1 INTRODUCTION

The Pambula River, Pambula Lake and Yowaka River catchment covers an area of over 300 square kilometres within the Bega Valley Council Local Government Area (LGA). As shown in **Figure 1**, the catchment extends across forested and rural areas, as well as the villages of Pambula, South Pambula, Pambula Beach, Broadwater, Greigs Flat, Nethercote and Lochiel.

During periods of heavy rainfall in the catchment there is potential for water to overtop the banks of the various creeks and rivers and inundate the adjoining floodplain, including parts of the villages identified above. Flooding has been experienced across the catchment on a number of occasions including 1970, 1971, 1973, 1978, 1983 and 1985, as well as more recent events in 2011, 2012 and 2016. The 1971 event is the largest flood on record.

Flooding across the catchment has the potential to result in damage to property and vehicles and may pose a risk to life during large floods. In addition, flooding can overtop major transportation links within the catchment including the Princes Highway, Nethercote Road, Mount Darragh Road and Back Creek Road, which can inconvenience and isolate many individuals and families.

Accordingly, Bega Valley Shire Council engaged Catchment Simulation Solutions to prepare a flood study for the Pambula River, Pambula Lake and Yowaka River catchment. It documents flood behaviour across the catchment for a range of historic and design floods. This includes information on flood discharges, levels, depths and flow velocities. It also provides estimates of the variation in flood hazard and provides an assessment of the potential impacts of climate change on existing flood behaviour.

The flood study comprises two volumes:

- Volume 1 (this document): contains the report text and appendices
- Volume 2: contains all figures and maps

The flood study forms the first stage in the development of a floodplain risk management plan for the Pambula River, Pambula Lake and Yowaka River catchment. This plan will, amongst other goals, aim to reduce the impact of flooding on the community and ensure that future development is compatible with the flood risk and does not create additional flooding problems.

2 CATCHMENT DESCRIPTION

The Pambula River, Pambula Lake and Yowaka River catchment is located in south-eastern New South Wales and occupies a total catchment area of 301 km^2. The catchment is fully contained within the Bega Valley Shire Council Local Government area. The extent of the catchment is shown in **Figure 1**.

The upper sections of the catchment are typically heavily forested with scattered rural residential development. However, the downstream sections of the catchment include more extensive urban development including the villages of Pambula, South Pambula, Pambula Beach, Broadwater, Greigs Flat, Nethercote and Lochiel. **Table 1** provides a summary of the different land uses across the catchment based on current land use zoning information contained within the Bega Valley Shire Council Local Environmental Plan 2013.

Table 1 Summary of Catchment Land Use based on Bega Valley Shire LEP 2013

Land Use	Area (km^2)	Percentage of Catchment
Rural	176.8	58.7%
Forest/Environmental	116.5	38.7%
Natural Waterways	3.8	1.3%
Residential	1.7	0.6%
Industrial	1.7	0.6%
Commercial/Business	0.2	0.1%
Special Activities	0.2	0.1%
Public Recreation	0.2	0.1%
TOTAL	301.1	100

The two primary watercourses in the catchment are the Pambula River and Yowaka River, which both drain into Pambula Lake near the Broadwater area. The Pambula Lake estuary, in turn, drains into the Tasman Sea near Pambula Beach via a permanently open entrance. The tidal limit extends upstream along the Pambula River to the Princes Highway and along the Yowaka River to Greigs Flat. Other major watercourses contained within the catchment include:

- Back Creek;
- Burtons Creek;
- Harts Gully; and,
- Old Hut Creek;

As shown in the digital elevation model (DEM) in **Figure 2**, the upper sections of the catchment comprise steep terrain with incised creek channels and minimal overbank/floodplain areas. However, the downstream sections of the catchment are characterised by a much broader floodplain and are commonly fringed by the villages described above.

The catchment is also traversed by several important transportation routes. This includes "local collector" roads (Back Creek Road and Nethercote Road), regional roads (Mount Darragh Road) as well as the Princes Highway which is the major transportation route between Pambula and the major adjoining towns of Eden, Merimbula and Bega. Many of watercourses within the catchment cross each of these roadways at multiple locations. As shown on the front cover of this report as well as **Plate 1** to **Plate 3**, the Princes Highway between Pambula and South Pambula is particularly susceptible to inundation which can create significant disruptions to traffic. In years gone by, inundation of the Princes Highway was considered to be a "regular, almost annual" event (George, 2012).

The focus of the current study is the lower, more developed sections of the catchment as well as areas what may be subject to development pressures in the future. Defining flood characteristics in the vicinity of each major roadway was also a key focus of the study.

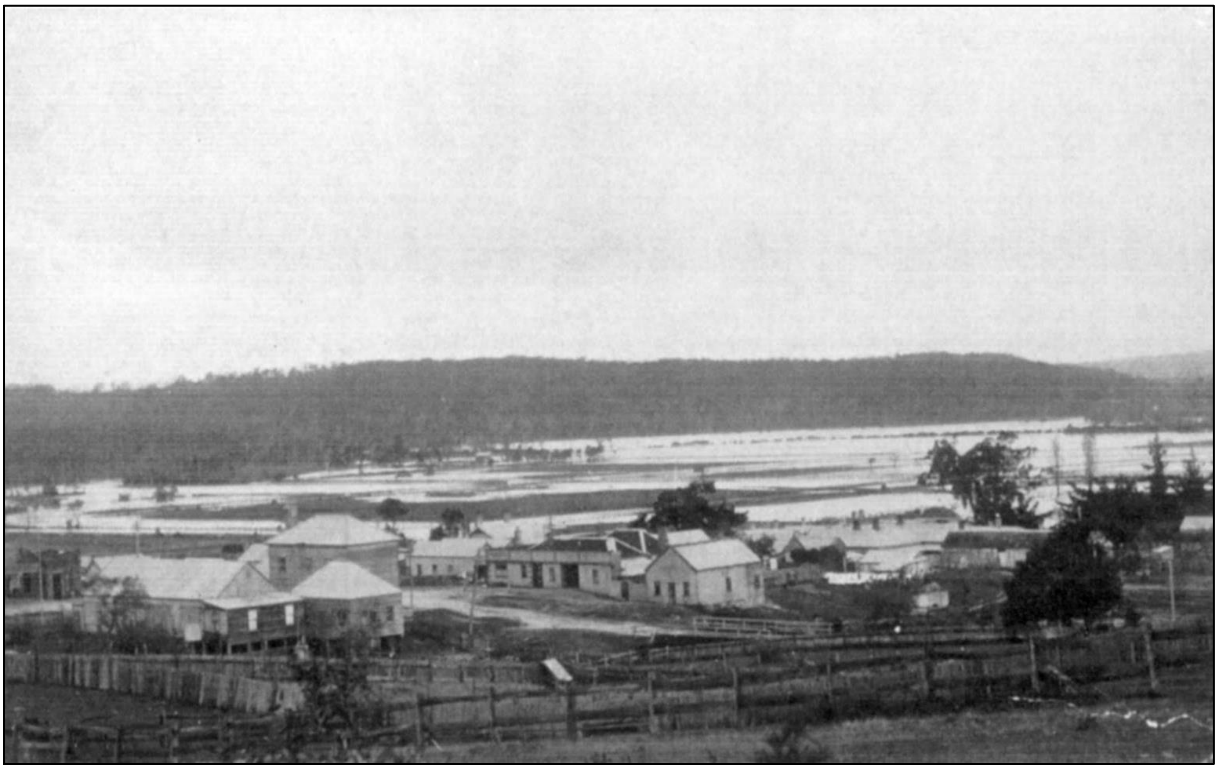


Plate 1 View looking from near the top of Monaro Street at Pambula looking north (date unknown)

Plate 2 View looking north from Pambula along Princes Highway showing flooding (date unknown) (photo courtesy of Dulcie's Cottage)

Plate 3 View looking from old Princes Highway bridge crossing of Pambula River taken during the 1971 flood (Photo © The estate of A. C. ("Bubby") George)

3 PROJECT METHODOLOGY

3.1 Study Objectives

Bega Valley Shire Council outlined a range of objectives for the Pambula River, Pambula Lake and Yowaka River catchment flood study. This included:

- to review available flood-related information and historic flood data for the catchment;
- to consult with the community to gain an understanding of flooding and drainage 'trouble spots' and gather information on past floods;
- to collect additional information to define the flow carrying capacity of the various creeks, rivers, stormwater pipes, bridges and culverts;
- to develop a computer-based hydrologic flood model to simulate the transformation of rainfall into runoff
- to develop a computer based hydraulic model to simulate the movement of runoff across the catchment;
- to validate the computer models against observed information on past floods;
- to use the validated computer models to estimate flood discharges, water levels, depths and velocities for the design 10%, 5%, 2%, 1%, 0.5% and 0.2% AEP floods as well as the probable maximum flood (PMF);
- to produce maps showing predicted floodwater depths, levels and velocities for the full range of design floods;
- to produce maps showing flood hazard and flood function (i.e., hydraulic categories) for the 5%, 1% and 0.2% AEP floods and the PMF;
- to produce emergency response precinct classification and roadway inundation mapping to assist the State Emergency Service with emergency response planning;
- to quantify the potential impact of climate change on existing design flood behaviour;
- to quantify the potential impact of future development on existing flood behaviour; and
- to provide information to assist with land use planning activities.

3.2 Adopted Approach

The general approach and methodology employed to achieve the study objectives involved:

- compilation and review of available flood-related information, collection of additional data and consultation with the community (Chapter 4);
- the development of a hydrologic model to simulate the transformation of rainfall into runoff and development of a hydraulic model to simulate the movement of floodwaters across the catchment (Chapter 5);
- validation of the computer models to reproduce historic floods (Chapter 6);
- use of the computer models to estimate "design" discharges, water levels, depths, flow velocities and flood extents for the full range of design events up to and including the PMF for existing topographic and development conditions (Chapter 7);

- use of the computer model results to generate flood hazard and flood function mapping as well as flood emergency response classifications (Chapter 8);
- testing the sensitivity of the results generated by the computer model to variations in model input parameters, future development and climate change (Chapter 9); and,
- use of computer model outputs and sensitivity analysis results to provide flood planning information (Chapter 10).

4 DATA COLLECTION AND REVIEW

4.1 Overview

A range of data was made available to assist with the preparation of the Pambula River, Pambula Lake and Yowaka River catchment flood study. This included:

- Previous reports: Section 4.2
- Rainfall and stream gauge data: Section 4.3
- Survey information: Section 4.4
- GIS data: Section 4.5
- Plans: Section 4.6

A description of each dataset and a synopsis of its relevance to the study is summarised below.

Consultation with the community was also completed to source additional information on historic floods and help identify flooding trouble spots. The outcomes of the community consultation is summarised in Section 4.9.

4.2 Previous Reports

4.2.1 Floods of February 1971 on the South Coast (1976)

The 'Flood of February 1971 on the South Coast' report was published by the Water Resources Commission of NSW. It describes the processes leading up to and the consequences of significant flooding that occurred across south-eastern NSW over a 2-week period in January and February 1971. At many locations it was the largest flood on record, including the Bega River and Towamba River basins. The Pambula River and Yowaka River catchments are considered to fall within the Towamba River basin.

The report provides information on antecedent catchment conditions and storm/rainfall characteristics. This includes rainfall isohyets maps which show the following rainfall characteristics in the vicinity the Pambula River, Pambula Lake and Yowaka River catchment:

- <u>28 January to 3 February 1971</u>: 5 to 7 inches of rainfall;
- <u>3 February to 8 February 1971</u>: 12 to 18 inches of rainfall (with around 6 inches falling on 5 February);

It also documents stream flow observations, peak flood levels at major gauges and stream crossings, and summarises flood damages incurred. The report notes the following details for the Pambula River gauge at Lochiel:

- Peak water height = 50.5-feet (previous maximum = 14.7-feet in 1970);
- Peak discharge = 15,000 ft^3/s (previous maximum = 6,200 ft^3/s)

Although the report does not provide any specific information on flood impacts across the catchment, the rainfall and stream flow information could be used to assist in the calibration of the hydrologic and hydraulic models developed as part of the current study.

4.2.2 Bald Hills Creek Flood Study (1983)

The 'Bald Hills Creek Flood Study' was prepared in 1983 by Willing & Partners for Mr John Norton. The report was prepared to quantify flood behaviour along the lower reaches of Bald Hills Creek for the 1 in 100 year ARI flood.

Bald Hills Creek drains into Merimbula Lake and is, therefore, located outside of the Pambula River, Pambula Lake and Yowaka River catchment. In addition, flood behaviour was defined using superseded hydrologic procedures (i.e., 1977 version of Australian Rainfall and Runoff) and modelling tools. As a result, it is considered that this study affords negligible information that can be used to assist the current study.

4.2.3 Pambula River Data Assessment Study (1990)

The 'Pambula River Data Assessment Study' was prepared in 1990 on behalf of Bega Valley Shire Council. Council, at that time, were considering preparing a flood study for the Pambula and Yowaka River catchments in response to development pressure in the catchment. As a result, Council engaged the NSW Public Works Department to compile all available flood related information to facilitate the preparation of the flood study.

The data assessment study includes a summary of known historic floods including newspaper extracts dating back to 1851. It also includes a range of historic rainfall information for the 1970, 1971, 1973, 1978, 1983 and 1985 events. This includes daily totals, hourly totals (from pluviographs), rainfall mass curves and isohyet maps.

Streamflow information is also provided for the stream gauge located on the Pambula River at Lochiel. It notes that the gauge measures water levels only and the water levels are converted to an equivalent flow using a rating table/curve. The report notes that the highest recorded rating corresponded to a flow of 12,980 ML/day (i.e., 150 m^3/s), which is well below the estimated peak discharges for the majority of historic floods (e.g., the 1971 estimated peak discharge was 823 m^3/s). As a result, the flow estimates at higher stages are subject to some uncertainty.

Recorded/surveyed historic flood levels were also provided for a number of floods. This included 17 flood marks for the November 1985 flood and 11 other flood marks for a range of other floods. The location of the flood marks is shown on **Figure 3**.

The report also includes surveyed cross-sections of the Pambula River that were collected in 1985 by consulting surveyors Ryan Firth and Company. The location of each cross-section is shown in **Figure 3**.

Although the data assessment study does not document more recent floods, it provides a significant amount of historic flood information for floods that occurred in the 1970s and 1980s which can be used in calibrating the computer flood models for the current study. It also provides information that can be used to assist with the development of the hydraulic computer model (e.g., river cross-sections).

4.2.4 Bridge Over Pambula River at Pambula (2004)

The 'Bridge Over Pambula River at Pambula' was prepared to support the upgrade of the Princes Highway between Pambula and South Pambula. In particular, the study focussed on assessing the potential impacts associated with three different upgrade options reflecting a 1 in 5, 1 in 10 and 1 in 20 year ARI level of service. The report notes that the existing highway (at that time) was predicted to be overtopped in a 1 in 2 year ARI flood.

The report includes photographs showing floodwaters in the vicinity of the Princes Highway in 1990 and 1992. A selection of these photographs are provided in **Plate 4** and **Plate 5**. The report estimates the 1990 floods was a 1 in 5 year (20% AEP) flood that closed the highway at that time from Friday afternoon until noon on Saturday. The 1992 flood was estimated to be a 1 in 20 year ARI (5% AEP) flood. The depth indicator on the left side of **Plate 5** indicates a water depth across the highway of just over 0.2 metres. However, as noted in the report, this photograph may not have been taken at the peak of the flood.

Peak discharges for the Pambula River were determined based upon a flood frequency analysis that was completed at the Pambula River @ Lochiel gauge, which is situated about 3 km upstream of the Princes Highway. The discharges where subsequently factored up based on the additional catchment area located between the gauge and the highway. The adopted design discharges at the highway are summarised in **Table 2**.

Table 2 Peak Design Discharges for Pambula River at Princess Highway (2004)

Design Event	Peak Discharge (m^3/s)	
	Lochiel Gauge	Princess Hwy
5 year ARI (20% AEP)	347	410
10 year ARI (10% AEP)	451	533
20 year ARI (5% AEP)	556	657
50 year ARI (2% AEP)	731	864
100 year ARI (1% AEP)	868	1026

Flood hydraulics were defined using a 1-dimensional HEC-RAS model that was developed using the cross-sections documented in the 'Pambula River Data Assessment Study' (1990) and shown in **Figure 3**, as well as detailed ground survey that was collected in the immediate vicinity of the highway.

The HEC-RAS model was calibrated against historic flood information for the 1985 flood (also extracted from the 1990 data assessment study). The HEC-RAS model was subsequently used to simulate a range of design floods. Simulated design floods levels in the vicinity of the Princes Highway are reproduced in **Table 3**.

It is understood that the 1 in 5 year ARI highway upgrade option was ultimately adopted and implemented in 2006. Plans of the upgraded bridge and culvert crossings of the Pambula River floodplain were acquired from the RTA/RMS (now Transport for NSW) and are discussed further in Section 4.6.

Plate 4 View looking south along Princes Highway during 1990 flood (RTA, 2004)

Plate 5 View looking south along Princes Highway during 1992 flood (RTA, 2004)

Table 3 Peak Design Flood Levels for Pambula River at Princes Highway (2004)

Design Event	Peak Flood Level (mAHD)			
	Existing	Proposed 1 in 5 year road	Proposed 1 in 10 year road	Proposed 1 in 20 year road
5 year ARI (20% AEP)	3.40	3.34	-	-
10 year ARI (10% AEP)	3.50	-	3.42	-
20 year ARI (5% AEP)	3.60	-	-	3.60
100 year ARI (1% AEP)	4.30	-	-	-

Overall, the results documented in this study were found to be useful in validating the results of the hydrologic model/flood frequency analysis and hydraulic model prepared for the current study.

4.2.5 Pambula River Estuary - Data Compilation Study (2008)

The 'Pambula River Estuary – Data Compilation Study' was prepared by NGHenvironmental on behalf of Bega Valley Shire Council as the first step in the preparation of an estuary processes study (refer Section 4.2.6). Although many of the datasets collated for estuary process purposes are not required as part of a typical flood study (e.g., water quality), some information was of benefit.

Most notably, bathymetric/hydrographic survey that was collected in 2003 by the then Department of Infrastructure Planning and Natural Resources is documented. The extent of the hydrographic survey is shown in **Figure 3** and further discussion on this dataset is provided in Section 4.4.3. The study notes that no other hydrographic survey is available for the Pambula River Estuary to define historic bathymetric conditions.

The report notes that the tides within the lake exhibit a semi-diurnal pattern that is dominated by oceanic processes. It also notes that the tidal range reduces from 1.55m at the ocean entrance to 1.04m in the upper Yowaka River and 0.68m in the upper Pambula River. Accordingly, catchment runoff is going to be the more dominant flooding mechanism moving upstream.

The report includes a small section dedicated to flooding, but this mainly references the 1990 data compilation study discussed above.

Overall, most of the information contained in this report is either not relevant or can be sourced from other reports. Nevertheless, the tidal information provides an understanding of the potential interaction between tidal and catchment runoff processes which was used to assist in establishing reliable ocean level boundary conditions as part of the design flood simulations.

4.2.6 Pambula River Estuary Processes Study (2012)

The 'Pambula River Estuary Processes Study' was prepared by Cardno for Bega Valley Shire Council. It builds upon the 'Pambula River Estuary – Data Compilation Study' (2008) to describe the various natural processes that characterise the Pambula River estuary.

Like the data compilation study, much of the content of this report is not of relevance to the current flood study. However, Section 5 of the report discusses hydraulic processes. The report also provides tidal plane characteristics for the estuary as well as the ocean (as defined by an ocean tide gauge at Eden), as summarised in **Table 4**.

