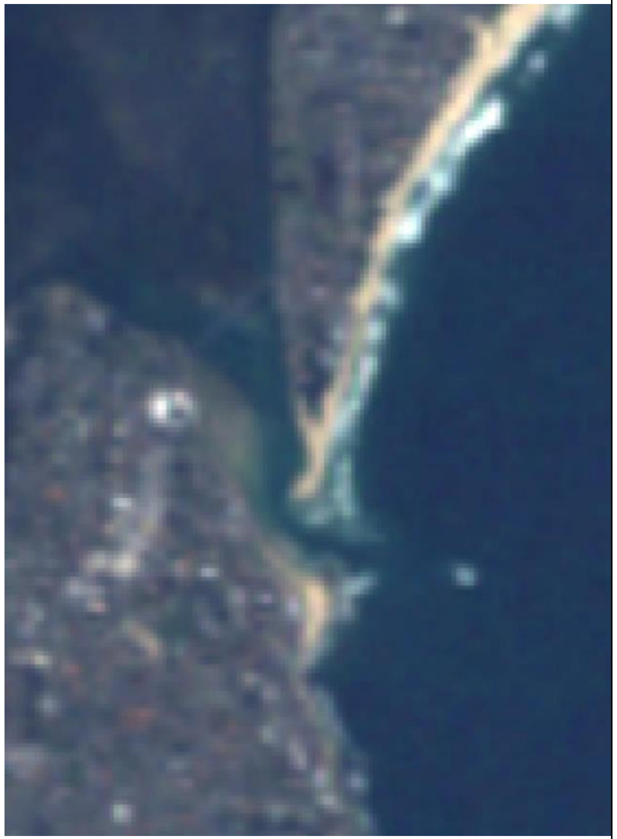
For the recent events in July 2022 and March 2021, it was found that PlanetLab images offered the best coverage during events. As the exact time of capture of these images was known, an estimation of the width of the channel was able to be made by cross-referencing the observed water levels at the Tuggerah Lakes Entrance and Patonga gauges. Using this approach, these images were used to supplement the derivation of the indicative pre- and post-event entrance configurations.

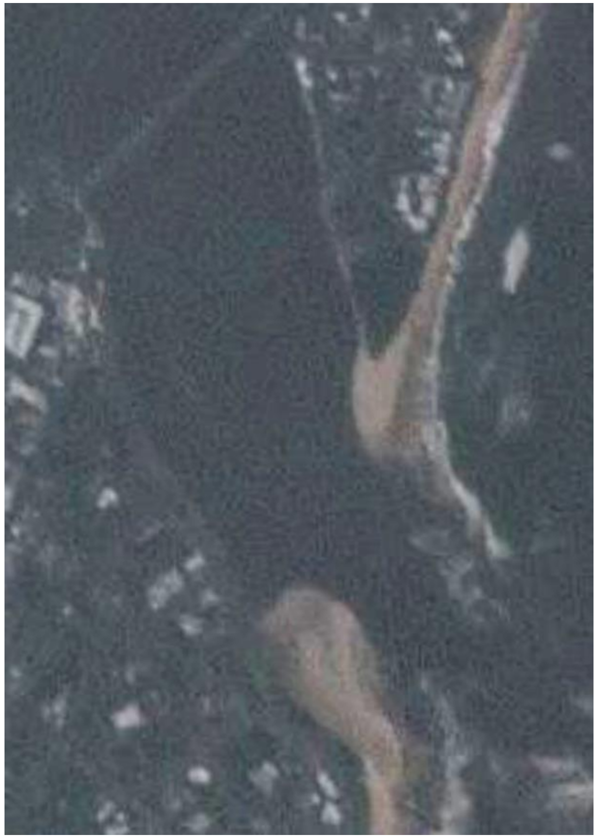
For the June 2007 event, a high-resolution GoogleEarth image from January 2007 was available. This image showed a similar berm, channel and shoal configuration to that observed ahead of the July 2022 event, and as such justified a similar setup and scour approach to this event. Landsat5 images were available nearer the occurrence of the event. However, their lower resolution prevented their use in determining the precise scour characteristics during the event, other than to reinforce the occurrence of a similar mechanism as was seen in July 2022.

For the March 2021 event, it can be observed that the entrance opening behaviour was significantly different from the July 2022 and the June 2007 events, with the entrance opening at the centre of the berm rather than the southern side and significant changes in berm shape occur.

Table 7.5 Satellite imagery showing the configuration of the entrance channel

Before	During	After
July 2022 calibration event, peak Tuggerah Lake at Long Jetty level occurred at 9:30pm 6 July 2022 AEST		
Captured: 9:21am 27 June 2022 AEST Source: Planet Channel width: 60 m (at 0.29 mAHD) 	Captured: 9:52am 8 July 2022 AEST Source: Planet Channel width: 130 m (at 1.38 mAHD) 	Captured: 9:36am 13 July 2021 AEST Source: Planet Channel width: 120 m (at 0.51 mAHD) 

Before	During	After
June 2007 calibration event, peak Tuggerah Lake at Long Jetty level occurred at 4:15am 10 June 2007 AEST		
Captured: 9:38am 13 May 2007 AEST Source: Landsat5 	Captured: 9:34am 22 June 2007 AEST Source: Landsat7 	Captured: 9:37am 30 June 2007 AEST Source: Landsat5 

Before	During	After
March 2021 validation event, peak Tuggerah Lake at Long Jetty level occurred at 4:45am 22 March 2021 AEST		
Captured: 10:11am 13 March 2021 AEST Source: Planet Channel width: 70 m (at 0.37 mAHD) 	No available imagery	Captured: 9:10am 25 March 2021 AEST Source: Planet Channel width: 200 m (at 0.50 mAHD) 

7.2.6.6 *Entrance photography*

A series of oblique photographs of the entrance channel were collected by WRL from an elevated position on the southern side of the entrance. While it was deemed unrealistic to accurately estimate the width of the channel using this photography, these data were predominately utilised to develop an understanding of the configuration of the entrance channel during the more recent historic flood events that occurred during the time of operation of the camera, particularly in respect to timing. **Table 7.6** exhibits a selection of photographs of key phases of the respective scour processes, including the time of image capture as indicated by the red vertical line, and water levels as recorded at Tuggerah Lakes Entrance in orange, and Sydney in blue. It is noted that these photographs are typically captured at 30-minute intervals during daylight hours, however sometimes this capture frequency is not achieved due to outages, which have been noted where relevant.

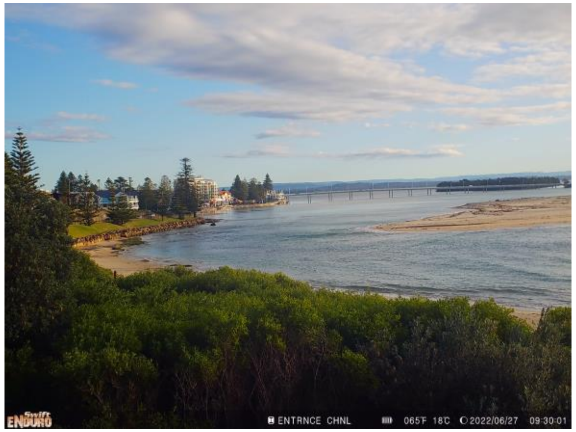
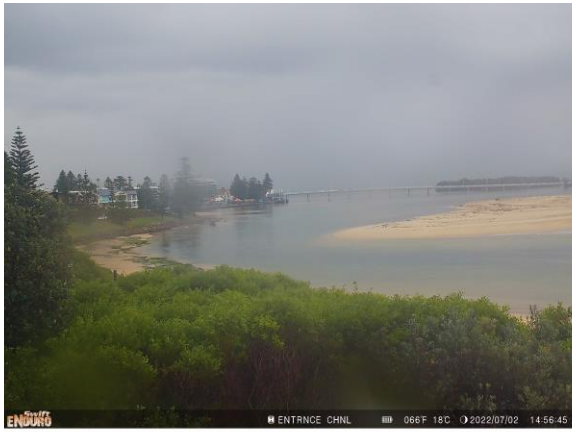
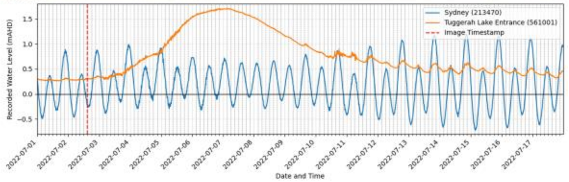
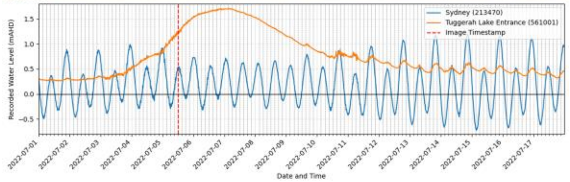
Additional images of the July 2022 event were also provided by Council which assisted in the determination of appropriate scour trigger times and rates for that event. One such image is presented below in **Figure 7.13**. This image also reaffirmed that despite the heavy sea conditions, breaking waves were not observed at the channel of the entrance itself, as discussed in **Section 7.2.5.2**.

Figure 7.13 Photograph looking north across The Entrance, taken on the afternoon of 7 July 2022, courtesy of Central Coast Council

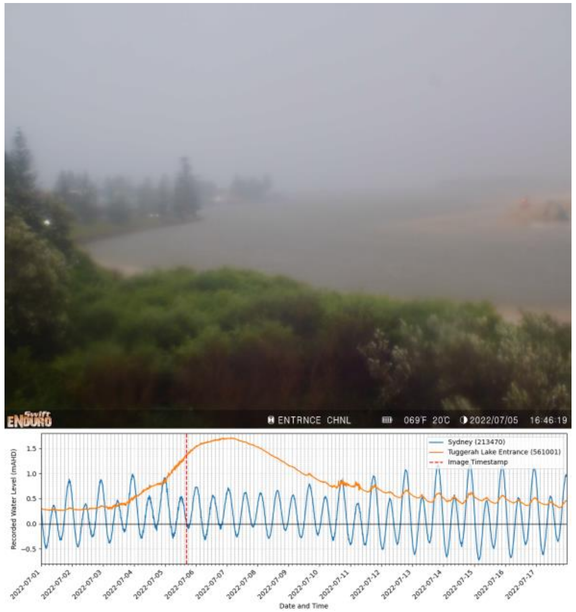
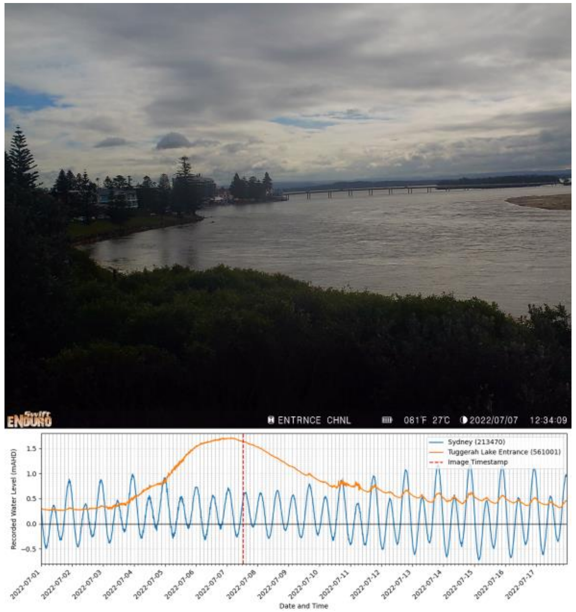
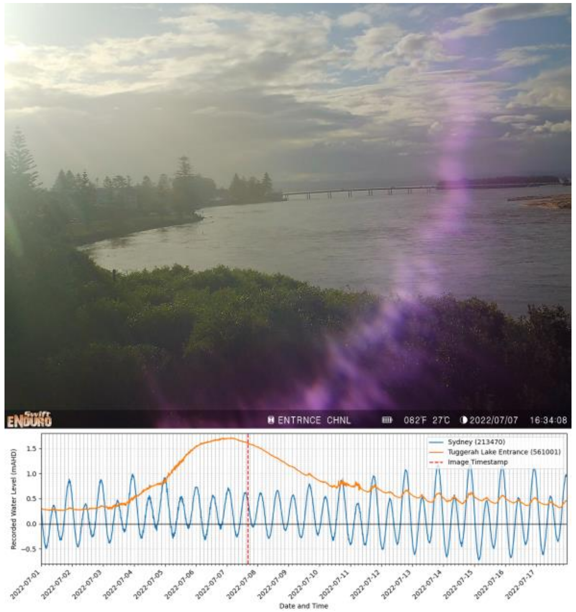
No continuous entrance imagery was able to be sourced for the June 2007 calibration event. An aerial photograph was sourced from the existing Tuggerah Floodplain Risk Management Study (2014) and is presented in **Figure 7.14**. The image shows the Tuggerah Lakes entrance in a typical configuration at the southern end of the beach.

Figure 7.14 Aerial photograph of The Entrance during the June 2007 calibration event – looking west (Tuggerah Floodplain Risk Management Study, 2014)

Table 7.6 WRL photographs showing the configuration and scour of the entrance channel

July 2022 calibration event		
27 June 2022 9:30 am Coincident with final pre-event satellite image 	2 July 2022 2:57pm Rain event commences  	5 July 2022 12:16pm Council commences berm scraping  

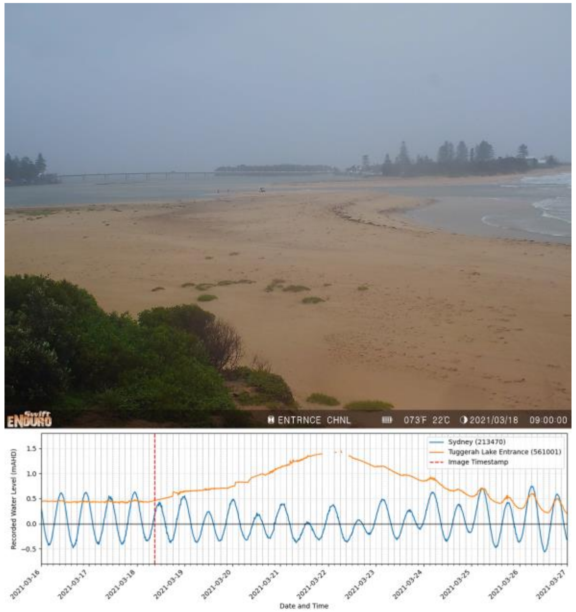
Classification: Public

5 July 2022 4:46pm	7 July 2022 12:34pm	7 July 2022 12:34pm
Council berm scraping ongoing at sunset	Next available image, post-peak	Final available image
		

March 2021 calibration event

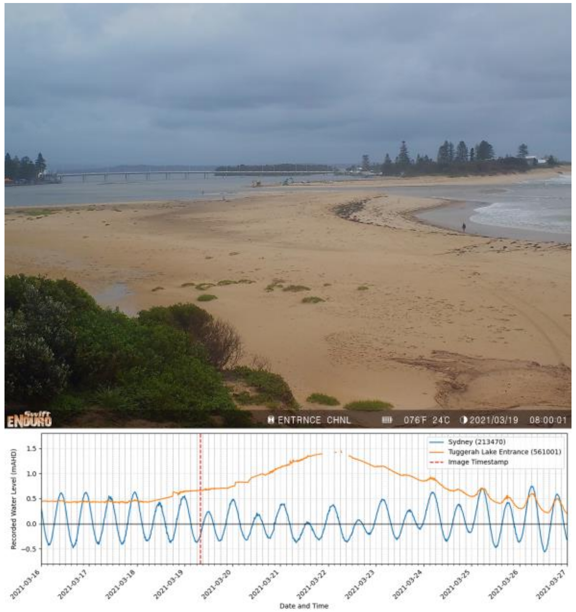
18 March 2021 9:00am

Rainfall event commences



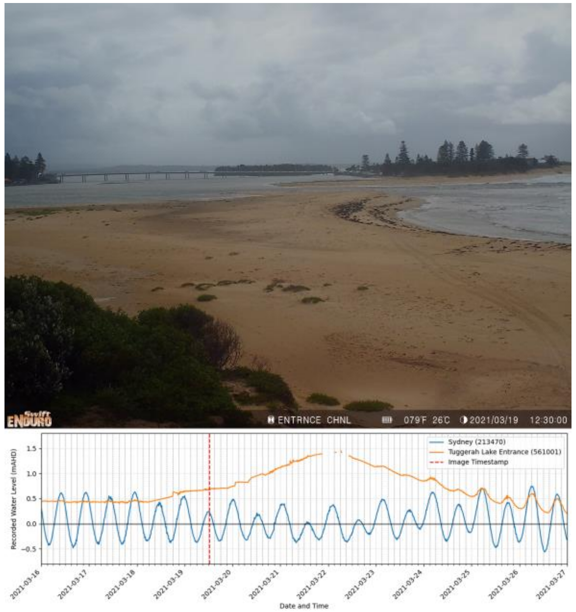
19 March 2021 8:00am

Council commences initial berm scraping



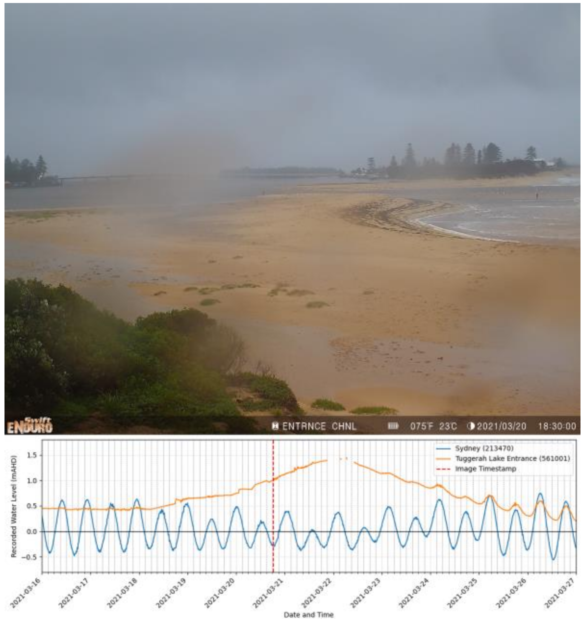
19 March 2021 12:30pm

Initial Council berm scraping concludes



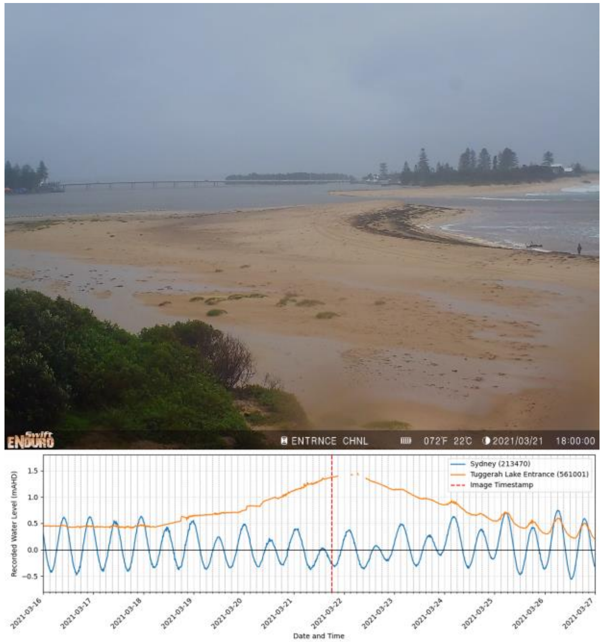
20 March 2021 6:30pm

Final picture before visual evidence erosion of northern berm overnight, ongoing erosion of southern berm suspected



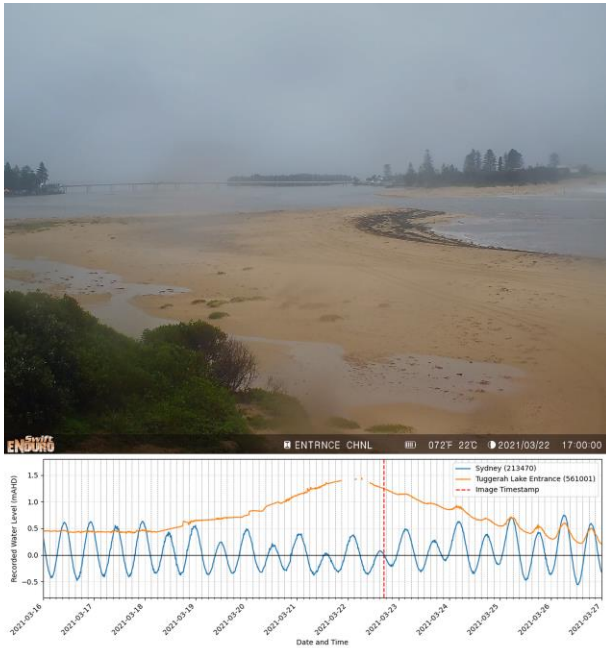
21 March 2021 6:00pm

Northern berm continues to slowly erode



22 March 2022 5:00pm

Northern berm undergoes faster erosion through peak



7.2.6.7 *Central Coast Council Manly Hydraulics Laboratory Flood Intelligence Tool (CCC MHLFIT)*

The CCC MHLFIT was developed by MHL and is used by Council to monitor the conditions of Tuggerah Lakes and other coastal lagoons, guiding Council intervention, when necessary, with the aim of mitigating the risk of flooding. The MHLFIT tool, which was developed as part of the Tuggerah Lakes Entrance Management Study, comprises a simplified representation of the Tuggerah catchment hydrology and lake inflows using a WBNM hydrologic model combined with a one-dimensional hydraulic representation of entrance flows to provide real-time forecasting of lake levels under a range of likely and hypothetical scenarios. Data and assumptions from these models were utilised in the development of the representative entrance configuration for the historical event replication as part of this study.

Furthermore, as part of the ongoing operation of this tool, the width of the entrance can be updated by Council officers. This estimate is typically derived through estimation using recently captured satellite imagery or visual observations. **Table 7.7** lists these estimated widths as recorded in the MHLFIT system during the calibration and validation events. It is noted that these estimates are intended to be of the channel width at 0 mAHD but are often made when water levels are above this, meaning these estimates are inherently approximate.

Table 7.7 Tuggerah entrance channel width estimated by MHLFIT during historic floods

Event	Time	Estimated entrance channel width at 0 mAHD (m)	Recorded lake level (mAHD)
June 2007	2007-06-05	40	~0.24
March 2021	2021-03-16	70	~0.45
June 2022	2022-06-26	50	~0.28
	2022-07-06 15:30	60	1.66
	2022-07-07 16:30	70	1.60
	2022-09-09 09:00	60	0.23

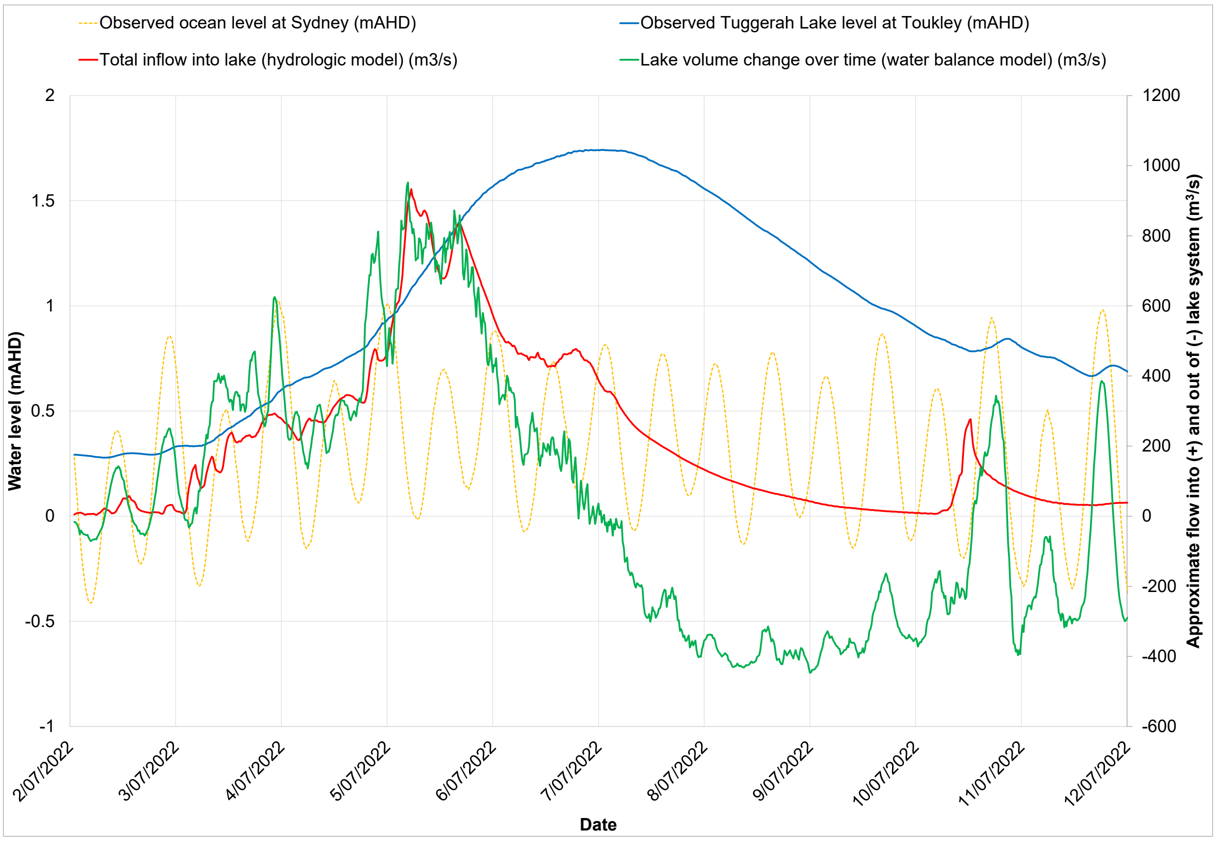
7.2.6.8 *Water balance analysis*

A simplified model was also developed to obtain an estimate of the water balance in the Tuggerah Lakes system. Hypsometric curves developed using the available bathymetric elevation data were defined to determine the volume of water in the lake for various water levels.

An example is provided for the July 2022 event in **Figure 7.15**. A 2-hour average lake level timeseries was created to remove the noise in water level generated by wind and small waves and is illustrated as a blue line. This timeseries was assessed to determine the difference in level between each timestep and hence, the difference in volume in the lake between each timestep. This lake volume change over time was converted into a flow and is illustrated as a green line. The total inflow into the lake obtained from the hydrologic modelling completed as part of the present study is illustrated as a red line, while the ocean water level is represented as a yellow dashed line. When assessing the change in volume in the lake, the following can be noted:

- The comparison of the total inflow from the hydrologic model with the estimated lake volume change over time highlights a strong correlation in shape which provides additional confidence in the results from the hydrologic model.
- The total inflow and the lake volume change over time commence to diverge when the lake reach a level of approximately 1.3-1.4 mAHD. It is expected that the scour would have commenced a little earlier (e.g., when the lake reaches 1.2-1.3 mAHD) but only becomes large enough to impact the levels from that time.
- The difference between the total inflow and the lake volume change over time on 6-10 July represents the estimated outflow generated by the entrance scour and when the hydrologic model inflow stops on 8 July 2022, the change in volume appears to stabilise around approximately -350 to -400 m^3/s. This is the expected outflow at the lake entrance when no inflow occurs.

Despite its simplified nature, this approach provided an estimate of the expected outflow through the entrance following the peak of the flood as well as additional confidence in the outputs of the hydrologic model during the rising limb of the event when significant scour is yet to occur.



Note: all values displayed are 2-hour averages

Figure 7.15 July 2022 calibration event – Tuggerah Lakes system water balance analysis

7.2.6.9 The Entrance Beach rock groyne investigations

The groyne constructed at the northern end of The Entrance Beach in 2017 has been found to influence sediment dynamics and entrance morphology, particularly under heavily constricted states. Assessments by Salients (2021-2025) indicate that the groyne has contributed to a reduction in sand cover over the rock platform immediately north of the structure during non-flood conditions, and a widening of the beach to the south. These changes are consistent with the groyne's intended function and are spatially limited. While the groyne may alter entrance configuration under low-flow or drought conditions, it is anticipated that such changes will have limited influence on flood behaviour during moderate to rare events, which are the primary focus of this study. During these larger events, the entrance typically scours and widens rapidly, diminishing the relative impact of pre-event morphological conditions. Nonetheless, the influence of the groyne is acknowledged and is to be considered in future entrance management and monitoring programs.

7.2.6.10 Conceptual entrance scour

Based on the analysis of the various information datasets described above, a conceptual model of the entrance has been developed and is presented in **Table 7.8**. The conceptual entrance model is largely based on a mix of data but predominantly reflects the entrance behaviour of the July 2022 event. This event was chosen due to the relatively large availability of relevant data, its typical configuration and the large size of the flood event.

The starting configuration of the entrance is shown as the first entry in **Table 7.8**. This configuration is based upon the September 2011 bathymetric survey, overlaid with the April 2022 berm photogrammetry survey. These data were then supplemented with timestamped satellite and oblique imagery to reproduce the observed starting configuration as closely as possible. An essential part of this configuration is that the starting width of the channel is customisable.

This starting configuration then evolves over a given timeframe into a final scoured configuration. The scoured configuration is an idealised trapezoidal channel, with a customisable width and depth of the main channel, and the eroded configuration of the shoals being based on the post-event bathymetric survey of July 2022.

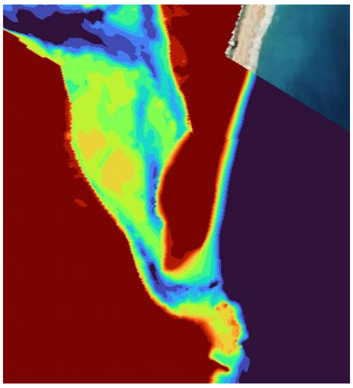
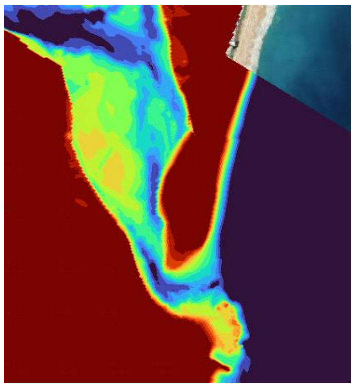
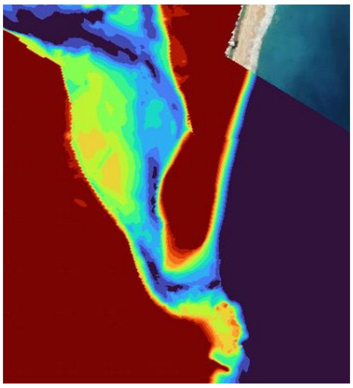
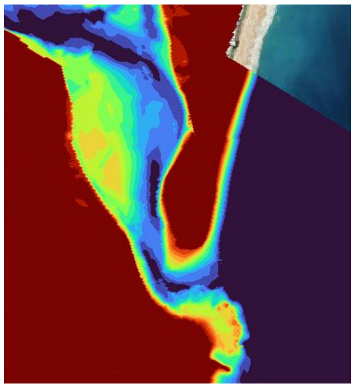
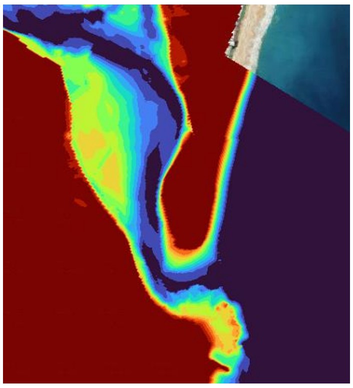
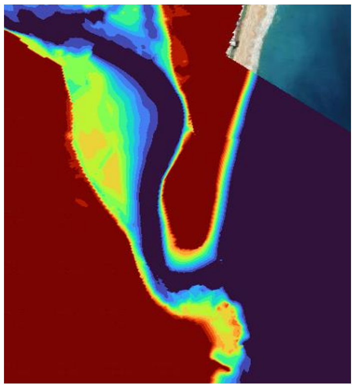
7.2.6.11 Summary

Based on the above listed information as well as other secondary information (e.g., expert opinions from similar studies, findings from other studies, observations from the local community and Council), behaviour of the entrance channel was modelled uniquely for each historic flood event. For this purpose, the entrance breakout was modelled using a time-varying topography level in the TUFLOW model. This allows for a dynamic change in ground and bed geometry from an initial elevation value to a scoured value over a set period.

As precise bathymetric data was not available immediately prior to any of the selected historic events and owing to the morphologically dynamic nature of the area, a representative entrance configuration had to be gleaned from a variety of sources and iteratively modified to define an appropriate initial channel configuration that could replicate the recorded hydrograph of each event.

As for defining the progression of scour during the event and the final configurations of the entrance, the availability of post-event surveys and imagery in May 2021 and July 2022 allowed for the development of a generalised post-scour configuration, although it is noted that the entrance would have undergone significant recovery between the end of the respective events and the capture of these data.

Table 7.8 Example of conceptual entrance opening for July 2022 calibration event

% scour	Elevation	% scour	Elevation
0		20	
40		60	
80		100	

To summarise, the entrance configurations before, during and after each of the simulated historical events were constructed so as to be based on a standardised configuration, whereby further specific optimisations to the initial condition of the channel, trigger points of scour, duration of scour, location and length of the scour, and the final condition of the channel were able to be made appropriately within this standardised approach.