Table 4 Tidal Plane Characteristics (2004)

Tidal Plane	**Water Level** (mAHD)	
	Pambula River Estuary	**Ocean Level (at Eden)**
High-High Water (Solstice Spring)	0.75	0.83
Mean High Water Spring	0.42	0.43
Mean High Water	0.32	0.32
Mean Sea Level	-0.06	0.00
Mean Low Water	-0.44	-0.60
Mean Low Water Spring	-0.54	-0.71
Indian Spring Low Water	-0.78	-0.99

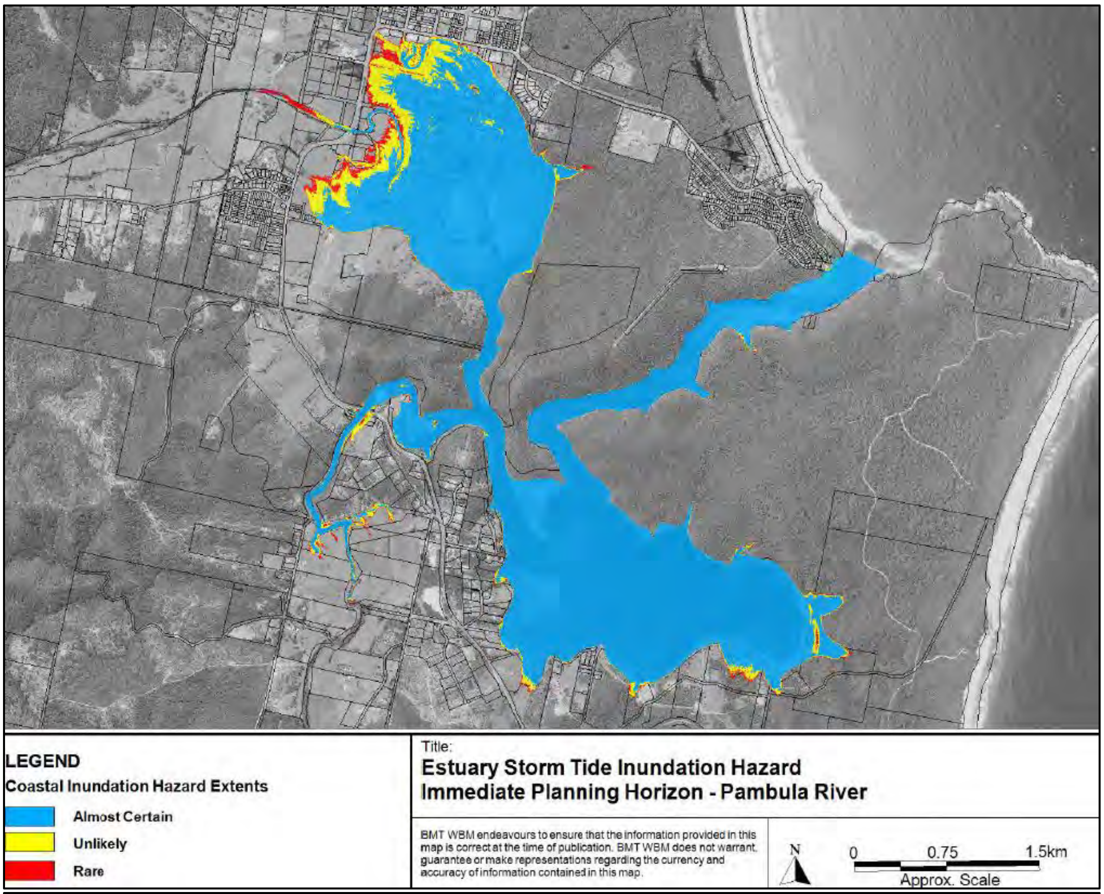
The study notes that, based on an analysis of historic tide information over the past 20 years, the tidal range for the estuary appears to be reducing resulting in gradual infilling of the entrance channel. It also states that significant scouring of the entrance channel only occurs during floods in excess of the 10 year ARI.

Although the study focusses on natural estuarine processes that are largely not relevant to flooding processes, the tidal information presented in this report is useful for assisting with the establishment of suitable ocean boundary conditions as part of the design flood simulations.

4.2.7 Bega Valley Shire Coastal Processes and Hazards Definition Study (2015)

The 'Bega Valley Shire Coastal Processes and Hazards Definition Study' was prepared by BMT WBM for Bega Valley Shire Council. The study was prepared to provide Council with a regional understanding of the potential hazards impacting on the coastal sections of the LGA.

The study included an assessment of potential coastal inundation extents. This assessment noted that for estuaries such as Pambula River/Pambula Lake, inundation associated with elevated ocean levels are impacted by the prevailing storm tide elevation (including the astronomical tide plus storm surge) as well as wave setup. A series of maps was subsequently prepared showing modelled inundation extent across the various estuaries for a range of planning timeframes including current/immediate, 2050 and 2100 for a range of different certainty levels (reflecting the uncertainties associated with future inundation estimates). An extract of the mapping is provided in **Plate 6** for the Pambula River estuary.



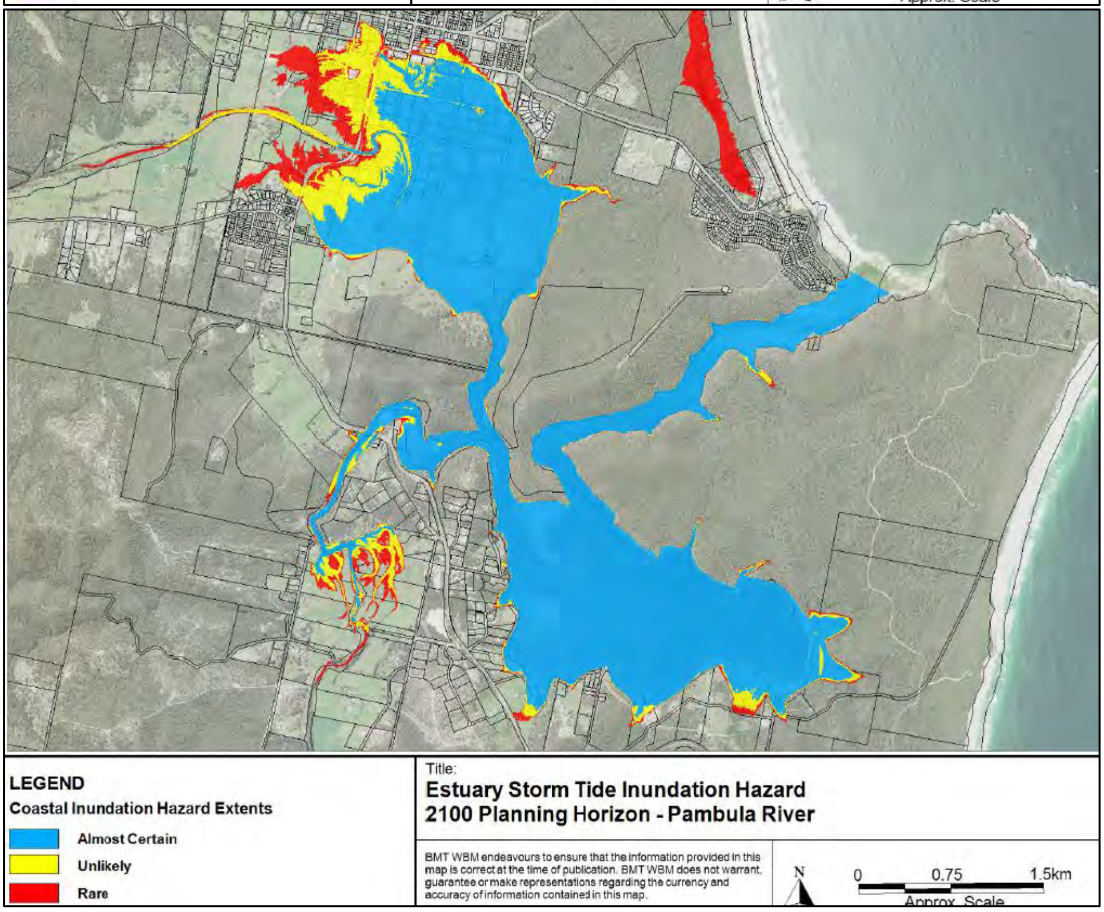


Plate 6 Coastal inundation maps for existing (top) and 2100 (bottom) timeframes (BMT, 2015)

The mapping provided in **Plate 6** shows inundation associated with elevated ocean levels extends across the Panboola wetlands and up to Bullara Street and just past the Princes Highway for existing conditions. Under 2100 conditions, coastal inundation potentially extends across Bullara Street, Monaro Street and the Princes Highway. Accordingly, elevated ocean levels have the potential to directly inundate low lying sections of the catchment even without rainfall in the catchment. Elevated ocean levels can also restrict or prevent water from draining from the catchment during heavy rainfall events, thereby exacerbating flooding. Although not considered as part of this study, this outcomes shows that the interaction between catchment runoff and coastal inundation is an important consideration of the current study, particularly when considering potential future flooding scenarios.

4.2.8 Merimbula and Back Lake Flood Study (2017)

The 'Merimbula and Back Lake Flood Study' was prepared by Cardno for Bega Valley Shire Council. The study was prepared to define the nature and extent of the existing flooding problem for the primary waterways draining the Merimbula urban area (i.e., Merimbula Lake and Back Lake and their tributaries). Due to its proximity to the current study area and the similar catchment outlet characteristics, the report contains information that can be transposed and used to assist with the current study.

As noted in the previous section, inundation can occur across the lower lying sections of the Pambula River and Yowaka River catchment as a result of elevated ocean levels only. This is also true for the Merimbula area. As a result, several "tide only" simulations were completed to assess tidal inundation extents for existing conditions as well as 2050 and 2100 sea level rise projections. Existing peak tide levels were based upon the High High Water Solstice Spring (HHWSS) level calculated at the Merimbula Wharf gauge. For each of the future sea level rise scenarios (i.e., 0.4m increase by 2050 and 0.9m increase by 2100), two simulations were completed assuming the entrance bed remained at the current elevations and another assuming the entrance bed level increased at the same rate as ocean levels.

As discussed, the interaction between catchment runoff and elevated ocean levels can have a significant impact on flood behaviour across tidally influenced areas. The potential interaction of joint catchment flooding and elevated ocean level inundation was considered based on guidance in the *'Floodplain Risk Management Guide. Modelling the Interaction of Catchment Flooding and Oceanic Inundation in Coastal Waterways' (OEH, 2015)*. This involved undertaking a range of catchment runoff and ocean level simulations and "enveloping" the results to provide a final result set for each design flood. The ocean levels summarised in **Table 5** were used as part of the design simulations. The timing of the simulations was setup such that the peak catchment outflow coincided with the peak ocean level. However, it should be noted that the hydrologic approach employed as part of this study was based on the 1987 version of Australian Rainfall & Runoff, rather than the 2019 version which reflects modern best practice (although sensitivity testing was completed using the 2016 version of Australian Rainfall & Runoff, which was in its infancy at the time this study was prepared).

Overall, this study is considered to reflect modern best practice with regard to representing the interaction between coastal and catchment flooding and a similar approach is appropriate for application as part of the current study.

Table 5 Adopted Ocean Level Boundary Conditions (Cardno, 2017)

Design Flood	**Ocean Level** (mAHD)
1% AEP	1.45
5% AEP	1.37
10% AEP	1.35
1 exceedance per year	1.25
Highest astronomical tide (HAT)	1.10

4.3 Hydrologic Data

4.3.1 Rain Gauge Data

A number of daily read and continuous (i.e., pluviometer) rainfall gauges are located within or adjacent to the Pambula River catchment. The location of each gauge is shown in **Figure 4**. Key information for each daily gauge is provided in **Table 6** and key information for each continuous rainfall gauge is summarised in **Table 7**.

The information provided in **Table 6** indicates that daily rainfall records in the vicinity of the study area are available dating back to 1890 (Wyndham Post Office gauge). However, **Table 7** shows that long term continuous rainfall records are only available from 1967 onwards and this gauge is located a significant distance south of the catchment (Green Cape Lighthouse). However, the Pambula River at Lochiel gauge is contained within the catchment and comprises continuous rainfall records extending back to 2009.

4.3.2 Stream Gauge Data

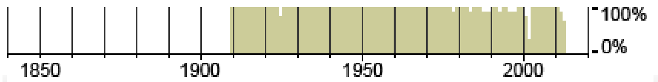
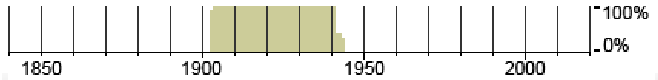
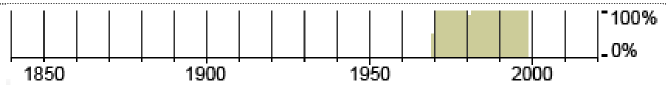
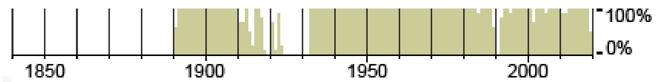
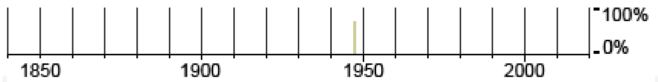
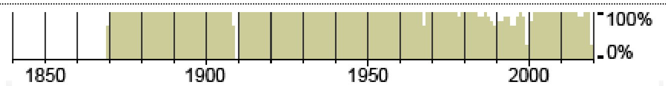
Figure 2 also shows the location of stream and water level gauges located in the vicinity of the catchment. Key information for each gauge is summarised in **Table 8**.

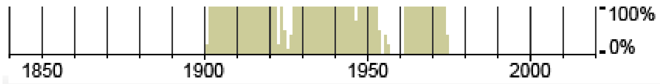
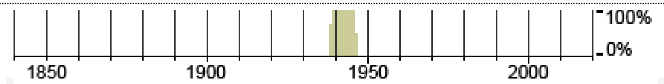
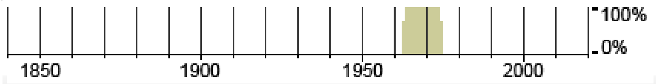
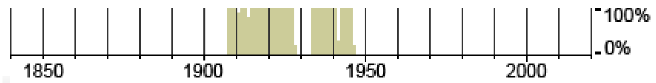
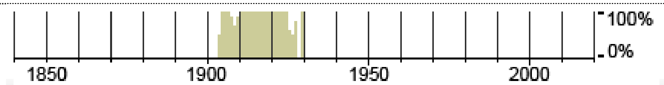
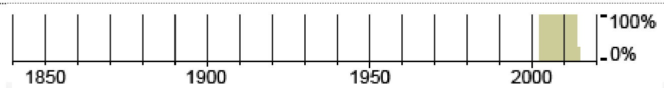
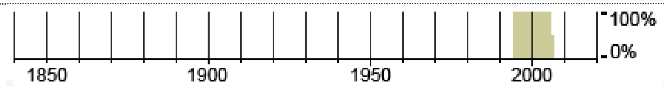
As shown in **Figure 2**, there are two stream gauge located within the catchment. This includes:

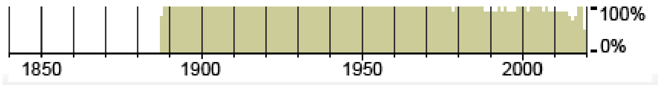
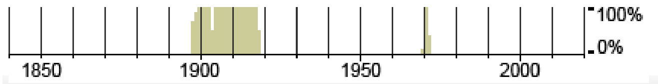
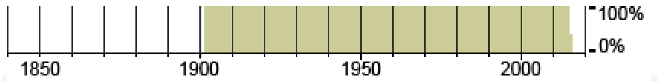
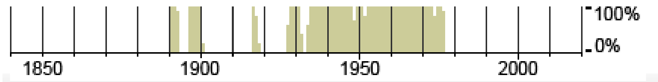
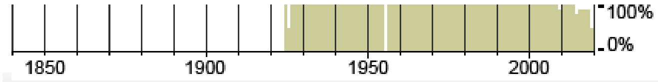
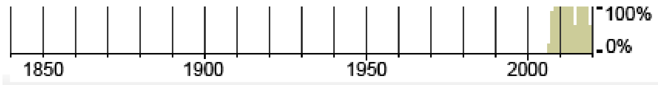
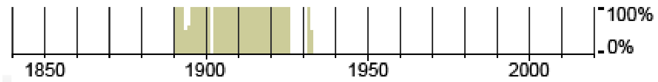
- Pambula River at Lochiel (gauge 220003): provides water levels and stream flow information (flows are estimated using water level information in conjunction with a rating curve);
- Pambula Lake (gauge 220415): provides water level information only.

As noted above, flow information for the Pambula River gauge at Lochiel is estimated using a rating curve/table. A copy of the most recent rating curve is provided in **Plate 7**. **Plate 7** also shows all "ratings" (i.e., water level and corresponding flow information collected at the gauge) that have been captured since the gauge was installed in 1966. The quality of the flow estimates is highly dependent on the quality, range of and number of ratings that have been collected. Although **Plate 7** shows considerable "scatter" of ratings at low flows, there is a considerably greater agreement at higher flows, which are of most interest for the current flood study. Unfortunately, the highest rating that has been collected corresponds to a peak gauge level of around 3 metres, which is well below the maximum recorded gauge level (6.81 metres). Accordingly, there is some uncertainty associated with flow estimates above the maximum gauging level.

Table 6 Available daily rain gauges

Gauge Number	Gauge Name	Gauge Type	Source*	Start of Records	End of Records	Distance from Centroid of Catchment (km)	Temporal Availability and Percentage of Annual Record Complete
069153	Lochiel (Carisbrook Farm)	Daily	BOM	Aug 2007	Jun 2019	1.28	
069024	Pambula Post Office	Daily	BOM	Jan 1909	Oct 2012	7.79	
069078	Nethercote	Daily	BOM	Feb 1902	Nov 1943	10.91	
069147	Merimbula Airport Aws	Daily	BOM	Feb 1998	Jul 2019	10.93	
069093	Merimbula Airport Comparison	Daily	BOM	Aug 1969	Dec 1998	10.94	
069011	Wyndham (Nyumbani)	Daily	BOM	Nov 2000	May 2010	11.75	
069066	Wyndham Post Office	Daily	BOM	Jun 1890	Jun 2019	14.22	
069109	Edrom	Daily	BOM	May 1947	Dec 1947	14.71	
069100	Dovewood	Daily	BOM	Jun 1968	Oct 1985	15.19	
069015	Eden (Marine Rescue Eden)	Daily	BOM	May 1869	Mar 2019	15.62	

Gauge Number	Gauge Name	Gauge Type	Source*	Start of Records	End of Records	Distance from Centroid of Catchment (km)	Temporal Availability and Percentage of Annual Record Complete
069073	Towamba (Nungatta St)	Daily	BOM	Jul 1976	Mar 2016	16.33	
069012	Burragate Post Office	Daily	BOM	Nov 1900	May 1974	17.1	
069009	Boyd East State Forest	Daily	BOM	May 1938	Jun 1946	17.14	
069151	Tura Beach (James Cook Court)	Daily	BOM	Apr 2006	Dec 2013	17.32	
069057	Towamba Lower	Daily	BOM	May 1962	Dec 1974	17.57	
069030	Toothdale	Daily	BOM	Feb 1907	Mar 1946	18.47	
069096	Chip Mill	Daily	BOM	Feb 1971	Feb 1974	18.84	
069083	Wolumla	Daily	BOM	Aug 1903	Dec 1929	19.39	
069110	Towamba (Rosebank)	Daily	BOM	May 1971	Dec 2001	20.69	
069069	Kanoona (Tillside)	Daily	BOM	Jan 2002	Mar 2014	22.81	
069146	Kanoona (Brindabella)	Daily	BOM	Jan 1994	Jun 2006	23.76	

Gauge Number	Gauge Name	Gauge Type	Source*	Start of Records	End of Records	Distance from Centroid of Catchment (km)	Temporal Availability and Percentage of Annual Record Complete
069013	Candelo Post Office	Daily	BOM	Apr 1887	Jun 2019	23.91	
069080	Pericoe	Daily	BOM	May 1897	Apr 1971	24.13	
069107	Kameruka (Kameruka Estate)	Daily	BOM	Jan 1901	Apr 2015	26.49	
069026	Rocky Hall Post Office	Daily	BOM	Jan 1890	Oct 1976	26.77	
069144	Black Range (Grandview Lane)	Daily	BOM	Dec 2014	Jul 2019	27	
069019	Cathcart (Mount Darragh)	Daily	BOM	Jan 1924	Jun 2019	28.02	
069152	Mount Darragh	Daily	BOM	Nov 2006	Jul 2019	28.34	
069077	Kingswood	Daily	BOM	Jan 1890	May 1932	30.82	

NOTE: * BOM = Bureau of Meteorology, SW = Sydney Water, SCA = Sydney Catchment Authority

Table 7 Available continuous rain gauges

Gauge Number	Gauge Name	Gauge Type	Source*	Start of Records	End of Records	Distance from Centroid of Catchment (km)	Timestep	Data Completeness
220003	Pambula River at Lochiel	Continuous	WaterNSW	April 2009	Aug 2019	2	Irregular	92%
069147	Merimbula Airport Aws	Pluvio	BOM	Sep 2010	Jul 2019	11	1 minute	83%
220410	Merimbula Wharf	Continuous	DPIE	Aug 1997	Sep 2001	12	15 minute	100%
069066	Wyndham Post Office	Pluvio	BOM	Jan 1993	May 2013	14	6 minute	85%
069015	Eden (Marine Rescue Eden)	Pluvio	BOM	Apr 1965	Dec 1966	16	6 minute	81%
069137	Green Cape Aws	Pluvio	BOM	Sep 2011	Jul 2019	39	1 minute	50%
069055	Green Cape Lighthouse	Pluvio	BOM	Mar 1967	May 2002	40	6 minute	57%