Investigations into the impact of the entrance configuration revealed that the channel width has an influence on outflows and hence, the peak flood level in the lake. The channel depth and the associated configuration of the shoals were also found to have an impact on lake levels, particularly during the tailing limb of an event. These findings are generally in agreement with those of the Tuggerah Lakes Entrance Management Study (2022). The channel configurations that produced the best outcomes are documented in **Table 7.9**, with results presented in **Section 7.3**.

The hydraulic model further indicated that for any of the selected historic events, the trigger point of initial scour was between 1.1 mAHD and 1.4 mAHD of the lake water level. This is consistent with the Tuggerah Lakes Entrance Management Study, which found that a lake level of 1.3m AHD is needed to successfully maintain the channel in an open state and allow the entrance to widen. Scour occurred over a period of 48-70 hours. The longer duration of scour observed for the July 2022 event could be a combination of several factors, including the severity of catchment flooding, higher lake levels, tidal behaviour, and the initial configuration of the entrance channel. The generally lower trigger and shorter duration of the March 2021 event is anticipated to be because of the significantly different entrance configuration, being more towards the north, with a straighter channel between the bridge and ocean allowing for higher velocities and erosion on both sides.

Table 7.9 Summary of entrance configuration and scour parameters for calibration and validation events

Flood phase	Parameter	Historic event		
		July 2022	June 2007	March 2021
Pre-scour	Channel width (m at 0 mAHD)	50 m	50 m	70 m
Scour	Trigger	1.40 mAHD	1.40 mAHD	1.10 mAHD
	Duration	70 hours	50 hours	40 hours
Post-scour	Channel width (m at 0 mAHD)	90 m	90 m	180 m

7.2.7 Model limitations and assumptions

The flood model is subject to the following limitations and assumptions:

- The selected 6 m by 6 m resolution of the model is adequate for representing flood behaviour but would have a limited representation of details smaller than the resolution.
- Buildings have been modelled as areas of high roughness. This approach can lead to observed flooding on the maps where buildings exist. These occurrences are anticipated to have only limited impact on modelled flooding behaviours but should be considered at the time of encoding flood affected properties as such.
- Wind and wave setup effects both for ocean levels and within the lake itself are not considered.
- A lack of timely bathymetric entrance surveys pre- and post-event means entrance opening conditions are largely assumed but based on alternative evidence available.
- The flood extent outside the lake area is indicative only; the actual extent should be obtained from an existing relevant overland or catchment flood study. Levels of upstream

tributaries will not be included in the final model results to minimise potential confusion about flood planning levels as compared to other relevant plans.

- The modelling of entrance initial conditions and scour dynamics relies on historical assumptions and limited post-event survey data. While the adopted approach reflects observed behaviour during calibration events, the response of the entrance during extreme events (e.g. 0.5% AEP or PMF) remains uncertain due to the absence of comparable historical data. These assumptions also may not adequately represent future changes in and around the entrance.
- Further, the modelling undertaken for this study does not directly model the morphological response of the entrance or lake system, instead relying on pre-defined entrance responses based on historical data and assumptions. Given the dynamic nature of sediment transport and entrance behaviour, a more detailed morphologic assessment would be necessary to fully evaluate the potential impacts of dredging or other activity on flood behaviour and estuarine processes.

7.3 Model calibration and validation

The hydraulic model was calibrated and validated for the same events as described in **Section 6.3**, namely, July 2022 and June 2007 for calibration, and March 2021 for validation. The findings of the hydraulic model calibration and validation are included in the sections below.

7.3.1 July 2022 calibration

The July 2022 flooding event saw intense rainfall which broke numerous longstanding records across much of the NSW east coast. A summary of the rainfall conditions that caused the event is provided in **Section 6.3.2**. The adopted entrance configuration for the July 2022 which best replicated the observations and data was described in **Section 7.2.6**.

It is important to analyse the data against which the model is to be calibrated. Foremostly, the purpose of the model is to appropriately replicate observed water levels within the Tuggerah Lakes. In accordance with this, water levels recorded at the Toukley, Long Jetty and Tuggerah Entrance Bridge gauges were compared as presented in **Figure 7.16**.

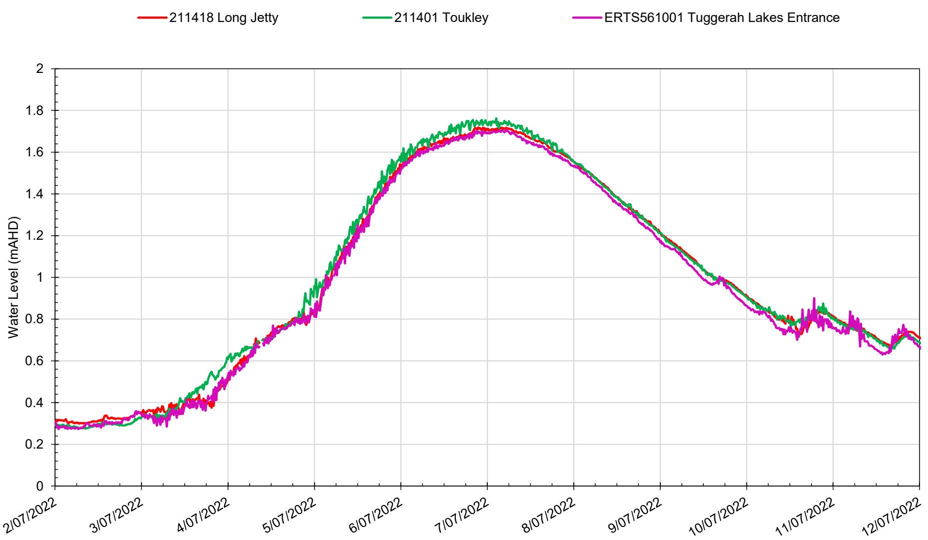


Figure 7.16 July 2022 calibration event – observed water levels in Tuggerah Lakes

The water level recorded at Tuggerah Lakes Entrance is generally similar to that at Long Jetty but tends to be slightly lower. This is in accordance with its relatively close proximity and similar overall positioning within the lake but also subject to the beginning of the hydraulic gradient between the lake and the ocean.

Less expectedly, it is noted that the recorded water levels at Toukley and Long Jetty vary in comparison to each other during this event. This was hypothesised to likely be because of wind setup across the open lake. To verify this, wind data as recorded at the closest nearby automated weather station at Norah Head were obtained from *theweatherchaser.com* and are presented in **Figure 7.17**.

The difference in water levels observed at Toukley and Long Jetty are presented in **Figure 7.18**, for comparison. In keeping with the Tuggerah Lakes Flood Study (Lawson & Treloar, 1994), the convention for a 'positive' setup was defined to mean that water level at Toukley in the north was higher than that at Long Jetty in the south.

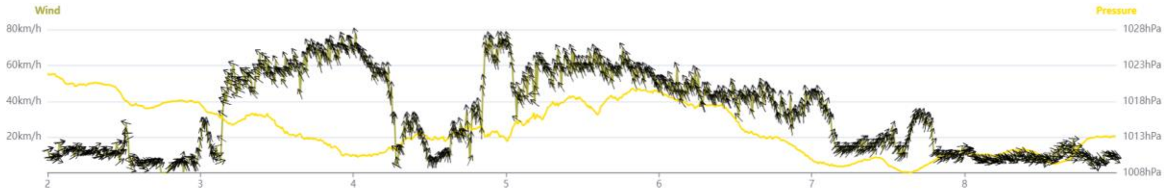


Figure 7.17 July 2022 calibration event – recorded windspeed and direction at Norah Head (61366)

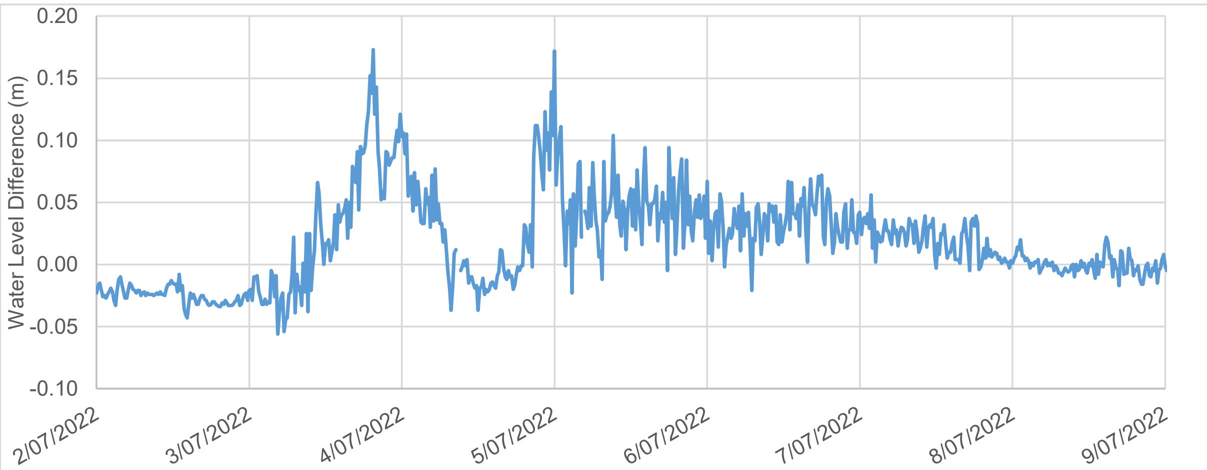


Figure 7.18 July 2022 calibration event – difference in recorded water levels between Toukley and Long Jetty

As can be seen in **Figure 7.17**, strong south and south-easterly winds were observed at Norah Head across most of 3 July and into the early hours of 4 July, with sustained windspeeds of approximately 60 km/h. Throughout the day on 4 July, these winds eased, before re-intensifying in the evening and early hours of 5 July to an average of 70 km/h. These winds then slowly subsided over the coming days, before abating significantly on 7 July. The relative speed and consistency in direction of these winds produces a clear response in lake setup, as can be seen in **Figure 7.18**, with the persistent southerly winds causing a significant difference between the two water level gauges due to the lake level expected to have a gradient and the level increase in the direction of the wind (i.e., southerly wind would result in a lower lake level in the south and a higher lake level in the north). This offset abates with the wind throughout the day on 4 July but strongly re-emerges in the evening before moderating over the following days.

The comparison performed above demonstrates that the divergence in observed water levels between the two distant sites within Tuggerah Lake is largely driven by wind setup effects during the July 2022 event. As a result, and since the modelled results do not consider these effects, the model was deemed to be most appropriately calibrated when the modelled lake level was between the levels recorded at the two distant lake gauges, particularly during periods of high wind.

Noting the above, a comparison between recorded water levels at the Toukley and Long Jetty and simulated water levels within Tuggerah Lake at Long Jetty is presented in **Figure 7.19**. Simulated water levels at Long Jetty were found to be effectively identical to those at Toukley and across Tuggerah Lake for this event. The figure shows the modelled results with an entrance that remains in its initial configuration throughout the event (dot dark blue line), and one with the adopted scour behaviour (solid dark blue line), as detailed in **Section 7.2.6**. A strong correlation between the simulated and recorded water levels within Tuggerah Lake can be observed, with the un-scoured scenario seeing a close correlation in the early phases of the event. This result demonstrates that the starting configuration of the entrance and hydrology represent the observations well.

A divergence between the unscoured and scour scenarios can be seen to emerge around the early hours of 6 July, which corresponds to the commencement of the scouring within the model and the commencement of mechanical berm scraping by Council and associated scour. Ultimately, modelled peak lake levels remain between the two lake gauge sites through the peak of the event, with a comparison in final peak level and timing exhibited in **Table 7.10**. An excellent match is seen in the falling limb, through to the re-emergence of tidal influences.

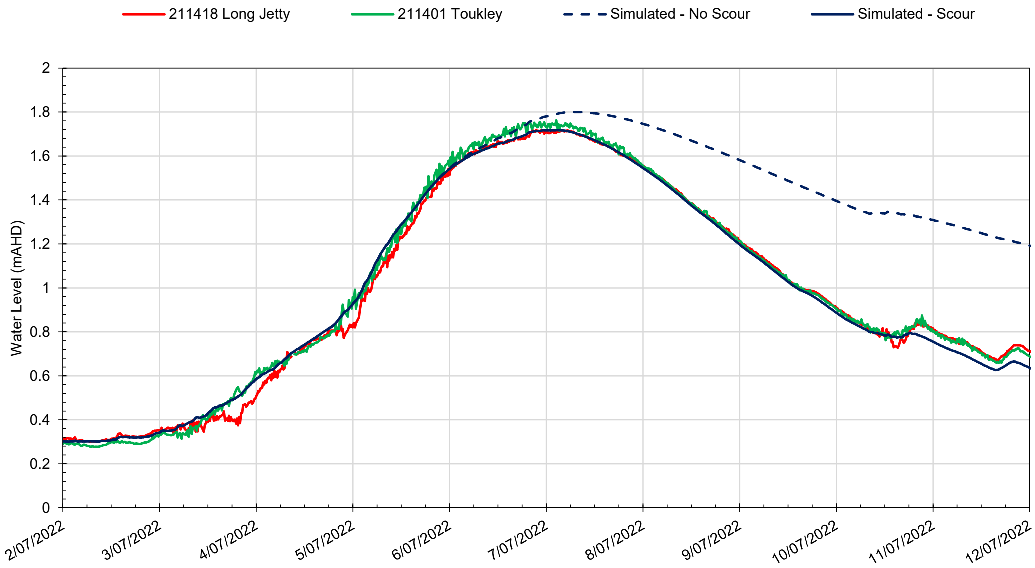


Figure 7.19 July 2022 calibration event – Tuggerah Lake water level (Long Jetty and Toukley)

Similar agreements can be seen at the Tuggerah Lakes Entrance water level gauge, as shown in **Figure 7.20**.

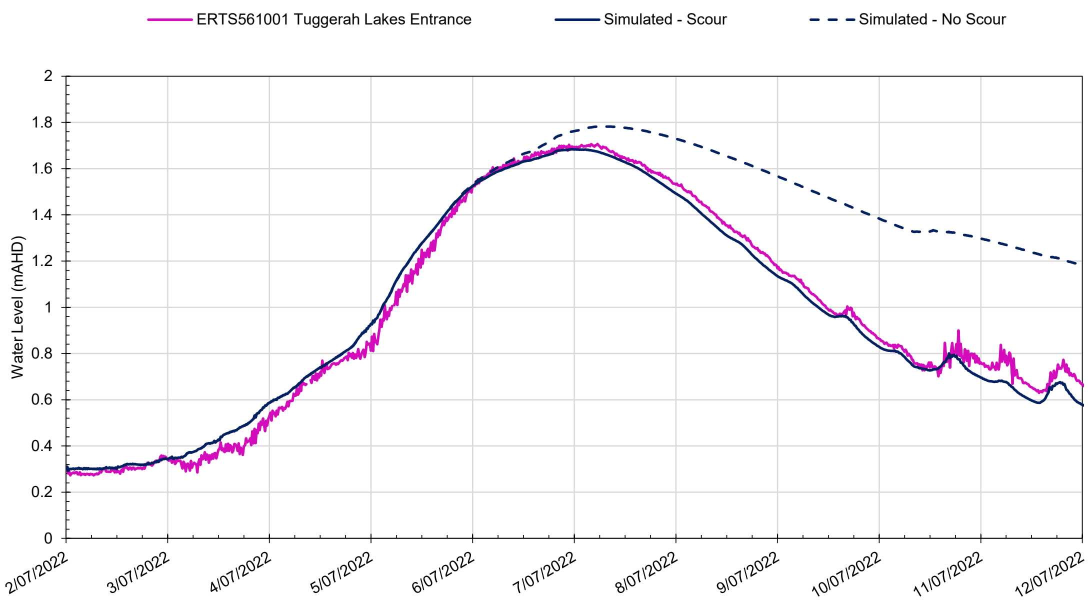


Figure 7.20 July 2022 calibration event – Tuggerah Lakes Entrance water level

Table 7.10 July 2022 calibration event peak summary

Gauge location	Observed		Simulated		Difference
	Level (mAHD)	Time (AEST)	Level (mAHD)	Time (AEST)	
Toukley	1.762	02:30 7 Jul	1.727	03:00 7 Jul	-0.035
Long Jetty	1.719	21:30 6 Jul			+0.008
Tuggerah Lakes Entrance	1.707	05:30 7 Jul	1.693	23:15 6 Jul	-0.014

7.3.2 June 2007 calibration

The June 2007 flooding event was associated with an East Coast Low that formed off the coast of NSW, just north of Newcastle. A summary of the rainfall conditions that caused the event is provided in **Section 6.3.3**. The adopted entrance configuration for the June 2007 which best replicated the observations and data was described in **Section 7.2.6**.

As mentioned in the previous section, the main objective of the model is to accurately replicate the observed water levels in the Tuggerah Lakes and water levels recorded at the Toukley and Long Jetty gauges were compared in **Figure 7.21**.

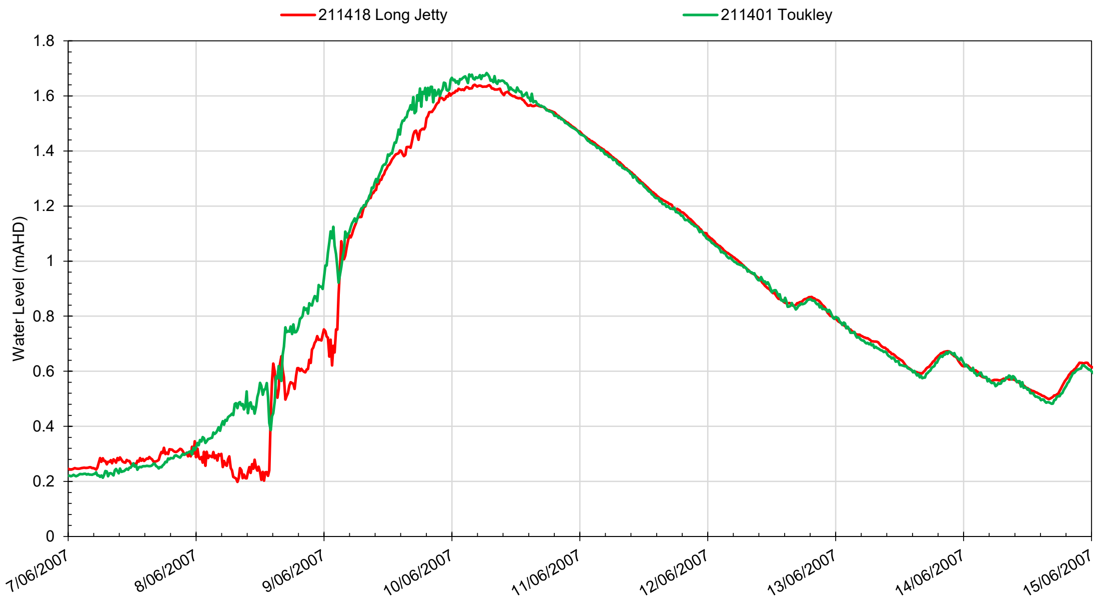


Figure 7.21 June 2007 calibration event – observed water levels in Tuggerah Lakes

The recorded water levels at Toukley and Long Jetty vary in comparison to each other during this event. As was the case during the July 2022 event, this was hypothesised to likely be because of wind setup across the open lake. To verify this, wind data as recorded at the closest nearby automated weather station at Norah Head were obtained from a BoM research report (Mills, et al., 2010) and are presented in **Figure 7.22**.

The difference in water levels observed at Toukley and Long Jetty are presented in **Figure 7.23**, for comparison.

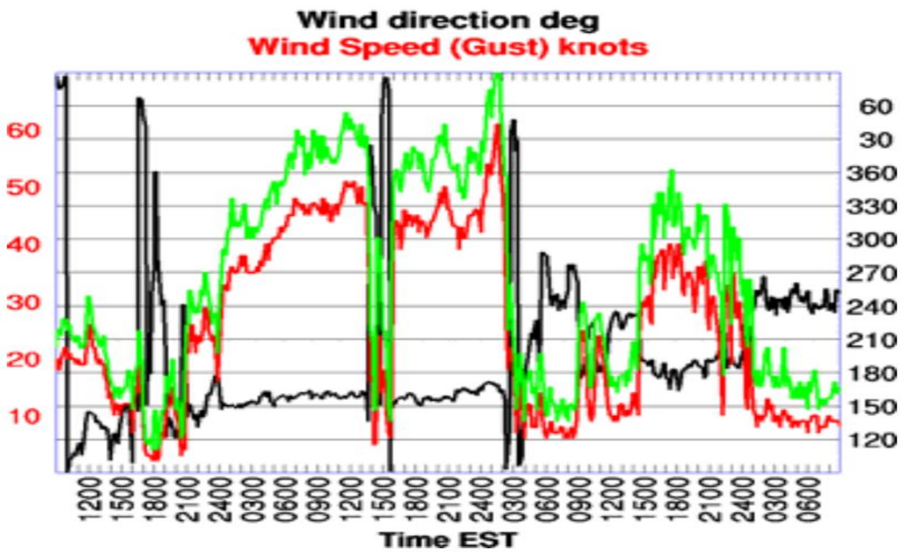


Figure 7.22 June 2007 calibration event – recorded wind direction (black), and mean (red) and gust (green) wind speed at Norah Head (61366), starting 0900 7 June 2007

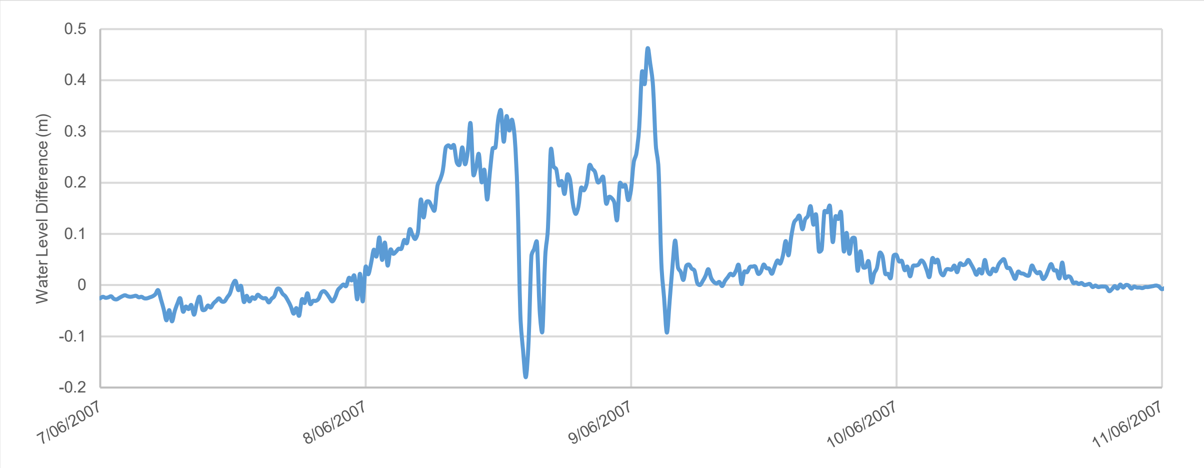


Figure 7.23 June 2007 calibration event – difference in recorded water levels between Toukley and Long Jetty

As can be seen in **Figure 7.22**, strong south and south-easterly winds were observed at Norah Head across most of 8 July and into the early hours of 9 July, with sustained windspeeds of up to 80 km/h. A lapse and reversal in wind direction in the afternoon of 8 July is also followed by a response in water level difference, before a general wind from the south is re-established later that day. The relative speed and consistency in direction of these winds produce a clear response in lake setup, as can be seen in **Figure 7.23**, with the persistent southerly winds causing two significant instances of lake levels increasing in a northward direction resulting in the large difference in water level between Toukley and Long Jetty recorded levels.

The comparison performed above demonstrates that the divergence in observed water levels between the two distant sites within Tuggerah Lake can be largely driven by wind setup effects during the June 2007 event. As a result, and since the modelled results do not consider these effects, the model was deemed to be most appropriately calibrated when the modelled lake level was between the levels recorded at the two distant lake gauges, particularly during periods of high wind.

Noting the above, a comparison between recorded water levels at the Toukley and Long Jetty and simulated water levels within Tuggerah Lake at Long Jetty is presented in **Figure 7.24**. Simulated water levels at Long Jetty were found to be effectively identical to those at Toukley and across Tuggerah Lake for this event. The figure shows the modelled results with an entrance that remains in its initial configuration throughout the event (dotted dark blue line), and one with the adopted scour behaviour (solid dark blue line), as detailed in **Section 7.2.6**. A strong correlation between the simulated and recorded water levels within Tuggerah Lake can be observed, with the un-scoured scenario seeing a close correlation in the early phases of the event. This result demonstrates that the starting configuration of the entrance and hydrology represent the observations well.

A divergence between the unscoured and scour scenarios can be seen to emerge around the night of 9 June, which corresponds to the commencement of the scouring within the model.

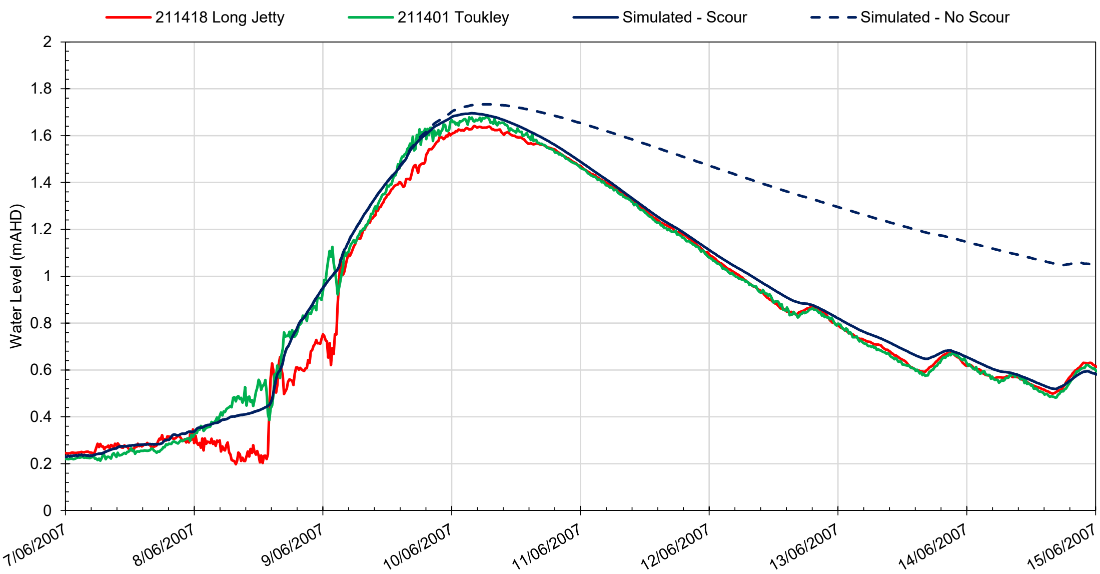


Figure 7.24 June 2007 calibration event – Tuggerah Lake water level (Long Jetty and Toukley)

Ultimately, modelled peak lake levels are slightly higher than recorded at the two lake gauge sites through the peak of the event, with a comparison in final peak level and timing exhibited in **Table 7.11**. An excellent match is seen in the falling limb through to the re-emergence of tidal influences.

Table 7.11 June 2007 calibration event – peak summary

Gauge location	Observed		Simulated		Difference
	Level (mAHD)	Time (AEST)	Level (mAHD)	Time (AEST)	
Toukley	1.683	06:30 10 Jun	1.696	03:45 10 Jun	+0.013
Long Jetty	1.641	04:15 10 Jun			+0.055

7.3.3 March 2021 validation

The March 2021 flooding event was associated with persistent, heavy rain which fell from March 16 to March 23 across central and northern NSW. A summary of the rainfall conditions that caused the event is provided in **Section 6.3.4**. The adopted entrance configuration for the March 2021 which best replicated the observations and data was described in **Section 7.2.6**.

As per the calibration events, water levels recorded at the Toukley and Long Jetty gauges were compared as presented in **Figure 7.25**. Data from the Tuggerah Entrance Bridge gauge was excluded due to periods of poor quality and missing data during this event.

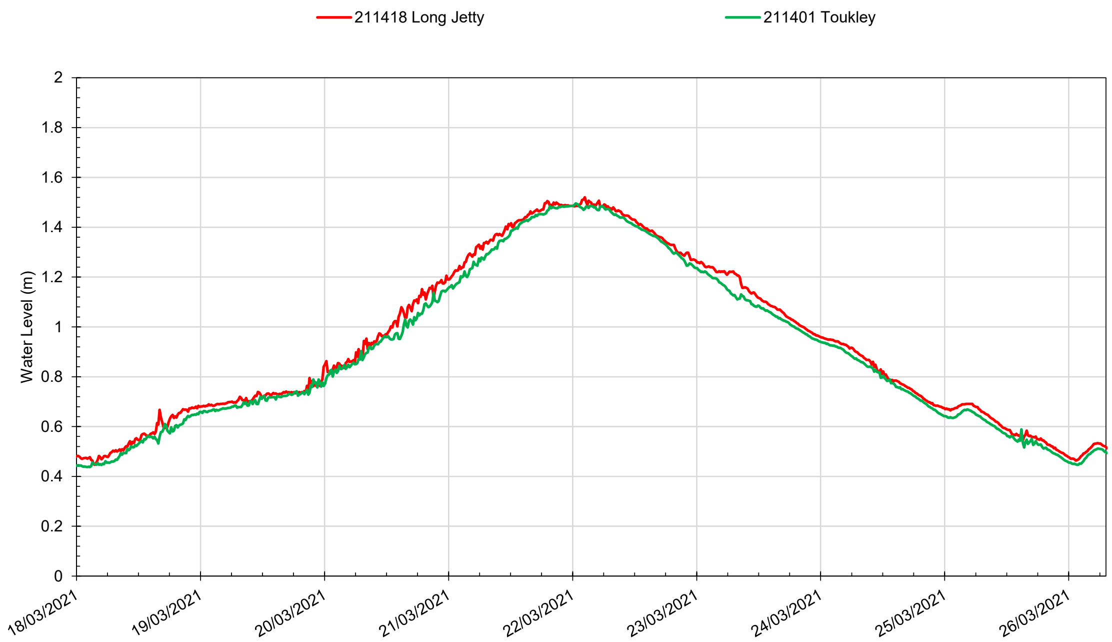


Figure 7.25 March 2021 validation event – observed water levels in Tuggerah Lakes

The water level recorded at the three lake sites are generally similar prior to the event. During the rising limb and peak, the Tuggerah Lakes Entrance site was subjected to periodic losses of data, and as such is not considered for comparison during this phase. The sites at Toukley and Long Jetty continue to closely represent each other throughout the event, in contrast to the other historical events considered above. This is likely due to the lack of strong winds from a predominant direction over significant periods of time associated with this event. A strong tidal signal can be seen to emerge at the Tuggerah Lakes Entrance site from 22 March onwards highlighting that the entrance scoured significantly by this time.

Noting the above, a comparison between recorded water levels at the Toukley and Long Jetty monitoring sites, and simulated water levels within Tuggerah Lake at Long Jetty is presented in **Figure 7.26**. Simulated water levels at Long Jetty were found to be effectively identical to those at Toukley and across Tuggerah Lake for this event. The figure shows the modelled results with an entrance that remains in its initial configuration throughout the event (dotted dark blue line), and one with the adopted scour behaviour (solid dark blue line), as detailed in **Section 7.2.6**. A good correlation between the simulated and recorded water levels within Tuggerah Lake can be observed, with the un-scoured scenario seeing a fair correlation in the early phases of the event until 20 March. A less accurate representation of the rising limb for this event on 20-21 March is attributable to the fact that the initial configuration and scour mechanism were represented using an idealised southern entrance opening which is significantly different to the actual configuration observed during this event, where the entrance was located towards the centre of the berm.

A divergence between the unscoured and scour scenarios can be seen to emerge during the day on 20 March, which corresponds to the commencement of the scouring within the model and the commencement of mechanical berm scraping by Council and associated scour.

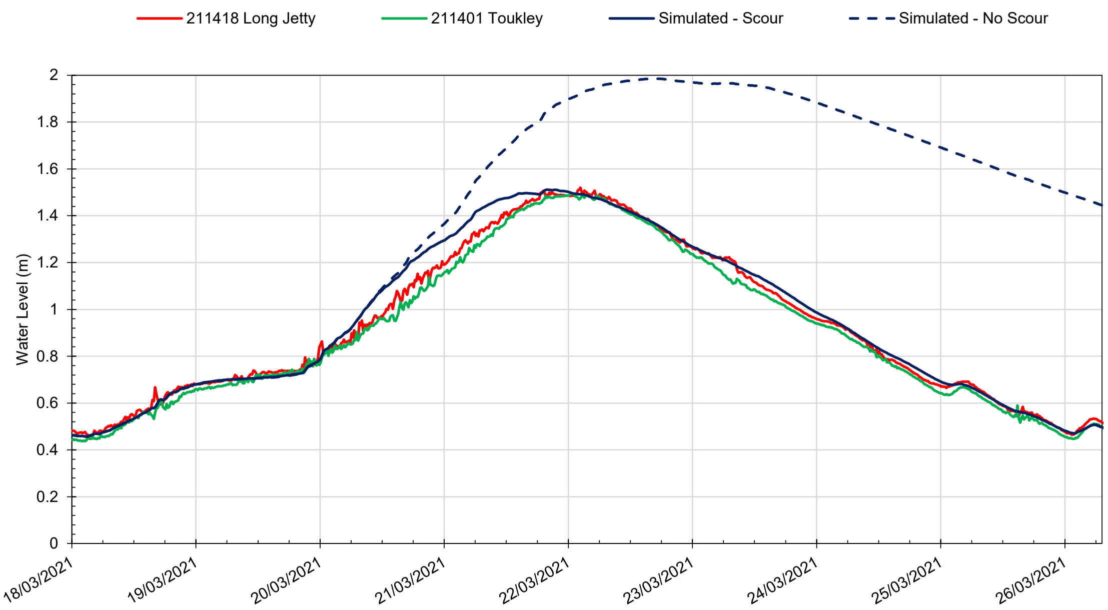


Figure 7.26 March 2021 validation event – Tuggerah Lake water level (Long Jetty and Toukley)

Ultimately, modelled peak lake level was between the two lake level monitoring sites albeit with a slightly earlier timing, with a comparison in final peak level and timing exhibited in **Table 7.12**. This demonstrates the applicability of an idealised entrance configuration across a variety of events with differing entrance configurations in representing peak lake flood levels. An excellent match is seen in the falling limb through re-emergence of tidal influences, highlighting that the final configuration of the entrance is appropriately modelled.

Table 7.12 March 2021 validation event – peak summary

Gauge location	Observed		Simulated		Difference
	Level (mAHD)	Time (AEST)	Level (mAHD)	Time (AEST)	
Toukley	1.496	03:00 22 Mar	1.511	22:15 21 Mar	+0.015
Long Jetty	1.520	04:45 22 Mar			-0.009

7.3.4 Discussion of model calibration and validation

The hydraulic model was calibrated using the July 2022 and June 2007 flood events and validated against the March 2021 flood event. The model successfully simulated the historic flood behaviour of Tuggerah Lakes, as depicted in **Figure 7.19**, **Figure 7.24** and **Figure 7.26**. Flood extent maps for the calibration and validation events are presented in , and . It should be noted that the flood extent over the lower reaches of the main tributaries to the lakes system (e.g. Wyong River, Ourimbah Creek, Tumbi Umbi, Wallarah Creek) and over the various overland areas is indicative only. Given the focus of this study is on the inundation level of the lakes, the most important factor is the replication of an appropriate volume into the lake over time. Inflows into the lakes system are located along the tributaries downstream reaches and have been lumped into source areas for overland areas. Therefore, for planning purposes, the actual extent in areas with elevated grounds not directly impacted by lake levels should be obtained from the existing relevant flood study or floodplain risk management study and plan.

The main purpose of the calibration and validation process was to provide some confidence in replicating the general behaviour of the lake entrance during a flood event and the model showed generally good agreement during the rising and falling limbs of the events.

Based on these results, this study suggests that the calibrated and validated hydraulic model is suitable for its intended purpose and ready to be used for design flood simulation. The calibration also highlighted the range of variation in entrance behaviour and the necessity for entrance configuration sensitivity assessment when defining the design flood event scenarios.

8 Design flood conditions

Design floods are hypothetical floods used for planning purposes and floodplain risk management investigations. They are broadly based on having a probability of exceedance, typically specified either as:

- Annual Exceedance Probability (AEP), expressed as a percentage chance of exceedance in any given year; or
- Average Recurrence Interval (ARI), expressed in years.

Design floods are developed using representative model inputs for progressively rarer scenarios. This report uses the recurrence frequency terminology as per current best practice as it highlights the fact that a significant event may occur in any single year, while the ARI terminology may give the wrong impression that they are occurring at a set interval of time. **Figure 8.1** provides a comparison of the various recurrence frequency terminologies and their preferred usage, including the different design floods considered as part of this study, as highlighted in red.

Frequency Descriptor	EY	AEP (%)	AEP (1 in x)	ARI
Very Frequent	12			
	6	99.75	1.002	0.17
	4	98.17	1.02	0.25
	3	95.02	1.05	0.33
	2	86.47	1.16	0.5
	1	63.21	1.58	1
Frequent	0.69	50	2	1.44
	0.5	39.35	2.54	2
	0.22	20	5	4.48
	0.2	18.13	5.52	5
Rare	0.11	10	10	9.49
	0.05	5	20	19.5
	0.02	2	50	49.5
	0.01	1	100	99.5
Very Rare	0.005	0.5	200	199.5
	0.002	0.2	500	499.5
	0.001	0.1	1000	999.5
Extreme	0.0005	0.05	2000	1999.5
	0.0002	0.02	5000	4999.5
			↓	
			PMP/ PMP Flood	

Figure 8.1 Comparison of recurrence frequency terminologies and preferred usage

8.1 Rainfall and runoff

8.1.1 ARR 2019

The methodology governing the derivation of design rainfall parameters is sourced from Chapter 3 of *Australian Rainfall and Runoff 2019* guidelines (Ball, et al., 2019). ARR (2019) defines statistical rainfall parameters covering Australia in its entirety based on historical observations. These parameters are extracted for the location of interest, in this case across the Tuggerah Lakes catchment, and used to produce design rainfall intensities for a variety of return frequencies and durations.

8.1.1.1 Intensity-Frequency-Duration data

The Australian Rainfall and Runoff (ARR) guidelines were updated in 2016, and revised in 2019, due to the availability of numerous technological developments, a significantly larger dataset since the previous edition (1987) and the development of updated methodologies. A key input to the process is information derived from rainfall gauges, and the dataset now includes a larger number of rainfall gauges, which continuously recorded rainfall (pluviometers), and a long record of storms, including additional rainfall data recorded between 1983 and 2012.

ARR 2019 recommended implementing the following features:

- Intensity, Frequency and Duration (IFD) rainfall data, pre-burst, and initial and continuing loss values across Australia;
- Critical duration derived from an ensemble assessment of 10 temporal patterns for each storm duration. The temporal pattern producing the mean level within each duration is selected. The critical duration is the duration for which the selected temporal pattern produces the maximum flood level;
- The inclusion of Areal Reduction Factors (ARFs) based on Australian data for short duration (12 hours and less), long duration (larger than 24 hours), and durations between 12 and 24 hours.

In the present study, the methodologies provided in ARR 2019 were implemented for design flood modelling, as these methodologies represent the best practice and would increase the longevity of the outputs of the Study.

Design rainfalls (ARR 2019 IFDs) were obtained from the Bureau of Meteorology (BoM) for specific AEP and duration combinations across the catchment. The Data Hub metadata is presented in **Appendix B**.

8.1.1.2 Temporal patterns

Temporal patterns describe how rain falls over time and form a component of storm hydrograph estimation. ARR 2019 has adopted a regionally specific ensemble of ten different temporal patterns for a particular design rainfall event. Given the rainfall-runoff response is catchment specific, using an ensemble of temporal patterns attempts to produce the median catchment response.

The ARR 2019 method provides patterns for 12 climatic regions across Australia, with Tuggerah Lakes catchment falling within the Southern Semi-arid region. ARR 2019 provides regional temporal patterns for each duration which are sub-divided into temporal pattern bins based on the frequency of the events. **Figure 8.2** shows the temporal pattern ranges (frequent, intermediate, rare, and very rare) for corresponding AEP ranges. In the area of overlap between the "rare" and "very rare" ranges, the "rare" patterns were adopted up to and including the 1% AEP event, and the "very rare" patterns were applied for the 1 in 200 and 1 in 500 AEP events. There are ten temporal patterns for each AEP/duration in ARR 2019 that have been utilised in this study for the 20% event to 1 in 500 AEP events.

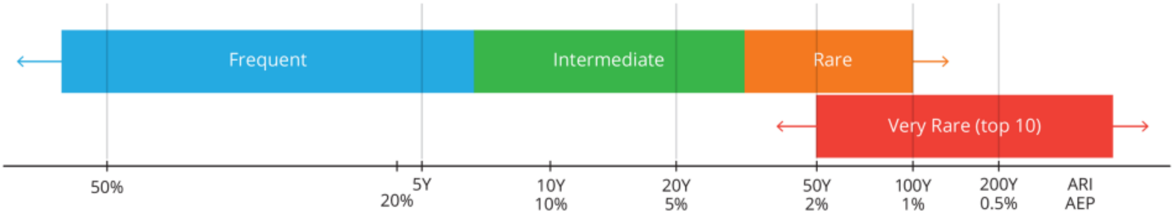


Figure 8.2 Temporal pattern ranges

Temporal patterns for this study were obtained from the ARR 2019 Data Hub (http://data.arr-software.org/). A summary of the data hub information at the catchment centroid is presented in **Appendix B**. The method employed to estimate the PMP utilises a single temporal pattern (Bureau of Meteorology, 2003), as is consistent with ARR 2019.

8.1.2 Areal temporal patterns

ARR 2019 recommends that Areal Temporal Patterns (ATP) should be considered in catchments larger than 75 km^2 to account for the spatial smoothing of rainfall that occurs over larger catchments. The Tuggerah Lakes catchment covers an area of 780 km^2 which is above the threshold of considering ATPs. ATPs are applicable for storm durations including and greater than 12 hours. Hence, ATPs were applied when assessing durations above or equal to this threshold in the hydrologic model.

8.1.3 Areal reduction factors

ARFs are defined as an estimate of how the intensity of a design rainfall event varies over a catchment. The main assumption in this estimate is that large catchments will not have a uniform depth of rainfall over the entire catchment. The ARFs were derived from the ARR 2019 Data Hub and applied in the WBNM models for all investigated design storm events. The ARF varies with AEP and duration, and the resulting set of ARFs for the design storms are provided in **Appendix B**. The ARF for the PMF has been set as 1 as per ARR 2019 recommendations.

8.1.4 Rainfall losses

The design rainfall losses applied in the hydrologic model were modified to match the calibrated parameters as summarised in **Section 6.3.5**, as per the hierarchy of preferred approaches in NSW outlined in ARR 2019 (Ball, et al., 2019). The adopted initial and continuing losses are specified below, with the initial loss rate being lower than that suggested by ARR 2019, but conversely with the initial loss being higher:

- Initial loss: 58 mm,
- Continuing loss: 1.0 mm/h.

8.1.5 Design events

The design events modelled in this study include:

- Frequent events – 20% AEP
- Rare events – 5% AEP and 1% AEP
- Very rare events – 1 in 200 AEP and 1 in 500 AEP
- Extreme event – Probable Maximum Flood (PMF).

The terminology of these events is defined as per the ARR 2019 guidelines presented in **Figure 8.1**. All events (except the PMF) use spatial and temporal patterns provided by the ARR 2019 Data Hub. The PMF uses a combination of other temporal and areal patterns as described in the following section.

8.1.6 Probable Maximum Flood event

The Probable Maximum Flood (PMF) is the largest flood event resulting from the Probable Maximum Precipitation (PMP). The PMP rainfall depth has been estimated using the ARR 2019 guidelines.

The AEP of a PMP/PMF event ranges between 10^{-5} % and 10^{-7} % AEP for a catchment the size of Tuggerah Lakes, as shown in **Figure 8.3**. This extremely rare probability is beyond the "credible limit of extrapolation". That is, it is not possible to use rainfall depths determined for the more frequent events, discussed in **Section 8.1.5**, to extrapolate to the PMF.

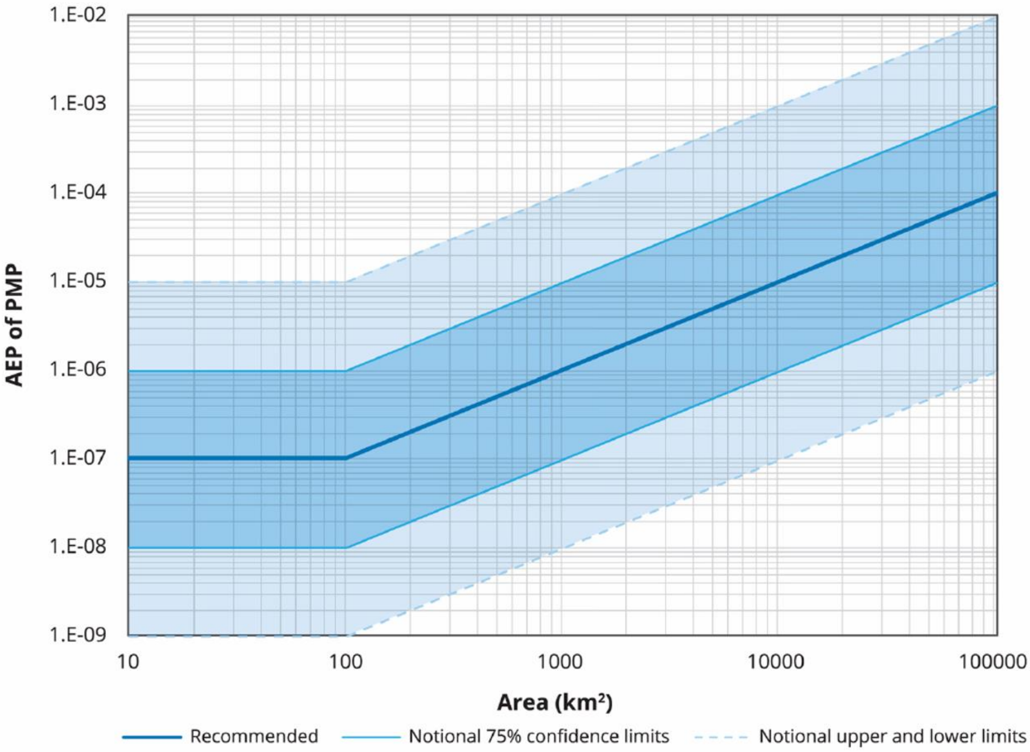


Figure 8.3 Recommended regional estimates for the AEP of PMP (Ball, 2019)

According to the PMP method zones diagram (Bureau of Meteorology, 2003), the Tuggerah Lakes catchment falls within the GSAM-GTSMR Coastal Transition Zone. Therefore, durations of up to 6-hours have been considered for the PMP in accordance with the Generalised Short

Duration Method (GSDM) derived by the Bureau of Meteorology (BoM) (Bureau of Meteorology, 2003) and durations of 24 hours or longer have been estimated using both the Generalised Southeast Australia Method (GSAM) (BoM, 2006) and the Generalised Tropical Storm Method (GTSMR) (BoM, 2005). Intermediary durations (i.e. 9 hr, 12 hr and 18 hr) have been estimated using all three methods and the maximum has been used for the PMF. A summary of the GSDM, GSAM and GTSMR results were provided in **Table 8.8**, **Table 8.9** and **Table 8.11**, respectively.

Table 8.1 GSDM summary for Tuggerah Lakes catchment

LOCATION INFORMATION					
Catchment Name:	Tuggerah Lakes		State:	NSW	
Duration Limit:	6.0 hrs	(3 – 6) hours	Area:	797.15 km^2	
Approx. Centroid	Easting		Northing		
Portion of Area Considered:					
Smooth, **S:**	0.00	(0.0 – 1.0)	Rough, **R:**	1.00	(0.0 – 1.0)
ELEVATION ADJUSTMENT FACTOR (EAF)					
Mean Elevation:	118 m	required if greater than 1500 m			
Adjustment for Elevation (- 0.05 per 300 m above 1500 m)			0.00		
EAF:	1.00	(0.85 – 1.00)			
GSDM MOISTURE ADJUSTMENT FACTOR (MAF)					
GSDM MAF:	0.72	(0.46 – 1.19)			

PMP Values (mm)

Duration (hours)	Initial Depth - Smooth (D_S)	Initial Depth - Rough (D_R)	PMP Estimate = (D_S×S+D_R×R)×MAF×EAF	Final PMP Estimate (from envelope)
0.25	-	110.52	80	80
0.5	-	163.86	118	120
0.75	-	211.32	152	150
1	-	254.18	183	180
1.5	-	339.68	245	240
2		399.79	288	290
2.5	-	447.22	322	320
3	-	484.48	349	350
4	-	549.84	396	400
5	-	585.94	422	420
6	-	623.66	449	450

Table 8.2 GSAM summary for Tuggerah Lakes catchment

LOCATION INFORMATION	
Catchment Name: Tuggerah Lakes	State: NSW
GSAM Zone: Coastal	Area: 797.15 km^2

CATCHMENT FACTORS			
Topographical Adjustment Factor	**TAF:** 1.46 (1.0 – 2.0)		
Annual Moisture Adjustment Factor	**MAF = EPW** $_{\text{seasonal catchment average}}$ **/ EPW** $_{\text{seasonal standard}}$		
Season	**EPW** $_{\text{seasonal catchment average}}$	**EPW** $_{\text{seasonal standard}}$	**MAF**
Summer (Annual)	74.44	80.80	0.92 (0.60 – 1.05)
Autumn	61.42	71.00	0.87 (0.56 – 0.91)

Summer PMP values (mm)			Autumn PMP values (mm)		
Duration (hours)	**Initial Depth (D_{summer})**	**PMP Estimate (D_s×TAF×MAF_s)**	**Duration (hours)**	**Initial Depth (D_{autumn})**	**PMP Estimate (D_a×TAF×MAF_a)**
24	665.12	893.71	**24**	495.88	625.64
36	750.56	1008.51	**36**	622.11	784.90
48	798.83	1073.37	**48**	738.39	931.61
72	858.86	1154.03	**72**	920.18	1160.97
96	909.05	1221.48	**96**	989.77	1248.77

Final GSAM PMP Estimates			
Duration (hours)	**Maximum of the Seasonal Depths**	**Preliminary PMP Estimate (nearest 10 mm)**	**Final PMP Estimate (from envelope)**
1	Where applicable, calculate GSDM depths (Bureau of Meteorology, 2003)	180	180
2		290	290
3		350	350
4		400	400
5		420	420
6		450	450
9	(no preliminary estimates available)		570
12	(no preliminary estimates available)		680
18	(no preliminary estimates available)		800
24	894	890	890
36	1009	1010	1010
48	1073	1070	1070
72	1161	1160	1160
96	1249	1250	1250

Table 8.3 GTSMR summary for Tuggerah Lakes catchment

LOCATION INFORMATION				
Catchment Name: Tuggerah Lakes			State: NSW	
GTSMR Zone: Coastal				
CATCHMENT FACTORS				
Topographical Adjustment Factor		**TAF:**	1.45	(1.0 – 2.0)
Decay Amplitude Factor		**DAF:**	0.80	(0.7 – 1.0)
Annual Moisture Adjustment Factor	$MAF_a = EPW_{catchment} / 120.00$			
$EPW_{catchment}$: 74.4		**MAF_a :**	0.62	(0.4 – 1.1)
Winter Moisture Adjustment Factor (where applicable)	$MAFw = EPW_{catchment\_winter} / 82.30$			
$EPW_{catchment-river}$: N/A		**MAF_w :**	N/A	(0.4 – 1.1)
PMP Values (mm) – Annual				
Duration (hours)	**Initial Depth (D_a)**	**PMP Estimate = D_a×TAF×DAF×MAF_a**	**Preliminary PMP Estimate (nearest 10 mm)**	**Final PMP Estimate (from envelope)**
1	Where applicable, calculate GSDM depths (Bureau of Meteorology, 2003)		180	180
2			290	290
3			350	350
4			400	400
5			420	420
6			450	450
9	(no preliminary estimates available)			570
12	(no preliminary estimates available)			670
18	(no preliminary estimates available)			810
24	1251.27	901.96	900	900
36	1489.82	1073.91	1070	1070
48	1713.40	1235.07	1240	1240
72	2105.41	1517.65	1520	1520
96	2373.03	1710.56	1710	1710
120	2502.93	1804.19	1800	1800

The temporal patterns used to derive the probable maximum flood (PMF) should be selected from an ensemble of patterns appropriate for use with the Probable Maximum Precipitation (PMP).

At present, the best source of ensemble temporal patterns for use with short duration PMF events are those derived by Jordan et al (2005) for durations up to 6 hours. The procedure to derive the design temporal patterns of the GSAM and GTSMR approaches for durations of 24 hours or longer uses the Average Variability Method of Pilgrim et al. (1969) (BoM, 2005, 2006). The GSDM, GSAM and GTSMR patterns were used for intermediary durations (i.e. 9 hr, 12 hr and 18 hr). The Jordan et al. (2005) patterns were derived specifically from storms associated with thunderstorm or deeply convective events while the GSDM, GSAM and GTSMR patterns are defined in the associated guidelines. The ellipse approach from the GSDM was applied to define the areal pattern for the shorter duration events.

These patterns were therefore adopted in this study and applied to the calculated PMP rainfall depth. The critical pattern was determined as per the typical ARR 2019 guidelines applied to the other design events.

8.1.7 Critical storm duration

For each design AEP event, 11 different durations were modelled ranging from 12 hours to 168 hours, except for the PMF which had twenty durations ranging from 15 minutes to 120 hours. Within each duration, 10 specific rainfall events were modelled (as recommended in ARR 2019) which varied the rainfall temporal pattern, though not the magnitude, over that period. This led to 110 individually modelled rainfall events per design event which were then analysed to pick the one event to use as design rainfall.

Critical durations were selected based on the methodology described in ARR 2019. This methodology consists of selecting, for each duration, the rainfall temporal pattern that is the closest to (and larger than) the mean flow obtained from the 10 specific patterns provided in the ARR 2019 database. This provides an automated approach that can then be adjusted for consistency in durations between the various events.

The location that was used to determine the critical duration of the Tuggerah Lakes was determined to be the outflow of the lakes to the ocean, which acted as a proxy for the water level in the lake. However, this location, and therefore the critical duration of the water level in the lakes, is dependent on the entrance configuration. Intuitively, a more constricted entrance would lead to longer critical durations, while a more open entrance state would result in shorter critical durations. A complication of this dependency is the fact that WBNM can only adequately model a static entrance state without the use of its weir scouring capabilities, which were deemed to be inappropriate to adequately represent the scouring mechanisms of the present study. This shortcoming is problematic, as the entrance state of the Tuggerah Lakes is inherently dynamic.

To resolve this, various static outflow rating curves were applied to the final lake catchment to perform a form of sensitivity analysis on the effect of entrance configuration on the critical duration of lake water levels. These rating curves were derived from the hydraulic model, ran using a variety of static entrance configurations, and displayed in **Figure 8.4**. While varying natural conditions led to some noise in these rating curves, the basic effect and behaviour of the entrance was considered adequately represented by the respective curves of best fit, as shown on the same plot as dotted lines.

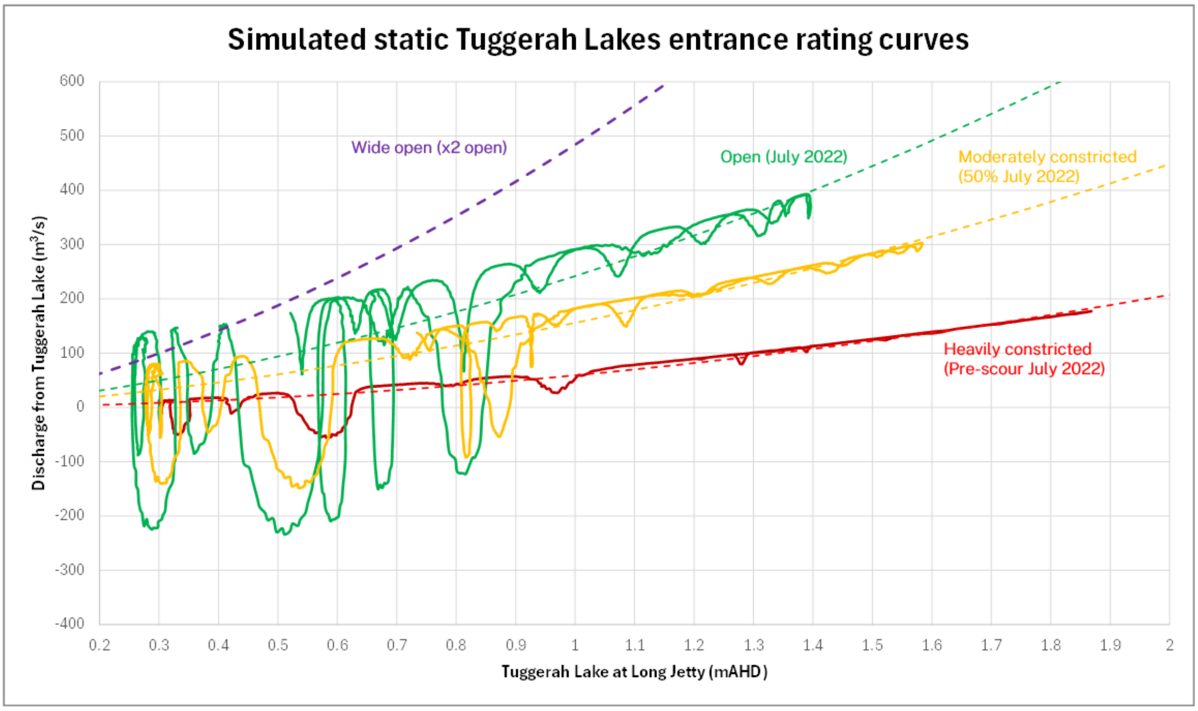


Figure 8.4 Simulated and adopted idealised static Tuggerah Lakes entrance rating curves

Using these representative static entrances in the hydrologic model, the extreme bounds of likely critical durations was defined, as summarised in **Table 8.4**. Durations within these extreme bounds were then taken forth for use in the hydraulic model, with a dynamic entrance configuration, to converge on the most appropriate critical duration. It is noted that the design storm for each AEP is the rainfall event which results in the median flow for the critical duration.

Table 8.4 Likely critical duration range limits from hydrological modelling (with static entrance configuration)

Event	Critical duration (hr) – static entrance configuration	
	Heavily constricted	Open
20% AEP	144	72
10% AEP	120	72
5% AEP	120	72
2% AEP	96	72
1% AEP	96	72
1 in 200 AEP	72	72
1 in 500 AEP	72	48
PMF	120	72

Figure 8.5 presents boxplots for the Tuggerah Lake outflows under the static heavily constricted and wide-open entrance conditions for the critical duration of the various design events. **Figure 8.6** shows boxplots for the Tuggerah Lake outflows under the static heavily constricted and wide-open entrance conditions for the 1% AEP event for all modelled durations, with **Figure 8.7** showing the accompanying hydrographs of all the temporal patterns for the respective critical duration.

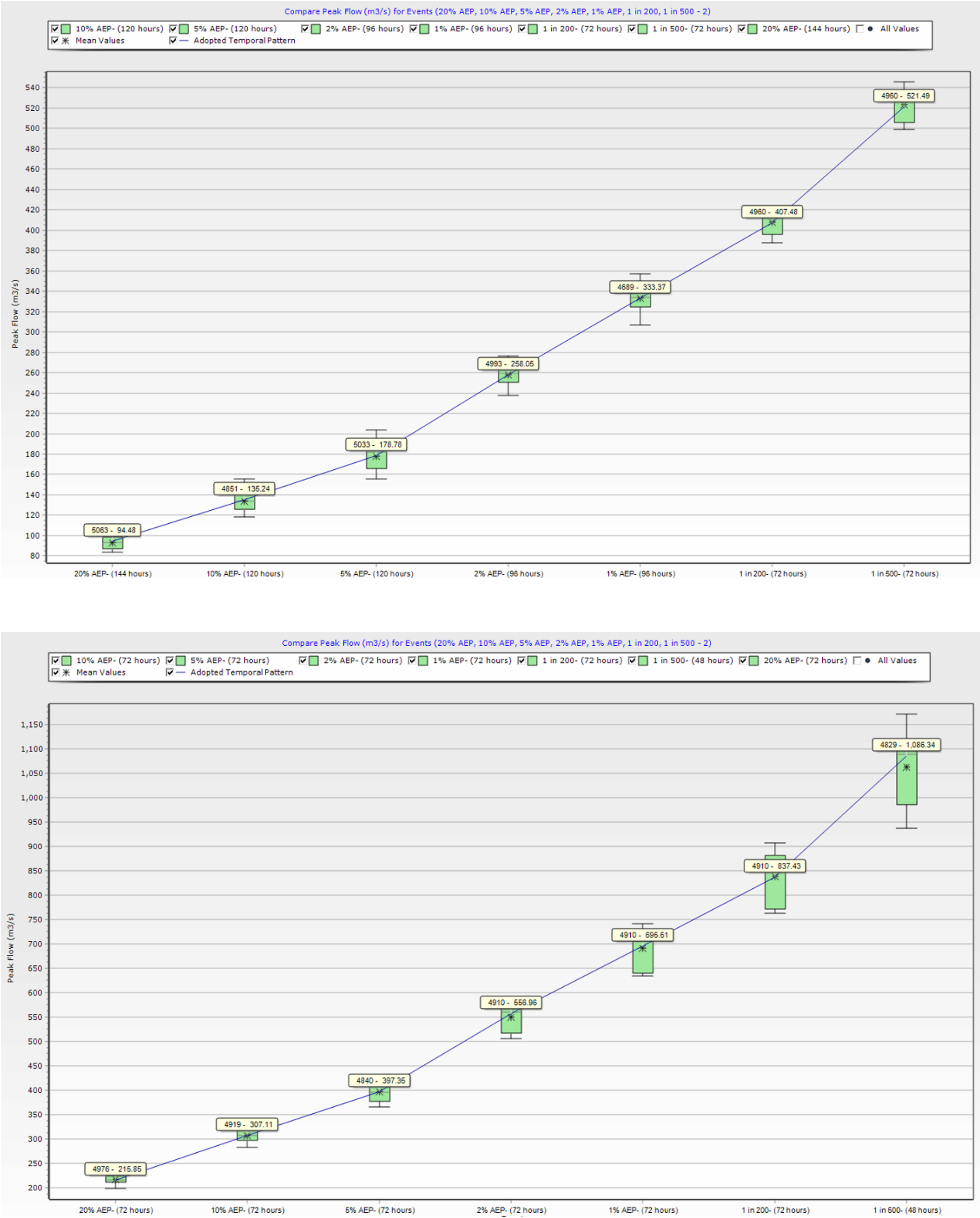


Figure 8.5 Heavily constricted (top) and open (bottom) peak entrance discharge for all IFD design events

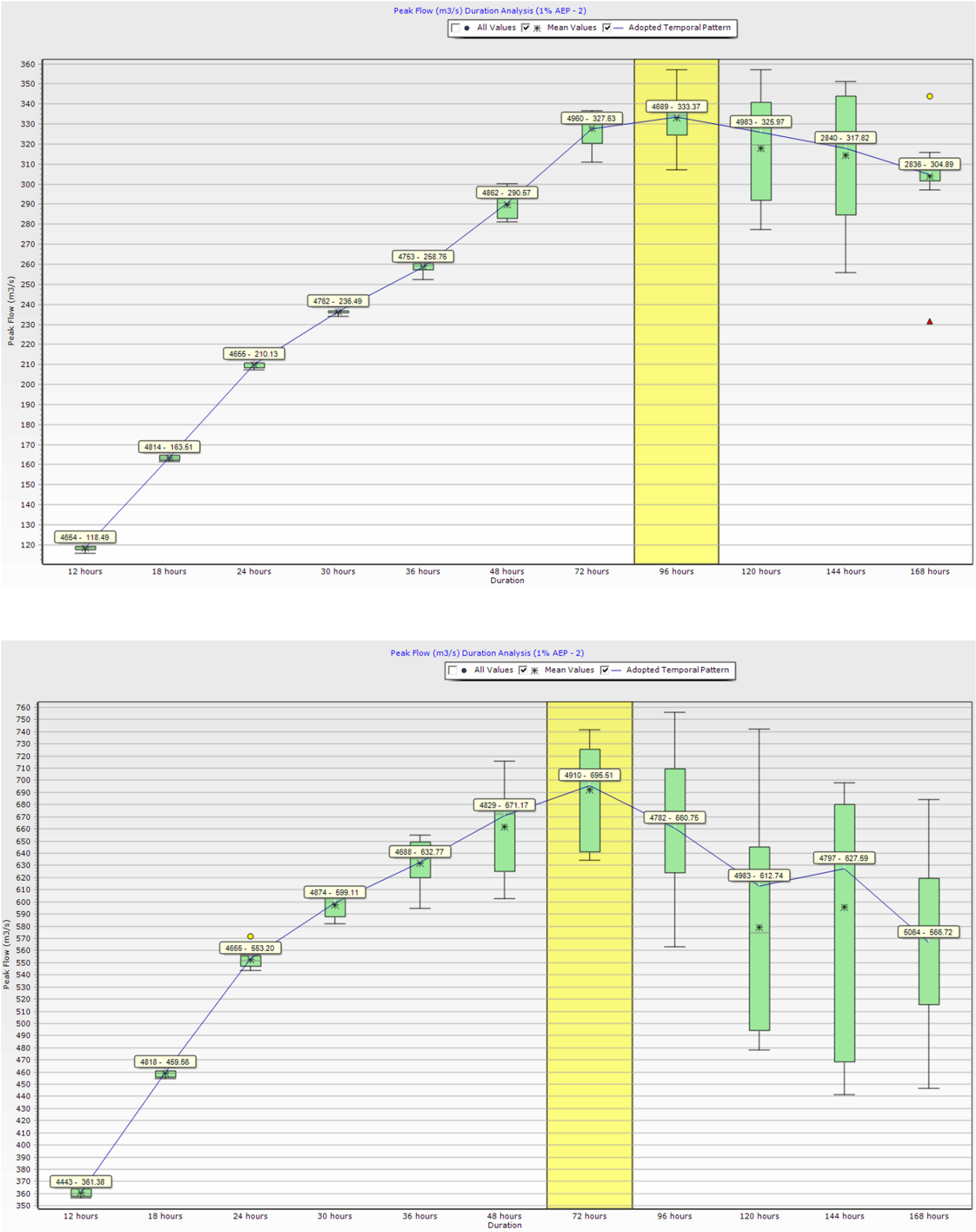
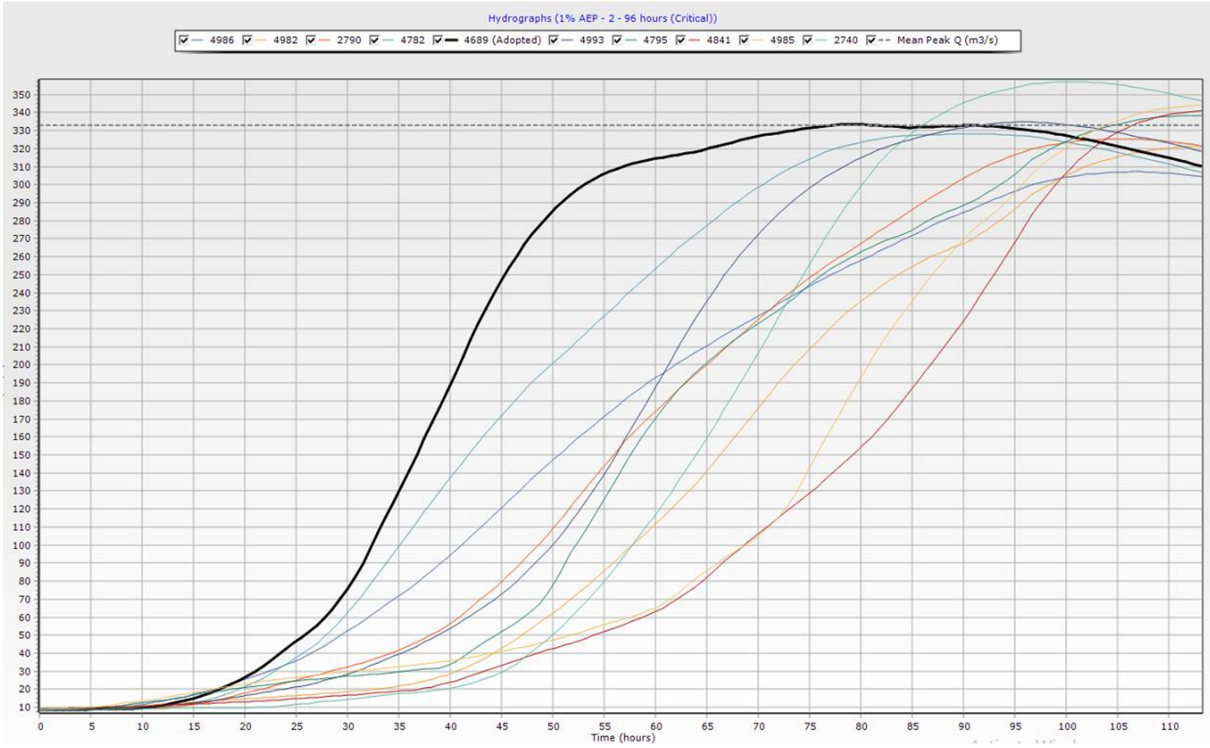