NOTE: * BOM = Bureau of Meteorology, DPIE = Department of Planning, Industry and Environment

Table 8 Available stream and water level gauges

Gauge Number	Gauge Name	Source*	Dataset Time Increments	Start of Records	End of Records	Located with study area?
220003	Pambula River at Lochiel	WaterNSW	Irregular	Aug 1966	Jul 2019	Yes
220415	Pambula Lake	DPIE	15 minute	Mar 1991	Aug 2019	Yes
219415	Back Lagoon	DPIE	15 minute	Feb 2009	Aug 2019	No
220410	Merimbula Wharf	DPIE	15 minute	Mar 1991	Aug 2019	No
220405	Merimbula Lake	DPIE	15 minute	May 1991	Aug 2019	No
220420	Lake Curalo	DPIE	15 minute	Jun 2007	Aug 2019	No
220470	Eden	DPIE	15 minute	Sep 1986	Aug 2019	No

NOTE: * DPIE = Department of Planning, Industry and Environment

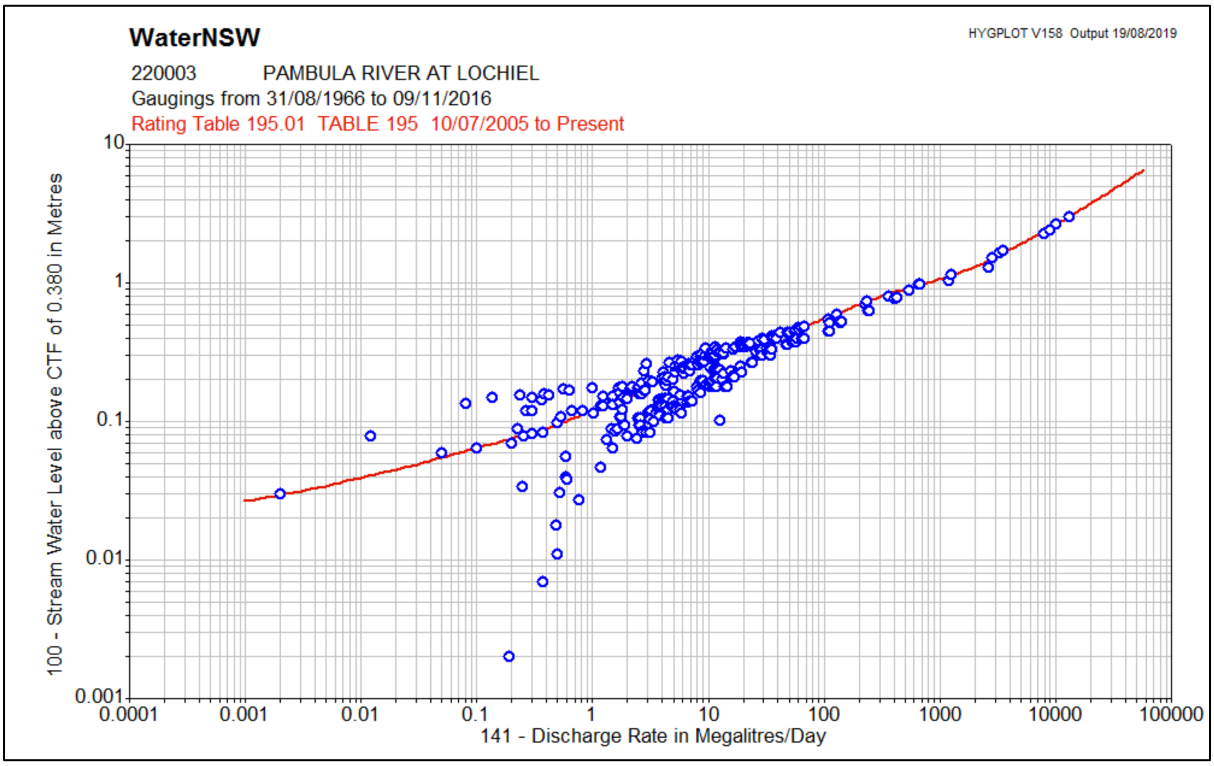


Plate 7 Rating curve (red) and recorded ratings (blue) for Pambula River at Lochiel stream gauge

4.4 Topographic and Hydrographic Information

The following topographic and hydrographic (i.e., bathymetric) datasets were provided for use in defining the variation in ground and river bed elevations across the catchment:

- 2013 Light Detection and Ranging (LiDAR) survey
- 2018 LiDAR survey
- 2003 Hydrographic Survey

Further detailed information on each topographic dataset is provided below.

4.4.1 2013 LiDAR Survey

LiDAR data was collected across part sections of the catchment in March 2013 by the NSW Government's Land and Property Information Department. The extent of the 2013 LiDAR coverage is shown in **Figure 3**. As shown in **Figure 3**, the 2013 LiDAR extends across the eastern sections of the catchment.

The LiDAR has a stated absolute horizontal accuracy of better than 0.8 metres and an absolute vertical accuracy of better than 0.3 metres and provides a minimum point density of 1.02 elevation points per square metre.

The 2013 LiDAR generally provides a good representation of the variation in ground surface elevations across the eastern parts of the catchment. However, LiDAR datasets can provide a less reliable representation of the terrain in areas of high vegetation density. This is associated with the laser ground strikes often being restricted by the vegetation canopy. Errors can also arise if non-ground elevation points (e.g., vegetation canopy, buildings) are not correctly removed from the raw dataset.

Plate 8 provides an example of the 2013 LiDAR ground points in the vicinity of Oregon and Monaro Streets at Pambula. **Plate 8** shows a high LiDAR point density across grassed and paved areas but reduced ground points in the vicinity of dense trees / vegetation. **Plate 8** also shows no ground points across buildings. Therefore, it appears that non-ground points have correctly been removed from the 2013 dataset and the resulting DEM derived from these LiDAR points will reflect the ground elevation only.

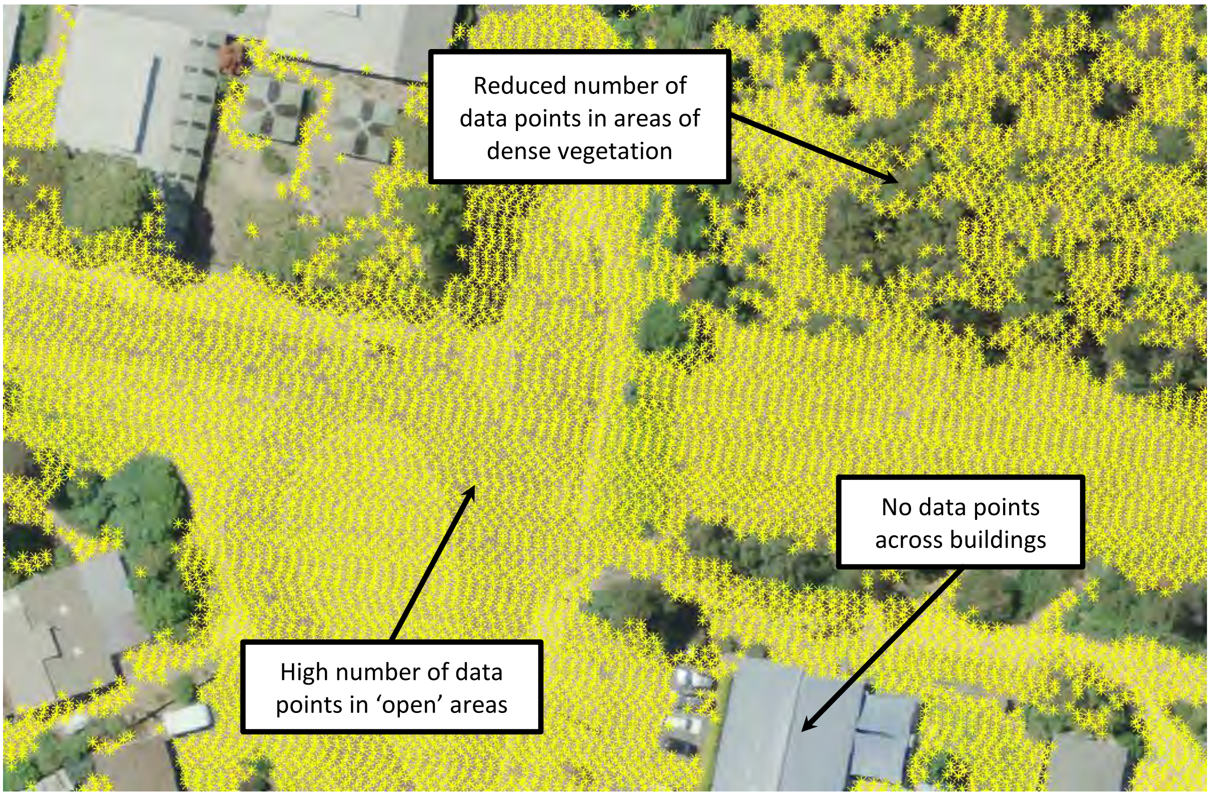


Plate 8 2013 LiDAR data points in the vicinity of Oregon and Monaro Streets

However, the LiDAR data will not pick up the details of drainage features that are obscured from aerial survey techniques, such as bridge and culvert dimensions. Although some bridge and culvert information is available from past studies and plans, there were some bridges and culverts where no detailed information was available. Therefore, survey of some bridges and culverts was also completed to ensure a reliable representation of these drainage structures were provided. Further details of the hydraulic structure survey are provided in Section 4.8.

LiDAR is also unable to penetrate water. Therefore, areas that are submerged at the time of the survey (e.g., tidal sections of the catchment) will not be represented in the terrain model. To quantify the ability for the LiDAR to reliably represent major conveyance areas which may be subject to water coverage, channel invert elevations defined in the 2013 LiDAR information were compared against channel invert information extracted from the cross-sections documented in the 'Pambula River Data Assessment Study' (1990) as well as the 2003 hydrographic survey (where available) for the Pambula River. The cross-section comparison locations are shown in **Figure 3** and the outcomes of the comparison is provided in **Table 9**. As shown in **Figure 3**, channel cross-section information from the 1990 study are available at 15 different locations along the Pambula River extending approximately 2.3 km upstream and 3.3 km downstream of the Princess Highway (cross-section 1 is the upstream most section and cross-section 15 is the downstream most section).

Table 9 Pambula River channel invert comparisons

Cross-Section ID	**Channel invert** (mAHD)		
	2013 LiDAR	**1990 Cross-Section**	**2003 Hydrosurvey**
1	3.98	4.25	N/A
2	3.08	2.95	N/A
3	2.32	2.40	N/A
4	2.08	1.90	N/A
5	1.64	1.35	N/A
6	1.61	1.35	N/A
7	1.40	1.95	N/A
Princes Highway			
8	1.04	1.00	N/A
9	0.16	-0.30	N/A
10	0.32	-0.40	-0.31
11	0.28	-0.50	-0.51
12	0.31	-1.10	-0.71
13	0.39	-2.50	-2.10
14	0.37	-2.10	-2.47
15	0.48	-4.60	-5.87

The comparison provided in **Table 9** shows that the LiDAR data is able to reproduce the 1990 cross-section inverts to within 0.3 metres at cross-sections 1 to 8. However, the LiDAR does not provide a good representation of the channel invert for cross-sections 9 to 15. Accordingly, the LiDAR information appears to provide a reasonable representation of the channel geometry across channel sections not subject to significant water coverage (i.e., non-tidal areas upstream of the Princes Highway). However, channel areas subject to significant water coverage are poorly reproduced by the LiDAR. Accordingly, it is necessary to supplement the LiDAR with river cross-section information as well as hydrographic survey across the estuarine sections of the catchment. Further information on the available hydrographic survey information is provided in Section 4.4.3 and details of the additional survey that was collected for the study is provided in Section 4.8.

4.4.2 2018 LiDAR Survey

LiDAR data was also collected across sections of the Pambula River and Yowaka River catchment in April 2018. The extent of the 2018 LiDAR coverage is provided in **Figure 3**. As shown in **Figure 3**, the 2018 LiDAR covers the western parts of the catchment and when combined with the 2013 LiDAR, it provides a complete topographic representation of the catchment. A digital elevation model (DEM) of the catchment was subsequently developed from the 2013 and 2018 LiDAR information and is shown in **Figure 2**.

The 2018 LiDAR has a stated absolute horizontal accuracy of better than 0.8 metres, an absolute vertical accuracy of better than 0.3 metres and provides a minimum point density of 0.34 elevation points per square metre. Accordingly, the 2018 LiDAR provides similar horizontal and vertical accuracy relative to the 2013 LiDAR, however, it provides less ground elevation data points per square metre. However, as the 2018 LiDAR extends across the less developed areas of the catchment that are not the focus of the current study, this is considered to be acceptable.

An example of the 2018 LiDAR ground points across a part section of the upper catchment is provided in **Plate 9**. Like the 2013 LiDAR, **Plate 9** shows that the 2018 LiDAR comprises higher point density across areas of open space and reduced density in areas of significant vegetation coverage. It also appears that non-ground points (e.g., building roof areas) have correctly being removed ensuring the resulting DEM provides ground surface elevations only.

4.4.3 2003 Hydrographic Survey

Hydrographic survey of the Pambula River estuary was collected by the former Department of Infrastructure Planning and Natural Resource in September and October 2003. The extent of the hydrographic survey is shown in **Figure 3**. The dataset reflects the only comprehensive hydrographic survey of the estuarine sections of the catchment that is available.

The hydrographic survey provides elevation points for the bed of the Pambula River, Pambula Lake and Yowaka River at typical intervals of 10 to 20 metres. The survey extends from Loala Point (located about 1 km offshore from the Pambula River entrance) upstream along the Pambula River to the southern edge of the Pamboola Wetlands and upstream along the Yowaka River to Greigs Flat.

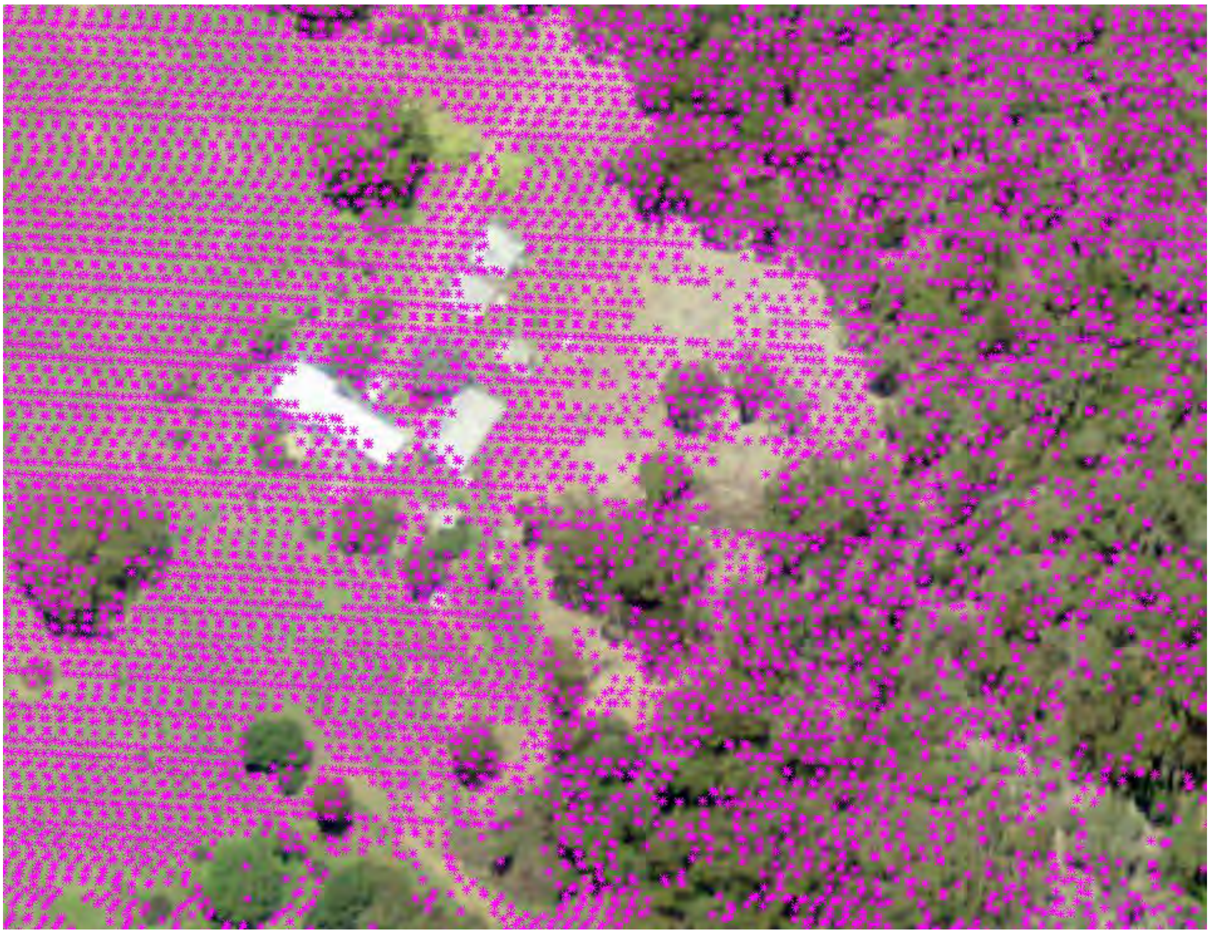


Plate 9 Example of 2018 LiDAR data points in upper catchment

This dataset is considered suitable for defining the bathymetry of the estuarine sections of the study area. However, it is noted that the natural estuarine processes have likely caused localised modification to the bathymetry since this dataset was collected. However, as a more contemporary dataset is not available, and these natural changes are likely to be small, this dataset is still considered to be the best available data for use in this flood study.

4.5 Geographic Information System (GIS) Data

A number of Geographic Information System (GIS) layers were also provided by Council to assist with the study. This included:

- Aerial Photography – provides ortho-rectified aerial imagery collected in 2018.
- Bridges – shows the location and attributes of each Council-owned bridge in the catchment (the extent of the bridges covered by this dataset is shown in **Figure 3**). The bridge attributes include bridge deck dimensions, number of spans and the lengths of each span. Overall, this layer provides sufficient detail to describe most bridges in the hydraulic model. However, it does not include non-Council owned drainage assets (e.g., structures on private property or owned by RMS). It also does not include invert elevations. However, it does include an attribute describing the height of the road above the bed of the stream which allows the inverts to be estimated from the LIDAR information.
- Drainage – shows the alignment of major watercourses in the catchment. A review of this dataset showed a low level of spatial precision with the watercourse lines often being

"offset" by >100 metres relative to the "correct" watercourse location (as defined in aerial imagery and LIDAR). As a result, this dataset was not relied upon as part of the study.

- Stormwater Pipes – Provides the location, alignment and attributes of Council owned stormwater pipes and culverts. The extent of the pipes and culverts described by this layer is shown in **Figure 3**. Due to the significant amount of information contained in this layer, a dedicated discussion is provided in the following section.
- Stormwater Pit – Provides the location and attributes of Council owned stormwater pits/inlet. The location of stormwater pits described by this layer is shown in **Figure 3**. Due to the significant amount of information contained in this layer, a dedicated discussion is provided in the following section.

In general, the GIS layers provide a suitable basis for preparing report figures as well as informing the computer flood model development. Further details on the outcomes of the review of the stormwater layers is provided below.

4.5.1 Stormwater Information

The stormwater system can play a significant role in defining flood behaviour across the "built up" sections of the catchment, particularly during more frequent events. Therefore, it was considered important to include a representation of the stormwater system in the flood model developed for the study.

As discussed, Council provided stormwater GIS layers that contain information for stormwater pits and pipes in the study area. A detailed review of these layers was completed to confirm if the available information was sufficient to include a representation of the stormwater system in the flood model.

The extent of the stormwater GIS layers is shown in **Figure 3**. The review of these GIS layers determined that there are 690 pipes and 397 pits located within the study area.

In general, the pit and pipe layers provide sufficient information to allow a representation of the stormwater system to be included in the flood model. However, some limitations were identified, including:

- 44 pipes did not include information describing the size/diameter of the pipe. However, this information could generally be estimated based upon inspection of the diameter of upstream and downstream pipes. The only exception was along Sir William McKell Drive and McPherson Circuit where none of the pipes included size information and, therefore, diameters could not be estimated. For this area, pipe diameters were measured in the field.
- Lintel lengths were generally not provided for pits with a kerb opening. A field inspection of pits across the Pambula area was completed and this determined a typical lintel length of 1.8 metres would be appropriate for application to the study area.
- Grate dimensions were typically not provided for pits that were defined as "grated inlets". A field inspection of pits across the Pambula area was completed and this determined a 0.45m by 0.9m grate was most common and would be suitable for application to the study area.

- 26 pits did not include any information describing the pit type (e.g., grate and lintel sizes). In such cases, a 1.8 metre lintel with no grate was adopted as it was the most common pit type across the urban areas.

It was noted that invert elevations are not provided in either dataset. However, the pit and pipe depths are often reported which allows the invert to be estimated by interrogating the overlying LiDAR elevation data. In instances where the pit/pipe depths were not provided, the invert elevations were estimated using the following approach:

- Invert elevation = LiDAR elevation – 0.5m cover – pipe diameter.

The suitability of the invert estimates was then confirmed by ensuring suitable "cover" was provided over the pipes at all locations (i.e., minimum of 0.5m depth of cover) and ensuring there were no adverse pipe slopes.

4.6 Engineering Plans

Council provided design and work-as-executed plans for ten drainage structures (mainly bridges) located within the catchment. The location of the drainage structures contained in the plans are shown in **Figure 3**.

The age and quality of the information contained in the plans is variable. However, they generally include information describing the size/dimensions of the structures including invert elevations and are sufficiently detailed for including a representation of these structures in the flood model.

Roads and Maritime Services (RMS) also provided plans for Princes Highway bridges and culverts. This includes bridge plans for the Pambula River and Yowaka River crossings as well as details for additional Princess Highway culverts located across the Pambula River floodplain. The location of each RMS structure is also shown in **Figure 3**.

4.7 Remote Sensing

In addition to providing elevations, the raw LiDAR also provides point descriptions (e.g., ground, buildings, trees), point intensity and multiple return information. This information can be used with aerial photography to assist with the identification of different land uses across the catchment. This, in turn, can be used to assist in defining the spatial variation in different land uses across the catchment which can inform Manning's 'n' roughness coefficients and rainfall losses in the computer flood models.

This technique of land use classification was based on research documented in a paper titled *'Using LiDAR Survey for Land Use Classification'* (C. Ryan, 2013) and was applied based upon the 2013 and 2018 LiDAR as well as the 2018 aerial imagery. The classification algorithm divided the study area into the following land use classifications:

- Buildings;
- Waterways;
- Sand;
- Trees;
- Long Grass;
- Short Grass;

- Concrete; and
- Roads.

It should be noted that perfect accuracy cannot be expected from any automated classification, particularly when the LiDAR and aerial imagery date from different periods. It was also noted that the 2018 LiDAR classifications were not as reliable as the 2013 LiDAR classifications most likely due to the reduced point density. As a result, manual updates to the remote sensing outputs were completed to ensure a reliable representation of the spatial variation in land use was provided across the catchment.

The final remote sensing output is shown in **Figure 5**.

4.8 Additional Data Collection

The various reports and datasets provided by Council afford a good description of the majority of features that will influence flood behaviour across the catchment. This includes ground surface elevations, riverbed elevations and major drainage structures such as bridges, culverts and stormwater pipes. However, it was noted that some drainage structures were not represented in the provided datasets and additional information would need to be captured to ensure these structures could be represented in the flood model. This additional information was captured through a combination of detailed ground survey (for those structures likely to have a significant impact on flood behaviour) and field measurements (for those structures less likely to significantly impact on flood behaviour).

The field measurements were collected using a Dewalt laser distance measurer. This device was used to collect details on the size of each structure (e.g., height and width), the number of spans/cells/pipes as well as the height of any overburden (i.e., height difference between the top of the structures and the road elevation). This information could then be used with the LiDAR information to estimate the invert elevations for each structure. A total of 4 structures were measured in the field and the location of each of these structures is shown in **Figure 6**.

Consulting surveyors, Veris, were engaged to undertake the detailed ground survey of hydraulic structures. A total of 5 culverts/causeways were surveyed and the location of each surveyed structure is shown on **Figure 6**.

4.9 Community Consultation

4.9.1 Community Questionnaire

A key component of the flood study involved development of computer flood models. The computer models are typically calibrated/validated to ensure they are providing a reliable representation of flood behaviour. This is completed by using the models to replicate floods that have occurred in the past (i.e., historic floods).

Only limited historic flood information is available for the catchment. However, it was considered that the community may be able to provide additional information on past floods to assist with the computer model validation. In this regard, a community questionnaire was prepared and was distributed to 318 properties located within the catchment. A copy of the questionnaire is included in **Appendix A**.

The questionnaire sought information from the community regarding whether they had experienced flooding, the nature of flood behaviour, if roads and houses were inundated and whether residents could identify any historic flood marks. A total of 21 questionnaire responses were received. A summary of all questionnaire responses is provided in **Appendix A**. The spatial distribution of questionnaire respondents is shown in **Figure A1**, which is also enclosed in **Appendix A**.

The responses to the questionnaire indicate that:

- The majority of respondents have lived in or around the catchment for at least 10 years.
- Nearly 30% of respondents have experienced some form of inundation or disruption as a result of flooding in the catchment. The spatial distribution of respondents that have reported past flooding problems is shown in **Figure A1** in **Appendix A** (refer red dots). The reported impacts included:
  - Inundation of front/back yards (1 respondent);
  - Traffic disruptions (3 respondents);
  - Flooded paddocks (3 respondents);
- Flooding problems were reported across the following roads:
  - Princes Highway
  - Chalkhills Road
  - Nethercote Road
  - Oaklands Road
- Some respondents believe flooding in the catchment is exacerbated by:
  - Blockage of the creek, stormwater inlets and/or drains (2 respondents)
  - Insufficient creek capacity (2 respondents)

A range of other useful observations were also provided as part of the questionnaire responses. This included:

- There are large springs located at the southern end of Pambula Lake that may interfere with flood flow calculations;
- The Princes Highway upgrade has likely increased flood levels on the western side of the highway;
- The earthworks that have been completed across the Pamboola Wetlands to create water bodies has likely restricted the available flow carrying capacity of this part of the floodplain.
- There were historic flood levels marked on the wall of the oyster bar at Pambula Lake but they have since been painted over.

A number of respondents provided information on floodwater depths and flow characteristics from past floods. Information on floods that occurred in March 2012 and June 2016 tended to be the most prolific and the information from these events is considered suitable for model calibration/validation purposes.

A limited number of photographs were also provided showing past floods. A selection of these photographs are provided in **Plate 10** to **Plate 12**.

Plate 10 Flooding across Greigs Flat (date unknown) (photo courtesy of Matt Barnes & Jack Gordon)

Plate 11 Flooding in June 2016 across rear of a Greigs Flat property

Plate 12 Floodwater extends across Princes Highway in March 2011

4.9.2 Public Exhibition

The draft 'Pambula River, Pambula Lake and Yowaka River Flood Study' (January 2021) was placed on Public Exhibition from the 25th March until 2nd May 2021. Printed copies of the draft report were made available at local libraries and an electronic version of the draft report was made available for review on Council's https://yoursay.northernbeaches.nsw.gov.au/website during this period.

Three community information sessions were also held during the public exhibition period. The sessions were held at the Pambula Town Hall at the following times:

- 28th April 2021, 4:00pm – 6:00pm
- 29 April 2021, 12:00pm – 2:00pm
- 29 April 2021, 4:00pm – 6:00pm

An online meeting was also arranged for the 28th April 2021 consultation session and a dedicated online meeting was also completed on 4th May 2021.

The community information sessions and online meetings provided an opportunity for the community to raise any concerns and ask questions with Council, Catchment Simulation Solutions', Department of Planning, Industry and Environment, State Emergency Service and Bureau of Meteorology staff. A total of twenty-five people attended the information sessions, and one person attended the online meeting on the 28th April (there were no attendees at the online meeting on 4th May 2021).

A total of 3 submissions were received during the public exhibition period. A summary of each submission is included in **Appendix O**.

As shown in **Appendix O**, the submissions generally related to the issues summarised below:

- The Princes Highway is frequently cut by floodwaters and the highway embankment serves as a significant barrier flow. The existing highway bridge and culverts do not have sufficient capacity resulting in a significant (i.e., 0.5 metre) build-up of water on the western side of the highway.
- Several other roads were identified as being subject to frequent overtopping resulting in isolation of some properties within the catchment. There was a concern that this issue would be exacerbated if future development of land continued.
- There were concerns that the flood study results may restrict the potential for future development of lots that have been newly identified as flood liable.
- Although not part of any formal submission, some property owners raised concerns of the potential impacts that the study may have on insurance premiums and property values.

Each submission was reviewed and, where necessary, updates to the flood mapping and/or reporting was completed. Formal letter responses were also provided to each submission by Council detailing how the submission was addressed as part of the final flood study report. A summary of the responses to each submission and the modifications that were completed to the flood study report to address each submission is also provided in **Appendix O**.

5 Computer Flood Models

5.1 General

Computer models are the most common method of simulating flood behaviour through a particular area of interest. They can be used to predict flood characteristics such as peak discharges, flood level and flow velocity.

Two computer models were developed to simulate flood behaviour across the Pambula River, Pambula Lake & Yowaka River catchment:

- A XP-RAFTS hydrologic model was developed to simulate the transformation of rainfall into runoff across the catchment; and,
- A TUFLOW hydraulic model was developed to simulate how the runoff would be distributed/move across the study area.

The following sections describe the model development process.

5.2 XP-RAFTS Model Development

5.2.1 Subcatchment Parameterisation

The Pambula River, Pambula Lake & Yowaka River catchment was subdivided into 432 subcatchments based on the alignment of major streams, topographic divides and the location of key infrastructure (e.g., bridge and culvert crossings). The subcatchments were delineated with the assistance of the CatchmentSIM software using a 10 metre Digital Elevation Model (DEM). The subcatchment layout is presented in **Figures 7.1** to **7.7**.

Key hydrologic properties including area, impervious proportion, roughness and average vectored slope were calculated automatically for each subcatchment using CatchmentSIM in conjunction with detailed remote sensing land use information (refer Section 4.7). The spatial distribution of the different land use types is shown in **Figure 5**.

Percentage impervious and pervious 'n' roughness values were assigned to each land use (refer **Table 10**) and were used to calculate weighted average percentage impervious and pervious 'n' values for each subcatchment. The adopted subcatchment parameters are summarised in **Appendix B**.

5.2.2 Stream Routing

The sub-catchment area, roughness, slope and percentage impervious parameters that are input into the XP-RAFTS model are used by the model to estimate the transformation of rainfall excess into runoff for each subcatchment. In addition to local subcatchment runoff, most sub-catchments will also carry flow from upstream catchments along the main watercourses. The flow along the watercourses in XP-RAFTS is represented using a "link" between successive subcatchment "nodes".

Table 10 Adopted Impervious Percentage and Pervious 'n' Values for XP-RAFTS Model

Land Use Description	Pervious "n'	Impervious (%)
Buildings	0.030	100
Paved Roads	0.019	100
Gravel Roads	0.030	0
Concrete	0.016	100
Trees	0.120	0
Long Grass	0.060	0
Short Grass	0.042	0
Sand	0.030	0
Wetland/Mangroves	0.140	100
Watercourse	0.060	100

For this study, time delay lag routing was employed to represent the routing of runoff along the main watercourses into downstream subcatchments. The time delay value for each stream segment was calculated by dividing the stream length by an average stream velocity. The average stream velocity was defined using peak 1% AEP design velocity outputs from a preliminary TUFLOW model simulation. The average channel velocity from the 1% AEP flood was determined at each grid cell and then the average velocity contained within each subcatchment was calculated to enable the time delay value to be calculated. The lag values that were used to represent the routing of flows through each subcatchment are provided in **Appendix B**.

5.2.3 Rainfall Loss Model

During a typical rainfall event, not all of the rain falling on a catchment is converted to runoff. Some of the rainfall may be intercepted and stored by vegetation, some may be stored in small depressions and some may infiltrate into the underlying soils.

To account for rainfall "losses" of this nature, the hydrologic model incorporates a rainfall loss model. For this study, the "Initial-Continuing" loss model was adopted, which is recommended in 'Australian Rainfall & Runoff' (Ball et al, 2019). This loss model assumes that a specified amount of rainfall is lost during the initial saturation/wetting of the catchment (referred to as the 'Initial Loss'). Further losses are applied at a constant rate to simulate infiltration/interception once the catchment is saturated (referred to as the 'Continuing Loss Rate'). The initial and continuing losses are deducted from the total rainfall over the catchment, leaving the residual rainfall to be distributed across the catchment as runoff.

The rainfall losses that were employed in the XP-RAFTS model were adjusted as part of the model calibration process. Further details on the model calibration are provided in Chapter 6.

5.2.4 Water Storages

The catchment includes a number of water bodies (primarily farm dams). These water bodies have the potential to attenuate downstream flows from the local catchment by storing runoff.

However, the volume of storage afforded by each of the farm dams is typically small when compared to the overall catchment area. Furthermore, there is no guarantee that storage volume will be available during rainfall events (i.e., there may have been some "lead up" rainfall which filled the dams prior to the main rainfall event). As a result, water storages/farm dams were not included in the XP-RAFTS model (i.e., it was assumed that all dams were "full" at the start of the rainfall event).

5.3 TUFLOW Model Development

5.3.1 Model Extent

The extent of the TUFLOW model area is shown in **Figures 8.1** to **8.6**. The overall TUFLOW model covers a total area of 83 km^2.

The TUFLOW model extends along a 31-kilometre length of the Pambula River, a 22-kilometre length of the Yowaka River and also includes each major tributary. The model also includes Pambula Lake and extends approximately 500 metres offshore from the Pambula River entrance at Pambula Beach.

5.3.2 Grid Size and Topography

The TUFLOW software uses a grid to define the spatial variation in topography and hydraulic properties (e.g., Manning's "n" roughness) across the model area. Accordingly, the choice of grid size can have a significant impact on the performance of the model. In general, a smaller grid size will provide a more detailed and reliable representation of flood behaviour relative to a larger grid size. However, a smaller grid size will take longer to perform all of the necessary hydraulic calculations. Therefore, it is typically necessary to select a grid size that makes an appropriate compromise between the level of detail provided by the model and the associated computational time required. A grid size of 4 metres was ultimately adopted and was considered to provide a reasonable compromise between reliability and simulation time.

Elevations were assigned to the grid cells within the TUFLOW model based on the Digital Elevation Model derived from the 2013 and 2018 LiDAR information. The 2013 data covers the majority of the TUFLOW model area with the 2018 data only being used to assign elevations to the very western sections of TUFLOW model.

5.3.3 Manning's "n" Values

The TUFLOW software uses land use information to define the hydraulic (i.e., Manning's 'n') properties for each grid cell in the model. The remote sensing information described in Section 4.7 was used as the basis for defining the variation in land use across the TUFLOW model (refer **Figure 4**). This land use information, in turn, was used as the basis for assigning the variation in Manning's "n" roughness values across the model area.

Manning's "n" is an empirically derived coefficient that is used to define the resistance to flow (i.e., roughness) afforded by different material types and land uses. It is one of the key input parameters used in the development of the TUFLOW model.

The "n" values listed in **Table 11** were initially estimated based on values in literature and were then refined as part of the model calibration process. Further details of the TUFLOW model calibration are provided in Section 6.

5.3.4 River and Creek Channels

During most floods, the majority of flow is conveyed within each of the major rivers/creeks. Therefore, it is important to ensure that these watercourses are well represented in the TUFLOW model.

Table 11 Manning's "n" Roughness Values

Land Use Description	Manning's "n"
Buildings	1.000
Paved Roads	0.018
Gravel Roads	0.025
Concrete	0.013
Trees	0.080
Long Grass	0.040
Short Grass	0.030
Sand	0.024
Wetland	0.060
Lower Pambula River	0.020
Sandy watercourses	0.024
Rocky watercourses	0.035
Oyster leases	0.050

There are two primary ways to represent watercourses in the TUFLOW model; as an embedded 1-dimensional domain or as part of the 2-dimensional domain. Both options have advantages and disadvantages. A 2-dimensional creek representation was ultimately adopted as it allows a better representation of flow momentum, hydraulic losses around bends as well as the potential for localised "break outs" from the channels.

Where available, the watercourse geometry was defined using the 2003 hydrosurvey information (refer Section 4.4.3). In areas where hydrosurvey was not available, the watercourse geometry was defined using "gully lines". The elevations and widths assigned to the gully lines were informed by the following sources (in order of priority):

- Hydraulic structure ground survey
- Hydraulic structure field measurements; and
- LiDAR DEM (in areas not obstructed by vegetation).

The location of the gully lines is shown in in **Figures 8.1** to **8.6**.

The main limitation associated with a 2-dimensional representation of the watercourses is that it does not always provide a sufficiently detailed representation of the conveyance capacity of the channel. The TUFLOW User Manual (BMT, 2018) suggests a minimum of five grid cells are generally required laterally to adequately represent watercourses. A review of the TUFLOW model grid indicates that between 3 and 10 cells generally extend across the various channels, with 6 cells being most common (refer **Plate 13**). Therefore, the adopted grid size generally appears to be adequate to represent each of the main watercourses in the flood investigation area. The 2-dimensional watercourse representation was validated against surveyed cross-sections to ensure there were no significant variations in cross-section area. An example of the cross-section comparisons are provided in **Plate 14** and **Plate 15.** This validation indicated that the 2-dimensional representation provided a channel area that was within 10% of the surveyed cross-sectional area.