Figure 8.6 Heavily constricted (top) and open (bottom) critical duration analysis for the 1% AEP design event



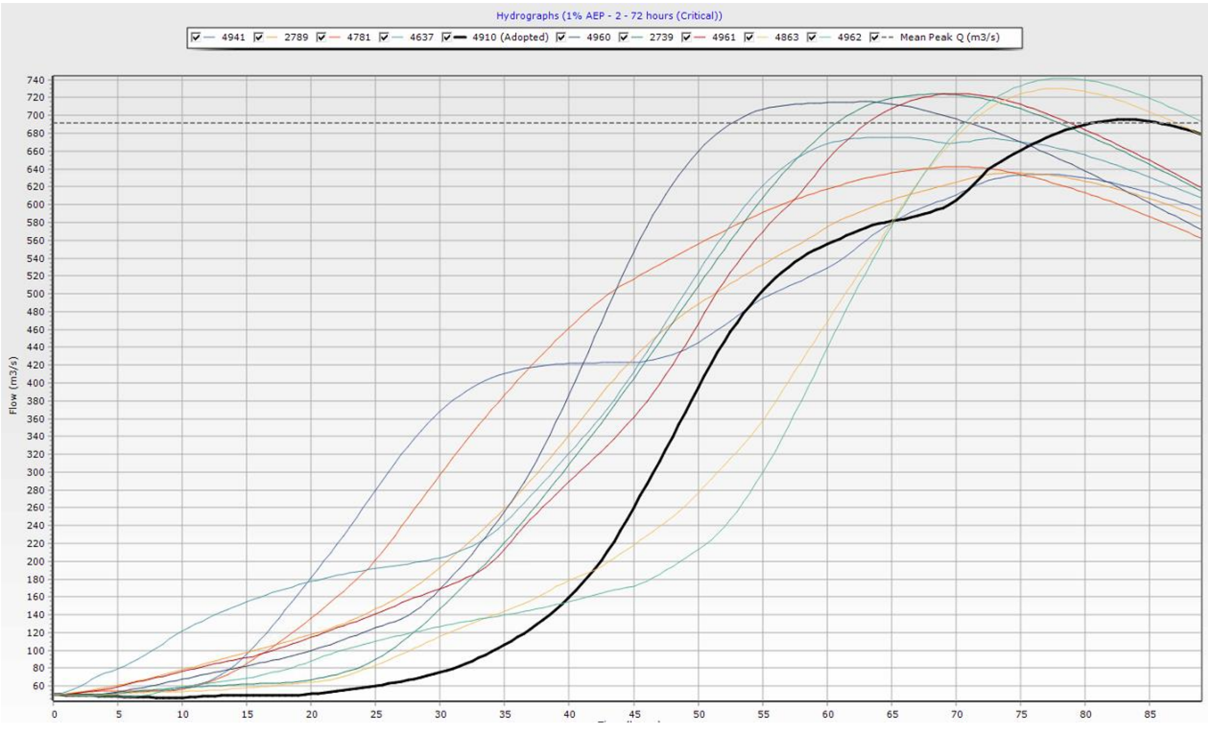


Figure 8.7 Heavily constricted (top) and open (bottom) temporal pattern hydrograph comparison for the critical duration 1% AEP design event

The selection of the ultimate critical duration under more realistic dynamic entrance conditions was based on sensitivity testing in the hydraulic model performed across the range of critical durations identified by the hydrologic model and is presented in **Table 8.4**. The adopted critical duration and the associated temporal pattern (from ARR 2019 Data Hub) for each event determined by this approach are presented in **Table 8.5**. As expected, critical durations are longer for smaller events, and shorter for larger events.

Table 8.5 Critical durations for each design event

Event	Adopted critical duration (hr)	Adopted temporal pattern (ARR 2019 Data Hub)
20% AEP	120	5041
10% AEP	120	4851
5% AEP	96	4643
2% AEP	96	4993
1% AEP	96	4689
1 in 200 AEP	72	4960
1 in 500 AEP	48	4829
PMF	72	GTSMR Coastal AVM

8.2 Entrance configuration and behaviour

The Tuggerah Lakes entrance channel is influenced by geomorphological changes due to regular tidal movements and episodic freshwater runoff from the catchment. The *Floodplain Risk Management Guide: Modelling the Interaction of Catchment Flooding and Oceanic Inundation in Coastal Waterways*, published by the former OEH in 2015, offers guidance on the modelling of these entrance morphology aspects.

The appropriate guidance from this document depends on the type of waterway entrance being assessed. According to the simplified waterway entrance classifications outlined in *Table 2.1* of this document, the Tuggerah Lakes catchment is identified as a Type C entrance, being an ICOLL.

The guidelines outline three broad modelling frameworks: simplistic, general, and detailed, each tailored to specific investigation purposes. Given the broad and important objectives of this flood study, a detailed approach was deemed most suitable, as any unnecessary conservatism from an unrealistic level of geomorphological constriction at the entrance would be unacceptable. Accordingly, an *unsteady state (dynamic) entrance conditions* approach was adopted, accurately simulating flood events. This approach allows for the representation of entrance behaviour across its likely dynamic range throughout flood events, effectively accommodating the impacts of varying shoaling and scouring effects. This approach is less conservative than using steady state entrance conditions but is more reflective of actual conditions that can be expected.

Within this approach, initial and final entrance geometry conditions were based on an understanding of non-flood entrance dynamics, physical limits (such as headlands, marine structures, rock shelfs, reefs, etc.) and historical data, especially with respect to the calibration and validation events. As part of this approach, multiple sensitivity simulations were also performed to capture the complexities of entrance behaviour.

The guidelines also observe that where entrances are managed, interventions under an entrance management policy are typically proposed to facilitate berm opening before a flood occurs or before the berm can contribute to elevated water levels in the waterway. In the case of Tuggerah Lakes, only an unadopted interim Entrance Management Procedure exists, serving only as a guide until formalised procedures are formally adopted. Consequently, it was determined that including the effects of any hypothetical interventions as the baseline case would be inappropriate at this stage. This acted to simplify the modelling by considering only natural processes. This decision reflects both the interim of Council's Entrance Management Procedure, and the practical limitations associated with implementing intervention during major flood events. In particular, Council may be unable to intervene due to constraints such as limited staff availability, restricted access to plant and equipment, or hazardous weather/berm conditions that prevent safe operation.

Further to this, and in line with the NSW Government's policy for managing ICOLLs, Council's current procedure is not necessarily aimed at maintaining an opening. Instead, it intends to allow the entrance to function as naturally as possible, with intervention only considered under specific conditions. This reflects the broader policy objective of preserving natural coastal processes and ecological values, while recognising the practical limitations of intervention during major flood events.

By excluding intervention from the design scenarios, the modelling reflects a more conservative condition in which the entrance evolves naturally, without human influence. This approach ensures that flood planning levels are robust under a range of operational limitations and aligns with the precautionary principles outlined in ARR 2019 and NSW flood risk management guidelines.

In any case, in determining design flood conditions, consideration is given to critical, but reasonable, entrance conditions and behaviour. Furthermore, an envelope of the highest computed water levels between the catchment and oceanic design flood scenarios is adopted to represent the maximum design flood conditions.

8.2.1 Catchment flooding

To determine the design conditions for the catchment flooding design event, it was first necessary to define an initial bed level in the entrance channel prior to the erosion induced by the flood. The pre-event configuration of the July 2022 event was adopted as initial channel conditions (see **Section 7.2.6**). The reasoning for this was that this configuration, with broad shoaling in the mid-channel and an approximate entrance throat width of approximately 50m at 0 mAHD, lies between the conceptualised definitions of the Moderately Constricted and Moderately Open entrance states, as defined in the Tuggerah Entrance Management Study, which were found to be the two most common states of the channel. Consequently, while the adopted channel conditions are not representative of the maximum possible degree of shoaling within the entrance as suggested by the guidelines, they do represent the most common configuration prior to the occurrence of a catchment flooding event, which was determined to be the most appropriate and relevant condition in this circumstance. This approach is also consistent with the 'detailed approach' framework, as outlined in the aforementioned 2015 guidelines. Sensitivity testing on the initial channel configuration was also performed to inform and quantify any uncertainty associated with the adopted approach. As a result of this reasoning, these conditions were adopted as the initial conditions for all design catchment flood simulations.

For smaller and more moderate return period flood events (up to the 5% AEP event), the entrance configuration used in the hydraulic model was based on the entrance behaviour observed during the model calibration events. This assumption was informed by the historical frequency of occurrence derived from long-term gauge data as part of the EVA (see **Chapter 5**), which indicates that entrance conditions similar to those observed in the representative calibration event is typical during events of this magnitude. By aligning the entrance configuration with historically representative conditions, the modelling approach ensures that the results reflect realistic and frequently observed entrance states for these event magnitudes. These smaller events are typically long in duration but spend only a brief period above the scour initiation threshold. Therefore, applying the final entrance configuration from the calibration events was considered a conservative yet practical representation for these scenarios.

In contrast, for extreme flood events exceeding the 5% AEP threshold, there were no direct observations or empirical data to inform an appropriate schematisation of entrance behaviour. Historical records indicate that large-scale lake flooding events of this magnitude occurred in the 1920s, 1940s, and 1964; however, detailed entrance condition data were not collected during these periods. Furthermore, there is no documented event in the historical record that clearly exceeds the approximate 1% AEP threshold, as determined by the extreme value analysis. As such, the modelling of entrance behaviour for these rare events necessarily relies on conceptual assumptions and extrapolation from more moderate events. This introduces a degree of uncertainty, which has been accounted for through conservative parameterisation and the application of a freeboard allowance in flood planning levels.

Consequently, a separate methodology was developed to estimate the extent of scour and the final entrance configuration for these larger events. This approach involved analysing the historical behaviour of the entrance in the wake of observed flood events. A volumetric analysis of tidal exchange through the entrance was conducted using observed lake water levels. Tidal exchange volumes were averaged over a 14-day period to account for variations due to the neap-spring tidal cycle, which could otherwise distort results from shorter sampling periods. These volumes were estimated by converting changes in lake level to volume using the hypsometric curve of the lake bathymetry. To ensure the reliability of this analysis, strict criteria were applied for the selection of appropriate reference events, namely that:

- the reference event exceeded at least 1.0 mAHD;
- the reference event featured a single distinct flood peak;
- the entrance was not significantly open prior to the reference event;
- the entrance position and morphology were generally representative of the design configuration;
- there were no significant inflows from tributary catchments during the tidal exchange sampling period; and
- no major artificial entrance modification or dredging occurred prior to the reference event.

Despite the usefulness of this method, some limitations were acknowledged, including that:

- a limited number of historical events met the selection criteria, reducing the sample size; and

- appropriate tidal exchange volume sampling periods were sometimes well after flood peaks, during which time entrance morphology could have changed due to wave activity or deposition, and as such, the entrance state used for the analysis may not accurately represent that which is relevant.

Noting the results of the EVA, the scour configuration resulting from the July 2022 baseline event was assumed to represent a typical 5% AEP event. Similarly, some of the events analysed as part of the tidal prism analysis were found to resemble a 20% AEP event. To connect observed and modelled entrance behaviours, the modelled entrance configurations representing these equivalent 5% AEP (July 2022) and 20% AEP (unscoured) events were subjected to a 14-day spring-neap tidal cycle without catchment inflows using the TUFLOW model. As shown in **Table 8.6**, the average daily net tidal exchange volumes simulated fairly matched those calculated from the suitable historical events, further validating the modelled entrance configurations for these return periods.

Table 8.6 Post-event entrance configuration quantification

Recurrence	Representative event	Average daily absolute tidal exchange (m^3)	
		Modelled	Observed
20% AEP	February 1992	7.81×10^6	8.16×10^6
	May 2001		7.34×10^6
	July 2011		7.68×10^6
5% AEP	July 2022	1.09×10^7	1.07×10^7

Next, a logarithmic equation relating the AEP of a given event to its effective final entrance width as represented by the design entrance configuration was derived using the effective entrance widths of the observed equivalent 20% and 5% AEP events and is exhibited in **Figure 8.8**.

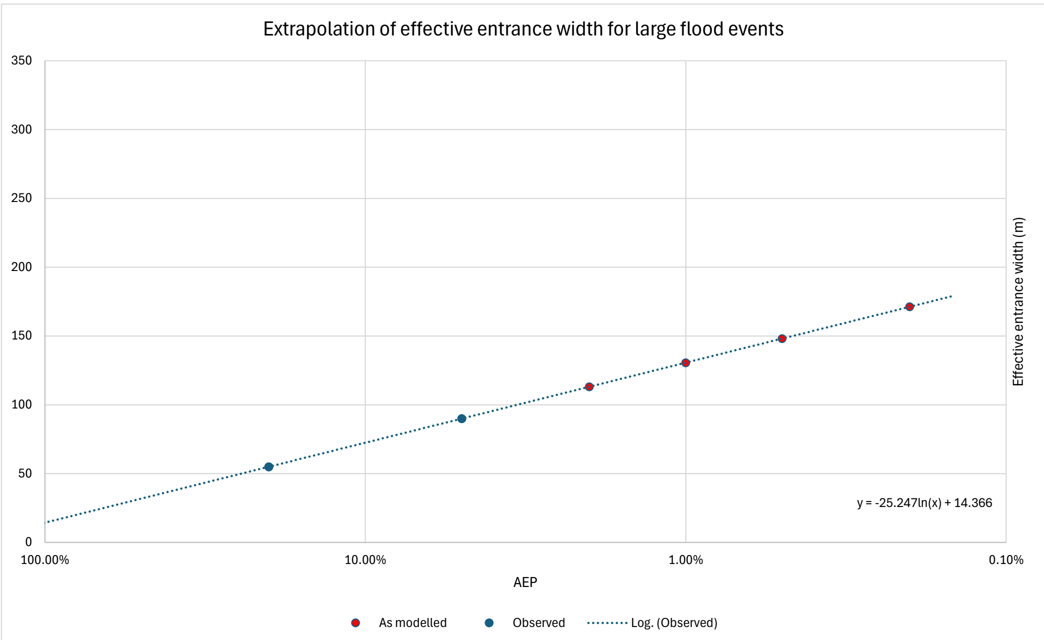


Figure 8.8 Extrapolation of effective entrance width for larger (< 5% AEP) flood events

This equation was then used to extrapolate the effective entrance width appropriate to be used for the larger events, with a summary of the adopted effective model entrance widths for these events exhibited in **Table 8.7**.

Table 8.7 Summary of scaling for larger event effective model entrance widths

Event	AEP	Effective model entrance width (at 0 mAHD)
20% AEP	0.20	55
5% AEP	0.05	90
2% AEP	0.02	113*
1% AEP	0.01	131*
1 in 200 AEP	0.005	148*
1 in 500 AEP	0.002	171*

*extrapolated (see **Figure 8.8**)

Finally, as the PMF lies beyond the reasonable limit of extrapolation using this approach, a maximum erosion configuration had to be determined for the PMF event. The maximum erosion configuration was the practical limit of erosion which could occur in a timeframe consistent with the duration of the most extreme flooding event in the lakes. Historical geotechnical data was provided by Central Coast Council on behalf of Transport for NSW showing the geotechnical character of the channel in the vicinity of The Entrance Bridge, an extract of which is exhibited in **Figure 8.9**.

By inspection of the data gathered as part of these bore tests, it could be concluded that the entrance channel consists of fine to coarse loose grey and white sands from the surface down to an average rectified depth of approximately 2-3 mAHD. This sand is then underlain with a similar but more compacted sand to depths ranging between 5-7 mAHD. Finally, below this, a stiffer clay layer appears to have been encountered.

It is noted that, while the entrance configuration adopted for design scenarios does not explicitly model the South Entrance Beach groyne structure, its influence on sediment transport and entrance morphology as detailed by Salients (2021-2025) is acknowledged. The groyne has been observed to affect entrance configuration under heavily constricted states; however, its impact is not expected to significantly influence flood behaviour during the moderate to rare events considered in this study, as entrance scour during such events dominates the hydraulic response. Furthermore, while this study includes sensitivity testing of entrance configurations, it does not constitute a detailed assessment of dredging impacts or long-term morphological changes. A dedicated morphologic or sediment transport study would be required to fully evaluate the implications of dredging on flood behaviour and estuarine processes, providing a more robust basis for future management decisions.

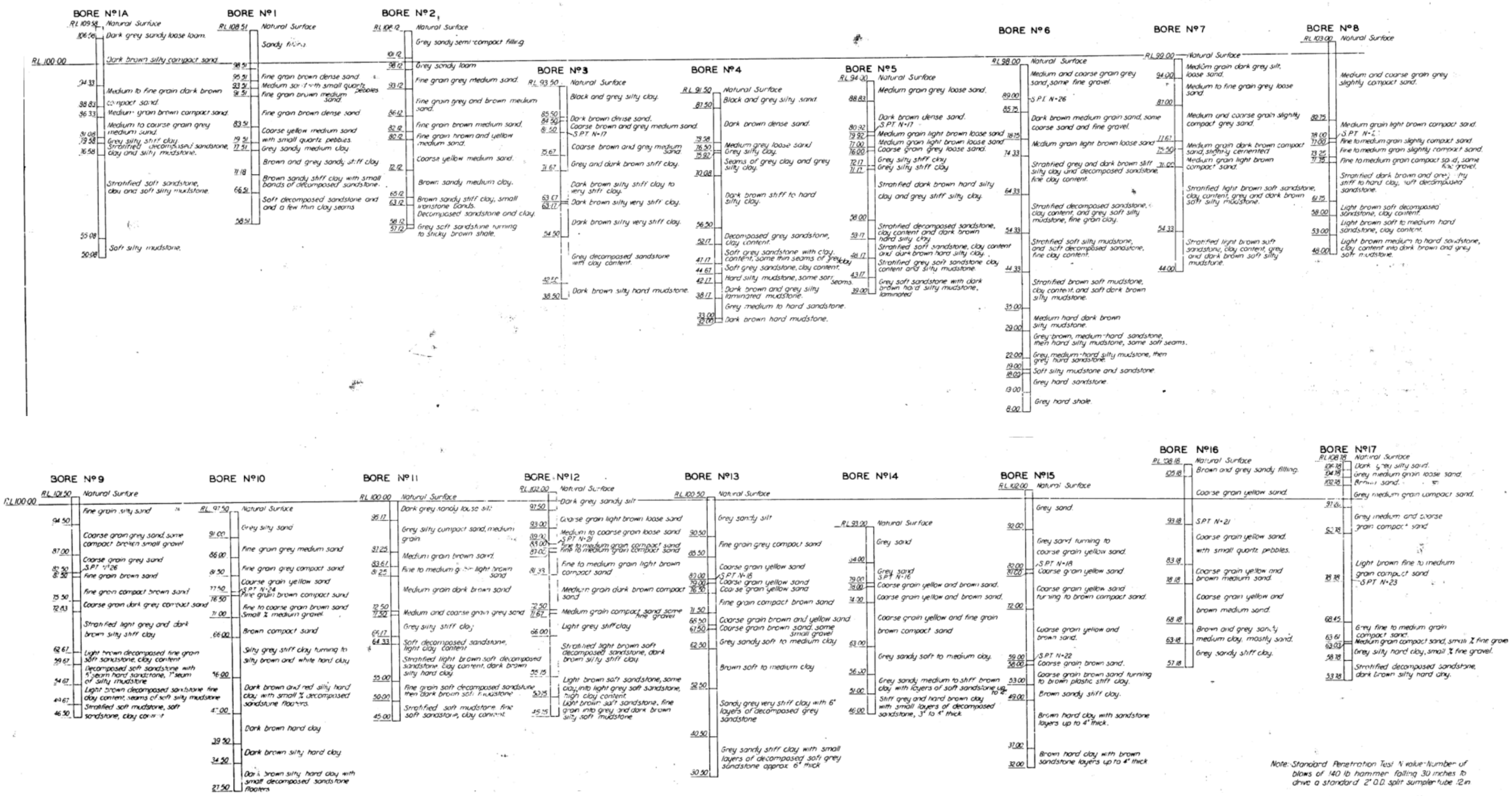


Figure 8.9 Geotechnical (bore hole) data as extracted from the engineering drawings for The Entrance Bridge (TfNSW, 1967)

As such, and consistent with previous dredging exercises, post-event survey data and other observations within the channel, it was considered that the first layer of relatively loose sands would easily shift in the moderate to rare flood events, while only in the largest event would disturb the underlying and more compacted sandy layers. Finally, it was considered a valid assumption that the underlying stuff clay layers would not significantly erode on the timescales of the PMF event.

Lastly, the regime by which the dynamic model evolved from the initial to the final state had to be defined. The trigger conditions for the entrance scouring processes were defined by reference to the lake level in the Tuggerah Lakes, and with reference to the findings of the calibration and validation processes (see **Section 7.2.6**) and the Tuggerah Lakes Entrance Management study, which found that an approximate level of 1.3 mAHD was critical in this respect.

An identical scouring approach and duration as adopted for the July 2022 baseline calibration event was deemed appropriate for use in the smaller design events. For events exceeding the 5% AEP threshold, the effective scour width became progressively wider. As such, and to address limitations of the scouring regime of the TUFLOW software, longitudinal scour zones were introduced which specifically defined the scour to occur as a progressive entrance widening, rather than a broad progressive lowering of bed levels. This additional measure enabled improved control over the spatial distribution of scour within the defined scour period.

Furthermore, for events larger than the 5% AEP, the scour duration was conceptually expected to be shorter due to the higher rate of scour associated with a larger head differential between the lake and the ocean. Consequently, the overall scour duration was shortened with respect to that of the calibration events to align more closely with the magnitude of larger events, with an adjustment to the scour finalisation duration to 30 hours determined to be appropriate for the 1% AEP event. This adjustment was primarily informed by scour duration sensitivity testing (see **Section 10.5.4**), an analysis of the hydrographs from the calibration and validation events, insights gained from the 2023 Lake Conjola Flood Summary Report model, and the EVA results. Additionally, for the 1% AEP event, the scour durations and final dimensions were found to be generally consistent with the approach adopted in the 1994 flood study.

Ultimately, the approach detailed above regarding the quantification and modelling of scour dynamics has embedded uncertainties. Consequently, conservatism was always favoured, with the EVA detailed in **Section 5** and the sensitivity analysis detailed in **Section 10** vitally important in quantifying these uncertainties, enabling a deeper understanding of the behaviour of the system, and ensuring the validity of the overall results garnered through this approach.

8.2.2 Ocean flooding

Sensitivity testing of the entrance configuration on the 1% AEP tailwater oceanic flooding was performed, comparing the base ocean flooding entrance condition (post-July 2022) to the pre-July 2022 and post-1% AEP catchment flood estimated entrance configurations, the results of which are presented in **Section 10.5.7**. A static, representatively 'open' entrance configuration used for the tidally driven flooding scenarios. The geometry of the entrance channel immediately after the July 2022 event, with an effective entrance width of 90 m, was adopted for this purpose (see **Section 7.2.6** for further details). This configuration was selected due to the availability of imagery and survey data, and since the entrance was categorised as being in the commonly occurring 'Moderately Open' configuration at that time.

8.3 Ocean tailwater

8.3.1 Catchment flooding

Similarly to the design entrance channel geometry, the *Floodplain Risk Management Guide: Modelling the Interaction of Catchment Flooding and Oceanic Inundation in Coastal Waterways*, published by the former OEH in 2015, offers guidance on the derivation of appropriate ocean water level boundary condition relevant to the entrance type and location for each design event. For this particular purpose, the guidelines again outline three broad modelling frameworks each tailored to specific investigation purposes.

In this case, the simplistic approach is based on a static and conservative elevated water level at the ocean boundary derived from a still water extreme value analysis performed on long-term data recorded at Fort Denison in Sydney. The guidelines note that tidal water levels increase from south to north along the NSW coastline, with Crowdy Head defined as the transition point for defining still water levels. The Tuggerah Lakes entrance lies south of Crowdy Head and thus falls into the southern zone for this purpose. A summary of peak design ocean water levels for the southern zone is exhibited in **Table 8.8**.

Table 8.8 Summary of peak design ocean water levels for various entrance categories (South of Crowdy Head)

Waterway entrance type	Peak design ocean water level (m AHD) South of Crowdy Head	
	1% AEP	5% AEP
A	1.45	1.40
B	2.00	1.90
C	2.55	2.35

This approach was considered too conservative in this case, and therefore the generalised approach was favoured. For this, the guidelines provide indicative time series of dynamic ocean water levels for adoption as oceanic tailwater boundary conditions. These time series have been based on observations of the hallmark May 1974 storm as recorded at Fort Denison in Sydney, factored slightly to peak at the design still water levels mentioned above. These time series for the various entrance configurations are shown for the HHWS(SS), 5% AEP and 1% AEP ocean tailwater conditions in **Figure 8.10**, **Figure 8.11**, and **Figure 8.12**, respectively.

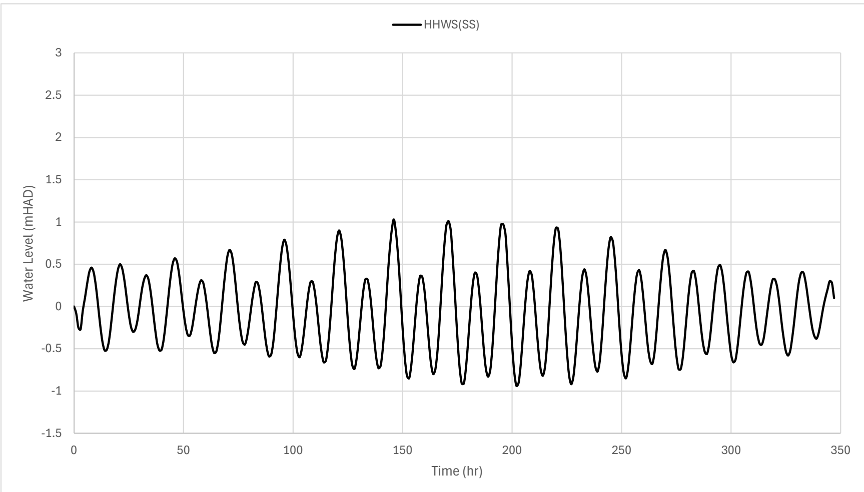


Figure 8.10 HHWS(SS) ocean water levels (South of Crowdy Head) (mAHD)

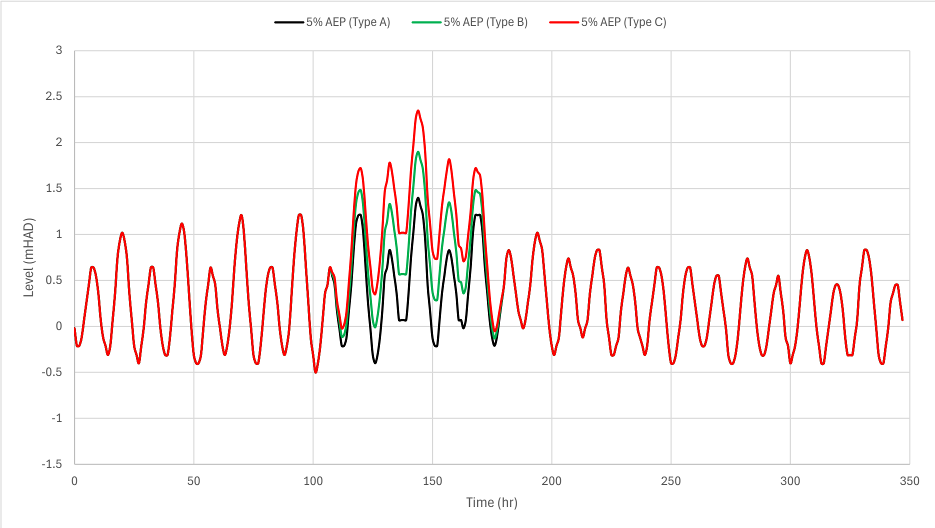


Figure 8.11 5% AEP ocean water levels for various entrance categories (South of Crowdy Head) (mAHD)

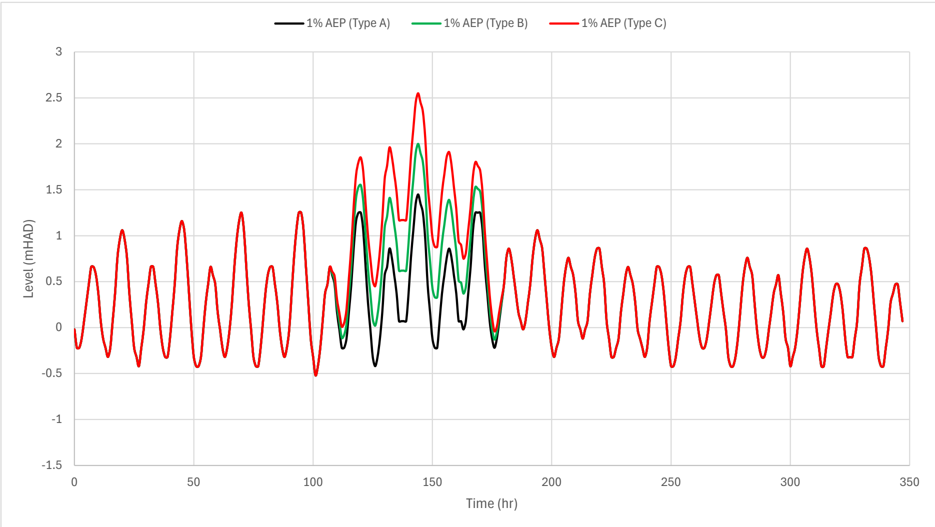


Figure 8.12 1% AEP ocean water levels for various entrance categories (South of Crowdy Head) (mAHD)

Although the Tuggerah Lakes system is classified as a Type C entrance per the 2015 OEH guidelines, the Type B tailwater approach was deemed more appropriate for this case. Several key factors make the Type B condition better suited to the Tuggerah Lakes. Notably, extreme wave setup, the primary driver of tailwater elevation above the Type A baseline, is less likely to occur in the Tuggerah Lakes compared to smaller ICOLL catchments. This is due to the relatively longer critical duration of the Tuggerah Lakes system. For a typical ICOLL with short critical duration, the wave setup may build up along the beach berm that may break quickly during the event and hence the flood water would be slowed down by this elevated ocean level. For an ICOLL with a long duration event such as Tuggerah Lakes, the berm will open over several hours or even days and hence the wave setup would dissipate while entering the lake prior to the lake level peak. Once the lake flood level peak would occur, the ocean would no longer be as elevated and a Type C entrance would therefore be largely conservative. As such, the Type B classification provides a more realistic representation of the tailwater conditions.