Plate 13 Example of TUFLOW grid cells across Pambula River channel

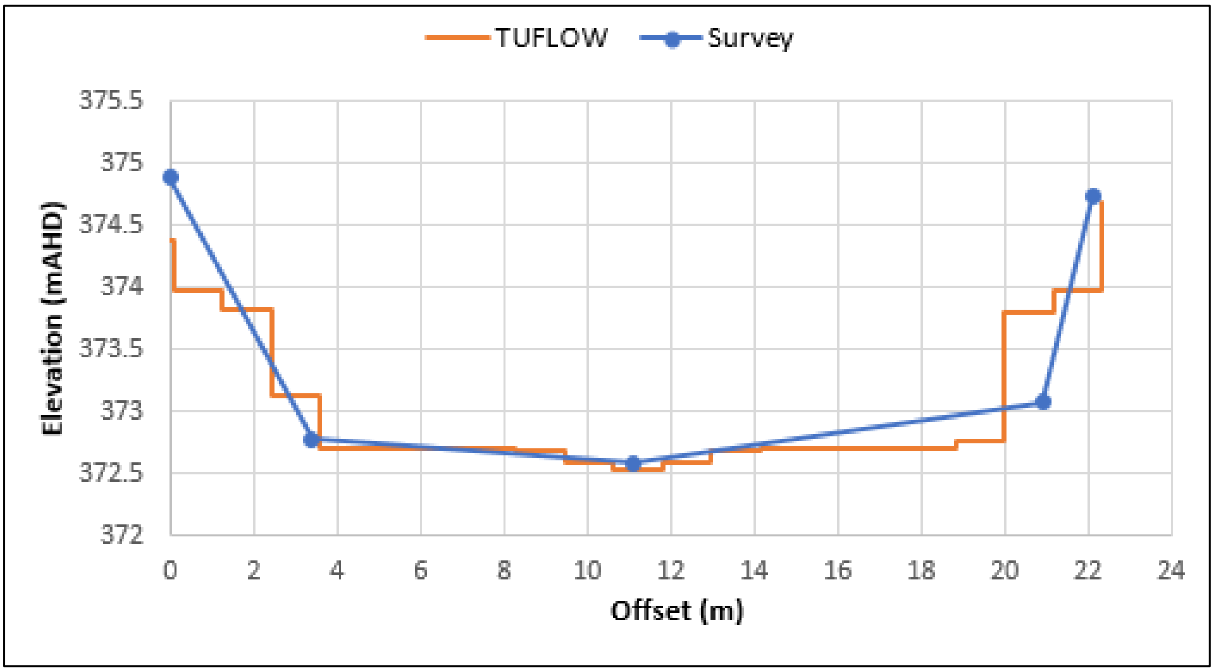


Plate 14 Example of 2-dimensional representation of Pambula River channel approximately 400 metres upstream of Princes Highway

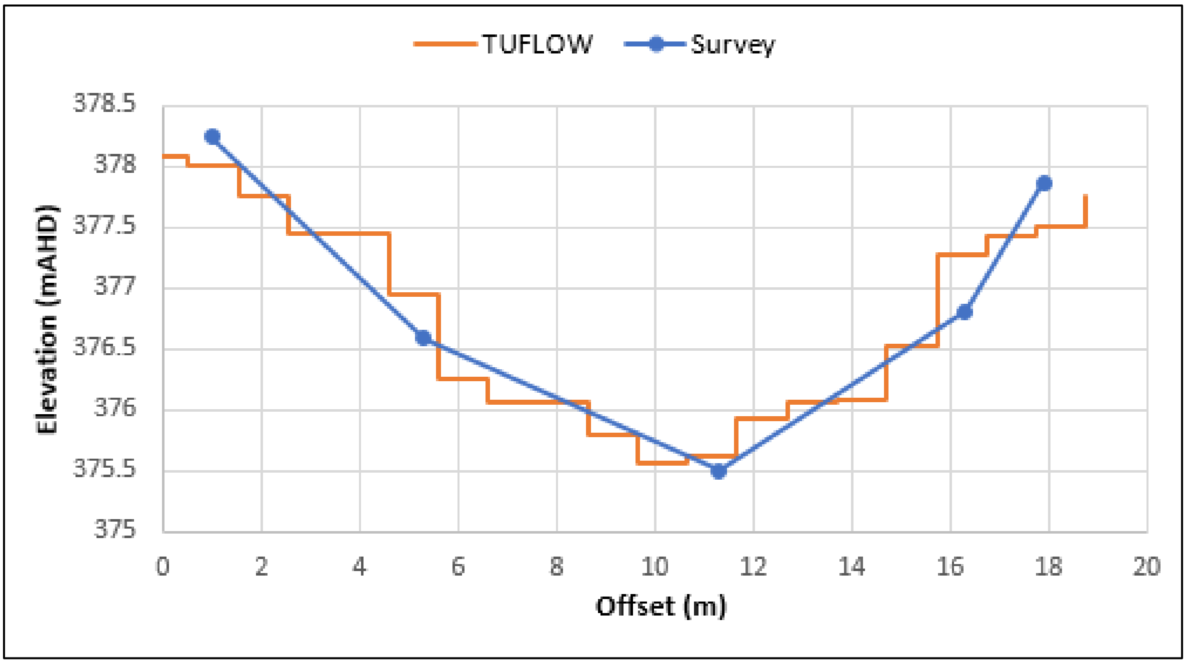


Plate 15 Example of 2-dimensional representation of Pambula River channel approximately 400 metres downstream of Princes Highway

5.3.5 Boundary Conditions

Upstream Boundary Conditions

As discussed, the XP-RAFTS model was used to simulate the transformation of rainfall into runoff and generate discharge hydrographs at discrete locations across the full extent of the catchment. The TUFLOW model extends across a part of the overall catchment. Therefore, the total flows from the upstream sections of the catchment as well as flows from the local subcatchments located within the TUFLOW model area must be accounted for. Accordingly, 'total' inflow hydrographs (i.e., hydrographs describing the total upstream contributing flow) were used to define the design inflows from those subcatchments draining into the upstream sections of the TUFLOW model. In addition, 'local' discharge hydrographs (representing flows from the local subcatchments only) were also extracted from XP-RAFTS and were used to represent inflows for those subcatchment contained within the TUFLOW model area. The local flow hydrographs were applied to the TUFLOW model at the outlet of each subcatchment. The location where local and total inflows were applied to the TUFLOW model is shown in **Figures 8.1** to **8.6**.

Downstream Boundary Conditions

Hydraulic computer models also require the adoption of a suitable downstream boundary condition in order to reliably define flood behaviour throughout the area of interest. The downstream boundary condition is typically defined as a known water surface elevation (i.e., stage). The downstream boundary of the computer model is located within the Tasman Sea. Accordingly, the water level across the downstream reaches of the model will be driven by the prevailing ocean tide levels.

Therefore, the downstream boundary condition was defined based upon a time varying water level. The time varying water level was based upon either recorded ocean heights at the Eden gauge (for historic floods) or a synthetic tide curve (for design floods). Further information on the adopted downstream boundary conditions is provided in Chapters 6 and 7.

5.3.6 Culverts and Bridges

Culverts and bridges can have a significant influence on flood behaviour, particularly if they become blocked during the course of the flood. Therefore, all major bridges and culverts within the TUFLOW model area were represented within the TUFLOW model as 1D hydraulic structures. The location of culverts and bridges that were included within the TUFLOW model is shown in **Figures 8.1** to **8.6**.

For circular and rectangular culverts, the surveyed/measured dimensions and invert elevations of the structures were included directly in the TUFLOW model. An entrance loss coefficient of 0.5 and an exit loss coefficient of 1.0 was adopted for all culverts.

The bridge deck and road surfaces above each culvert were represented as part of the 2D domain. Therefore, flow through each of the structures below the road level was represented in 1D and flow across the road surface (i.e., once the capacity of the structure is exceeded) was represented in 2D.

All bridges were represented using 2-dimensional layered flow constriction lines in TUFLOW. The use of the layered flow constriction allows separate blockage factors and energy losses to be defined for the bridge substructure, deck and hand railings. Energy losses were defined using procedures outlined in *'Hydraulics of Bridge Waterways'* (Bradley, 1978). Blockage factors were assigned as followings:

- Substructure: bridge pier width / total bridge length
- Deck: 100% blockage
- Hand /guard rails (where present): 50% blockage

Blockage

During a typical flood, sediment, vegetation and urban debris (e.g., litter, fence palings, bins) from the catchment can become mobilised leading to blockage of downstream culverts and bridges. Consequently, bridges and culverts will typically not operate at full efficiency during most floods. This can increase the severity of flooding across areas located adjacent to these structures.

In recognition of this, blockage factors were calculated for all bridges and culverts. The blockage factors were calculated based on blockage guidelines contained in 'Australian Rainfall and Runoff: A Guide to Flood Estimation' (Ball et al, 2019). The blockage calculations are summarised in **Appendix D** for each culvert and bridge located within the TUFLOW model area. The blockage factors were applied to the bridge substructure only and are in addition to the blockage afforded by the bridge piers.

5.3.7 Stormwater System

The stormwater system has the potential to convey a significant proportion of runoff across the "built up" sections of the catchment during relatively frequent rainfall events. Therefore, it was considered important to incorporate the stormwater system in the TUFLOW model to ensure the interaction between piped stormwater and overland flows was reliably represented.

The full stormwater system contained within the catchment was included within the TUFLOW model as a dynamically linked 1D network. This allowed representation of the conveyance of flows by the stormwater system below ground as well as simulation of overland flows in two dimensions once the capacity of the stormwater system is exceeded.

The properties of the stormwater system (e.g., pits types/sizes, pipe lengths/diameters) were defined based on information contained in Council's stormwater GIS asset database. As discussed in Section 4.5.1, not all required information was provided in this database, therefore, some properties of the stormwater system were estimated. The extent of the stormwater system included within the TUFLOW model is shown in **Figures 8.1** to **8.6**.

5.3.8 Water Storages

As discussed in Section 4.2.4, the catchment incorporates a number of farm dams that may attenuate downstream flows during rainfall events. However, the amount of storage volume that they afford is considered to be small relative to the overall volume of runoff during a typical rainfall event and there is no guarantee that the dams will have storage volume available during significant rainfall events. Accordingly, all dams were represented as being "full" in the TUFLOW model. This included the Panboola Wetland waterbodies.

6 COMPUTER MODEL CALIBRATION

6.1 Overview

Computer flood models are approximations of a very complex process and are generally developed using parameters that are not known with a high degree of certainty and/or are subject to natural variability. This includes catchment roughness as well as blockage of hydraulic structures. Accordingly, the model should be calibrated using rainfall, flow and flood mark information from historic floods to ensure the adopted model parameters are producing reliable estimates of flood behaviour.

Calibration is typically completed using the following process:

- Hydrologic model calibration: Recorded rainfall is first applied to the hydrologic model. Simulated flows are extracted from the hydrologic model results at locations where recorded flow hydrographs are available. Hydrologic model calibration is completed by iteratively adjusting the model parameters within reasonable bounds to achieve the best possible match between simulated and recorded flow hydrographs.
- Hydraulic model calibration: The calibrated flows from the hydrologic model are then routed through the hydraulic model. Simulated flood levels/depth are compared against surveyed flood levels from the historic flood or anecdotal reports of inundation depths. The hydraulic model parameters are adjusted until the best correlation between simulated and surveyed/reported flood levels/depths is achieved.

The following sections describe the historic floods that were selected for calibration purposes and the outcomes of the hydrologic and hydraulic model calibration.

6.2 Calibration Events

6.2.1 Available Rainfall Data

Continuous rainfall data are required to define the temporal (i.e., time-varying) distribution of rainfall in the hydrologic computer model for the nominated calibration event. There are several continuous rainfall gauges located within or adjacent to the catchment. Data for one continuous gauge dates back to 1971, however, the majority of the continuous gauges came into service between 2009 and 2011.

There are also several daily read rainfall gauges located within or adjacent to the catchment. The daily read rainfall records can be used to provide an indication of the spatial variation in rainfall during any historic event. There are several gauges with records that extend back to the late 1800s and early 1900s. When this daily data is combined with the continuous gauge data, there is sufficient information to describe the spatial and temporal variation in rainfall during any significant rainfall event that has occurred since 1971.

6.2.2 Available Stream Gauge Data

Recorded stream flow estimates are required to perform a meaningful hydrologic model calibration. Recorded stream flow data are generally obtained using gauges that record the time variation in stream water height in conjunction with a suitable rating curve/table to convert the stream heights to an equivalent discharge. Although two stream height gauges are located within the catchment, only one has a rating curve (i.e., Pambula River @ Lochiel). This gauge has records dating back to 1966. The other gauge (Pamula Lake) only comprises water level records dating from 1991 (rating curves are not typically prepared for tidal gauge as the variations in water levels introduced by the tide will lead to erroneous discharge estimates).

6.2.3 Adopted Events

The following criteria were employed to select events suitable for the purpose of model calibration and verification:

- Minimum of five significant flood events (ie., larger floods preferred over smaller floods).
- Floods after 2011 preferred as it provides the most comprehensive rainfall information.
- Events where flood marks are available are preferred so the same events can be used for both hydrologic and hydraulic model calibration.

Based on these criteria, the following events were selected for model calibration and verification:

- 1971
- 1985
- 2011
- 2012
- 2016

The historic floods were simulated in reverse chronological order as the more contemporary events (i.e., 2011, 2012 and 2016) provided a greater amount of rainfall and stream flow/level information for calibration purposes.

6.3 2016 Flood

6.3.1 XP-RAFTS Modelling

Rainfall

The 2016 flood occurred as a result of rain falling between the 4th and 7th of June. The rainfall was generated by an East Coast Low that produced significant rainfall along the coast of NSW. As shown in **Plate 16**, parts of the South Coast of NSW experienced more than 400 mm of rainfall. However, as shown in **Table 12**, the Pambula and Yowaka Rivers catchment experienced rainfall totals of between 190 and 377 mm.

Accumulated rainfall totals for each rainfall gauge that was operational during the 2016 event were used to develop a rainfall isohyet (i.e., rainfall depth contour) map for the event, which is shown in **Figure 9**.

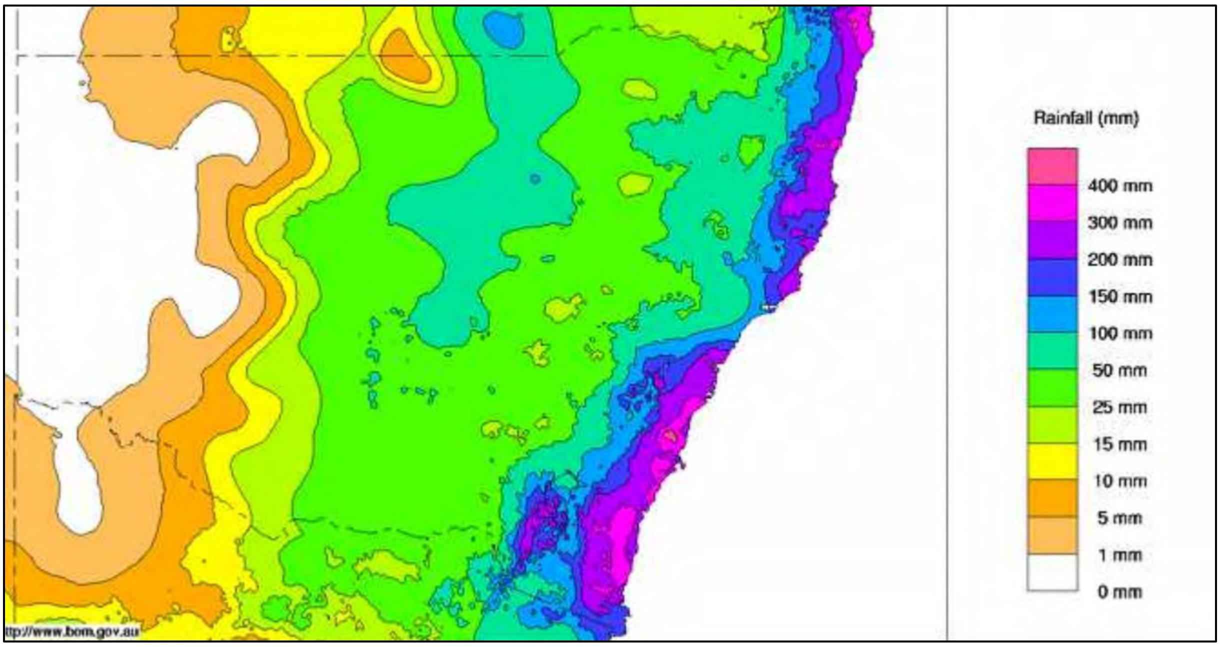


Plate 16 Four-day rainfall totals for NSW for June 2016 event (Bureau of Meteorology, 2016)

Table 12 Historic Rainfall Statistics

Event	Dates		Catchment Rainfall (mm)		
	Start	End	Minimum	Average	Maximum
2016	4th June	7th June	190	289	377
2012	1st Mar	2nd Mar	150	166	199
2011	20th Mar	25th Mar	116	230	330
1985	25th Nov	30th Nov	178	219	257
1971	4th Feb	8th Feb	295	373	475

The isohyet map and information included in **Table 12** indicates that there was some notable spatial variation in rainfall across the catchment during the 2016 event, with rainfall totals across the western sections of the catchment being approximately double of those recorded along the coast. In recognition of the variation in rainfall across the catchment during this event, the isohyets shown in **Figure 9** were used as the basis for defining spatially varying rainfall across the catchment as part of the 2016 flood simulation. This involved calculating a weighted average rainfall for each subcatchment in the XP-RAFTS model.

The temporal (i.e., time-varying) distribution of rainfall was determined based on the closest continuous rainfall gauge that provided reliable recorded rainfall information for the event. This was determined to be the Merimbula Airport gauge (Gauge #69147).

The continuous rainfall information was also analysed relative to design rainfall-intensity-duration information. This information is presented as **Figure D1** in **Appendix D** and indicates that the 2016 event produced rainfall that was around the same severity as a 20% AEP design rainfall event for some periods.

Rainfall Losses

As discussed in Section 4.2.3, the initial-continuing loss model was employed to represent rainfall losses across the catchment. The rainfall losses were initially informed based upon information downloaded from the *'Australian Rainfall and Runoff – A Guide to Flood Estimation'* (Ball et al, 2019) data hub:

- Storm initial loss: 21 mm
- Storm Continuing loss rate: 2.48 mm/hr

Initial calibration simulations with the loss rate of 2.48 mm/hr did not generate acceptable calibration results for any of the simulated floods. Therefore, the continuing loss rate was revised based upon calibrated loss rates for the adjoining Towamba River catchment as documented in the *'Eden, Twofold Bay, Towamba River Flood Study'* (Rhlem, 2019). This study employed a continuing loss rate of 1 mm/hour for pervious catchment areas.

The 1 mm/hour continuing loss rate was subsequently adjusted, as part of each calibration simulation to best reproduce the volume of runoff that was recorded at the Lochiel stream gauge. As shown in **Table 13**, a loss rate of 1.5 mm/hour was adopted for the 2016 simulation for pervious sections of the catchment. **Table 13** also shows that no rainfall losses were applied to impervious sections of the catchment (this is also consistent with the *'Eden, Twofold Bay, Towamba River Flood Study'*).

Table 13 Adopted Rainfall Losses for Calibration Simulations

Event	Initial Loss (mm)		Continuing Loss Rate (mm/hr)	
	Pervious	Impervious	Pervious	Impervious
2016	21	0	1.5	0.0
2012	21	0	1.8	0.0
2011	21	0	0.5	0.0
1985	0	0	1.0	0.0
1971	21	0	1.0	0.0

Results

The XP-RAFTS model was used to simulate rainfall-runoff behaviour for the 2016 flood based upon the rainfall and rainfall loss information presented in the preceding sections. This enabled discharge hydrographs to be generated for each subcatchment. Peak discharges for each XP-RAFTS model subcatchment for the 2016 flood are included in **Appendix E.** Peak discharges at key locations throughout the catchment are also summarised in **Table 14.**

A simulated discharge hydrograph was also extracted at the location of the Lochiel stream gauge. This simulated hydrograph is presented in the **Figure D2** in **Appendix D**. Also included on **Figure D2** is the recorded discharge hydrograph.

Figure D2 shows that the XP-RAFTS hydrograph provides a reasonable reproduction of the recorded hydrograph for the Pambula River at Lochiel gauge. More specifically, the general shape of the recorded hydrograph, the timing of the dual peaks and the magnitude of the peak discharge (simulated = 317m^3/s versus recorded = 300m^3/s) is reproduced by the XP-RAFTS model.

Table 14 Peak Discharge at Key Locations for Historic Flood Simulations

Location		Peak Discharge (m^3/s)				
		2016	2012	2011	1985	1971
Pambula River	Lochiel Gauge	317	257	354	430	577
	Princes Hwy	361	290	383	488	652
	River entrance/Tasman Sea	847	733	836	1,167	1,600
Yowaka River	Nethercote Road bridge	147	126	171	203	275
	Princes Hwy	386	332	406	530	719

The hydrographs generated by the XP-RAFTS model were also routed through the TUFLOW model. Further discussion on the TUFLOW model simulation is provided below.

6.3.2 TUFLOW Modelling

Modifications to Reflect Historic Conditions

A review of historic aerial imagery determined that there have not been any significant changes in catchment conditions since the 2016 flood. Therefore, no modifications were completed to the TUFLOW model that was developed to reflect contemporary catchment conditions to reflect catchment conditions at the time of the 2016 flood.

Inflow Boundary Conditions

Discharge hydrographs generated by the XP-RAFTS hydrologic model were used to define inflows to the TUFLOW model.

Downstream Boundary Conditions

Hydraulic computer models also require the adoption of a suitable downstream boundary condition to reliably define flood behaviour throughout the area of interest. The downstream boundary condition is typically defined as a known water surface elevation (i.e., stage). The downstream boundary of the TUFLOW model is located within the Tasman Sea (approximately 500 metres offshore from Pambula Beach). Accordingly, the water level in this area will be governed by the prevailing ocean tide level at the time of the flood.

Although there is a water level gauge located within Pambula Lake, water levels at this location will also be influenced by catchment runoff. Therefore, this gauge was not suitable for defining ocean water levels. The next closest gauge that would not be strongly influenced by catchment runoff is located at Merimbula Wharf. Therefore, the recorded water levels at this gauge were used to define the downstream boundary conditions for the 2016 flood simulation.

Results

Calibration of the TUFLOW computer model was attempted based upon four (4) anecdotal reports of flood behaviour as well as recorded water levels at the Lochiel and Pambula Lake gauges. In general, the anecdotal flooding reports only provided information on areas that were flooded (specific flood depths or levels were not available).

Peak floodwater depths were extracted from the results of the 2016 flood simulation and are included on **Figures 10.1** to **10.6**. A comparison between the peak flood depths generated by the TUFLOW model and the anecdotal reports of flooding for the 2016 flood is also provided in **Figures 10.1** to **10.6** as well as **Table 15**.

Table 15 Comparison between simulated floodwater depths and anecdotal flooding reports for the 2016 flood

Anecdotal Flooding Report	Simulated Floodwater Depth (m)
1 metre of water within creek	0.85
Flooding of paddock	1.52
Unknown height in Pambula River	3.03
Flooding near Harts Bridge	0.40

The time variation in simulated water levels at the Pambula River at Lochiel gauge and Pambula Lake gauge were also extracted and are provided in **Figure D3** and **D4** in **Appendix D**.

The comparison provided in **Table 15** shows that the TUFLOW model is reproducing the observations from the 2016 flood. The only depth information that was reported for this event is reproduced by the model to within 0.15 metres.

Figure D3 also shows that the simulated stage hydrograph provides a reasonable replication of the time variation in recorded stages at the Lochiel gauge. More specifically the timing and magnitude of the dual peaks is well reproduced by the TUFLOW model (both peak water levels are reproduced to within 0.1 metres).

Figure D4 also shows the TUFLOW model provides a reasonable reproduction of the recorded Pambula Lake stage hydrograph. In particular, the timing of the various ebb and flood tidal peaks is closely replicated as is the overall peak stage (1.46 mAHD recorded versus 1.41 mAHD simulated).

6.4 2012 Flood

6.4.1 XP-RAFTS Modelling

Rainfall

The 2012 flood occurred as a result of rain falling on the 1st and 2nd of March. Accumulated rainfall totals for each active rain gauge over this two-day period are presented in **Figure 11**. As shown in **Figure 11** and **Table 12**, total rainfall depths across the catchment during this event varied between 150 and 199 mm.

The isohyets shown in **Figure 11** were used as the basis for defining spatially varying rainfall across the catchment as part of the 2012 flood simulation. The temporal distribution of rainfall was determined based on the closest continuous rainfall gauge that provided reliable recorded rainfall information for the event. This was determined to be the Lochiel gauge.

The continuous rainfall information was also analysed relative to design rainfall-intensity-duration information. This information is presented in **Figure D1** in **Appendix D** and indicates that the 2012 event produced rainfall that was between a 50% AEP and 20% AEP design rainfall event. Therefore, the 2012 event produced the lowest total rainfall depths and was the smallest event (in terms of rainfall severity) of all the events considered for calibration.

Rainfall Losses

The rainfall losses summarised in **Table 13** were applied as part of 2012 flood simulation. As shown in **Table 13**, a higher continuing loss rate of 1.8 mm/hr was required for the 2012 simulation as the 1 mm/hr loss rate generated too much runoff volume at the Lochiel stream gauge.

Results

The XP-RAFTS model was used to simulate rainfall-runoff behaviour for the 2012 flood based upon the rainfall and rainfall loss information presented in the preceding sections. This enabled discharge hydrographs to be generated for each subcatchment. Peak discharges for each XP-RAFTS model subcatchment for the 2012 flood are included in **Appendix E.** Peak discharges at key locations throughout the catchment are also summarised in **Table 14.**

A simulated discharge hydrograph was also extracted at the location of the Lochiel stream gauge. This simulated hydrograph is presented in the **Figure D5** in **Appendix D**. Also included on **Figure D5** is the recorded discharge hydrograph.

Figure D5 shows that the XP-RAFTS hydrograph provides a good reproduction of the recorded hydrograph for the Pambula River at Lochiel gauge. More specifically, the shape of the recorded hydrograph and the magnitude of the peak discharge (simulated = 256m^3/s versus recorded = 264m^3/s) is well reproduced by the XP-RAFTS model.

6.4.2 TUFLOW Modelling

Modifications to Reflect Historic Conditions

A review of historic aerial imagery determined that there have not been any significant changes in catchment conditions since the 2012 flood. Therefore, no modifications were completed to the TUFLOW model to reflect 2012 catchment conditions.

Inflow Boundary Conditions

Discharge hydrographs generated by the XP-RAFTS hydrologic model were used to define inflows to the TUFLOW model.

Downstream Boundary Conditions

The downstream boundary condition for the TUFLOW model was defined based on recorded water levels at the Merimbula Wharf gauge.

Results

Calibration of the TUFLOW computer model was attempted based upon six (6) anecdotal reports of flood behaviour/flood photographs as well as recorded water levels at the Lochiel and Pambula Lake gauges.

Peak floodwater depths were extracted from the results of the 2012 flood simulation and are included on **Figures 12.1** to **12.6**. A comparison between the peak flood depths generated by the TUFLOW model and the anecdotal reports of flooding for the 2012 flood is also provided in **Figures 12.1** to **12.6** as well as **Table 16**.

Table 16 Comparison between simulated floodwater depths and anecdotal flooding reports for the 2012 flood

Anecdotal Flooding Report	Simulated Floodwater Depth (m)
Shallow flow across Princess Highway	0.13
~1m deep at entrance to Oaklands	0.84
Water extending onto carpark of Oaklands	0.39
Flooding of paddock	1.23
Unknown height in Pambula River	2.75
Flooding near Harts Bridge	0.39

The time variation in simulated water levels at the Pambula River at Lochiel gauge and Pambula Lake gauge were also extracted and are provided in **Figure D6** and **D7** in **Appendix D**.

The comparison provided in **Table 16** shows that the TUFLOW model is reproducing the observations from the 2012 flood. The only depth information that was reported (at the entrance to Oaklands) is reproduced by the model to within 0.16 metres.

Figure D6 also shows that the simulated stage hydrograph provides a reasonable reproduction of the time variation in recorded stages at the Lochiel gauge. Although the rising limb of the simulated hydrograph occurs sooner than the recorded hydrograph, the timing and magnitude of the peak stage is well represented.

Figure D7 also shows the TUFLOW model provides a reasonable reproduction of the recorded Pambula Lake stage hydrograph. In particular, the timing and magnitude of the various ebb and flood tidal peaks is well replicated although the simulated maximum water level is 0.14 metres higher than the recorded maximum level.

6.5 2011 Flood

6.5.1 XP-RAFTS Modelling

Rainfall

The 2011 flood occurred as a result of rain falling over a 6-day period (i.e., from 20th March to 25th March). Accumulated rainfall totals for each active rainfall gauge over this two-day period are presented in **Figure 13**. As shown in **Figure 13** and **Table 12**, total rainfall depths across the catchment during this event varied between 116 and 300 mm. **Figure 13** also shows there was notable spatial variation in rainfall across the catchment during the 2011 event, with considerably more rainfall recorded across the western sections of the catchment relative to the coast. The isohyets shown in **Figure 13** were used as the basis for defining spatially varying rainfall across the catchment as part of the 2011 flood simulation.

The temporal distribution of rainfall was determined based on the closest continuous rainfall gauge that provided reliable recorded rainfall information for the event. This was determined to be the Lochiel gauge.

The continuous rainfall information was also analysed relative to design rainfall-intensity-duration information. This information is presented in as **Figure D1** in **Appendix D** and indicates that the 2011 event produced rainfall that was roughly equivalent to the 20% AEP design rainfall event. Accordingly, the severity of rainfall during the 2011 flood was similar to the 2016 event.

Rainfall Losses

The rainfall losses summarised in **Table 13** were applied to the RAFTS model as part of 2011 flood simulation. As shown in **Table 13**, a continuing loss rate of 0.5 mm/hr was required for the 2011 simulation to reproduce the runoff volume at the Lochiel stream gauge.

Results

The XP-RAFTS model was used to simulate rainfall-runoff behaviour for the 2011 flood. Peak discharges for each XP-RAFTS model subcatchment for the 2011 flood simulation are included in **Appendix E.** Peak discharges at key locations throughout the catchment are also summarised in **Table 14.**

A simulated discharge hydrograph was also extracted at the location of the Lochiel stream gauge. This simulated hydrograph is presented in **Figure D8** in **Appendix D**. Also included on **Figure D8** is the recorded discharge hydrograph.

Figure D8 shows that the XP-RAFTS hydrograph provides a reasonable reproduction of the overall shape of the recorded hydrograph as well as the timing of the dual peaks. The XP-RAFTS model produces a slightly lower peak discharge (simulated = 368m^3/s versus recorded = 384m^3/s), however, this is still considered to be a reasonable outcome (i.e., peak discharges agree to within 5%).

6.5.2 TUFLOW Modelling

Modifications to Reflect Historic Conditions

A review of historic aerial imagery determined that there have not been any significant changes in catchment conditions since the 2011 flood. Therefore, no modifications were completed to the TUFLOW model to reflect 2011 catchment conditions.

Inflow Boundary Conditions

Discharge hydrographs generated by the XP-RAFTS hydrologic model were used to define inflows to the TUFLOW model.

Downstream Boundary Conditions

The downstream boundary condition for the TUFLOW model was defined based on recorded water levels at the Merimbula Wharf gauge during the 2011 event.

Results

Calibration of the TUFLOW computer model was attempted based upon three (3) anecdotal reports of flood behaviour as well as recorded water levels at the Lochiel and Pambula Lake gauges.

Peak floodwater depths were extracted from the results of the 2011 flood simulation and are included on **Figures 14.1** to **14.6**. A comparison between the peak flood depths generated by the TUFLOW model and the anecdotal reports of flooding for the 2011 flood is also provided in **Figures 14.1** to **14.6** as well as **Table 17.**

Table 17 Comparison between simulated floodwater depths and anecdotal flooding reports for the 2011 flood

Anecdotal Flooding Report	Simulated Floodwater Depth (m)
Water covering Nethercote Road	0.26
Unknown height Pambula River	3.32
Flooding near Harts Bridge	0.19

The time variation in simulated water levels at the Pambula River at Lochiel gauge and Pambula Lake gauge were also extracted and are provided in **Figure D9** and **D10** in **Appendix D**.

The comparison provided in **Table 17** shows that the TUFLOW model is reproducing the observations from the 2011 flood.

Figure D9 also shows that the simulated stage hydrograph provides a reasonable reproduction of the recorded stages at the Lochiel gauge. The simulated hydrograph provides a good reproduction of the timing of the dual peaks although the simulated maximum water level is about 0.2 metres lower than the recorded maximum (although the first peak level is reproduced to better than 0.05 metres).

Figure D10 also shows the TUFLOW model provides a reasonable reproduction of the recorded Pambula Lake stage hydrograph. The timing and magnitude of the various tidal peaks is generally replicated, and the maximum recorded level is reproduced to within 0.03 metres.

6.6 1985 Flood

6.6.1 XP-RAFTS Modelling

Rainfall

The 1985 flood occurred as a result of rain falling between the 25th and 30th of November. Accumulated rainfall totals for this event are presented in **Figure 15**. As shown in **Figure 15** and **Table 12**, total rainfall depths across the catchment during this event varied between 178 and 257 mm.

Figure 15 also shows there was some spatial variation in rainfall across the catchment during the 1985 event. However, the spatial variability of rainfall during this event was not nearly as significant as some of the other calibration events. Nevertheless, it was still considered important to reflect the spatially varying rainfall in the XP-RAFTS model. Therefore, the isohyets shown in **Figure 15** were used as the basis for assigning rainfall to each subcatchment as part of the 1985 flood simulation.

The temporal distribution of rainfall during the 1985 simulation was based on recorded rainfall at the closest active sub-daily rain gauge. This was determined to be the Green Cape Lighthouse rain gauge which is located over 30 km south-east of the catchment.

The continuous rainfall information for the Lochiel gauge was also analysed relative to design rainfall-intensity-duration information. This information is presented in as **Figure D1** in **Appendix D** and indicates that the 1985 event produced rainfall that was roughly equivalent to the 10% AEP design rainfall event at times.

Rainfall Losses

The rainfall losses summarised in **Table 13** were applied to the RAFTS model as part of 2011 flood simulation. As shown in **Table 13**, a lower initial rainfall loss of 0 mm was adopted as part of the 1985 simulation in order to best replicate the early stages of the recorded hydrographs at the Lochiel stream gauge. A review of antecedent rainfall records indicates that more 30 mm of rain fell in the week preceding the main rainfall event. As a result, the catchment would have already been “wet” and an initial rainfall loss of 0 mm can be justified.

Results

The XP-RAFTS model was used to simulate rainfall-runoff behaviour for the 1985 flood. Peak discharges for each XP-RAFTS model subcatchment for the 1985 flood simulation are included in **Appendix E.** Peak discharges at key locations throughout the catchment are also summarised in **Table 14.**

A simulated discharge hydrograph was also extracted at the location of the Lochiel stream gauge. This simulated hydrograph is presented in the **Figure D11** in **Appendix D**. Also included on **Figure D11** is the recorded discharge hydrograph.

Figure D11 shows that the XP-RAFTS hydrograph provides a reasonable reproduction of overall shape of the recorded hydrograph as well as the magnitude of the peak discharge (simulated = 429m^3/s versus recorded = 450m^3/s). The XP- RAFTS model hydrograph peaks slightly before the recorded hydrograph. However, this may be associated with the adopted temporal pattern at Green Cape not being fully representative of rainfall across the catchment itself.

6.6.2 TUFLOW Modelling

Modifications to Reflect Historic Conditions

A review of historic aerial imagery determined that there have been some changes across sections of the lower Pambula River catchment since the 1985 flood occurred. This includes:

- Princess Highway upgrade between Pambula and South Pambula;
- Oaklands development; and

- Filling/development south of Bullara Street (e.g., Robert Smith Homemakers centre).

As these developments have the potential to impact on flood behaviour, each of the developments was removed from the hydraulic model to better represent floodplain conditions at the time of the 1985 flood. Specific survey information from this time period was not available. Therefore, an approximation of the landform was made by incorporating "z shapes" in the TUFLOW model. The z shapes were used to remove the filling associated with each development (the additional Princes Highway culverts were also removed from the model). Although this is unlikely to exactly represent "pre-development" conditions, the size of each development relative to overall Pambula River floodplain is small. Therefore, any uncertainties should not have a significant impact on results.

Inflow Boundary Conditions

Discharge hydrographs generated by the XP-RAFTS hydrologic model were used to define inflows to the TUFLOW model.

Downstream Boundary Conditions

Unlike the 2011, 2012 and 2016 floods, no recorded water level information is available for nearby gauges to assist in defining the downstream boundary conditions for the 1985 flood. However, the 'Pambula River Data Assessment Study' (1990) includes tabulated water level versus time information from a gauge near Eden for the 1985 event. Therefore, this tabulated information was extracted and was used to define the downstream boundary in the TUFLOW model.

Results

Calibration of the TUFLOW computer model was completed based upon seventeen (17) flood marks that were surveyed following the 1985 flood. A recorded stage hydrograph was also available for the Lochiel gauge.

Peak floodwater depths were extracted from the results of the 1985 flood simulation and are included on **Figures 16.1** to **16.6**. A comparison between the peak flood levels generated by the TUFLOW model and the surveyed flood marks is also provided in **Figures 16.1** to **16.6** as well as **Table 18.**

The time variation in simulated water levels at the Pambula River at Lochiel gauge were also extracted and is provided in **Figure D12** in **Appendix D**.

The flood level comparison provided in **Table 18** shows that the TUFLOW model is providing a good reproduction of the surveyed flood mark elevations. Most flood mark elevations are reproduced to within 0.15 metres with the average absolute difference being 0.10 metres.

Figure D12 also shows that the simulated stage hydrograph provides a reasonable reproduction of the recorded stages at the Lochiel gauge. The simulated hydrograph provides a good reproduction of the peak water level at the gauge (within 0.05 metres), although the timing of the peak is slightly off. As discussed, this may be associated with the timing of the recorded rainfall at the Green Cape gauge not being fully representative of the timing of rainfall across the catchment.

Table 18 Comparison between simulated flood levels and surveyed flood marks for the 1985 flood

#	Surveyed Flood Mark (mAHD)	Simulated Flood Level (mAHD)	Difference (m)
1	3.69	3.92	0.23
2	4.39	4.27	-0.12
3	4.81	4.77	-0.04
4	4.78	4.73	-0.05
5	4.25	4.12	-0.13
6	4.20	4.25	0.05
7	2.54	2.47	-0.07
8	2.55	2.46	-0.09
9	3.57	3.44	-0.13
10	3.57	3.48	-0.09
11	2.97	3.06	0.09
12	3.69	3.78	0.09
13	3.90	3.76	-0.14
14	3.99	4.09	0.10
15	3.65	3.76	0.11
16	3.33	3.19	-0.14
17	2.45	2.52	0.07

6.7 1971 Flood

6.7.1 XP-RAFTS Modelling

Rainfall

The 1971 flood occurred as a result of significant rain falling between the 4th and 8th of February. As shown in **Figure 17** and **Table 12**, nearly 500 mm of rain fell across parts of the catchment making it the largest flood on record.

Accumulated rainfall totals for each rainfall gauge that was operational during the 1971 event were used to develop a rainfall isohyet (i.e., rainfall depth contour) map for the event, which is shown in **Figure 17**. Similar to the other calibration events, higher rainfall depths were recorded across the western parts of the catchment relative to the coastal areas.

The temporal distribution of rainfall was to be based on the closest active continuous rainfall gauge during this event. Unfortunately, the closest continuous gauge with data for the 1971 event was determined to be the Green Cape Lighthouse gauge which is located more than 30 km south of the catchment. Attempts were made to use this gauge as part of the calibration; however, the calibration outcomes were poor. A subsequent review of the 1971 rainfall records for this gauge showed inconsistencies relative to daily rainfall records for gauges located closer to the catchment. More specifically, the Green Cape gauge recorded a total rainfall depth of only 156mm (i.e., well under half the rainfall that was experienced across most of the catchment). Secondly, as shown in **Plate 17**, the majority of rainfall recorded at the Green Cape occurred on the 6th February, while the daily gauges recorded the majority of rainfall on the 5th February. Therefore, the Green Cape gauge was not considered to be representative of the rain that fell across the catchment during the 1971 event. Unfortunately, no other active rainfall gauges were available for this event. Therefore, as a last resort, the daily rainfall information at the catchment was broken down into hourly increments and the rainfall was varied linearly based on a maximum rainfall intensity of 23.2 mm/hour at midnight on the 5th February. The adopted rainfall distribution is shown on **Figure D13** in **Appendix D**.

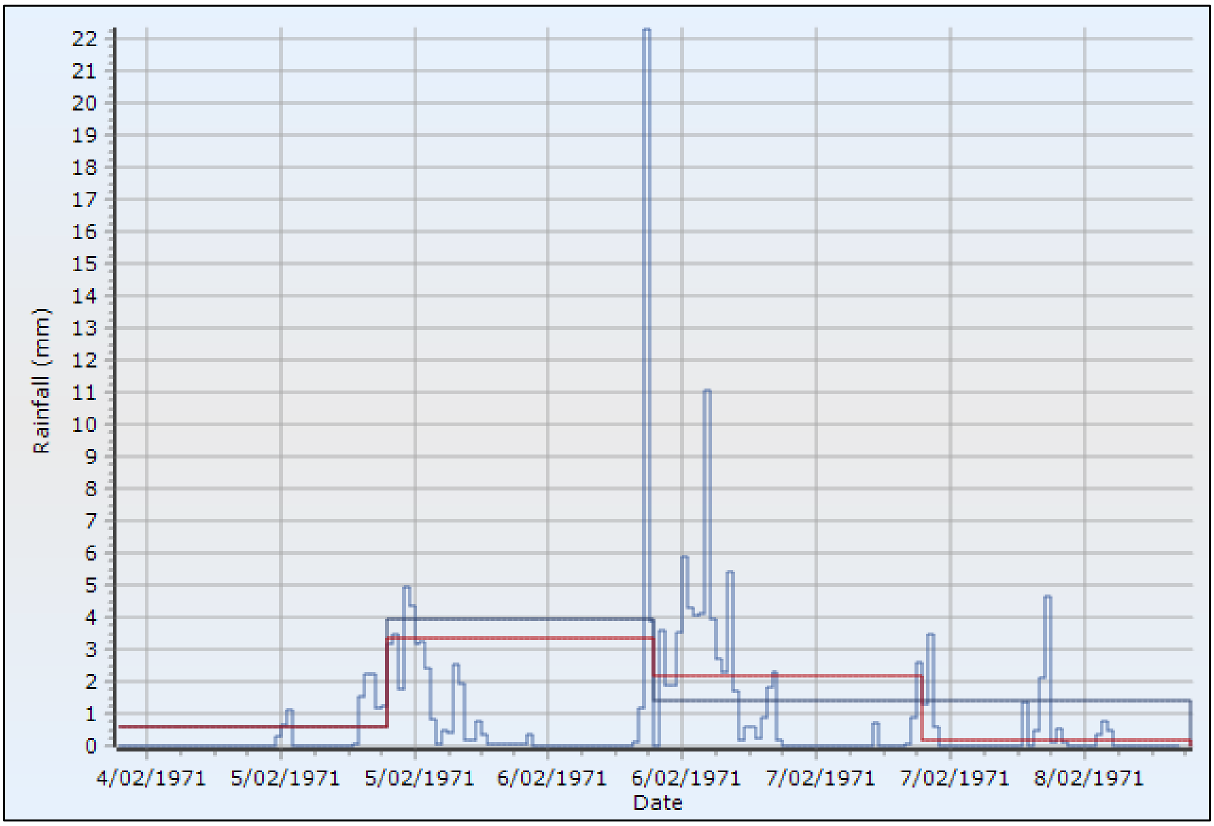


Plate 17 1971 rainfall records for Green Cape (sub-daily), Pambula Post office (daily) and Merimbula Airport (daily) gauges

Owing to the uncertainty in rainfall information, the rainfall was not varied spatially as part of the simulation. That is, a single storm was applied across the catchment based upon the average rainfall depth.