The Type B approach was also chosen for its conservatism, as compared to the detailed analysis performed as part of the 1994 study, including joint probability and wave setup modelling. That study estimated a 0.07 m wave setup in conjunction with 1% AEP design catchment runoff conditions, based on offshore waves with a significant height of 4.5 m, which was the most likely scenario deemed to coincide with events of this magnitude.

In conclusion, using the Type B tailwater condition better reflects the actual risks to the Tuggerah Lakes system, without assuming the worst-case wave setup of Type C conditions, while still being more conservative than previous detailed modelling and following the recommendations from the 2015 OEH guidelines. This balanced approach provides a more appropriate and realistic solution for the unique characteristics of the Tuggerah Lakes entrance.

The relevant combinations of catchment flooding and oceanic tailwater scenarios recommended in *Table 8.1* of the 2015 OEH guidelines are tabulated in **Table 8.9**.

Table 8.9 Recommended combinations of catchment flooding and oceanic inundation scenarios for various design AEPs

Design AEP	Catchment scenario	Ocean tailwater
20%	20% AEP	HHWS(SS)
10%	10% AEP	HHWS(SS)
5%	5% AEP	HHWS(SS)
2%	2% AEP	5% AEP
1% (Level)	5% AEP	1% AEP
	1% AEP	5% AEP
1% (Velocity)	1% AEP	ISLW
0.5%	0.5% AEP	1% AEP
0.2%	0.2% AEP	1% AEP
PMF	PMF	1% AEP

For each scenario, the peak of the catchment flooding in the lakes, independent from the oceanic tailwater, was ensured to coincide with the peak of the respective oceanic tailwater condition.

8.3.2 Ocean flooding

The non-flood, ocean-driven flooding scenarios exhibited in **Table 8.10** were also analysed to assess the impact of elevated ocean levels on the entrance under various conditions. The purpose of this exercise was to examine how changes in oceanic tailwater during higher tidal or storm surge events, would affect the lake water levels, even in the absence of catchment-induced flooding conditions. As there was no probabilistic constraint to align the presence of any potential wave setup with the catchment flooding scenario, and for conservatism, it was determined that the Type C setup was to be used for this analysis. This is despite the fact that it is likely that, for the reasoning outlined in **Section 8.3.1**, wave setup effects may be even more diminished in this scenario as a result of the comparatively wider entrance configuration.

Furthermore, the analysis assessed the baseline case for the present year (i.e., 2025, immediate planning horizon), 2040, 2070, and 2120, using the median values for the SSP2-4.5 climate change scenario (see **Section 8.5**), to understand the potential future impacts of climate-induced sea level rise on tidally-driven inundation over time.

Table 8.10 Oceanic inundation scenarios

Scenario	Catchment scenario	Sea level rise planning horizon	Oceanic tailwater
1	Non-flood	Present: 2025	MHWS
2			HHWS(SS)
3			5% AEP
4			1% AEP
5		20-year: SSP2-4.5 2040	MHWS
6			HHWS(SS)
7			5% AEP
8			1% AEP
9		50-year: SSP2-4.5 2070	MHWS
10			HHWS(SS)
11			5% AEP
12			1% AEP
13		100-year: SSP2-4.5 2120	MHWS
14			HHWS(SS)
15			5% AEP
16			1% AEP

8.4 Initial water level

For the dynamic modelling of estuaries, the initial water level in the waterway also needs to be established. In the case of ICOLLs, the 2015 OEH guidelines note that initial water levels are often independent of ocean levels, and as such that they can be determined using the following approaches:

1. Considering estuary management strategies, which often include a maximum water level in the ICOLL as a trigger for management response, such as berm opening.
2. Recorded water levels in the estuary, where sufficient record exists.
3. The maximum historic height of the berm, noting that this approach is likely to be conservative.

Owing to the significant history of record in the Tuggerah Lakes recorded at both Toukley and Long Jetty, the long-term median and most frequent water levels as recorded in the lake at these locations was first determined. The results of this process are shown in **Figure 8.13** and **Figure 8.14**, respectively and tabulated in **Table 8.11**.

With reference to these results, the guidelines and for simplicity, an initial lake water level of 0.36 mAHD was adopted for the base case design runs. Sensitivity testing regarding the effects of the initial lake water level on the 1% AEP event was performed and is presented in **Section 10.3**.

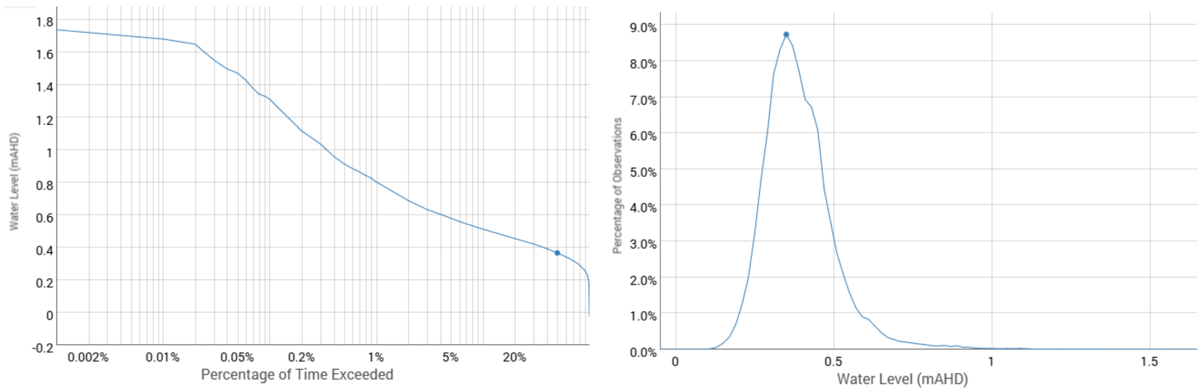


Figure 8.13 Tuggerah Lake water level exceedance curve and frequency distribution at Long Jetty (211418) (DCCEEW, 2025)

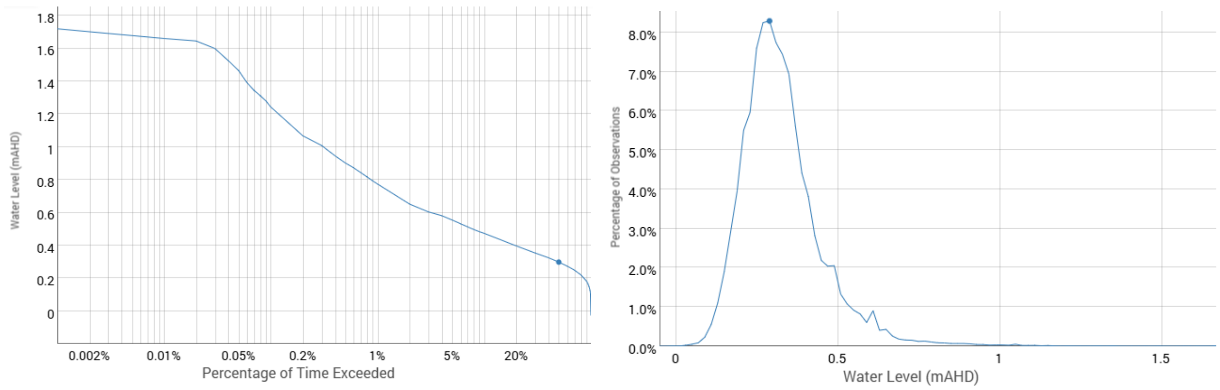


Figure 8.14 Tuggerah Lake water level exceedance curve and frequency distribution at Toukley (211418) (DCCEEW, 2025)

Table 8.11 Tuggerah Lake long-term median and most frequent water levels at Long Jetty (211418) and Toukley (211418)

Station	Water level (m AHD)	
	Median	Most frequent
Long Jetty 211418	0.366	0.35
Toukley 211401	0.299	0.29

8.5 Climate change

An account of the impacts of climate change and its consequent impacts on climate-related factors, such as rainfall, runoff patterns, and sea level rise, is crucial in any contemporary flood risk assessment. Changes in extreme rainfall are likely to represent the primary mechanism for increases in flood risk across most Australian catchments. This section details the revised design rainfall estimates as well as temporal patterns, loss parameters, and sea level rises adopted to quantify the effects of climate change on the flooding behaviour of the Tuggerah Lakes over the next century. It is noted that the climate change analysis performed as part of this study predated the release of the revised Book 6 of ARR and the corresponding updates to the Flood Risk Management guidelines.

8.5.1 Planning horizons and climate projections

To perform an appropriate climate change assessment, the future years and climate change projection scenario of interest must first be established.

In terms of selecting appropriate future planning horizons for climate change purposes, reference was made to the Open Coast and Coastal Lagoons Coastal Hazard Assessment 2024 commissioned by Central Coast Council. This study assessed SLR for periods of 20, 50, and 100 years into the future from a reference time of 2020, namely in 2040, 2070, and 2120. To maintain consistency with this existing study, both the regular catchment flood study climate change assessment and oceanic inundation scenarios performed as part of this study were also performed using the same future years.

Shared Socioeconomic Pathways (SSPs) are a set of scenarios developed by the scientific community to explore different possible futures based on varying levels of socioeconomic development, population growth, and technological advancements. SSPs are used to examine the interactions between climate change and societal factors, helping researchers assess the potential impacts of climate change under different global development pathways. These scenarios are a key tool in climate modelling and help inform policy decisions aimed at reducing climate risks and preparing for future challenges. A summary of the key assumptions underlying each SSP is provided in **Table 8.12**.

Table 8.12 Summary of key assumptions underlying the SSP scenarios

SSP scenario	Description
SSP1-1.9	Holds warming to approximately 1.5°C above 1850-1900 in 2100 after slight overshoot (median) and implies net zero CO2 emissions around the middle of the century.
SSP1-2.6	Stays below 2.0°C warming relative to 1850-1900 (median) with implied net zero emissions in the second half of the century.
SSP2-4.5	Approximately in line with the upper end of aggregate Nationally Determined Contribution (NDC) emission levels by 2030. SR1.5 assessed temperature projections for NDCs to be between 2.7 and 3.4°C by 2100, corresponding to the upper half of projected warming under SSP2-4.5. New or updated NDCs by the end of 2020 did not significantly change the emissions projections up to 2030, although more countries adopted 2050 net zero targets in line with SSP1-1.9 or SSP1-2.6. The SSP2-4.5 scenario deviates mildly from a ‘no-additional- climate-policy’ reference scenario, resulting in a best-estimate warming around 2.7°C by the end of the 21st century relative to 1850-1900.
SSP3-7.0	A medium to high reference scenario resulting from no additional climate policy under the SSP3 socioeconomic development narrative. SSP3-7.0 has particularly high non-CO2 emissions, including high aerosols emissions.
SSP5-8.5	A high reference scenario with no additional climate policy. Emission levels as high as SSP5-8.5 are not obtained by Integrated Assessment Models (IAMs) under any of the SSPs other than the fossil fuelled SSP5 socioeconomic development pathway.

The relevant SSP scenario adopted as part of the Central Coast Council Draft Flood Policy is yet to be finalised, however the median value for SSP2-4.5 is favoured at this stage. Noting this, and at the directive of Council in the meantime, all modelling has assumed that the SSP2-4.5 scenario will be adopted. As summarised in ARR 2019 and shown in **Figure 8.15**, this scenario will see a continuation in the trend of rising temperatures since the baseline period

(1961-1990) beyond the end of the century, with projected temperature increases for the future years of interest summarised in **Table 8.14** in **Section 8.5.5**.

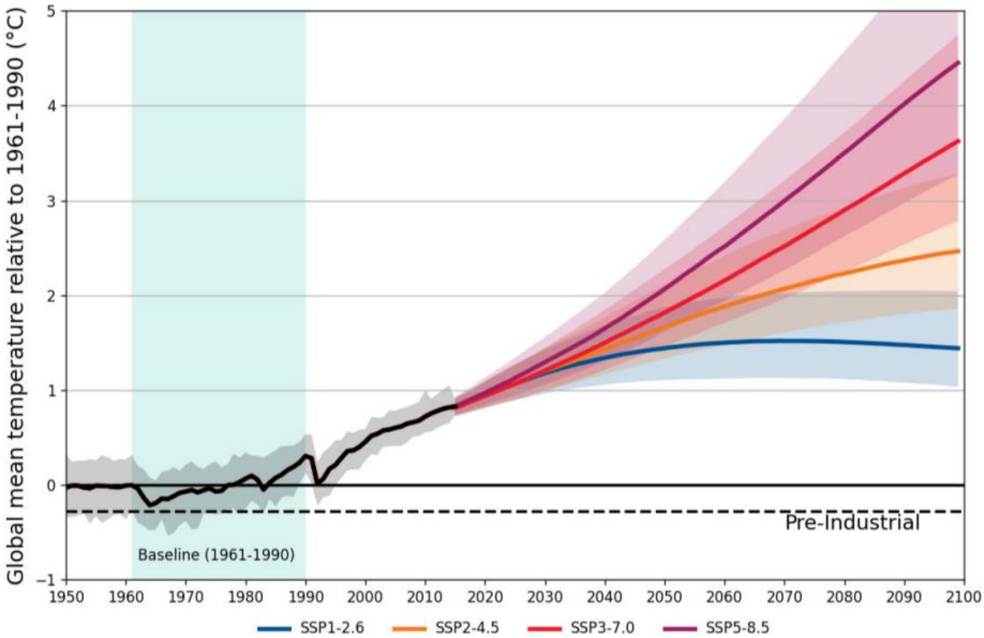


Figure 8.15 Projected temperature increases associated with AR6 socioeconomic pathways relative to 1961-1990 and their associated uncertainty (Ball, et al., 2019)

8.5.2 Rainfall and runoff

The IFD curves, and thus the relevant rainfall depths as provided by the ARR 2019 IFD portal, are based upon data largely collected during the baseline period. This is also the case for the initial losses and continuing losses. ARR 2019 recommends that these design rainfall depths, as well as estimates of the PMP and initial and continuing loss values, should be adjusted using the below equation:

$$I_p = I \times \left(1 + \frac{\alpha}{100}\right)^{\Delta T}$$

In this equation, I_P is the adjusted parameter, I is the original parameter, α is the relevant rate of change, and ΔT is the relevant temperature increase from the baseline period relating to the SSP and future year in question. **Table 8.13** presents the relevant rates of change for each relevant parameter that was used in this equation, as provided by ARR 2019, and the assumption underlying the adoption of each.

Table 8.13 Recommended rates of change (α) for rainfall depth, initial and continuing loss escalations associated with future climate change (Ball, et al., 2019)

Parameter	Rate of change *α* (% per °C)	Assumption
Rainfall	8.0	Central (median) estimate, >24hr duration
Initial loss	2.0	Central (median) estimate, East Coast South region
Continuing loss	3.8	

A summary of the calculated factors for the three abovementioned parameters is presented in

Table 8.14.

8.5.3 Temporal patterns

Currently there is no published methodology for quantifying the effect of changing temporal patterns on design flood estimates, nor published literature on the implications or their impacts on design flood estimates (Ball, et al., 2019). Although there is some evidence that climate change will influence spatial patterns of extreme rainfall, there are considerable uncertainties around such changes for localised regions (Ball, et al., 2019). As such, there is insufficient justification for amending spatial patterns or areal reduction factors in this case.

8.5.4 Sea level rise

Sea level rise is expected to have significant long-term implications on the flooding behaviour of the Tuggerah Lakes. According to the median confidence sea level rise projections under the SSP2-4.5 scenario, shown in **Figure 8.16**, sea levels are anticipated to increase steadily throughout the 21st century. As such, the oceanic tailwater conditions for each relevant future year were raised by this amount, with a summary of these levels provided in **Table 8.14**.

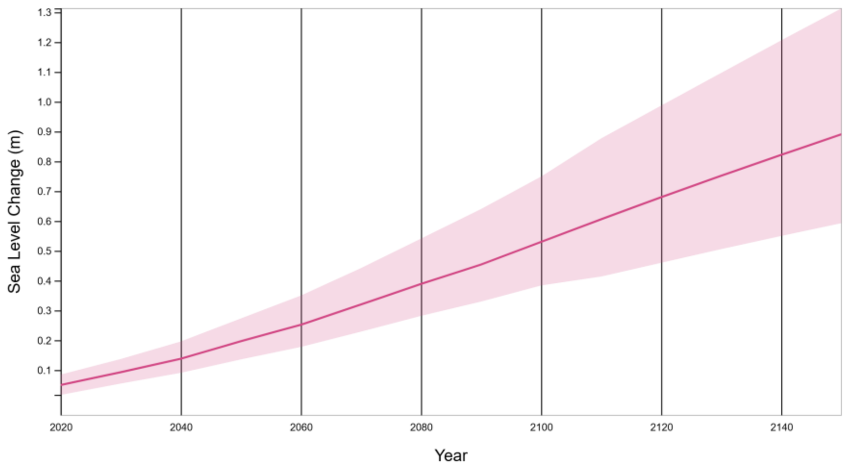


Figure 8.16 Projected sea level rise under the median confidence SSP2-4.5 scenario at Sydney (Fort Denison), with shaded uncertainty envelopes

8.5.5 Other factors

Sea level rise is anticipated to have other long-term impacts on factors that may affect the flooding behaviour of the Tuggerah Lakes. For example, an increase to the baseline sea level is anticipated to increase the average non-flood level of the Tuggerah Lakes and also increase the height to which the entrance berm is built over time due to elevated oceanic water levels and therefore sand deposition. It is noted that these processes are highly complex and therefore a precise quantification of the potential effects of sea level rise on these parameters is not presently feasible.

Nevertheless, and for simplicity, it was determined that a simple way to account for these effects would be to raise both the initial water level of the lake and initial berm heights directly by the relevant sea level rise increase, presented in **Table 8.14**. The raising of the berm level by this amount also resulted in an extension of the scour duration timing, to account for the additional sand volume anticipated to be required to be scoured during entrance opening.

8.5.6 Summary

Table 8.14 presents a summary of the modelled and calculated climate change factors for the relevant parameters relating to flooding in the Tuggerah Lakes, in accordance with ARR 2019 and the Central Coast Council Draft Flood Policy.

Table 8.14 Summary of projected temperatures and sea level rises, and rainfall and runoff loss increase factors associated with climate change in the relevant future years

Year	Rainfall and runoff				Sea level rise (m)
	Temperature change (°C)	Rainfall factor	Initial Loss factor	Continuing Loss factor	
2040	+1.4	1.11	1.03	1.05	+0.138
2070	+2.1	1.18	1.04	1.08	+0.320
2120	+2.7*	1.23	1.05	1.11	+0.680
Source	(ARR 2019, Section 6.4) (Ball, et al., 2019)				(NASA, IPCC, 2025)

*extrapolated, as ARR 2019 temperature increase projections do not go beyond 2100

9 Design flood results

9.1 Flood summary

9.1.1 Design floods and PMF

9.1.1.1 Present

The TUFLOW hydraulic model was run for eight (8) flood events including the 20%, 10%, 5%, 2%, 1%, 1 in 200 AEP, 1 in 500 AEP and PMF flood events. The results of these runs are presented in **Figure 9.1**, **Figure 9.2**, and **Table 9.1**, with respective flood mapping provided in **Appendix F**.

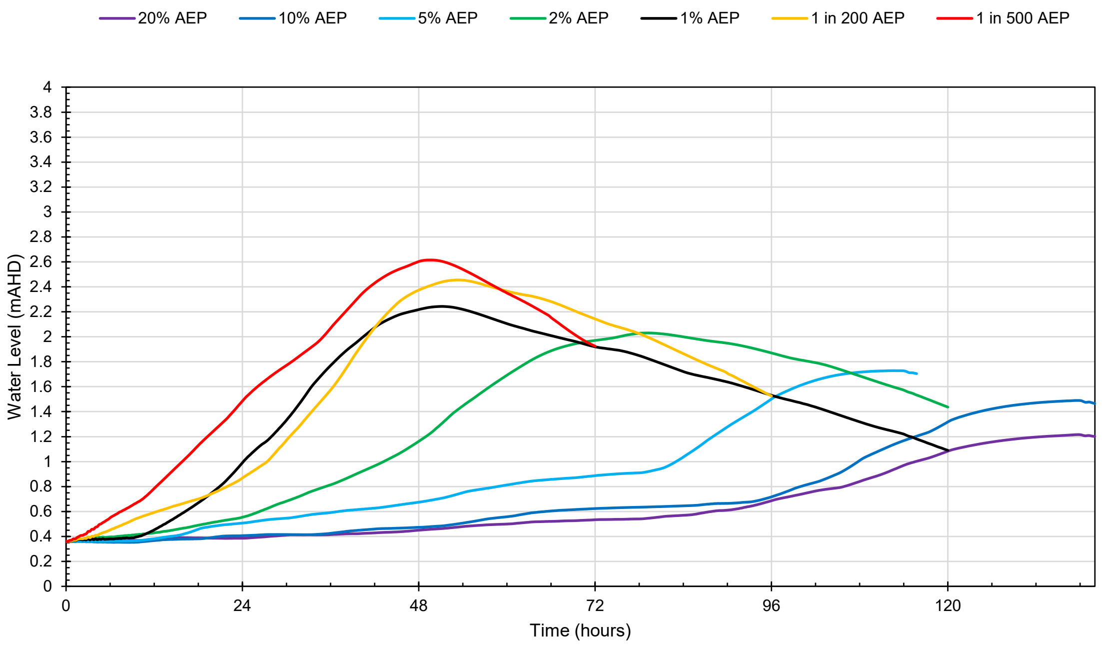


Figure 9.1 Tuggerah Lakes design hydrographs (20% AEP to 1 in 500 AEP)

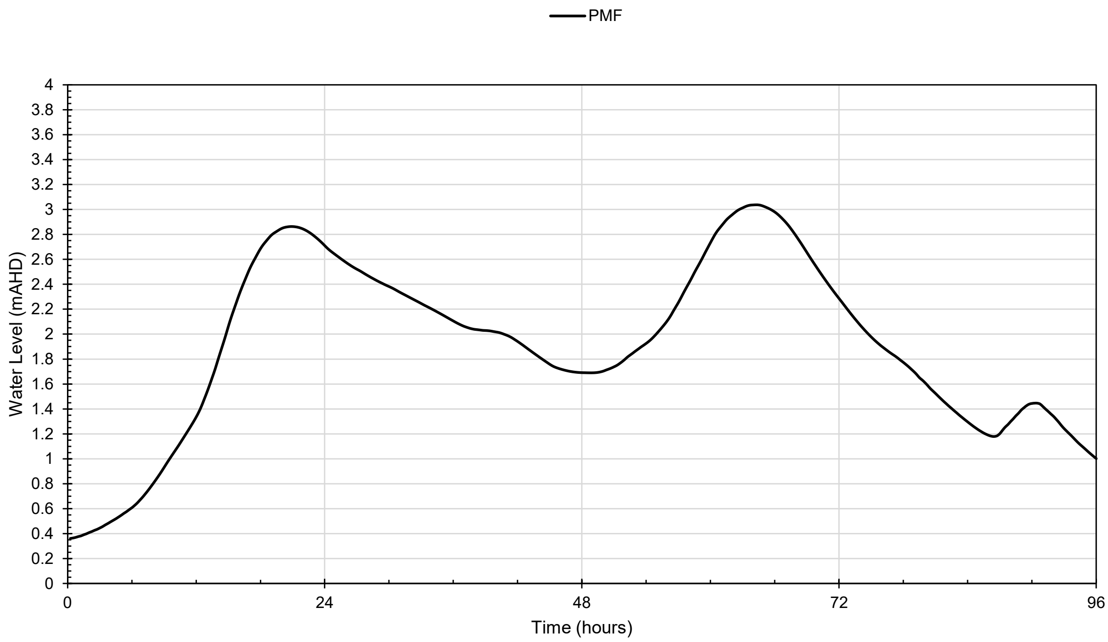


Figure 9.2 Tuggerah Lakes PMF design hydrograph

Classification: Public

Table 9.1 Tuggerah Lakes peak design level summary and comparison with previous study and EVA results

Event	Peak Tuggerah Lakes flood level (mAHD)				
	1994 study		Present study		
	Extreme Value Analysis	Hydrologic and hydraulic modelling	Annual Maximum Series Extreme Value Analysis	Peak-Over-Threshold Extreme Value Analysis	Hydrologic and hydraulic modelling
PMF		2.70			3.04
1 in 500 AEP			2.35 – 2.45		2.62
1 in 200 AEP			2.25 – 2.33		2.46
1% AEP	2.20	2.23	2.13 – 2.21		2.24
2% AEP			1.98 – 2.06		2.03
5% AEP	1.90	1.80	1.73 – 1.78		1.73
10% AEP			1.50 – 1.53	1.34	1.49
20% AEP	1.35	1.36		1.07	1.22
50% AEP	0.90	0.91		0.76	

Table 9.1 presents a comparison of peak flood levels at Tuggerah Lakes from the 1994 study, the updated EVA using both AMS and POT methods (see **Section 5**), and the hydrologic and hydraulic modelling undertaken in the present study.

The comparison reveals a nuanced pattern across the range of AEPs. For more frequent events (e.g. 20%, 10%, and 5% AEP), both the EVA and hydraulic modelling results from the present study show a noticeable reduction in peak flood levels compared to the 1994 study. This reduction is primarily attributed to the availability of approximately 30 additional years of continuous water level data, which has captured a broader range of moderate and minor flood events. These events were underrepresented in earlier datasets and have shifted the statistical distribution, resulting in lower central estimates for frequent recurrences.

The hydrologic and hydraulic modelling reflects this trend, as the updated rainfall inputs, refined loss modelling, and improved entrance representation produce more realistic runoff volumes and lake responses for these event magnitudes.

In contrast, for less frequent and extreme events, the present study generally reports higher peak flood levels than the 1994 study. This is particularly evident in the PMF scenario, where the modelled lake levels are significantly elevated. The increase is largely due to the incorporation of dynamic entrance scour behaviour, updated ARR 2019 rainfall inputs, modern modelling techniques and software, and more conservative assumptions regarding tailwater conditions and entrance blockage. These enhancements provide a more robust representation of lake response under extreme conditions, where entrance dynamics and ocean interactions play a dominant role.

Interestingly, the 1% AEP level from the 1994 study (2.23 mAHD) is closely aligned with the hydraulic modelling result of the present study (2.24 mAHD), while the EVA suggests a slightly lower range (2.13–2.21 mAHD).

Overall, the comparison highlights the evolution of flood level estimation over time, driven by improved data availability, updated design inputs, and more sophisticated modelling techniques. The hydrologic and hydraulic modelling results presented here are intended to supersede previous design levels and form the basis for future flood planning and development controls across the Tuggerah Lakes floodplain.

The comparison shows varying flood levels across the various AEPs, with the present study generally reporting higher peak flood levels than the 1994 study for events larger than the 2% AEP event, especially for more extreme events like the Probable Maximum Flood (PMF) and the 1 in 500 AEP, where the levels are significantly elevated.

9.1.1.2 Climate change (1% AEP)

The TUFLOW hydraulic model was run for three future climate change scenarios for the 1% AEP flood event as discussed in **Section 8.5**. The results of these runs are summarised in **Figure 9.8** and **Table 9.2**, with respective flood mapping provided in **Appendix F**.

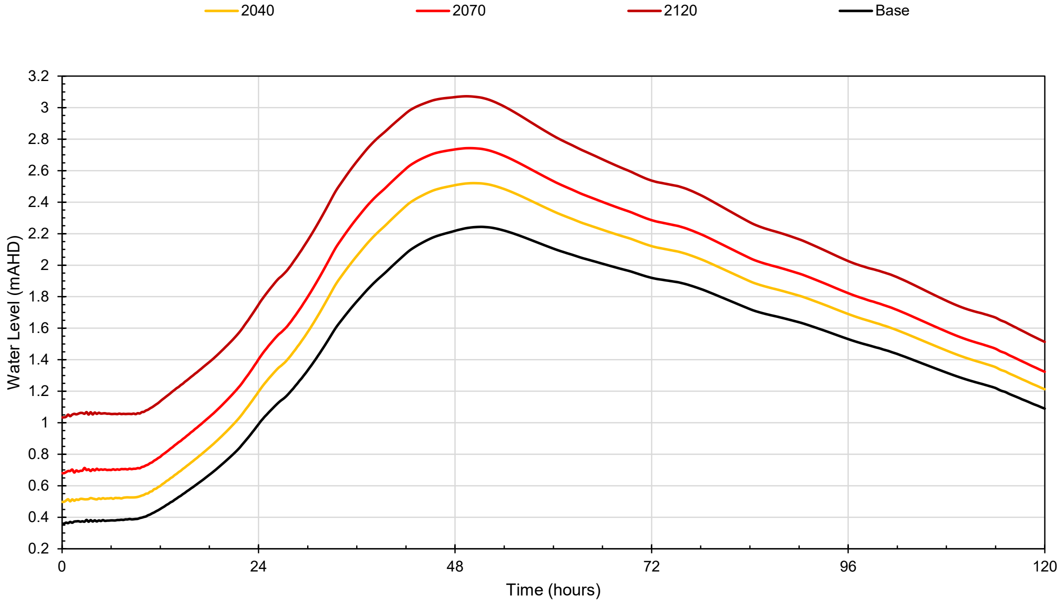


Figure 9.3 Tuggerah Lakes design hydrographs (1% AEP with future climate change)

Table 9.2 Tuggerah Lakes peak flood level summary (1% AEP future climate change)

Event	Peak Tuggerah Lakes flood level (mAHD)			
	Present	2040	2070	2120
1% AEP	2.24	2.52	2.74	3.07
Difference	0	+0.28	+0.50	+0.83

The climate change results shown above exhibit a general increase above the baseline, present-day case. These increases are to be expected as a combined result of the elevation of the tailwater levels associated with sea level rise, and the net increase in catchment runoff. It is worth noting that the 1% AEP may exceed the present day PMF level by 2120.

9.1.2 Ocean flooding

Results for the oceanic inundation scenarios in the present and future climate change scenarios are presented in **Figure 9.4** to **Figure 9.7**, and summarised in **Table 9.3**, with respective flood mapping provided in **Appendix F**.

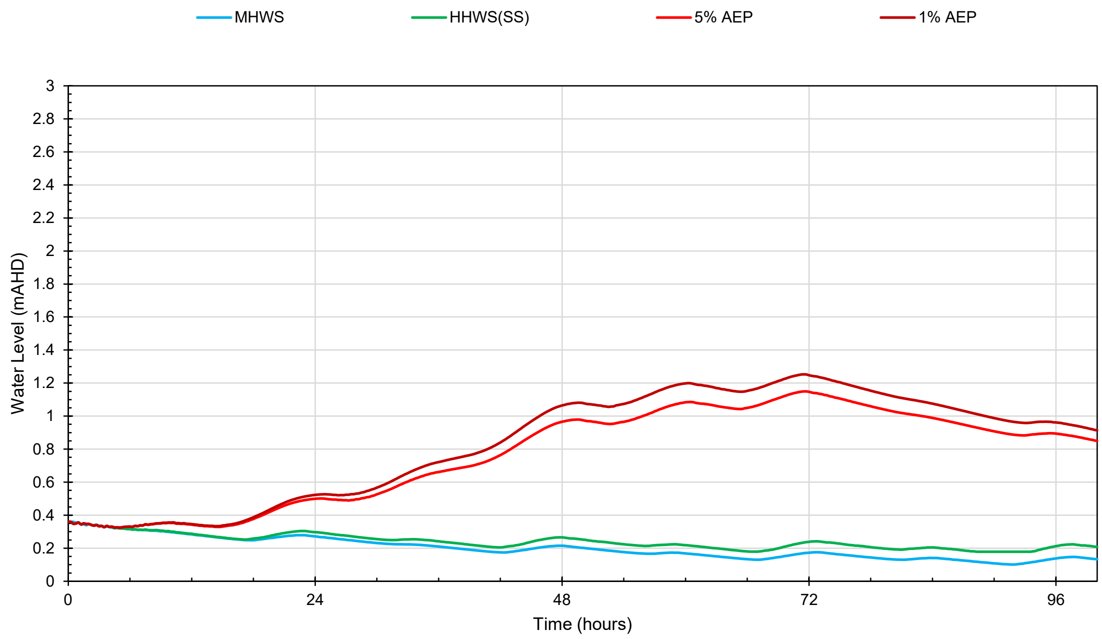


Figure 9.4 Tuggerah Lakes oceanic inundation hydrographs (present conditions)

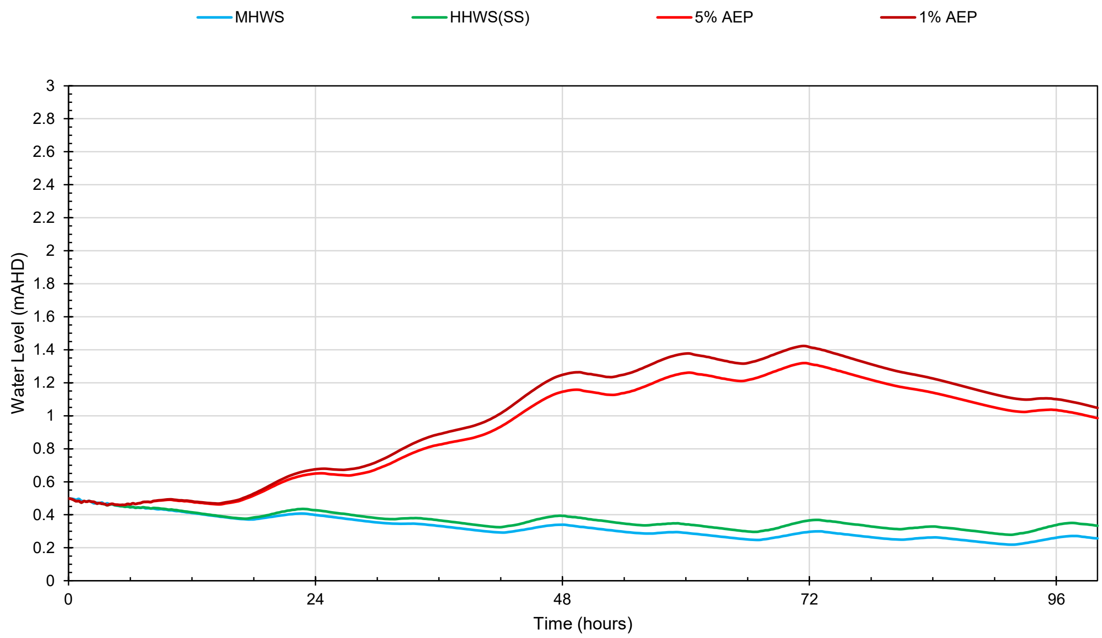


Figure 9.5 Tuggerah Lakes oceanic inundation hydrographs (2040 conditions)

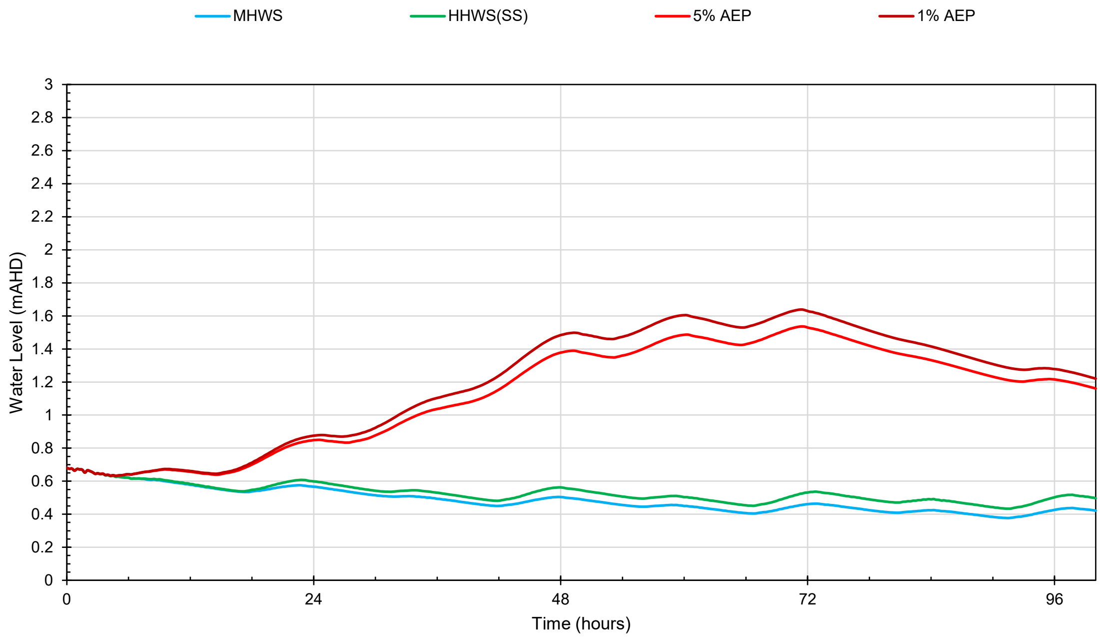


Figure 9.6 Tuggerah Lakes oceanic inundation hydrographs (2070 conditions)

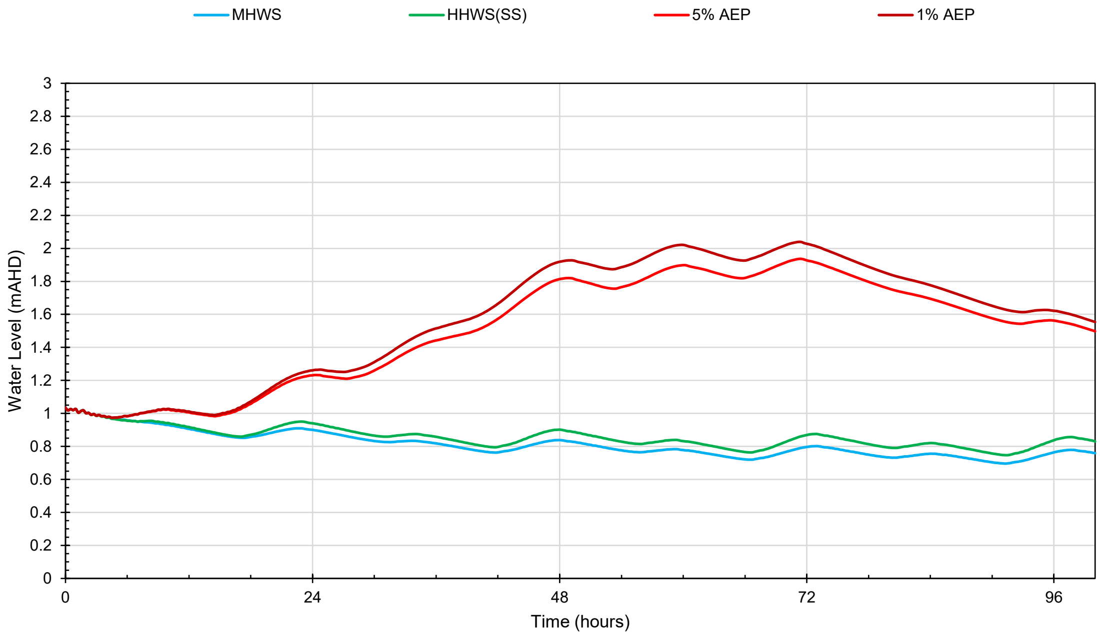


Figure 9.7 Tuggerah Lakes oceanic inundation hydrographs (2120 conditions)

Table 9.3 Tuggerah Lakes peak flood level summary (1% AEP future climate change)

No Flood Event	Peak Tuggerah Lakes flood level (mAHD)			
	Present	2040	2070	2120
MHWS	*	*	*	*
HHWS(SS)	*	*	*	*
5% AEP	1.15	1.32	1.54	1.94
1% AEP	1.25	1.42	1.64	2.04

*peak did not surpass initial lake water level

All oceanic inundation scenarios with the non-storm MHWS and HHWS(SS) tailwaters saw a tendency for the lake levels to fall from the initial lake water level. This may be since the long-term median lake level that was adopted as the baseline tailwater condition is likely resulting from an entrance configuration that is substantially more constricted than that adopted in these scenarios.

For the climate change scenarios, the results can be seen to uniformly rise in line with sea level rise. This is to be expected due to the relatively long duration of the elevated ocean water level events allowing flows to enter the lake at a similar rate across the future climate change scenarios. The shape of the response in water level during the respective climate change scenarios is nearly identical.

9.2 Flood mapping

9.2.1 Peak water levels and depths

Flood mapping presenting the peak flood level, depth and velocity of each event is provided in **Appendix F**. To maintain focus on lake-driven flood dynamics, mapping was capped to the maximum flood level observed within the lake body and reprojected onto the DEM to align extents with terrain.

To account for broader flood influences, these lake-based results were enveloped with outputs from adjoining tributary and overland flow studies where available. Where these studies indicated flooding beyond that driven by the lake alone, the affected areas were highlighted using hatched overlays referencing the relevant study. In cases where corresponding event data were unavailable, results from the next larger available event were used. The purpose of these overlays is to clearly identify transition zones where results determined in this study may not represent the worst-case scenario at that location for a given AEP, but rather the lake-driven component only.

In some instances, tributary or overland flood studies assumed or modelled higher tailwater levels in the lakes than those adopted in this study, resulting in their extents extending into the lake bodies. In these instances, the hatched overlay areas align with the respective model domains. Future planning will need to consider these transition zones carefully, as they represent areas where flooding may be influenced by both lake and tributary/overland sources.

Once the flood mapping was completed for these primary parameters, it became possible to determine the flood function, preliminary flood hazard and preliminary flood emergency response classifications resulting from these data. Development of such categorisations is described in subsequent sections.

9.2.2 Flood hazard

A starting point for the assessment of Flood Hazard categories is to better understand the flood hazard. The Flood Hazard (FB03) guideline of the Flood Risk Management Manual (2023) refers to the set of hazard vulnerability curves presented by the Australian Disaster Resilience Handbook, shown in **Figure 9.8**. This diagram shows how combinations of various flood depth and velocity conditions affect the stability of vehicles, pedestrians and buildings.

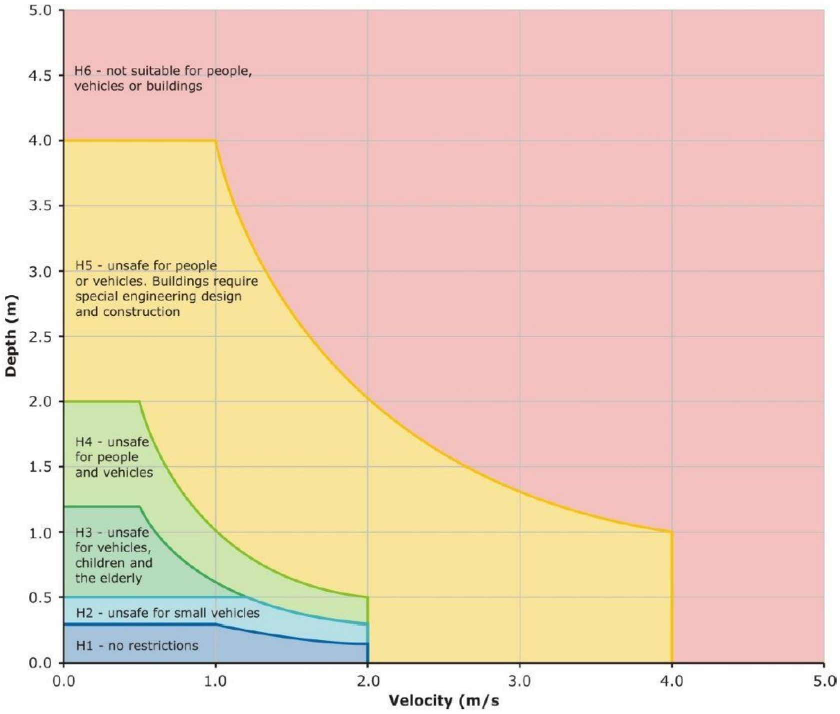


Figure 9.8 General flood hazard vulnerability curves (AIDR, 2017)

The above hazard vulnerability categories have been mapped for the 20%, 10%, 5%, 2%, 1%, 1 in 200 and 1 in 500 AEP and PMF events across the study area and are presented in **Appendix G**. It is noted that the mapping of flood hazard was focussed on flooding associated with the Tuggerah Lakes and areas solely affected by tributary catchment and overland flooding were not assessed.

It is noted that most of the areas affected by lake inundation have a very low to zero flow velocities, and as such their hazard categorisation is predominantly dependent on the depth of the floodwater. In other words, the hazard categorisation as defined in **Figure 9.8** can be simply defined through a reading of the y-axis alone. Key exceptions to this generality include the channels between the Tuggerah Lakes, the entrance channel, and tributary channels, where velocities are higher.

During a 1% AEP flood event, the extent of hazard conditions between H3 and H6 are typically concentrated within and along the Tuggerah Lakes, the entrance channel, tributaries and drainage channels, with most of the lake foreshore areas ranging from H4 to H1 as depths decrease. Pockets of note along the foreshore area affected by hazard categorisations that hinder access (>H2) include the low-lying areas around the Saltwater Creek in Killarney Vale, Chittaway Point, Tacoma South, Tuggerawong, and The Entrance North.

The PMF flood event sees the incursion of higher hazard ratings into those areas identified along the lake foreshore identified above, with the corresponding increase in depths resulting in a consummate increase in flood hazard and extent of affected areas. New areas of significant hazard include Budgewoi, Tuggerawong, Rocky Point, Killarney Vale and Tumbi Umbi.

9.2.3 Preliminary flood function

Flood function categorisation is a useful tool in assessing the suitability of land use and development in flood-prone areas. The Flood Function (FB02) guideline (2023) of the Flood Risk Management Manual describes the following three hydraulic categories of flood-prone land:

- **Floodway** – generally areas which convey a significant portion of water during floods and are particularly sensitive to changes that impact flow conveyance. They often align with naturally defined channels.
- **Flood Storage** – generally areas, outside of floodways, that store a significant proportion of the volume of water and where flood behaviour is sensitive to changes that impact on the storage of water during a flood.
- **Flood Fringe** – areas within the extent of flooding for the event but which are outside floodways and flood storage areas. Flood fringe areas are not sensitive to changes in either flow conveyance or storage.

These qualitative descriptions do not prescribe specific thresholds for determining the hydraulic categories in terms of model outputs, and such definitions may vary between floodplains depending on flood behaviour and associated impacts.

For the purposes of the Tuggerah Lakes Flood Study Review, hydraulic categories have been defined as per the criteria in **Table 9.4**. The floodway criterion has been selected as it provides satisfactory continuity of flow along the various key flow paths into, between and out of the Tuggerah Lakes.

To determine an appropriate depth threshold between areas to be designated as flood storage and flood fringe, further analysis was performed to quantify the storage loss and associated lake level rise at the 1% AEP flood level, for various flood storage/fringe depth thresholds.

A worst-case, and therefore conservative, scenario was assumed, being that all areas with depths of less than the chosen threshold (i.e., all flood fringe areas) were to be filled in and assessed the impact of this total volume of filling on the lake level.

This analysis yielded the relationship presented in **Figure 9.9**. The x-axis shows the flood storage to fringe depth threshold and the y-axis shows the associated increase in flood level above the 1% AEP level, in centimetres.

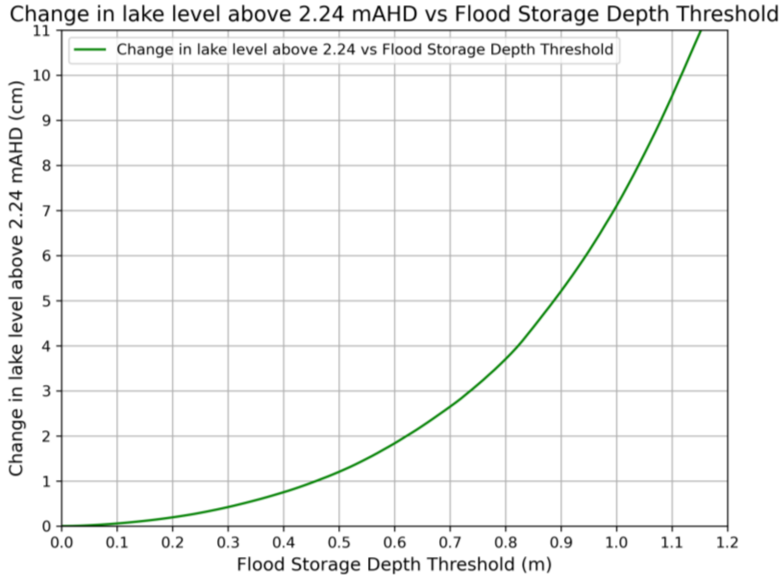


Figure 9.9 Increase in 1% AEP lake level for various flood fringe/storage depth thresholds

It was found that a depth threshold of 0.5 m would result in an approximate 1.3 cm rise in lake levels at the 1% AEP level (2.24 mAHD) and therefore is appropriate to use as a threshold.

Table 9.4 Flood function criteria

Flood function	Criteria	Description
Floodway	Velocity x Depth ≥ 0.25 m^2/s	Flow paths and channels where a significant proportion of flood flows are conveyed
Flood Storage	Depth ≥ 0.5 m Not Floodway	Areas that temporarily store floodwaters and attenuate flood flows
Flood Fringe	Depth ≤ 0.5 m, Not Floodway or Flood Storage	Generally shallow, low velocity areas within the floodplain that have little influence on flood behaviour

It is also noted that these criteria are generally similar to those used in various recent studies around NSW, including other similar catchments on the Central Coast such as the Coastal Lagoons Catchments Overland Flood Study.

Flood function mapping for the 1% AEP and PMF design events is presented in **Appendix H**. It is noted that the mapping of flood function was focussed on flooding associated with the Tuggerah Lakes and areas solely affected by tributary catchment and overland flooding were not assessed.

During a 1% AEP flood event, the floodways typically remain within the lakes, the channels between the lakes, the entrance channel, the main lake tributaries and drainage channels. The most significant exceptions to this include breakout areas along the Wyong River at Tuggerah Nature Reserve, and from Ourimbah Creek at Hanalei Avenue and Henry Street. Many properties along the lake foreshore are located within the flood storage area. Most of the inundated area behind Wilfred Barrett Drive in The Entrance North and in Budgewoi is classified as flood fringe, with some pockets of flood storage. In the case of The Entrance North, inundation during the 1% AEP event is primarily the result of overtopping of Wilfred Barrett Drive, which acts as a levee-like structure under flood conditions. The modelling assumes that the flood gates in this area remain closed during such events, and that the levee crest height is consistent with that in the adopted DEM. As such, the flood extent behind Wilfred Barrett Drive reflects the volume of water that overtops the road embankment, rather than backflow through the drainage system. This is based on an assumption that the inverted floodgates along Wilfred Barret Drive to prevent backflow through the drainage network remain closed and effective during design events. Most of the area fronting the lakes is classified as flood storage.

During a PMF event, the areas designated as floodway are much more substantial, with the majority of the lake bodies, lake channels and the entrance channel designated as floodway. Significant areas of floodway breakout areas are observed from the Wyong River and Ourimbah Creek, forming a broad, almost contiguous floodway area from these tributaries stretching from Tuggerawong to Berkeley Vale. Many properties along the lake foreshore are located within the flood storage area. Most of the inundated area behind Wilfred Barrett Drive in The Entrance North and in Budgewoi is classified as flood storage, with some pockets of flood fringe. Floodway areas are also noted along roadways in The Entrance North.

9.2.4 Preliminary flood emergency response classifications

To assist in the planning and implementation of response strategies, DCCEEW developed the support for emergency management planning guideline (EM01) to classify communities according to the ease of evacuation (DPE, 2023d). The guideline classifies communities as presented in **Figure 9.10**.

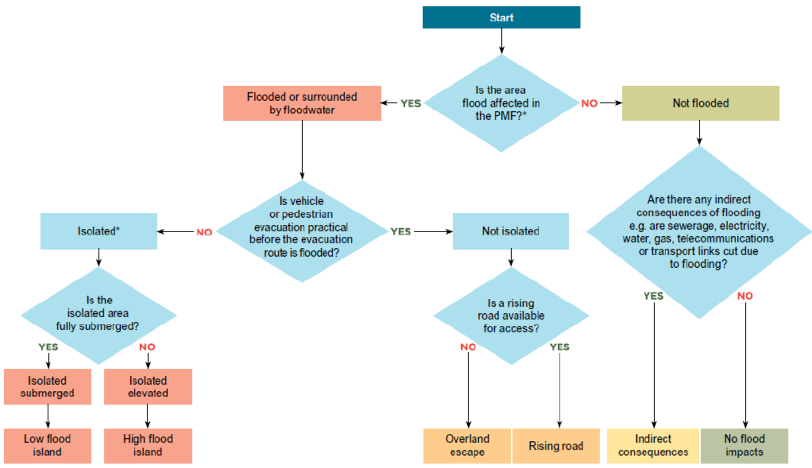


Figure 9.10 Flow chart for determining flood emergency response classifications (DPE, 2023d)

Flood Emergency Response Classifications (FERCs) can be based upon a variety of design events, in this case being the 20% AEP, 1% AEP and PMF event. Some consideration has been given to building locations on a block affected by flooding, but no consideration has been given to building styles. Isolated areas may also be known as flood islands, where areas are isolated solely by flood waters. Where flood islands are completely submerged in a particular event, these may be called low-flood islands. Where flood islands have elevated areas above the particular event, they may be called high-flood islands. Properties classified as high-flood islands (Isolated elevated) indicate that the buildings remain dry (no flood above the floor level);

however, access to the properties is cut off by flood water.

Mapping FERCs is to a degree a subjective exercise. Nevertheless, it serves to highlight areas most at risk in the event of severe flooding where people fail to evacuate early or shelter in houses is unsuitable for that purpose. For the purposes of this study, the FERCs were determined using the hazard mapping as discussed in **Section 9.2.2**. These results were geometrically compared computationally to assess whether a viable escape route was available either on foot (<=H2) or using a vehicle (H1). This process does not assess the practical viability or safety of these escape routes and solely determines the escape viability from the geometric properties of the hazard categorisation data. Subsequently, a manual process was undertaken to further categorise areas where practical road access may have been cut.

A further key assumption of the above approach was that during key flooding events, lake levels could rise from harmless to peak flood conditions in less than the typical 8–10-hour overnight sleep period. Consequently, individuals located in areas classified as low flood islands, typically due to their high peak hazard rating, could feasibly remain unaware of the escalating danger and be unable to evacuate without warning or intervention during the overnight sleep period. Therefore, these areas were conservatively retained within the low flood island classification. This exercise was completed for the 20% and 1% AEP, and the PMF, using the modelled flood results detailed above. The summary of the Flood Emergency Response Classification is presented in **Appendix I**. It is noted that the mapping of Emergency Response Classifications was focussed on flooding associated with the Tuggerah Lakes and areas solely affected by tributary catchment and overland flooding were not assessed.

10 Model sensitivity

Model sensitivity testing is an essential procedure in hydraulic modelling that evaluates how changes in input parameters influence model outputs. By altering key input factors, it becomes possible to identify and quantify the variables that have the most significant effect on the modelled results. This testing is vital for predicting system behaviour under varying conditions and for addressing risks linked to uncertainties in input data. Gaining insights into a model's sensitivity aids in decision-making and strengthens the overall reliability of hydraulic analyses.

Several factors were subjected to a sensitivity analysis prior to progressing with the design runs. These factors included:

- hydrological parameters, including:
    - losses: no losses and doubling the adopted design base case ARR 2019 losses;
    - catchment lag: ±10% from the adopted design base case WBNM catchment lag factor;
- roughness: ±20% from the adopted design base case roughness coefficient;
- initial lake water level: elevated (0.5 mAHD) and reduced (0.2 mAHD) from the adopted design base case (0.36 mAHD);
- tailwater level:
    - peak tailwater level: Type A, Type B and Type C waterway entrances (see **Section 8.3**);
    - timing of tailwater peak: ±6 hours from the adopted design base case peak tailwater timing, which was aligned with the catchment-driven peak
- entrance configuration and behaviour parameters, including:
    - initial berm level: +0.3m from the adopted design base case initial berm level, with corresponding scaling in the scour duration
    - initial channel width: ±20m from the adopted design base case initial channel width, with corresponding scaling in the scour duration
    - scour trigger: ±0.2m from the adopted design base case scour trigger lake level
    - scour duration: ±20 hours from the adopted design base case scour duration
    - final channel level: +0.5m and -1m from the adopted design base case scour trigger lake level
    - shoals and ebb channel configuration: a scenario with a pre-dredged channel

Sensitivity results are provided and discussed further in the following sections.

10.1 Hydrologic parameters

10.1.1 Rainfall losses

To analyse the influence of losses on the flood behaviour, the following scenarios were modelled:

- No loss scenario with neither continuing losses nor initial losses in the pervious areas for the 1% AEP flood event.
- Double the calibrated losses, with 2.0 mm/hr continuing losses and 116 mm initial losses in the pervious areas for the 1% AEP flood event.

An initial loss of 58 mm and continuing loss of 1.0 mm/hr were adopted for the baseline 1% AEP event. These scenarios were modelled for the adopted critical duration and temporal pattern under otherwise standard design conditions, with the results shown as compared to the baseline run in **Figure 10.1** and **Table 10.1**.

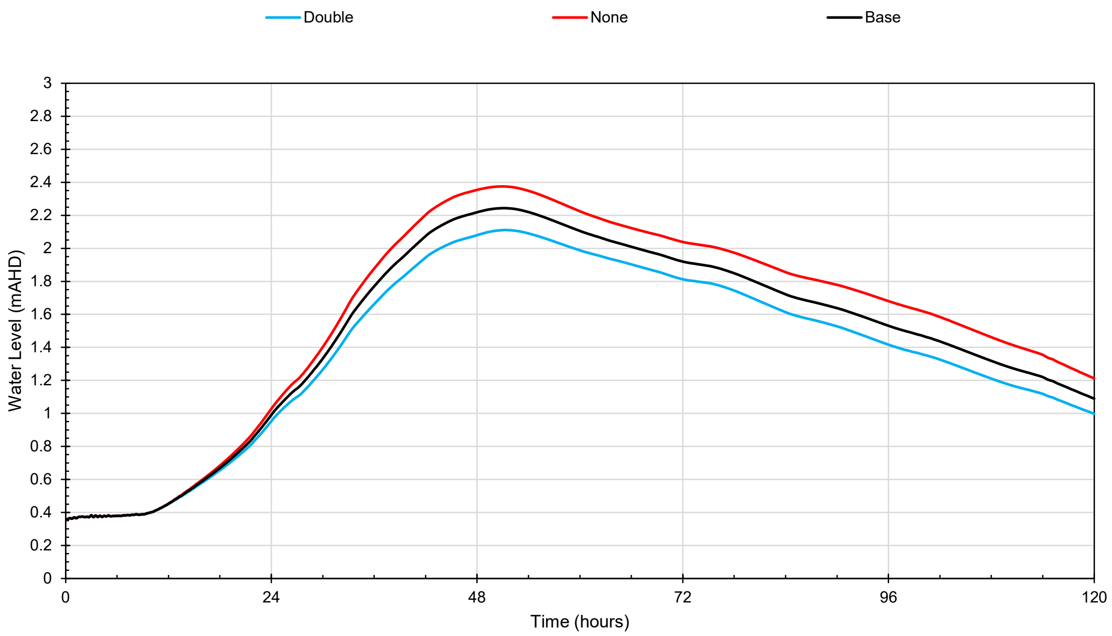


Figure 10.1 Rainfall loss sensitivity – Tuggerah Lakes water level

Table 10.1 Rainfall loss sensitivity – Tuggerah Lakes peak water level

<table>
<tr><th>Difference (m)</th><th colspan="3">Peak water level (mAHD)</th><th>Difference (m)</th></tr>
<tr><th colspan="2">Double rainfall losses</th><th>Baseline</th><th colspan="2">No rainfall losses</th></tr>
<tr><td>-0.13</td><td>2.11</td><td>2.24</td><td>2.38</td><td>+0.14</td></tr>
</table>

The results demonstrate that rainfall losses have a pronounced influence on peak lake levels. Removing losses entirely resulted in a peak increase of 0.14 m, while doubling the losses reduced the peak by 0.13 m. This range and symmetry of the response highlights a sensitivity to this parameter, given the slow-onset nature of lake flooding, where cumulative rainfall volume over extended durations drives inflows. These findings reinforce the importance of accurate loss parameterisation, particularly under future climate scenarios where antecedent moisture conditions may vary significantly.

10.1.2 Catchment lag

To analyse the influence of catchment lag on the flood behaviour, the following scenarios were modelled:

- 90% catchment lag scenario, with a WBNM C-factor of 1.44 for the 1% AEP flood event.
- 110% catchment lag scenario, with a WBNM C-factor of 1.76 for the 1% AEP flood event.

A WBNM C-factor of 1.60 was adopted for the baseline 1% AEP event. These scenarios were modelled for the adopted critical duration and temporal pattern under otherwise standard design conditions, with the results shown as compared to the baseline run in **Figure 10.2** and **Table 10.2.**

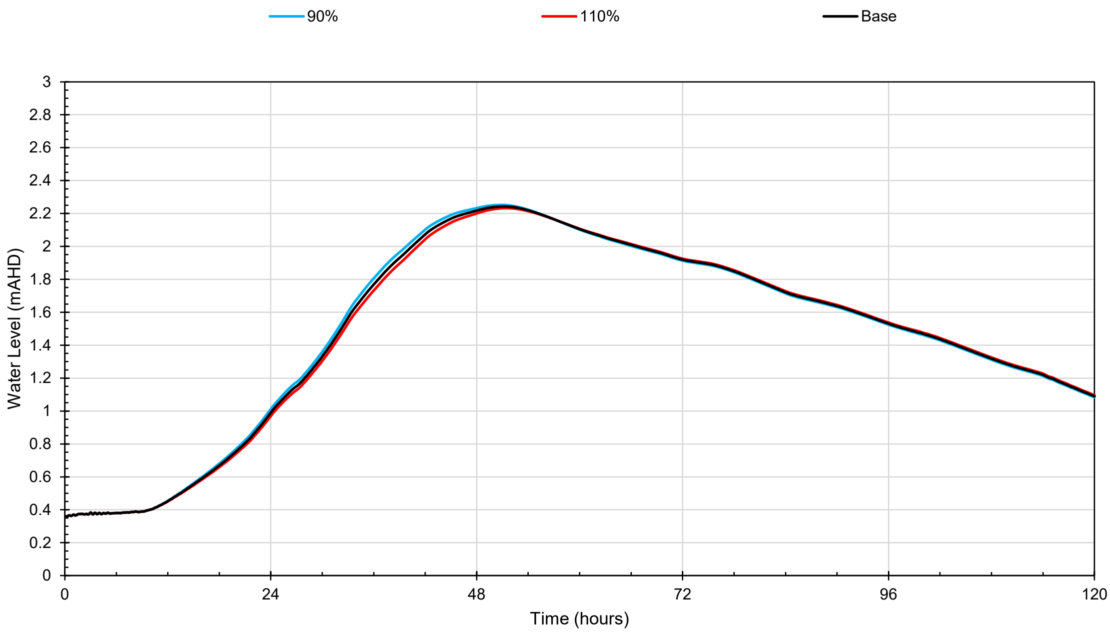


Figure 10.2 Catchment lag sensitivity – Tuggerah Lakes water level

Table 10.2 Catchment lag sensitivity – Tuggerah Lakes peak water level

Difference (m)	Peak water level (mAHD)			Difference (m)
90% catchment lag		Baseline	110% catchment lag	
+0.01	2.25	2.24	2.23	-0.01

Adjusting catchment lag by ±10% produced minimal changes in peak lake levels (±0.01 m), with the primary impact observed on the timing of the rising limb. This suggests that while lag influences the hydrograph shape, it does not materially affect the total volume entering the lake system. The insensitivity of peak levels to lag adjustments is consistent with the buffering capacity of the lake and its large catchments and the dominance of cumulative rainfall volume over shorter-term timing effects. This result supports the robustness of the adopted lag values and indicates that minor variations in lag estimation are unlikely to have a significant effect.

10.2 Roughness

To analyse the influence of material hydraulic roughness on the flood behaviour, the following scenarios were modelled:

- Low roughness scenario with roughness reduced by 20% for the 1% AEP flood event.
- High roughness scenario with roughness increased by 20% for the 1% AEP flood event.

These scenarios were modelled for the adopted critical duration and temporal pattern under otherwise standard design conditions, with the results shown as compared to the baseline run in **Figure 10.3** and **Table 10.3.**

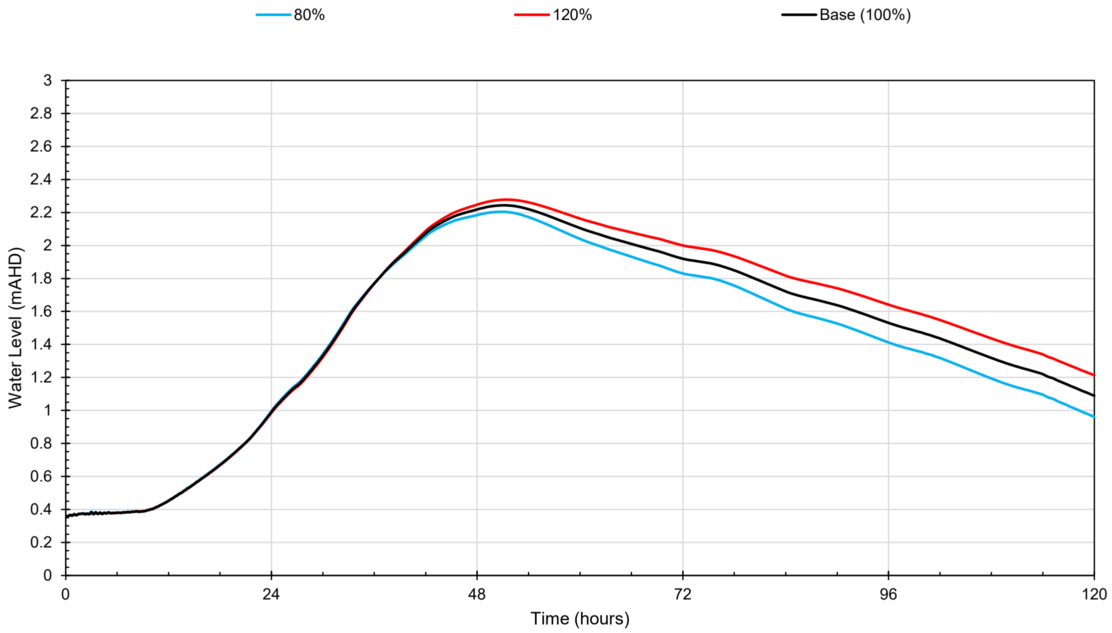


Figure 10.3 Roughness sensitivity – Tuggerah Lakes water level

Table 10.3 Roughness sensitivity – Tuggerah Lakes peak water level

Difference (m)	Peak water level (mAHD)			Difference (m)
80% roughness		Baseline	120% roughness	
-0.04	2.20	2.24	2.28	+0.04

Adjusting material roughness parameters by ±20% resulted in peak level changes of ±0.04 m. Reduced roughness facilitated faster recession and slightly lower peaks, while increased roughness led to prolonged inundation and marginally higher levels. These outcomes reflect the influence of the conveyance efficiency of the entrance channel on lake drainage, particularly during the falling limb of the hydrograph, due to the shallow depth and high velocities at the entrance when the lake levels are elevated during the peak and falling limb phases of the flood event. Further, although the impact on peak levels is modest, roughness plays a more significant role in flood duration. It is noted that the timing of the peak flood level does not significantly vary between the two roughness scenarios and the baseline conditions.