The continuous rainfall information at Green Cape was analysed relative to design rainfall-intensity-duration information. This information is presented in **Appendix D** and indicates that the 1971 approached that of a 1% AEP design rainfall event for some periods. However, as noted above, this may not be representative of what was experienced in the catchment.

Rainfall Losses

The rainfall losses summarised in **Table 13** were applied to the RAFTS model as part of 1971 flood simulation. Due to the uncertainty in rainfall, no attempt to adjust the rainfall losses was completed as part of the calibration.

Results

The XP-RAFTS model was used to simulate rainfall-runoff behaviour for the 1971 flood based upon the rainfall and rainfall loss information presented in the preceding sections. A summary of peak discharges for each XP-RAFTS model subcatchment for the 1971 flood are included in **Appendix E.**

A simulated discharge hydrograph was also extracted at the location of the Lochiel stream gauge. This simulated hydrograph is presented in the **Figure D13** in **Appendix D**. Also included on **Figure D13** is the recorded discharge hydrograph.

Figure D13 shows that simulated hydrograph provides a reasonable reproduction of the recorded hydrograph considering the uncertainty with the rainfall information.

6.7.2 TUFLOW Modelling

Modifications to Reflect Historic Conditions

The same TUFLOW modifications that were completed to reflect 1985 catchment conditions were retained for the 1971 flood simulation.

Inflow Boundary Conditions

Discharge hydrographs generated by the XP-RAFTS hydrologic model were used to define inflows to the TUFLOW model.

Downstream Boundary Conditions

Tabulated water level information for a gauge near Eden for the 1971 flood were extracted from the 'Pambula River Data Assessment Study' (1990) and was used to define the downstream boundary in the TUFLOW model.

Results

Calibration of the TUFLOW computer model was completed based upon five (5) surveyed flood marks for the 1971 flood as well as a recorded stage hydrograph for the Lochiel gauge.

Peak floodwater depths were extracted from the results of the 1971 flood simulation and are included on **Figures 18.1** to **18.6**. A comparison between the peak flood levels generated by the TUFLOW model and the surveyed flood marks is also provided in **Figures 18.1** to **18.6** as well as **Table 19.**

The time variation in simulated water levels at the Pambula River at Lochiel gauge were also extracted and is provided in **Figure D14** in **Appendix D**.

The flood level comparison provided in **Table 18** shows that the TUFLOW model is generally providing a good reproduction of the surveyed flood mark elevations. Most flood mark elevations are reproduced to within 0.2 metres with the average difference being -0.11 metres. The only major exception is at location #3, where the simulated water levels are

0.7 metres lower than the surveyed flood level. However, this surveyed level is much higher than the surrounding surveyed levels indicating it may not be reliable or may have been subject to external factors that cannot be represented in the modelling (e.g., wave action).

Table 19 Comparison between simulated flood levels and surveyed flood marks for the 1971 flood

#	Surveyed Flood Mark (mAHD)	Simulated Flood Level (mAHD)	Difference (m)
1	5.51	5.32	-0.19
2	4.08	4.09	0.01
3	4.02	3.32	-0.70
4	3.42	3.41	-0.01
5	3.00	3.35	0.35

Figure D12 also shows that the simulated stage hydrograph provides a reasonable reproduction of the recorded stages at the Lochiel gauge. The simulated hydrograph provides a good reproduction of the peak water level at the gauge (within 0.1 metres), although the timing of the peak is slightly off. As discussed, this may be associated with the timing of the recorded rainfall at the Green Cape gauge not being fully representative of the timing of rainfall across the catchment.

7 DESIGN FLOOD ESTIMATION

7.1 General

Design floods are hypothetical floods that are commonly used for planning and floodplain management investigations. Design floods are based on statistical analysis of rainfall and flood records and are typically defined by their probability of exceedance. This is often expressed as an Annual Exceedance Probability (AEP).

The AEP of a flood flow or level or depth at a particular location is the probability that the flood flow or level or depth will be equalled or exceeded in any one year. For example, a 1% AEP flood is the best estimate of a flood that has a 1% chance of being equalled or exceeded in any one year.

Design floods can also be expressed by their Average Recurrence Interval (ARI). For example, the 1% AEP flood can also be expressed as a 1 in 100 year ARI flood. That is, the 1% AEP flood will be equalled or exceeded, on average, once in 100 years.

It should be noted that there is no guarantee that a 1% AEP flood will occur once in a 100-year period. It may occur more than once, or at no time at all in the 100-year period. This is because design floods are based upon a long-term statistical average. Therefore, it is prudent to understand that the occurrence of recent large floods does not preclude the potential for another large flood to occur in the immediate future.

Design floods are typically estimated by applying design rainfall to the computer model and using the model to route the rainfall excess across the catchment to determine design flood level, depth and velocity estimates. The procedures employed in deriving design flood estimates for the Pambula River and Yowaka River catchment are outlined in the following sections.

7.2 Hydrology

Design hydrology was defined as part of the flood study based upon the 2019 revision of Australian Rainfall and Runoff (ARR2019) (Ball et al, 2019). This included a flood frequency analysis (FFA) based upon records for the Pambula River at Lochiel stream gauge as well as application of ARR2019 design storms to the calibrated XP-RAFTS model.

The following sections describe the FFA as well as the XP-RAFTS inputs and outputs.

7.2.1 Flood Frequency Analysis

A flood frequency analysis (FFA) allows peak design discharges to be estimated based on recorded information at stream gauges. This involves applying different probability distributions to find the distribution that provides the best “fit” to the historic gauge records and then using that distribution to estimate design discharges for defined frequencies (e.g., 1% AEP discharge).

An FFA was completed as part of the current study for the Pambula River at Lochiel stream gauge. The outcomes of this assessment are presented in **Appendix F**.

Overall, it was determined that Generalised Extreme Value probability distribution provided the best "fit" to recorded data at the Lochiel gauge. As a result, the GEV discharge estimates were selected and are summarised in **Table 20**. Also included in **Table 20**, are the design discharge estimates at the Lochiel stream gauge provided by the XP-RAFTS model, which is discussed in more detailed in the following section.

Table 20 Peak Design Discharge Estimates at Lochiel Stream Gauge

AEP	Peak Flow (m^3/s)	
	FFA	XP-RAFTS ARR2019
10%	424	318
5%	513	387
2%	601	483
1%	652	552
0.5%	693	663
0.2%	735	807

7.2.2 Hydrologic Modelling

Rainfall

Point design rainfall depths were downloaded from the Bureau of Meteorology's IFD webpage. The design rainfall intensities were extracted at four locations in an attempt reflect the spatial variation in design rainfall across the catchment. The locations are shown in **Plate 6**.

A copy of the design rainfall information downloaded from the Bureau of Meteorology's IFD database is included in **Appendix G** at each location.

As part of the flood study it was also necessary to define flood characteristics for the Probable Maximum Flood (PMF). The PMF is considered to be the largest flood that could conceivably occur across a particular area.

The PMF is estimated by routing the Probable Maximum Precipitation (PMP) through the XP-RAFTS model. The PMP is defined as the greatest depth of rainfall that is meteorologically possible at a specific location.

PMP depths were derived for a range of storm durations up to and including the 6-hour event based on procedures set out in the Bureau of Meteorology's *'Generalised Short Duration Method'* (GSDM) (Bureau of Meteorology, 2003). The GSDM PMP calculations are included in **Appendix G**.

Plate 18 Locations where IFD data were extracted

Areal Reduction Factors

The design rainfall intensities presented in the preceding section are only applicable for catchment areas of up to 1 km^2. Therefore, ARR2019 includes areal reduction factors that recognise that there is unlikely to be a uniformly high rainfall intensity across all sections of large catchments.

The primary input variable to calculate the areal reduction factors is the contributing catchment area. Although the overall catchment area is 301 km^2, this area is only applicable at the catchment outlet. Across the "built up" sections of the catchment that are of primary interest for the study, the contributing catchment area is much smaller, namely:

- Lochiel - 107 km^2
- South Pambula - 119 km^2
- Pambula – 120 km^2
- Greigs Flat – 133 km^2

Based on the contributing catchment areas summarised above, a representative catchment area of 120 km^2 was adopted for the areal reduction factor calculations. The resulting reduction factors are summarised in **Table 21**. These reduction factors were applied to the point rainfall intensities described in the previous section before application of the temporal patterns described in the following section.

Table 21 Areal reduction factors

Rainfall Duration	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP
5 min	0.462	0.455	0.447	0.440	0.433	0.425
10 min	0.593	0.586	0.576	0.569	0.562	0.553
15 min	0.653	0.646	0.636	0.628	0.621	0.611
20 min	0.690	0.682	0.672	0.664	0.656	0.646
25 min	0.716	0.708	0.697	0.688	0.680	0.669
30 min	0.735	0.726	0.715	0.706	0.698	0.686
45 min	0.771	0.762	0.749	0.739	0.730	0.717
1 hour	0.793	0.782	0.768	0.758	0.747	0.733
1.50 hour	0.818	0.805	0.789	0.776	0.764	0.747
2 hours	0.832	0.818	0.799	0.785	0.771	0.752
3 hours	0.850	0.835	0.814	0.798	0.783	0.762
4.50 hours	0.875	0.862	0.844	0.831	0.818	0.801
6 hours	0.897	0.889	0.878	0.870	0.862	0.851
9 hours	0.919	0.915	0.909	0.904	0.900	0.893
12 hours	0.928	0.923	0.917	0.912	0.908	0.902
18 hours	0.961	0.960	0.960	0.959	0.959	0.958
24 hours	0.965	0.965	0.964	0.963	0.963	0.962
30 hours	0.967	0.967	0.966	0.966	0.965	0.964
36 hours	0.969	0.969	0.968	0.967	0.967	0.966
48 hours	0.972	0.971	0.970	0.970	0.969	0.969
72 hours	0.975	0.974	0.974	0.973	0.973	0.972
96 hours	0.977	0.977	0.976	0.975	0.975	0.974
120 hours	0.979	0.978	0.977	0.977	0.976	0.975
144 hours	0.980	0.979	0.978	0.978	0.977	0.977
168 hours	0.981	0.980	0.979	0.979	0.978	0.977

Rainfall Losses

As discussed, the XP-RAFTS model was developed to include the “initial-continuing loss” model to account for rainfall that is intercepted and does not contribute to runoff.

ARR2019 recommends a hierarchical approach for determining the most appropriate initial loss and continuing loss values to apply as part of design simulations. The hierarchy of approaches recommends the adoption of calibrated rainfall loss information in preference to more generic rainfall loss information, such as that located on the ARR2019 Data Hub.

As outlined in Chapter 6, the XP-RAFTS model was calibrated against five historic rainfall events. Continuing loss rates varying between 0.5 and 1.8 mm/hour were adopted for the calibration events for pervious sections of the catchment. When a range of loss rates are used for calibration, ARR2019 recommends the adoption of an average loss rate. Therefore, the average of the calibrated continuing loss rates (i.e., 1.16 mm/hour) was adopted for the design flood simulations.

The calibration simulations utilised initial rainfall losses that varied between 0 and 21 mm. ARR2019 recommends the average calibrated initial rainfall loss (i.e., 16.8mm) is used with probability neutral loss information on the ARR2019 Data Hub site to develop "burst losses" for each AEP and storm duration. It was noted that no probability neutral rainfall losses are provided on the ARR2019 data hub for storm durations less than 1 hour. Therefore, it was assumed that the burst rainfall losses for the 1 hour storm also applied for storm durations less than 1 hour. In addition, no probability neutral losses are provided for events rarer than the 1% AEP. Therefore, the 1% AEP losses were also applied to the 0.5% and 0.2% AEP floods. The final burst losses for pervious surfaces are provided in **Table 22**. A burst/initial loss of 0 mm was adopted for the PMP simulations in line with recommendations in Chapter 4 of Book 8 of ARR2019.

Table 22 Burst Rainfall Losses for Design Storms

Duration	Burst Loss (mm)			
	10% AEP	5% AEP	2% AEP	1% AEP, 0.5% AEP & 0.2% AEP
<1 hour	9.4	9.2	8.8	5.5
1 hour	9.4	9.2	8.8	5.5
1.50 hour	9.1	8.2	7.8	4.4
2 hours	8.7	8.1	7.8	4.3
3 hours	7.8	6.8	7.7	3.7
6 hours	7.8	7.0	7.8	2.4
12 hours	9.6	8.2	9.1	3.8
18 hours	11.3	9.5	10.3	5.2
24 hours	13.8	11.3	11.3	5.4
36 hours	16.7	12.8	16.8	7.3
48 hours	19.5	19.3	18.8	8.9
72 hours	24.1	25.5	22.6	10.0

For impervious surfaces, a burst loss of 0 mm and a continuing loss rate of 0 mm/hr was adopted (as per the calibration simulations).

Temporal Patterns

ARR2019 employs 10 different temporal patterns for each AEP/storm duration to define the time variation in rainfall depth during each storm. The use of a variety of different temporal patterns is intended to reflect the natural variability of a typical rainfall event (i.e., no two storms will be the same).

The temporal patterns for the study area were downloaded from the ARR2019 data hub and were used to simulate the temporal distribution of rainfall for each design storm(a copy of the data hub download is included in **Appendix H**). In accordance with ARR2019 for catchments with an area greater than 75 km^2, the "areal" temporal patterns rather than "point" temporal patterns were selected to describe the temporal variation in rainfall. The temporal patterns for the 500 km^2 reference area were used.

For the PMP, a single temporal pattern was adopted for each PMP storm simulation in line with the approach recommended in the *'Generalised Short Duration Method'* (GSDM) (Bureau of Meteorology, 2003).

Results

The XP-RAFTS model was used to simulate rainfall runoff processes for the complete suite of design storms. The design 10%, 5%, 2%, 1% AEP, 0.5% and 0.2% storms were simulated in addition to the PMP.

As discussed, a suite of ten temporal patterns were used to represent the temporal variation in rainfall for each design flood frequency up to and including the 0.2% AEP. The peak discharges from the full suite of temporal patterns for each design event were reviewed to determine the critical storm duration for each subcatchment. The critical storm duration was defined by calculating the average discharge for each storm duration (based on all 10 temporal patterns). The duration that generated the highest average discharge was selected as the critical duration for that particular subcatchment. The resulting critical storm durations for each subcatchment are presented in **Appendix H**. The results of the hydrologic analysis indicate that the critical duration across the catchment is most commonly 12 hours. However, there are more than 10 unique critical storms for each design flood when considering all subcatchments.

Once the critical duration was determined, a representative temporal pattern was selected for that duration. The temporal pattern that generated the peak discharge immediately above the mean discharge was selected as the most representative temporal pattern for each subcatchment. The adopted temporal pattern for each subcatchment along with the peak discharge generated by the representative temporal pattern is also provided in **Appendix H**. Peak design discharges were also extracted at key locations across the catchment and are summarised in **Table 23**.

Box plots were also prepared to display the full range of results produced as part of the ARR2019 hydrologic analysis. The box plots are provided in **Appendix H** for the Princes Highway bridge crossings of the Pambula River and Yowaka River. The box plots present the following information:

Table 23 Raw XP-RAFTS Peak Design Discharges at Key Locations

Location		XP-RAFTS ID	Peak Discharge (m^3/s)						
			10%AEP	5%AEP	2%AEP	1%AEP	0.5%AEP	0.2%AEP	PMP
Pambula River	Chalk Hills Road	17.11	101	123	154	179	214	260	795
	Wolumla Peak Road	1.14	217	264	329	377	456	553	,1638
	Princes Highway	1.27	358	437	543	621	746	908	2,992
	Upstream of Yowaka River confluence	1.31	408	498	620	710	852	1037	3,375
	Downstream of Pambula Lake	1.36	836	1,023	1,277	1,479	1,776	2,164	6,453
	Ocean outlet	1.39	840	1,028	1,283	1,491	1,790	2,173	6,471
Yowaka River	Back Creek Road	114.11	124	152	190	220	264	319	954
	Nethercote Road	114.14	148	182	228	265	319	387	1,137
	Pipeclay Creek confluence	114.21	382	469	588	679	814	991	2,748
	Princes Highway	114.24	390	479	601	695	833	1,013	2,804
	Upstream of Pambula River confluence	114.25	396	487	610	705	845	1,029	2,844
Other Watercourses	Centipede Creek @ Nethercote Road	145.04	37.4	45.6	56.7	65.4	77.6	95.0	256
	Old Hut Creek @ Nethercote Road	133.11	114	139	173	201	240	291	755
	Back Creek @ Back Creek Road	49.02	3.32	4.02	5.00	5.75	6.95	8.51	43.5
	Back Creek @ Mount Darragh Road	47.05	20.9	26.1	32.4	37.0	43.7	53.7	240
	Burtons Creek @ Mount Darragh Road	_junc_43	53.6	65.4	81.5	94.1	114	138	602
	Seven Mile Creek @ Mount Darragh Road	17.08	65.2	79.3	98.8	115	136	168	528
	Chalk Hills Creek Upstream of Pambula River	1.12	102	125	155	180	214	263	733

- Median discharge for each storm duration (represented by the blue horizontal line contained within each green box)
- Average discharge for each storm duration (defined by the "✳")
- The first and third quartiles (defined by the green box), which illustrated the 25th percentile and 75th percentile discharge values
- The highest and lowest discharge value (represented by the "T" attached to the end of the green box)
- The critical storm duration is highlighted in yellow

7.3 Hydraulics

7.3.1 Boundary Conditions

Inflow Boundaries

Inflows to the TUFLOW model were defined using the critical design discharge hydrographs generated by the XP-RAFTS hydrologic model. However, as discussed in the previous section, more than ten different critical storms were identified as part of the hydrologic analysis. Although the XP-RAFTS model runs in a matter of seconds and can run a large number of storms in a relatively short amount of time, the hydraulic model takes multiple days to run a single storm. Therefore, it was not considered feasible to run all unique combinations of storm durations and temporal patterns through the hydraulic model in a timely manner.

Therefore, the assessment of critical durations and temporal patterns was restricted to the areas of primary interest to the study (i.e., the more urbanised, eastern sections of the catchment). This assessment identified three temporal patterns (6261, 6262, 6266) as being most commonly critical and, in all cases, produce peak design discharges very close to the mean discharge for each subcatchment in the main areas of interest (refer to **Plate 19** for an example of 1% AEP hydrographs). However, temporal pattern 6262 was ultimately selected for each design flood as it showed the quickest rate of rise and, therefore, would be more crucial when quantifying emergency response details such as road overtopping times.

As discussed in Section 7.2.1, a flood frequency analysis (FFA) was completed for the Pambula River at Lochiel stream gauge. **Table 20** provides a comparison between the FFA discharges and the ARR2019 discharges generated by the XP-RAFTS hydrologic model at Lochiel. This comparison shows that the ARR2019 discharges are generally lower than the FFA discharges. It was considered preferential to adopt the more robust FFA discharges which are based on statistical analysis of stream gauge records for the local catchment in preference to the ARR2019 discharges which are based on more regional information. Therefore, the design ARR2019 discharge hydrographs for temporal pattern 6262 were factored to match the calculated FFA discharges at the Lochiel gauge. The adopted adjustment factors are provided in **Table 24** and the factored peak XP-RAFTS discharges are included in **Appendix H**.

Simulations were also completed with longer storms (e.g., 18 hours) to confirm if a longer storm with more runoff volume but with a lower peak discharge may produce higher water levels. These simulations confirmed that the 12 hour storm produced the highest water levels.