10.3 Initial lake water level

To analyse the influence of the initial lake water level on the flood behaviour, the following scenarios were modelled:

- Depressed initial lake water level scenario of 0.2 mAHD, reduced by 160mm for the 1% AEP flood event;
- Elevated initial lake water level scenario of 0.5 mAHD, increased by 140mm for the 1% AEP flood event.

An initial lake water level of 0.36 mAHD was adopted for the baseline 1% AEP event. These scenarios were modelled for the adopted critical duration and temporal pattern under otherwise standard design conditions, with the results shown as compared to the baseline run in **Figure 10.4** and **Table 10.4**.

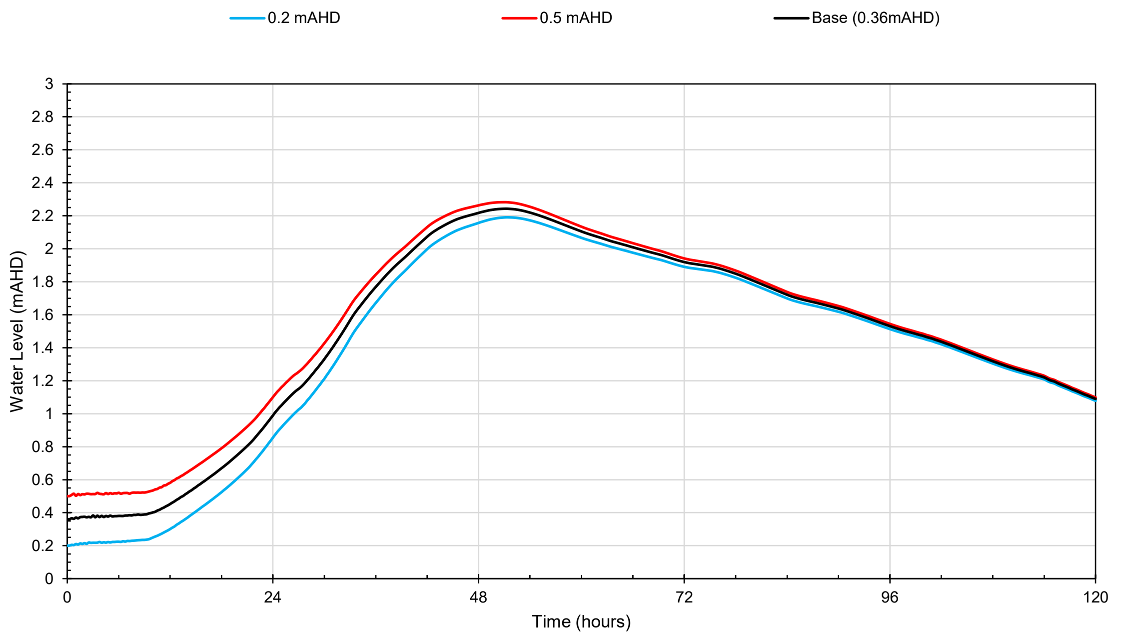


Figure 10.4 Initial lake water level sensitivity – Tuggerah Lakes water level

Table 10.4 Initial lake water level sensitivity – Tuggerah Lakes peak water level

Difference (m)	**Peak water level (mAHD)**			**Difference (m)**
0.2 mAHD		**Baseline**	**0.5 mAHD**	
-0.05	2.19	2.24	2.28	+0.04

Varying the initial lake level to 0.2 mAHD and 0.5 mAHD produced peak level differences of -0.05 m and +0.04 m respectively. The influence was most pronounced early in the event, with convergence toward baseline levels over time. This behaviour reflects the capacity of the lake to absorb inflows and the dominance of event-driven runoff over initial conditions. While initial lake level affects early warning and evacuation timing, its limited impact on peak levels suggests that planning levels can be generally based on a standardised initial condition.

10.4 Tailwater level

10.4.1 Peak level

To analyse the influence of the tailwater level on the flood behaviour, the following scenarios were modelled:

- 5% AEP water level for a Type A waterway entrance in the Tasman Sea (peaking at 1.40 mAHD);
- 5% AEP water level for a Type A waterway entrance with an assumed wave setup of 0.07 m (as per the 1994 study) in the Tasman Sea (peaking at 1.47 m AHD);
- 5% AEP water level for a Type C waterway entrance in the Tasman Sea (peaking at 2.35 mAHD).

A 5% AEP water level for a Type B waterway entrance in the Tasman Sea (peaking at 1.90 mAHD) was adopted for the baseline 1% AEP event. These scenarios were modelled for the adopted critical duration and temporal pattern under otherwise standard design conditions, with the results shown as compared to the baseline run in **Figure 10.5** and **Table 10.5**.

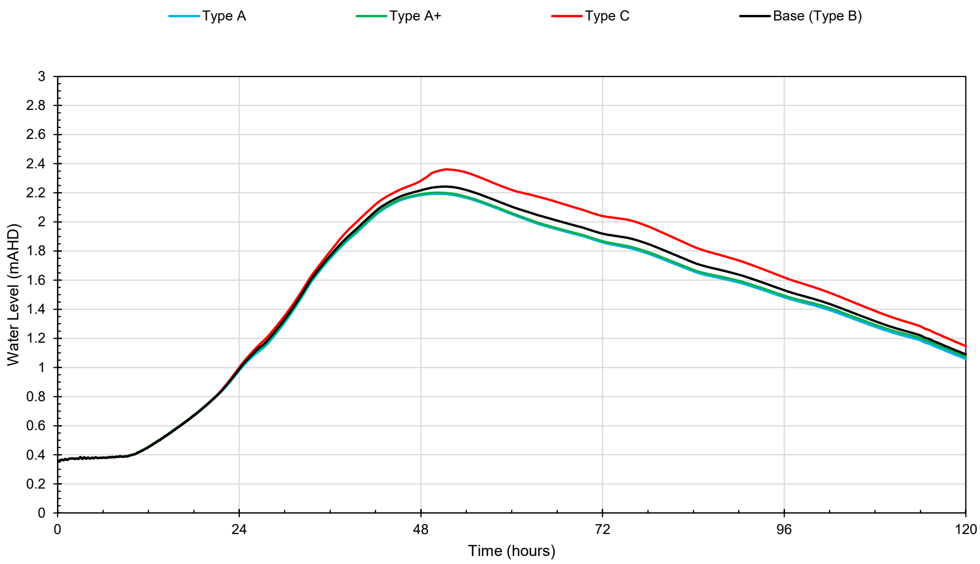


Figure 10.5 Tailwater level sensitivity – Tuggerah Lakes water level

Table 10.5 Tailwater level sensitivity – Tuggerah Lakes peak water level

Difference (m)	Peak water level (mAHD)			Difference (m)
Type A (1.45 mAHD)		Baseline (2.00 mAHD)	Type C (2.55 mAHD)	
-0.05	2.19	2.24	2.36	+0.12

It was observed that changes in tailwater conditions resulted in corresponding but attenuated variations in peak lake levels, particularly during the peak and descending limbs of the hydrograph. However, it is important to note that the peak water level in the Type C tailwater exceeds the 1% AEP lake level. Under these circumstances, inflows can be driven into the lake from the ocean, rather than the usual outflow to the ocean typically seen during peak catchment flood conditions. This tidal inflow effect is evident in the Type C hydrograph, where the peaks of the tidal cycles further raise lake water levels, independently of the catchment inflow behaviour. As shown in **Figure 10.5**, both Type A tailwater conditions (with and without the 0.07 m wave setup increase) are nearly identical, and as such **Table 10.5** exhibits these scenarios as a combined result only.

10.4.2 Timing

To analyse the influence of the tailwater timing on the flood behaviour, the following scenarios were modelled:

- 5% AEP water level for a Type B waterway entrance in the Tasman Sea (peaking at 1.90 mAHD) brought forward 6 hours from concurrent runoff-driven and tailwater peaks;
- 5% AEP water level for a Type B waterway entrance in the Tasman Sea (peaking at 1.90 mAHD) pushed back 6 hours from concurrent runoff-driven and tailwater peaks.

A 5% AEP water level for a Type B waterway entrance in the Tasman Sea (peaking at 1.90 mAHD) with concurrent runoff-driven and tailwater peaks was adopted for the baseline 1% AEP event. These scenarios were modelled for the adopted critical duration and temporal pattern under otherwise standard design conditions, with the results shown as compared to the baseline run in **Figure 10.6** and **Table 10.6**.

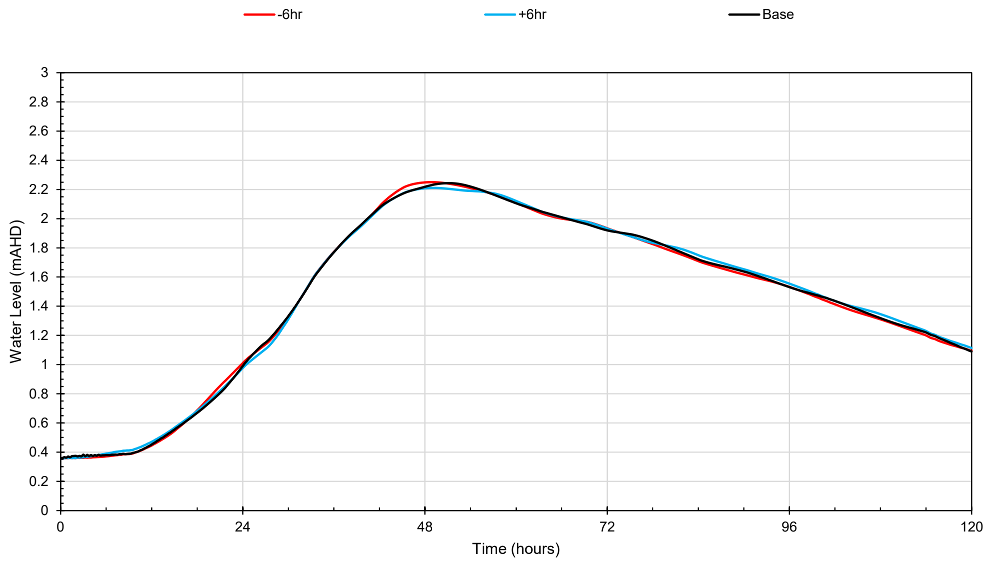


Figure 10.6 Tailwater timing sensitivity – Tuggerah Lakes water level

Table 10.6 Tailwater timing sensitivity – Tuggerah Lakes peak water level

Difference (m)	Peak water level (mAHD)			Difference (m)
-6 hours		Baseline	+6 hours	
+0.01	2.25	2.24	2.21	-0.03

A minor variance was observed between the sensitivity and baseline scenarios in this case, with a slightly higher peak water level noted when the peak timing of the tailwater conditions was brought forward. This indicates that the tailwater timing has a limited effect on the overall flood behaviour in this scenario when within the 12-hour window aligning with the peak runoff-driven conditions.

10.5 Entrance configuration and behaviour

10.5.1 Initial berm level

To assess the influence of the initial berm elevation on lake flood levels, the following scenarios were modelled:

- A raised berm scenario, with an initial elevation 0.3 m above the baseline;
- A lowered berm scenario, with an initial elevation 0.3 m below the baseline.

An initial channel configuration identical to that of the July 2022 calibration event (see **Section 7.2.6**) was adopted for the baseline 1% AEP event. The area of the berm raised as part of this scenario encompasses the 'adjusted berm' and 'April 2022 berm' areas shown in **Figure D.20**. This scenario was modelled for the adopted critical duration and temporal pattern under otherwise standard design conditions, with the results shown as compared to the baseline run in **Figure 10.7** and **Table 10.7**.

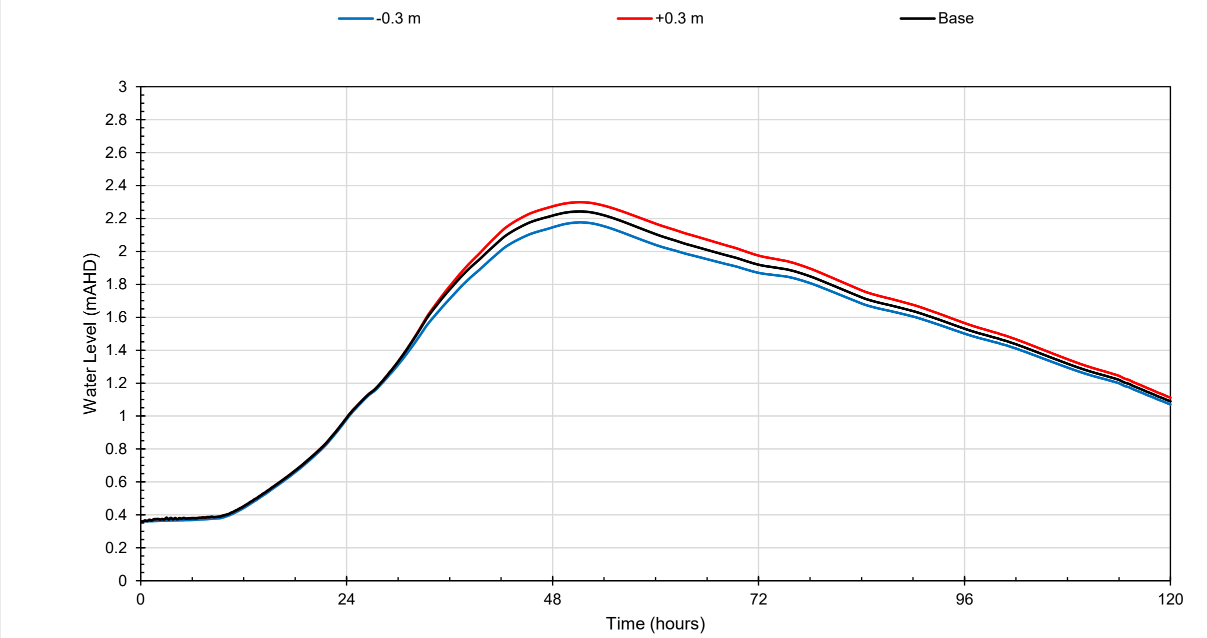


Figure 10.7 Initial berm level sensitivity – Tuggerah Lakes water level

Table 10.7 Initial berm level sensitivity – Tuggerah Lakes peak water level

Difference (m)	Initial channel width (mAHD)			Difference (m)
-0.3 m		Baseline	+0.3 m	
-0.06	2.18	2.24	2.30	+0.06

Raising the berm increased peak lake levels by 0.06 m; while lowering it reduced peak levels by an identical magnitude. While berm elevation would typically exert greater influence during the early stages of flooding, particularly in scenarios involving a fully closed entrance where scour initiation is governed by overtopping, in this case, the entrance was already open. As such, the berm elevation primarily influences the cross-sectional area of the berm and scour duration, with its effects on lake levels becoming apparent later in the flood hydrograph rather than during initial onset.

10.5.2 Initial channel width

To analyse the influence of the initial channel width on the flood behaviour, the following scenarios were modelled:

- A narrower channel, with an initial width of 30 m at 0 mAHD;
- A wider channel, with an initial width of 70 m at 0 mAHD.

An initial channel configuration identical to that of the July 2022 calibration event, which had an initial width of 50 m at 0 mAHD (see **Section 7.2.6**), was adopted for the baseline 1% AEP event. These scenarios were modelled for the adopted critical duration and temporal pattern under otherwise standard design conditions, with the results shown as compared to the baseline run in **Figure 10.8** and **Table 10.8**.

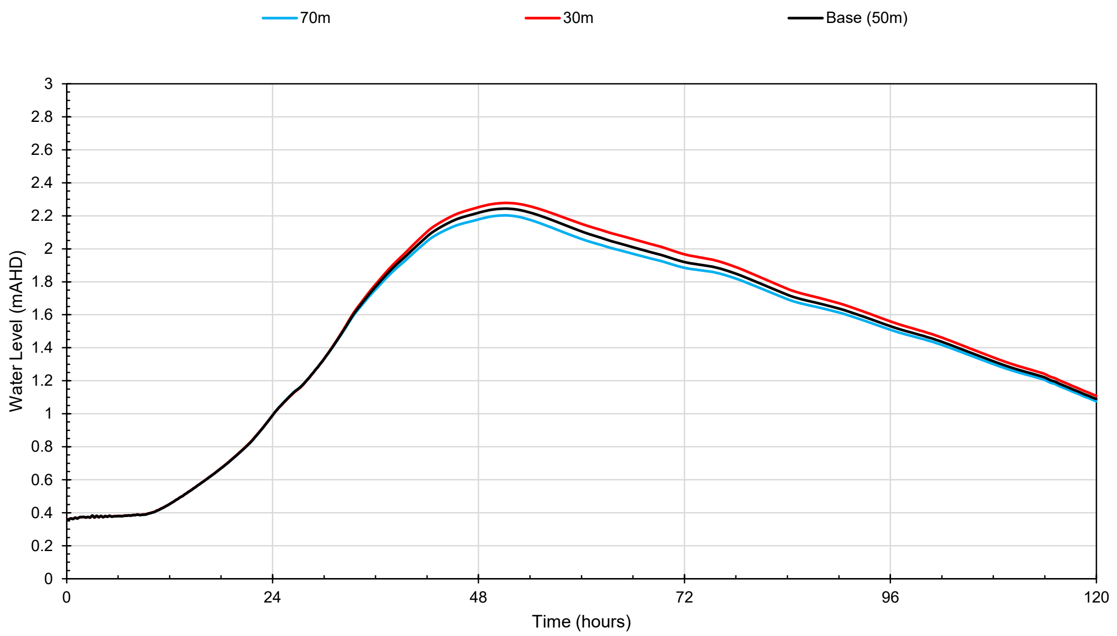


Figure 10.8 Initial channel width sensitivity – Tuggerah Lakes water level

Table 10.8 Initial channel width sensitivity – Tuggerah Lakes peak water level

Difference (m)	Initial channel width (mAHD)			Difference (m)
70 m		Baseline	30 m	
-0.04	2.20	2.24	2.28	+0.04

It was found that narrower initial channel width results in a slightly elevated peak lake level, while a wider configuration leads to a modest reduction compared to the baseline scenario. Although the overall impact on peak water level is small, the results highlight that entrance geometry can influence flood behaviour. Notably, the rising limb of the hydrograph remains largely consistent across all scenarios, with minimal variation observed prior to the peak. The most significant divergence occurs at the flood peak itself, as expected. It is important to note that for the purpose of this sensitivity test, the duration over which the transition from the initial to the final entrance configuration occurs was held constant. Finally, the tailing limbs of the hydrographs tend to converge with the baseline case, reflecting the fact that the final entrance geometry was identical in each instance.

10.5.3 Scour trigger

To analyse the influence of the scour trigger on the flood behaviour, the following scenarios were modelled:

- An earlier trigger, set as 1.1 mAHD in Tuggerah Lake;
- A later trigger, set as 1.5 mAHD in Tuggerah Lake.

A scour trigger of 1.3 mAHD in Tuggerah Lake was adopted for the baseline 1% AEP event. These scenarios were modelled for the adopted critical duration and temporal pattern under otherwise standard design conditions, with the results shown as compared to the baseline run in **Figure 10.9** and **Table 10.9**.

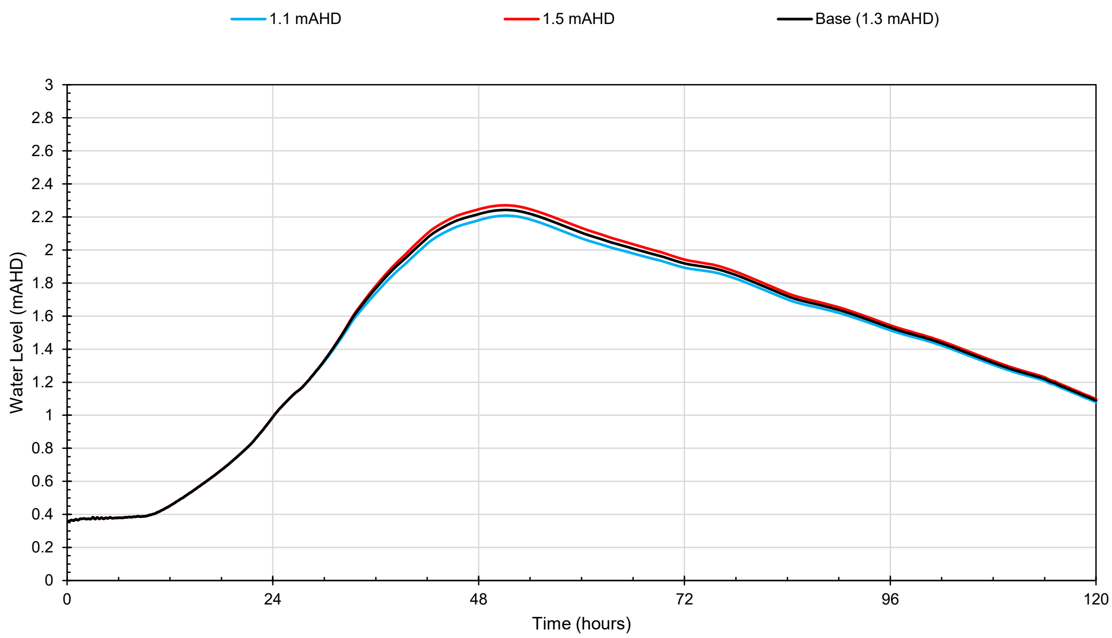


Figure 10.9 Scour trigger sensitivity – Tuggerah Lakes water level

Table 10.9 Scour trigger sensitivity – Tuggerah Lakes peak water level

Difference (m)	Peak water level (mAHD)			Difference (m)
1.1 mAHD		Baseline	1.5 mAHD	
-0.03	2.21	2.24	2.27	+0.03

The later trigger results in a slightly higher peak, while the earlier trigger leads to a slightly lower peak compared to the baseline. The results indicate a small effect on the peak water level. The rising limb, occurring before the scour trigger, remains consistent across all scenarios, showing no significant change. In contrast, the tailing limb of the hydrograph tends to align more closely with the baseline case after the trigger event, regardless of the trigger timing.

10.5.4 Scour duration

To analyse the influence of the scour duration on the flood behaviour, the following scenarios were modelled:

- A faster scour duration, with a total duration of 10 hours;
- A slower scour duration, with a total duration of 70 hours.

A three-phase, 30-hour scour duration was adopted for the baseline 1% AEP event. These scenarios were modelled for the adopted critical duration and temporal pattern under otherwise standard design conditions, with the results shown as compared to the baseline run in **Figure 10.10** and **Table 10.10**.

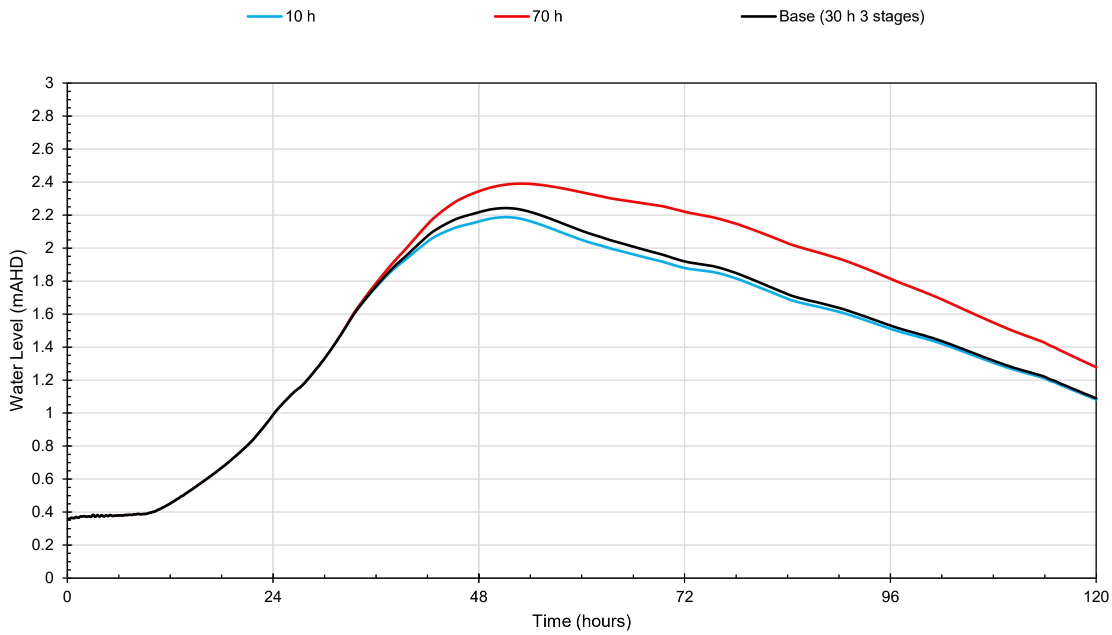


Figure 10.10 Scour duration sensitivity – Tuggerah Lakes water level

Table 10.10 Scour duration sensitivity – Tuggerah Lakes peak water level

Difference (m)	Peak water level (mAHD)			Difference (m)
10 hours		Baseline	70 hours	
-0.05	2.19	2.24	2.39	+0.15

The scour duration scenario revealed that slower scour development leads to higher peak lake levels, while faster scour reduces peaks. This reflects the timing mismatch between inflow and outflow capacity. When scour occurs rapidly, the entrance channel expands early in the event, allowing floodwaters to exit before peak accumulation. Conversely, delayed scour results in temporary storage within the lake, elevating peak levels. The sensitivity of the system to scour timing highlights the need for accurate representation of entrance evolution in flood models.

10.5.5 Final channel level

To analyse the influence of the final channel level on flood behaviour, the following scenarios were modelled:

- A deeper final channel level of -3.0 mAHD;
- A shallower final channel level of -1.5 mAHD.

A -2.0 mAHD final channel level was adopted for the baseline 1% AEP event. These scenarios were modelled for the adopted critical duration and temporal pattern under otherwise standard design conditions, with the results shown as compared to the baseline run in **Figure 10.11** and **Table 10.11**.

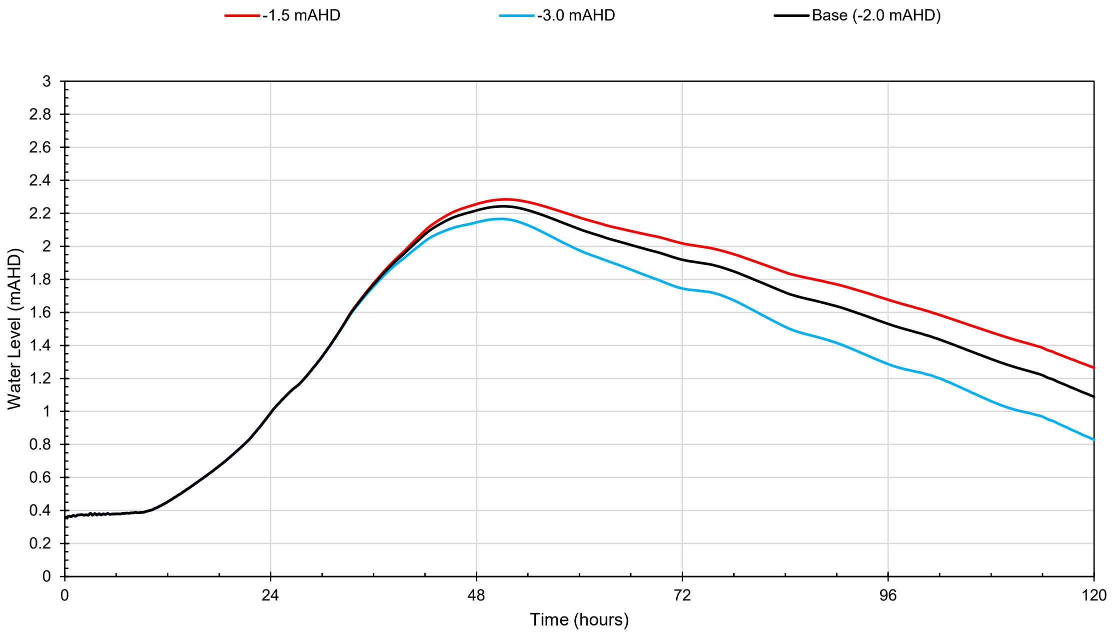


Figure 10.11 Final channel level sensitivity – Tuggerah Lakes water level

Table 10.11 Final channel level sensitivity – Tuggerah Lakes peak water level

Difference (m)	Peak water level (mAHD)			Difference (m)
-3.0 mAHD		Baseline	-1.5 mAHD	
-0.07	2.17	2.24	2.28	+0.04

The peak flood level showed moderate variation compared to the baseline scenario, with a deeper final channel level leading to a reduced peak water level and a shallower final channel level resulting in a higher peak water level. This effect becomes especially pronounced in the tailing limb of the flood hydrograph. As water levels recede, the availability of additional cross-sectional area at lower levels in the case of a deeper channel amplifies the difference in water levels during the tailing limb. Conversely, for the shallower channel, the opposite effect occurs, leading higher water levels for longer in the tailing limb.

10.5.6 Shoals and ebb channel configuration

In order to analyse the influence of shoal and ebb channel configuration on flood behaviour, a scenario was ran with an initial configuration in accordance with the post-dredge entrance survey conducted in January 2019, which captured the dredging activity performed by Central Coast Council across December 2018 (see **Figure D.22**). This configuration was also slightly modified to include a deepened section connecting the entrance channel and the northern Tuggerah Lakes channel, as illustrated in the *Tuggerah Lakes Entrance Management Study* (see **Figure D.23**). This scenario involved the removal of sand from the flood shoal and ebb channel area, resulting in an estimated volume difference of 83,500 m^3.

An initial channel configuration identical to that of the July 2022 calibration event (see **Section 7.2.6**) was adopted for the baseline 1% AEP event. This scenario was modelled for the adopted critical duration and temporal pattern under otherwise standard design conditions, with the results shown as compared to the baseline run in **Figure 10.12** and **Table 10.12**.

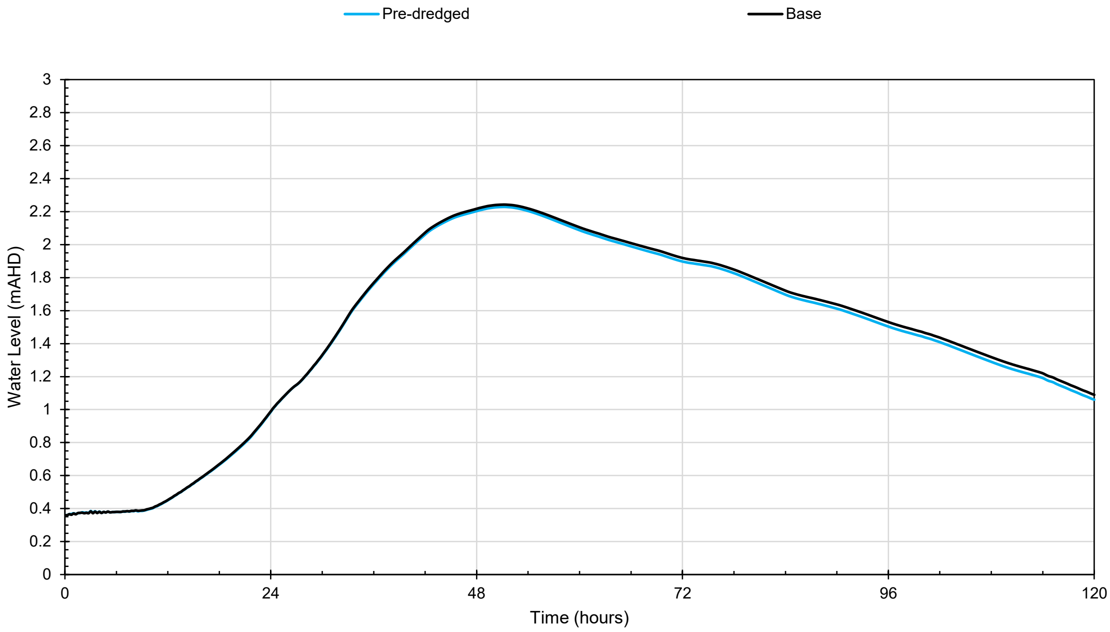


Figure 10.12 Shoal and ebb channel configuration sensitivity – Tuggerah Lakes water level

Table 10.12 Shoal and ebb channel configuration sensitivity – Tuggerah Lakes peak water level

Peak water level (mAHD)		Difference (m)
Baseline	**Pre-dredged entrance**	
2.24	2.23	-0.01

The peak flood level with a pre-dredged channel configuration showed a negligible variation compared to the baseline scenario. This effect becomes slightly more pronounced in the tailing limb of the flood hydrograph, which may be since the discrepancy in conveyance between the dredged and un-dredged post-scour shoals becomes greater as lake levels fall. While the results indicate a relatively modest reduction in peak lake levels for the 1% AEP event, this does not suggest that the dredging regime would have similarly negligible impacts under all conditions. It is anticipated that the relative impact of dredging would be more pronounced for more frequent events, where entrance conditions exert greater control on lake outflows due to the smaller hydraulic head differential between the lake and the ocean.

10.5.7 Entrance under elevated oceanic conditions

To analyse the influence of the entrance configuration on tidally driven flood behaviour (i.e., no catchment inflows), the following scenarios were modelled:

- the pre-July 2022 event configuration, which was adopted as the typical configuration of the entrance prior to scouring associated with the runoff related events;
- the post-1% AEP event configuration

The post-July 2022 event configuration was adopted as the typical 'open' configuration. Each of these entrance scenarios was subjected to the 1% AEP tailwater condition associated with Type C entrances, and minimal catchment inflows, with the results shown as compared to the baseline run in **Figure 10.13** and **Table 10.13**.

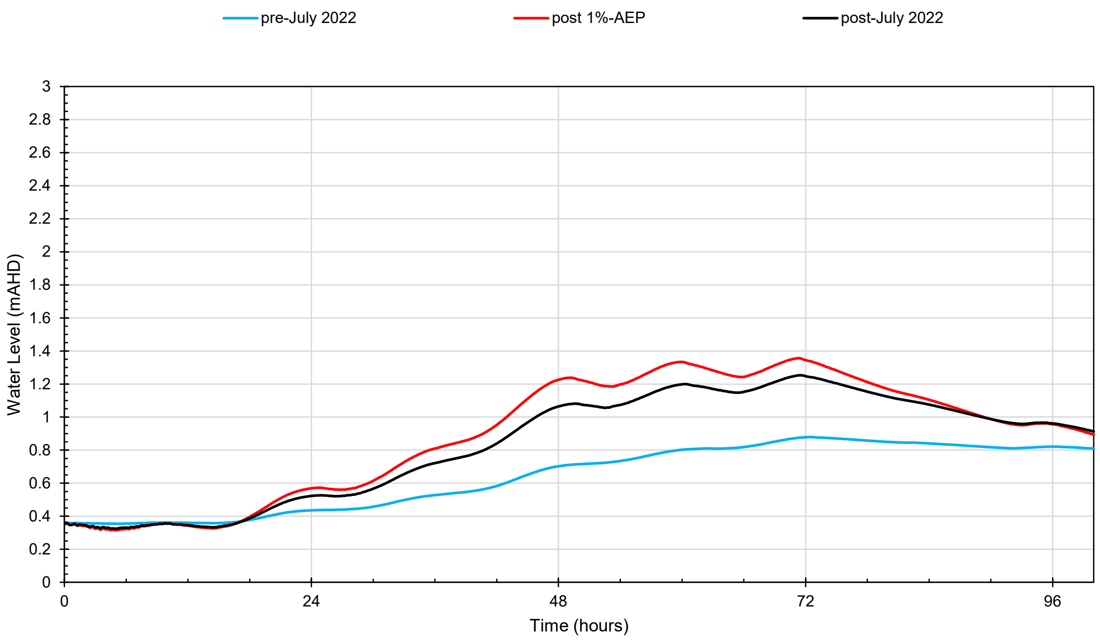


Figure 10.13 Oceanic inundation entrance sensitivity – Tuggerah Lakes water level

Table 10.13 Oceanic inundation entrance sensitivity – Tuggerah Lakes peak water level

Difference (m)	Peak water level (mAHD)			Difference (m)
pre-July 2022		Baseline	post-1% AEP	
-0.37	0.88	1.25	1.36	+0.11

As expected, wider and more open entrance configurations exhibited more responsiveness to elevated ocean levels than the more constricted case. It is noted that the post-July 2022 and post 1%-AEP configurations were more similar than the pre-July 2022 case, indicating that the post-July 2022 configuration substantially accounts for the behaviour of an open entrance.

10.6 Summary

This chapter has explored the influence of key hydrologic and hydraulic parameters on flood behaviour within the Tuggerah Lakes system, with a particular focus on the 1% AEP design event. The sensitivity testing presented has demonstrated that while the system is relatively stable under most conditions, certain parameters exert a more pronounced influence on peak lake levels and hydrograph shape.

Table 10.14 summarises the results of all sensitivity scenarios tested. It provides a consolidated view of the change in peak lake level relative to the baseline scenario, allowing for direct comparison across parameters. The table highlights that rainfall losses, scour duration, and tailwater conditions are the most influential factors, with changes in these parameters resulting in peak level variations of up to ±0.15 m. In contrast, parameters such as catchment lag and initial lake level produced relatively minor changes, typically less than ±0.05 m.

Table 10.14 Model sensitivity summary

Parameter	Difference	-	Baseline	+	Difference
Rainfall losses (Double, adopted, none)	-0.13	2.11	2.24	2.38	+0.14
Catchment lag (+10%, adopted, -10%)	-0.01	2.23		2.25	+0.01
Roughness (-20%, adopted, +20%)	-0.04	2.20		2.28	+0.04
Lake IWL (0.2, 0.36, 0.5 mAHD)	-0.05	2.19		2.28	+0.04
Oceanic tailwater level (Type A, B, C)	-0.05	2.19		2.36	+0.12
Oceanic tailwater timing (+6 h, catchment peak, -6 h)	-0.03	2.21		2.25	+0.01
Initial berm level (-0.3 m, adopted, +0.3 m)	-0.06	2.18		2.30	+0.06
Initial channel width (70, 50, 30 m)	-0.04	2.20		2.28	+0.04
Scour trigger level (1.1, 1.3, 1.5 mAHD)	-0.03	2.21		2.27	+0.03
Duration of scour (all in 10 h, adopted, all in 70 h)	-0.05	2.19		2.39	+0.15
Final channel level (-3, -2, -1.5 mAHD)	-0.07	2.17		2.28	+0.04
Shoals and ebb channel (post-2019 dredge channel)	-0.01	2.23		-	-
Oceanic event entrance (pre-2022, post-2022, post-1% AEP)	-0.37	0.88	1.25	1.36	+0.11

The entrance configuration scenarios, covering berm elevation, channel width and depth, and scour timing, collectively underscore the importance of entrance dynamics in modulating flood peaks. Delayed or slower scour was shown to significantly elevate lake levels, reinforcing the need for considered assumptions in entrance modelling where empirical data is limited. It is noted that while this study includes sensitivity testing of entrance configurations, it does not constitute a detailed assessment of dredging impacts on entrance morphology or long-term sediment dynamics. Given the complexity of shoal evolution and ebb channel behaviour, a dedicated morphologic or sediment transport study would be required to fully understand the implications of dredging on flood behaviour and estuarine processes. Such investigations could provide a more robust basis for evaluating dredging as a potential flood risk management measure in future planning.

The results also confirm that the response of the lakes to changes in roughness and initial conditions is modest, suggesting that these parameters, while important for hydrograph shape and hazard classification, are less critical in determining peak levels. This finding supports the robustness of the adopted baseline values and provides confidence in the stability of the model under typical conditions.

Overall, the sensitivity testing has provided valuable insight into the relative importance of each parameter and has informed the selection of appropriate freeboard allowances and planning levels in subsequent sections. The outcomes of this chapter will be carried forward into the flood planning and risk assessment components of the study, ensuring that the recommendations are grounded in a thorough understanding of model behaviour and uncertainty.

11 Preliminary analysis of flood consequences on the community

The impact of flooding on the community is described in this section. The first step of understanding the impact of flooding on the community is to determine the flood behaviour within the catchment and identify key problem areas. Preliminary flood impact and road closure assessments can then be made, with more details provided in this section. It is noted that further detailed assessments, including flood damages, are anticipated to be completed at a subsequent Flood Risk Management Study and Plan stage. In addition to the sections outlined below, **Appendix C** provides comprehensive information to support emergency management planning. This includes design flood and gauge height relationships, typical flood emergency response classification of community information summaries, road closure details, and a sequential key flood impact summary.

11.1 Flood behaviour

Flooding in the Tuggerah Lakes system is characterised by a relatively slow onset and long duration, primarily driven by extended rainfall events of moderate intensity. Hydrologic modelling confirms critical durations ranging between 72 and 144 hours as shown in **Table 8.5,** with lake levels rising gradually over several days. This behaviour is typical of lake-based flooding, which differs from flash flooding or tributary flooding in its timing and impact.

This flood behaviour has important implications for emergency response planning. The gradual rise in lake levels provides extended lead time for evacuation, public warnings, and coordination of emergency services. The historical calibration events (e.g. 2007, 2021, 2022) demonstrated peak lake levels occurring 3–4 days after rainfall onset, allowing for proactive measures to be taken. It is also noted that the rarer events were modelled to peak in the order of 1–2 days after rainfall onset. However, the slow recession of floodwaters also results in prolonged disruption, including extended road closures, isolation of properties, and sustained impacts to infrastructure and services. Emergency planning frameworks must therefore account for both the extended warning window and the duration of community impacts.

Key areas identified as vulnerable to lake flooding include low-lying foreshore regions such as Chittaway Point, Tacoma and Tacoma South, Tuggerawong, Rocky Point and The Entrance North (behind the Wilfred Barrett Drive levee). These areas, among others, are particularly sensitive to prolonged inundation and should be prioritised in future flood risk management and emergency response strategies.

Further to the above discussion, **Table 11.1** summarises the number of lots modelled to be inundated at least partially by the respective catchment flooding events.

Table 11.1 Number of lots affected by flooding events

Event	Lots affected
Total number of lots in study area	34,170
PMF	8,964
1 in 500 AEP	7,814
1 in 200 AEP	7,313
1% AEP	6,581
2% AEP	5,624
5% AEP	4,526
10% AEP	3,654
20% AEP	2,398

11.2 Key infrastructure assets

There are two main types of key infrastructure assets as presented below:

- The first type includes facilities that are occupied by emergency responders such as police stations, fire stations or SES Centres.
- The second type includes facilities with particularly vulnerable residents such as schools, childcare centres, aged care facilities and hospitals.

The locations of these key assets have been sourced from publicly available information (e.g., Google Maps). A list of these facilities is provided in **Table 11.2** along with a brief description of the flood affectation of each asset.

Table 11.2 Summary of flood risk of key infrastructure assets

Location	Comments on Flood Risk
Police and Fire Stations	
Tuggerah Rural Fire Station	Not affected by Tuggerah Lakes flooding. However, it is noted that flooding from Ourimbah Creek may have an impact at this location (refer to Ourimbah Creek FRMSP).
Berkeley Vale Fire Station	Not affected by Tuggerah Lakes flooding. However, it is noted that flooding from Ourimbah Creek may have an impact at this location (refer to Ourimbah Creek FRMSP).
SES Centres	
SES Wyong	Not flood affected.
Hospital and Ambulance Stations	
N/A	No Hospitals or Ambulance Stations were noted as affected by Tuggerah Lakes flooding.

Location	Comments on Flood Risk
Schools	
Chittaway Bay Public School	Not affected by Tuggerah Lakes flooding. However, it is noted that flooding from Ourimbah Creek may have an impact at this location (refer to Ourimbah Creek FRMSP).
Tacoma Public School	The school property is not affected by Tuggerah Lakes flooding, however road access to the school would be cut during the 1% AEP event. It is noted that flooding from the Wyong River may also have an impact at this location (refer to Wyong River FRMSP).
Tuggerawong Public School	A small section of the school property may be flood impacted during a PMF event; however, access is not impacted.
Glenvale School	The school is within the 1% AEP extent. Road access to the school would also be cut during the 1% AEP event.
St Cecilia's Primary School, Wyong	The school property is affected by the 5% AEP extent; however, access is not impacted. It is noted that flooding from the Wyong River may also have an impact at this location (refer to Wyong River FRMSP).
HopeTown School	The school property is affected by the 5% AEP extent. Access is maintained until the 2% AEP event. It is noted that flooding from the Wyong River may also have an impact at this location (refer to Wyong River FRMSP).
Childcare Facilities and Preschools	
Killarney Vale Preschool	A small section of the school property is affected by a PMF event. It is noted that local tributary flooding may also have an impact at this location (refer to Tuggerah Lakes Southern Catchments FRMSP).
Budgewoi Preschool	The preschool is within the PMF extent. A small section of the preschool property may be impacted by flood during a 1 in 500 AEP event, but access is maintained.
Little Souls Early Leaning Centre Long Jetty	The preschool is within the PMF extent. A small section of the preschool property may be impacted by flood during a 1 in 200 AEP event. Access is not flood affected.
Coast Community Preschool	The school property is not affected by Tuggerah Lakes flooding, however road access to the school would be cut during the PMF event. It is noted that local tributary flooding may also have an impact at this location (refer to Tuggerah Lakes Southern Catchments FRMSP).
Wyong Preschool Kindergarten	Not affected by Tuggerah Lakes flooding. However, it is noted that flooding from the Wyong River may have an impact at this location

Location	Comments on Flood Risk
	(refer to Wyong River FRMSP).
Spotted Frog Kindergarten	The preschool is within the 5% AEP extent, with access also affected. A small section of the preschool property may be impacted by flood during a 10% AEP event.
Aged Care Facilities and Retirement Villages	
Killarney Vale Care Community	The aged care facility is located within the PMF extent. Access to the nursing home may be affected in the 1 in 200 AEP event.
Don Small Retirement Village	The aged care facility is located within the 5% AEP extent. Access to the nursing home may be affected in the 10% AEP event. It is noted that flooding from the Wyong River may also have an impact at this location (refer to Wyong River FRMSP).
Meander Village	A small section of the aged care facility property may be flood affected during a 10% AEP. Significant inundation occurs across the property in the 5% AEP event. Access from the site is affected in the 1% AEP event. It is noted that flooding from the Wyong River may also have an impact at this location (refer to Wyong River FRMSP).
Alino Living Killarney Court	A small section of the aged care facility property may be flood affected during a PMF event. Access to the nursing home may also become difficult in the PMF event. It is noted that local tributary flooding may also have an impact at this location (refer to Tuggerah Lakes Southern Catchments FRMSP).

11.3 Road closure

Driving through floodwaters is one of the main causes of death during flood events. Therefore, an assessment of the frequency and hazard of road inundation is important for understanding the risk of vehicles becoming unstable, posing a risk to life for their drivers and passengers. It is also important for understanding evacuation risks, informing the classification of communities according to flood emergency response planning considerations. Measures to increase the flood immunity of critical roads may be considered because of this assessment as part of a subsequent Flood Risk Management Study and Plan.

The various maps exhibited in **Appendix J** depict the peak inundation depth, and anticipated time until and duration of inundation which would result in a road closure for each modelled flood event. A road closure depth of water over road threshold was determined following discussion with the SES. While it is understood that SES does not recommend driving through **any** floodwaters, a value of 0.15 m was found to be a practical limit for the purpose of road closure determination.

Some minor sections of road that were observed to become sufficiently inundated during a 20% AEP event to necessitate road closure included:

- Lucinda Avenue in Killarney Vale,

- Aloha Drive, Geoffrey Road, Kalua Drive and Henry Street in Chittaway Point,
- Tuggerah Parade in The Entrance,
- some local access roads within Budgewoi Holiday Park.

During a 1% AEP flood, a significant number of additional roads become inundated at various locations around the lakes, including:

- a number of roads leading to the key frontage roads mentioned as part of the 20% AEP closures,
- Tuggerah Parade and joining roads in Long Jetty,
- Lakedge Avenue and Kerry Crescent in Tumbi Umbi and Berkeley Vale,
- Most lake frontage and joining roads in Chittaway Point and Berkeley Vale,
- local roads in in Rocky Point,
- Tuggerawong Road,
- Natuna Avenue, Cudgegong Street, Weemala Street and Lake Street in Budgewoi.

During a probable maximum flood event, numerous roads become cut around the lakes and some major roads become inundated including the Central Coast Highway at Budgewoi, The Entrance North and The Entrance, and the Pacific Highway at Wallarah Creek.

Comprehensive road closure details are presented in **Appendix J** and tabulated in **Table C.3**.

11.4 Flood planning area

The Flood Planning Area (FPA) defines the extent of land subject to flood-related development controls and is based on a Defined Flood Event (DFE) flood level plus an appropriate freeboard. The section below details the determination of an FPA. It is noted that the FPA will be reviewed as part of a future FRMSP stage.

The DFE should be selected by considering aspects such as tipping points beyond which significant changes in flood extent may occur such as levee overtopping. The main levee located within the Tuggerah Lakes catchment is the Wilfred Barrett Drive levee. This levee commences to overtop between the 2% and the 1% AEP events. Therefore, it is proposed to use the 1% AEP as DFE for the FPA definition.

The purpose of a freeboard is to provide a factor of safety against the inherent uncertainties and practical limitations associated with hydrological and hydraulic modelling processes as well as input data. Historically, a 0.5 m freeboard was considered appropriate for the purposes of flood planning, to account for these inherent uncertainties. However, to remain effective in its purpose, a freeboard should be based on the flood risk specific to the catchment in question.

As such, the sources of uncertainty that would govern the magnitude of an appropriate freeboard in the given 1% AEP event for the Tuggerah Lakes are quantified in **Table 11.3**.

Table 11.3 Sources and quantification of modelling uncertainties

Type	Source	Uncertainty (m)	Comment
Inflow	Hydrology	±0.1	Catchment losses and lag, see **Section 10.1**
Lake and entrance	Hydraulics	±0.1	Model schematisation (e.g., material roughness), see **Section 10.2**
	Initial lake water level	±0.1	See **Section 10.3**
	DEM and bathymetry	±0.3	Primary DEM has a vertical accuracy of 0.3 m to 95% confidence, see **Section 3.2**
	Entrance configuration and dynamics	±0.2	See **Section 10.5**
	Lake wave setup	±0.2	Assuming sustained 20 m/s (~70 km/h) winds from a single direction across the longest lake fetch length, which would be unlikely and thus conservative noting the regional wind climate, and a 15% wave height-setup factor
	Lake wind setup	±0.2	Assuming sustained 20 m/s (~70 km/h) winds from a single direction, which would be unlikely and thus conservative noting the regional wind climate, see *Tuggerah Lakes Flood Study (1994)*
Tailwater	Level and timing	±0.1	Timing and magnitude of wave setup, tidal anomaly, storm surge, etc., see **Section 10.4**

The uncertainties detailed above primarily stem from the variability and limited data concerning the entrance configuration during the largest flood events. This model is not a morphological model, and as such sand movement has not been directly assessed. Rather, berm and entrance channel configurations and dynamics have been specified directly, based on historical observations and simplified assumptions around entrance behaviour in large events. Further to this, the potential impacts of wind and wave setup effects within the lakes causing a deviation from the average still water level were considered and determined as part of the modelling undertaken in this study.

Based on the above quantification of uncertainty, and in accordance with the NSW Flood Risk Management Manual (2023), a freeboard value of 0.5 m has been adopted for this study. This value reflects a standardised planning approach that balances the need to account for modelling uncertainty with the practicalities of land use planning. Sensitivity testing undertaken as part of this study identified several influential parameters (such as entrance scour behaviour, tailwater levels, and rainfall losses) that can affect peak lake levels. However, the combined impact of these factors was found to be within the range typically addressed by a 0.5 m allowance. Importantly, while each parameter introduces some uncertainty, the likelihood of all factors simultaneously contributing to an increase in flood level is low. Therefore, it was determined that the standard 0.5 m freeboard forms a reasonable uncertainty buffer. From this, the flood planning area was therefore determined to be set by the 1% AEP event plus a freeboard of 0.5 m, with the FPA extent presented in **Appendix F**.

Table 11.4 exhibits a comparison between the present 1% AEP result and the results of the future climate change 1% AEP and PMF events to assess the scale in which the adopted freeboard sits. It is noted that the 2070 1% AEP event was 0.50 m higher than the present day 1% AEP event, while the 2120 climate change 1% AEP results were modelled to reach levels similar to a PMF event at an approximate 0.80 m above the present 1% AEP event. While future climate scenarios and PMF events may exceed the present-day 1% AEP level by more than the adopted freeboard of 0.5 m, this value reflects current planning standards and is not intended to account for future climate change impacts. Such climate change impacts will be addressed by the Flood Risk Management Policy currently being finalised by Council and this policy will adopt varying planning horizons and associated sea level rise levels depending on the type of development.

Table 11.4 Comparison of present and future 1% AEP and PMF peak Tuggerah Lakes flood levels

Event	1% AEP	PMF	2070 1% AEP	2120 1% AEP
Peak Tuggerah Lakes flood level (mAHD)	2.24	3.04	2.74	3.07
Difference (m)	-	+0.80	+0.50	+0.83

References

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Glossary

Annual Exceedance Probability (AEP)	The chance of a flood of a given or larger size occurring in any one year, usually expressed as a percentage. For example, if a peak flood discharge of 500 m3/s has an AEP of 5%, it means that there is a 5% chance (that is one-in-20 chance) of a 500 m3/s or larger events occurring in any one year (see ARI).
Australian Height Datum (AHD)	A common national surface level datum approximately corresponding to mean sea level.
Average Annual Damage (AAD)	Depending on its size (or severity), each flood will cause a different amount of flood damage to a flood prone area. AAD is the average damage per year that would occur in a nominated development situation from flooding over a very long period of time.
Average Recurrence Interval (ARI)	The long-term average number of years between the occurrence of a flood as big as or larger than the selected event. For example, floods with a discharge as great as or greater than the 20-year ARI flood event will occur on average once every 20 years. ARI is another way of expressing the likelihood of occurrence of a flood event.
Berm Level/Berm Height	Level of the sand at the entrance of a waterbody
Design Blockage	Blockage is an obstruction which makes movement of flood water or flow through a drainage system difficult or impossible. Design blockage is the blockage obtained following the Australian Rainfall and Runoff 2019 recommendations. Blockage is defined as a percentage of reduction in flow capacity through a drainage structure (e.g. pit, pipe, culvert, bridge, etc.)
Double Design Blockage	Minimum of double of the design blockage or 100% blockage (i.e. fully blocked)
Catchment	The land area draining through the main stream, as well as tributary streams, to a particular site. It always relates to an area above a specific location.
Computer Models	The mathematical representation of the physical processes involved in runoff generation and stream flow. These models are often run on computers due to the complexity of the mathematical relationships between runoff, stream flow and the distribution of flows across the floodplain.
Consent Authority	The council, government agency or person having the function to determine a development application for land use under the EP&A Act. The consent authority is most often the council, however legislation or an EPI may specify a Minister or public authority (other than a council), or the Director General of OEH, as having the function to determine an application.
Defined flood event (DFE)	The flood event selected for the management of flood hazard for the location of specific development as determined by the appropriate authority.

Defined flood level (DFL)	The flood level associated with a defined flood event (DFE) relative to a specified datum. The DFL plus the freeboard determines the extent of the flood hazard area.
Development	"Is defined in Part 4 of the Environmental Planning and Assessment Act (EP&A Act). Infill Development: refers to development of vacant blocks of land that are generally surrounded by developed properties and is permissible under the current zoning of the land. Conditions such as minimum floor levels may be imposed on infill development. New Development: refers to development of a completely different nature to that associated with the former land use. For example, the urban subdivision of an area previously used for rural purposes. New developments involve rezoning and typically require major extensions of existing urban services, such as roads, water supply, sewerage and electric power. Redevelopment: refers to rebuilding in an area. For example, as urban areas age, it may become necessary to demolish and reconstruct buildings on a relatively large scale. Redevelopment generally does not require either rezoning or major extensions to urban services."
Disaster Plan (DISPLAN)	A step-by-step sequence of previously agreed roles, responsibilities, functions, actions and management arrangements for the conduct of a single or series of connected emergency operations, with the object of ensuring the coordinated response by all agencies having responsibilities and functions in emergencies.
Discharge	The rate of flow of water measured in terms of volume per unit time, for example, cubic metres per second (m3/s). Discharge is different from the speed or velocity of flow, which is a measure of how fast the water is moving for example, metres per second (m/s).
Effective Warning Time	The time available after receiving advice of an impending flood and before floodwaters prevent appropriate flood response actions being undertaken. The effective warning time is typically used to move farm equipment, move stock, raise furniture, evacuate people and transport their possessions.
Emergency Management	A range of measures to manage risks to communities and the environment. In the flood context it may include measures to prevent, prepare for, respond to and recover from flooding.
ESD	Using, conserving and enhancing natural resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future, can be maintained or increased. A more detailed definition is included in the Local Government Act, 1993. The use of sustainability and sustainable in this manual relate to ESD.
Finished floor level	The uppermost surface of the finished floor, not including any floor covering such as carpet, tiles and the like.
Flash Flooding	Flooding which is sudden and unexpected. It is often caused by sudden local or nearby heavy rainfall. Often defined as flooding which peaks within six hours of the causative rain.

Flood Awareness	Awareness is an appreciation of the likely effects of flooding and a knowledge of the relevant flood warning, response and evacuation procedures.
Flood Control Lot	Property (or Lot) located within the flood planning area and subject to flood-related development controls.
Flood Education	Flood education seeks to provide information to raise awareness of the flood problem so as to enable individuals to understand how to manage themselves and their property in response to flood warnings and in a flood event. It invokes a state of flood readiness.
Flood Fringe Areas	The remaining area of flood prone land after floodway and flood storage areas have been defined.
Flood Hazard Area (FHA)	the area (whether or not mapped) encompassing land lower than the flood hazard level (FHL) which has been determined by the appropriate authority. The area relates to that part of the allotment on which a building stands or is to be erected.
Flood Hazard Level (FHL)	The flood level used to determine the height of floors in a building and represents the defined flood level (DFL) plus the freeboard.
Flood Liable Land	Is synonymous with flood prone land, i.e., land susceptible to flooding by the PMF event. Note that the term flood liable land covers the whole floodplain, not just that part below the FPL (see flood planning area).
Flood Planning Area	Area that defines when a property is classified as a flood control lot.
Flood Planning Levels (FPLs)	Are the combinations of flood levels (derived from significant historical flood events or floods of specific AEPs) and freeboards selected for floodplain risk management purposes, as determined in management studies and incorporated in management plans.
Flood Prone Land	Land susceptible to flooding by the PMF event. Flood prone land is synonymous with flood liable land.
Flood Proofing	A combination of measures incorporated in the design, construction and alteration of individual buildings or structures subject to flooding, to reduce or eliminate flood damages.
Flood Readiness	Readiness is an ability to react within the effective warning time.
Flood Risk	Potential danger to personal safety and potential damage to property resulting from flooding. The degree of risk varies with circumstances across the full range of floods. Flood risk in this manual is divided into 3 types, existing, future and continuing risks. They are described below. Existing Flood Risk: the risk a community is exposed to as a result of its location on the floodplain. Future Flood Risk: the risk a community may be exposed to as a result of new development on the floodplain. Continuing Flood Risk: the risk a community is exposed to after floodplain risk management measures have been implemented. For a town protected by levees, the continuing flood risk is the consequences of the levees being overtopped. For an area without any floodplain risk management measures, the continuing flood risk is simply the existence of its flood exposure.

Flood Storage Areas	Those parts of the floodplain that are important for the temporary storage of floodwaters during the passage of a flood. The extent and behaviour of flood storage areas may change with flood severity, and loss of flood storage can increase the severity of flood impacts by reducing natural flood attenuation. Hence, it is necessary to investigate a range of flood sizes before defining flood storage areas.
Flood Study	Is a technical investigation of flood behaviour in the study area. It describes the extent, depth and velocity of flood waters as well as the variation in flood hazard during a range of historical as well as hypothetical 'design' floods. The 'design' floods are based on statistical analysis of flooding that has occurred in the past.
Floodplain	Area of land which is subject to inundation by floods up to and including the probable maximum flood event, that is, flood prone land.
Floodplain Risk Management Options	The measures that might be feasible for the management of a particular area of the floodplain. Preparation of a floodplain risk management plan requires a detailed evaluation of floodplain risk management options.
Floodplain Risk Management Plan	A management plan developed in accordance with the principles and guidelines in this manual. Usually includes both written and diagrammatic information describing how particular areas of flood prone land are to be used and managed to achieve defined objectives.
Floodway Areas	Those areas of the floodplain where a significant discharge of water occurs during floods. They are often aligned with naturally defined channels. Floodways are areas that, even if only partially blocked, would cause a significant redistribution of flood flow, or a significant increase in flood levels.
Freeboard	Provides reasonable certainty that the risk exposure selected in deciding on a particular flood chosen as the basis for the FPL is actually provided. It is a factor of safety typically used in relation to the setting of floor levels, levee crest levels, etc. Freeboard is included in the flood planning level.
Hazard	A source of potential harm or a situation with a potential to cause loss. In relation to this study the hazard is flooding which has the potential to cause damage to the community.
Heavily Parallelised Compute (HPC)	In the context of the TUFLOW software, HPC is a solver which allows for the parallelisation of the hydraulic calculations within a single model. This allows a single model to run across numerous computational cores in parallel, which can significantly reduce model run times.
Historical Flood	A flood which has actually occurred.
Hydraulics	Term given to the study of water flow in waterways; in particular, the evaluation of flow parameters such as water level and velocity.
Hydrograph	A graph which shows how the discharge or stage/flood level at any particular location varies with time during a flood.

Hydrology	Term given to the study of the rainfall and runoff process; in particular, the evaluation of peak flows, flow volumes and the derivation of hydrographs for a range of floods.
Impervious lag factor	The impervious lag factor is a coefficient used in WBNM to reduce the lag parameter for impervious surfaces to consider the fact that impervious surfaces allow for faster response in flow than pervious surfaces.
Lag Parameter	The lag parameter C in the runoff routing model WBNM has been derived from recorded storms on 54 catchments in Queensland, NSW, Victoria and South Australia. Parameter C was found to be independent of flood size, catchment area, stream slope, and various storm and catchment characteristics.
Local Drainage	Smaller scale problems in urban areas. They are outside the definition of major drainage in this glossary.
Local Overland Flooding	Inundation by local runoff rather than overbank discharge from a stream, river, estuary, lake or dam.
Mainstream Flooding	Inundation of normally dry land occurring when water overflows the natural or artificial banks of a stream, river, estuary, lake or dam.
Major Drainage	"Councils have discretion in determining whether urban drainage problems are associated with major or local drainage. For the purposes of this manual major drainage involves: The floodplains of original watercourses (which may now be piped, channelised or diverted), or sloping areas where overland flows develop along alternative paths once system capacity is exceeded; and/or Water depths generally in excess of 0.3m (in the major system design storm as defined in the current version of Australian Rainfall and Runoff). These conditions may result in danger to personal safety and property damage to both premises and vehicles; and/or Major overland flow paths through developed areas outside of defined drainage reserves; and/or The potential to affect a number of buildings along the major flow path."
Managed Berm Level	Level at which the sand berm is managed by Council to prevent continuous build up to levels that may exacerbate flood risk to residents around the lagoon.
Minimum Floor Level (MFL)	Minimum floor level at which a building should be constructed. Also named Flood Hazard Level (FHL).
Minor, Moderate and Major Flooding	Both the State Emergency Service and the Bureau of Meteorology use the following definitions in flood warnings to give a general indication of the types of problems expected with a flood. Minor flooding: Causes inconvenience such as closing of minor roads and the submergence of low-level bridges. The lower limit of this class of flooding on the reference gauge is the initial flood level at which landholders and townspeople begin to be flooded. Moderate flooding: Low lying areas are inundated requiring removal of stock and/or evacuation of some houses. Main traffic routes may be covered. Major flooding: Appreciable urban areas are flooded and/or extensive

	rural areas are flooded. Properties, villages and towns can be isolated.
Modification Measures	Measures that modify either the flood, the property or the response to flooding.
Peak Discharge	The maximum discharge occurring during a flood event.
Probability	A statistical measure of the expected chance of flooding (see annual exceedance probability).
Probable Maximum Flood (PMF)	The PMF is the largest flood that could conceivably occur at a particular location, usually estimated from probable maximum precipitation, and where applicable, snow melt, coupled with the worst flood producing catchment conditions. Generally, it is not physically or economically possible to provide complete protection against this event. The PMF defines the extent of flood prone land, that is, the floodplain. The extent, nature and potential consequences of flooding associated with a range of events rarer than the flood used for designing mitigation works and controlling development, up to and including the PMF event should be addressed in a floodplain risk management study.
Probable Maximum Precipitation (PMP)	The PMP is the greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends (World Meteorological Organisation, 1986). It is the primary input to PMF estimation.
Quadtree	In the context of the TUFLOW software, Quadtree allows for the fixed grid mesh underlying the model to vary in cell size, enabling higher resolutions where more refined hydraulic calculations are needed, and lower resolutions where there is little variation in topography or less detail is required.
Risk	Chance of something happening that will have an impact. It is measured in terms of consequences and likelihood. In the context of the manual, it is the likelihood of consequences arising from the interaction of floods, communities and the environment.
Runoff	The amount of rainfall which actually ends up as streamflow, also known as rainfall excess.
Seiche	A temporary disturbance or oscillation in the water level of a lake or partially enclosed body of water, often caused by changes in atmospheric pressure or wave energy
Stage	Equivalent to water level (both measured with reference to a specified datum).
Stage Hydrograph	A graph that shows how the water level at a particular location changes with time during a flood. It must be referenced to a particular datum.
Survey Plan	A plan prepared by a registered surveyor.
TUFLOW	A 1-dimensional and 2-dimensional flood simulation software. It simulates the complex movement of floodwaters across a particular area of interest using mathematical approximations to derive information on floodwater depths, velocities and levels.

Velocity	The speed or rate of motion (distance per unit of time, e.g., metres per second) in a specific direction at which the flood waters are moving.
Water Surface Profile	A graph showing the flood stage at any given location along a watercourse at a particular time.
WBNM	Watershed Bounded Network Model. The WBNM is a conceptual, event-based, model developed for simulation of flood hydrographs and estimation of design floods