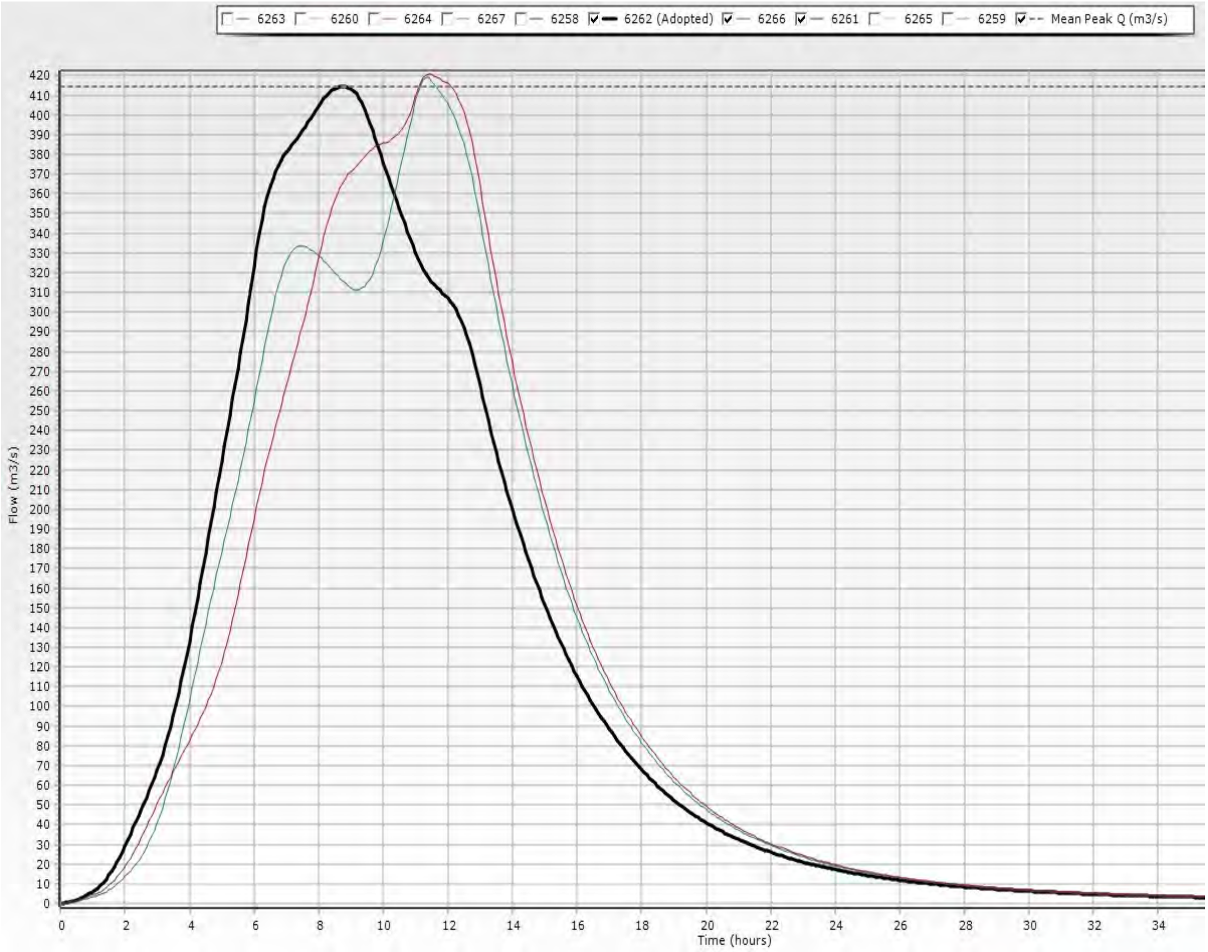


Plate 19 Sample of ARR2019 1% AEP hydrographs for the Pambula River at Princes Highway

Table 24 ARR2019 Hydrograph Adjustment Factors

AEP	Factor
10%	1.38
5%	1.36
2%	1.27
1%	1.18
0.5%	1.05
0.2%	0.92

Ocean Boundary

The Pambula River drains into the Tasman Sea near Pambula Beach. Therefore, the ocean level at the time of the flood can have an impact on flood behaviour across the lower-lying, estuarine sections of the catchment.

The ocean boundary condition was defined based on guidance provided in the *'Floodplain Risk Management Guide. Modelling the Interaction of Catchment Flooding and Oceanic Inundation in Coastal Waterways'* (Office of Environment & Heritage*, 2015).* Based on information contained in this guideline, the combination of catchment runoff and ocean boundary conditions summarised in **Table 25** was adopted for each design simulation.

Table 25 Adopted ocean boundary conditions for design flood simulations

Design Flood Event	Catchment Flood Scenario	Ocean Level (Ocean Level at Time of Peak Catchment Outflow)
20% AEP	20% AEP	High High Water Spring (HHWS) tide (1.03 mAHD)
10% AEP	10% AEP	HHWS (1.03 mAHD)
5% AEP	5% AEP	HHWS (1.03 mAHD)
2% AEP	2% AEP	5% AEP (2.35 mAHD)
1% AEP (flood level)	1% AEP	5% AEP (2.35 mAHD)
	5% AEP	1% AEP (2.55 mAHD)
1% AEP (velocity)	1% AEP	Indian Spring Low Water (ISLW) tide (-0.82 mAHD)
0.5% AEP	0.5% AEP	1% AEP (2.55 mAHD)
0.2% AEP	0.2% AEP	1% AEP (2.55 mAHD)
PMF	PMF	1% AEP (2.55 mAHD)

NOTE: * A design flood level envelope was developed for the 1% AEP flood based upon consideration of a 1% AEP catchment runoff event with a 5% AEP ocean level plus a 5% AEP catchment runoff event with a 1% AEP ocean level. An ISLW was also included in the development of the peak 1% AEP velocity envelope.

The 'Bega Valley Shire Coastal Processes and Hazards Definition Study' (BMT WBM 2015) defines the Pambula River as having a wave-dominated, shallow open entrance which places the entrance in "group 3" (i.e., entrance type C) of the OEH guide. The peak design ocean levels for Type C entrances, as defined in the OEH guide, are also provided in **Table 25**.

A time varying ocean (i.e., tide) level was included for all design simulations. However, the peak design ocean level was arranged so that it coincided with the peak catchment outflow (the only exception was the 1% AEP ISLW simulations where a "low tide" level was adopted to maximise velocities). The adopted ocean boundary conditions are shown in **Plate 20**.

As shown in **Table 25**, each catchment runoff event was typically combined with a single ocean boundary condition to represent each design flood. The only exception is the 1% AEP event, where two additional combinations of catchment runoff and ocean level conditions were simulated to encompass an expanded range of runoff and tidal interactions given the importance of this design flood for planning purposes.

A "static" river entrance geometry was adopted for all design flood simulations. That is, the potential for scour of the river entrance during the flood was not explicitly modelled. This is a common approach, particularly in flood studies in New South Wales. Sensitivity to entrance scour can be investigated during a subsequent floodplain risk management study, if sufficient potential risk to warrant the analysis is identified.

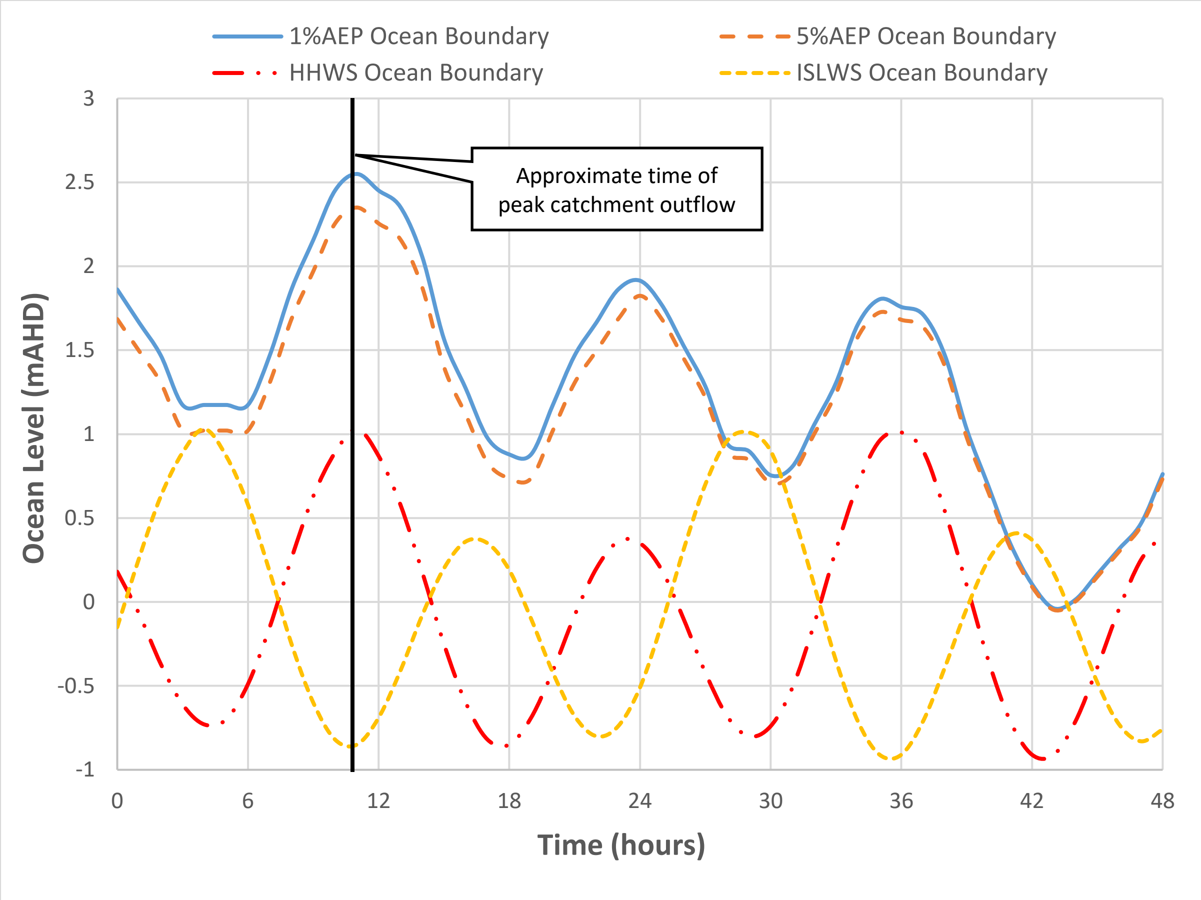


Plate 20 Adopted ocean level hydrographs for design flood simulations

7.3.2 Hydraulic Structure Blockage

'Base' blockage factors for each bridge and culvert in the catchment were estimated based upon recommendations in Chapter 6 of Book 6 of 'Australian Rainfall & Runoff' (Ball et al, 2019). This document also recommends adjusting the 'base' blockage factors up or down depending on the severity of the event (i.e., higher blockage factors during larger floods and lower blockage factors during smaller floods). A summary of the blockage scenarios that were adopted for each design flood is provided in **Appendix F** and is also summarised below:

- Low Blockage Scenario –10% AEP event
- Medium Blockage Scenario – 5%, 2%, 1% and 0.5% AEP events
- High Blockage Scenario – 0.2% AEP and PMF events

However, it was noted that application of blockage to each hydraulic structure effectively creates a number of small storages across the catchment that serve to attenuate flows and reduce water levels downstream of each structure. In recognition of the potential attenuation effects provided by the blockage factors and the understanding that structure blockage can be highly variable, each design flood was also simulated with no structure blockage. This was completed to ensure the flood risk downstream of each hydraulic structure was not underrepresented.

The impact of no blockage as well as complete blockage of culverts and bridges was assessed as part of the sensitivity analysis (refer Section 9).

7.4 Results

7.4.1 Design Flood Envelope

As discussed, a range of design storms, ocean levels and blockage scenarios were simulated for each design flood. Therefore, the results from each simulation for each design flood were interrogated and combined to form a "design flood envelope" for each design flood. It is this "design flood envelope" comprising the most critical depths, velocities and levels from a risk management perspective that forms the basis for the results documented in the following sections.

7.4.2 Presentation of Results

The results of the flood simulations were reviewed, and it was noted that several areas were only exposed to shallow water depths that would not present a significant flood hazard. Therefore, it was considered necessary for the results of the computer simulations to be "filtered" to distinguish between areas of significant inundation depth / flood hazard and those areas subject to negligible inundation. Therefore, a minimum depth threshold of 0.10 metres was adopted as the filter criteria for the study. That is, only areas where design water depths are predicted to exceed 0.1 metres are displayed in the flood mapping.

7.4.3 Peak Depths, Levels and Velocities

Results were extracted from the final design flood envelopes and were used to prepare a range of flood mapping for the 10% AEP, 5% AEP, 2% AEP, 1% AEP, 0.5% AEP, 0.2% AEP and PMF events. This includes:

- Floodwater depths and flood level contours: **Figures 19.1** to **25.6**
- Floodwater velocities (including velocity vectors which show the direction of water movement): **Figures 26.1** to **32.6**

Peak flood levels, depths and velocities were also extracted at key locations across the catchment and are provided in **Table 26**, **Table 27** and **Table 28** respectively.

Figures 19.1 to **25.6** shows that floodwaters are typically contained in close proximity to each of the main watercourses across most of the upper catchment. Flow velocities in these areas are generally in excess of 2 m/s during each design flood. When floodwaters reach the more expansive floodplains located south of Pambula, at Greigs Flat and Pambula Lake, floodwaters slow appreciably (i.e., velocities are most commonly less than 1 m/s) and cover a more extensive areas of land. This includes number of rural properties at Greigs Flat as well as the southern fringe of Pambula.

7.5 Results Verification

The XP-RAFTS and TUFLOW models developed as part of this study were calibrated against recorded and observed flood information for five historic floods. In general, the models were found to provide a good reproduction of historic flood mark elevations. However, the outcomes of the calibration only provide evidence that the model is providing a reliable representation of flood behaviour at isolated locations (i.e., at recorded flood mark or stream gauge locations).

Table 26 Peak Design Water Levels at Key Locations

Location		Peak Water Level (mAHD)						
		10%AEP	5%AEP	2%AEP	1%AEP	0.5%AEP	0.2%AEP	PMP
Pambula River	Chalk Hills Road	81.5	81.9	82.2	82.3	82.4	82.6	86.0
	Wolumla Peak Road	62.4	62.8	63.4	63.7	63.8	64.0	69.3
	Princes Highway	3.92	3.98	4.04	4.08	4.13	4.19	7.20
	Upstream of Yowaka River confluence	1.98	2.28	3.14	3.40	3.49	3.59	6.58
	Downstream of Pambula Lake	1.61	1.85	2.79	3.03	3.09	3.16	5.04
	Ocean outlet	1.04	1.04	2.35	2.55	2.56	2.57	2.75
Yowaka River	Back Creek Road	121	121	121	122	122	122	124
	Nethercote Road	28.7	29.0	29.3	29.5	29.7	29.8	33.7
	Pipeclay Creek confluence	5.31	5.82	6.35	6.67	6.88	7.09	11.79
	Princes Highway	2.84	3.25	3.93	4.19	4.31	4.44	7.90
	Upstream of Pambula River confluence	1.97	2.27	3.15	3.41	3.50	3.60	6.62
Other Watercourses	Centipede Creek @ Nethercote Road	62.5	62.6	62.7	62.8	62.8	62.9	64.0
	Old Hut Creek @ Nethercote Road	51.3	51.6	51.9	52.1	52.2	52.3	55.0
	Back Creek @ Back Creek Road	93.7	93.9	94.1	94.2	94.3	94.3	97.0
	Back Creek @ Mount Darragh Road	16.2	16.6	17.4	17.6	17.6	17.7	20.7
	Burtons Creek @ Mount Darragh Road	26.2	26.4	26.6	26.8	26.9	26.9	29.9
	Seven Mile Creek @ Mount Darragh Road	106	106	106	106	106	106	109
	Chalk Hills Creek Upstream of Pambula River	73.3	73.8	74.2	74.4	74.6	74.8	79.2

Table 27 Peak Design Water Depths at Key Locations

Location		Peak Water Level (mAHD)						
		10%AEP	5%AEP	2%AEP	1%AEP	0.5%AEP	0.2%AEP	PMP
Pambula River	Chalk Hills Road	2.81	3.12	3.42	3.59	3.71	3.83	7.30
	Wolumla Peak Road	4.80	5.18	5.75	6.05	6.23	6.38	11.7
	Princes Highway	3.20	3.25	3.31	3.35	3.40	3.46	6.47
	Upstream of Yowaka River confluence	5.40	5.69	6.56	6.81	6.91	7.01	10.0
	Downstream of Pambula Lake	6.94	7.18	8.12	8.35	8.42	8.49	10.4
	Ocean outlet	3.10	3.11	4.42	4.62	4.62	4.63	4.81
Yowaka River	Back Creek Road	3.21	3.54	3.82	3.98	4.07	4.16	6.28
	Nethercote Road	3.01	3.30	3.61	3.81	3.95	4.10	8.03
	Pipeclay Creek confluence	5.11	5.62	6.15	6.47	6.68	6.89	11.6

	Princes Highway	3.93	4.34	5.02	5.28	5.40	5.53	8.99
	Upstream of Pambula River confluence	4.62	4.93	5.80	6.06	6.15	6.26	9.27
Other Watercourses	Centipede Creek @ Nethercote Road	3.28	3.43	3.54	3.61	3.65	3.69	4.85
	Old Hut Creek @ Nethercote Road	3.36	3.71	3.93	4.13	4.23	4.34	7.09
	Back Creek @ Back Creek Road	0.83	1.00	1.17	1.29	1.37	1.43	4.12
	Back Creek @ Mount Darragh Road	2.11	2.53	3.29	3.51	3.55	3.65	6.65
	Burtons Creek @ Mount Darragh Road	2.27	2.48	2.70	2.81	2.90	2.99	5.98
	Seven Mile Creek @ Mount Darragh Road	1.80	2.02	2.21	2.34	2.44	2.54	5.34
	Chalk Hills Creek Upstream of Pambula River	3.32	3.78	4.20	4.44	4.62	4.80	9.24

Table 28 Peak Design Flow Velocities at Key Locations

Location		Peak Water Level (mAHD)						
		10%AEP	5%AEP	2%AEP	1%AEP	0.5%AEP	0.2%AEP	PMP
Pambula River	Chalk Hills Road	2.62	2.76	2.85	2.86	2.91	2.93	3.09
	Wolumla Peak Road	3.30	3.38	3.47	3.49	3.48	3.49	3.54
	Princes Highway	2.08	2.15	2.22	2.28	2.30	2.33	2.62
	Upstream of Yowaka River confluence	1.60	1.74	1.67	2.00	1.77	1.83	2.74
	Downstream of Pambula Lake	1.63	1.80	1.73	2.05	1.86	1.94	3.11
	Ocean outlet	1.08	1.31	0.51	2.65	0.66	0.74	2.08
Yowaka River	Back Creek Road	2.19	2.30	2.42	2.48	2.55	2.61	3.93
	Nethercote Road	2.94	3.09	3.16	3.17	3.18	3.19	3.18
	Pipeclay Creek confluence	1.37	1.38	1.39	1.39	1.39	1.39	1.69
	Princes Highway	2.78	2.96	2.91	3.16	3.07	3.15	4.42
	Upstream of Pambula River confluence	2.06	2.39	2.35	2.79	2.60	2.73	4.34
Other Watercourses	Centipede Creek @ Nethercote Road	0.99	1.09	1.19	1.24	1.28	1.32	2.25
	Old Hut Creek @ Nethercote Road	2.33	2.50	2.69	2.74	2.74	2.76	2.85
	Back Creek @ Back Creek Road	0.88	0.88	0.88	0.87	0.89	0.88	0.95
	Back Creek @ Mount Darragh Road	1.20	1.25	1.25	1.28	1.27	1.26	1.33
	Burtons Creek @ Mount Darragh Road	2.74	2.93	3.04	3.12	3.15	3.16	3.73
	Seven Mile Creek @ Mount Darragh Road	3.19	3.31	3.42	3.52	3.47	3.49	4.55
	Chalk Hills Creek Upstream of Pambula River	2.42	2.51	2.58	2.62	2.66	2.70	3.38

Therefore, additional verification of the models was completed by comparing the results generated by each model against past studies as well as alternate calculation techniques. Further details on the outcomes of the model verification is presented below.

7.5.1 Comparison with Alternate Modelling Approaches

Project 5 of the Australian Rainfall & Runoff revision process included the development of a regional flood frequency estimation (RFFE) approach that enables peak design discharges to be estimated for ungauged catchments. As discussed in Section 7.2.1, a stream gauge is located within the catchment at Lochiel which enabled a flood frequency analysis to be completed. In addition, an XP-RAFTS hydrologic model was developed to simulate rainfall-runoff processes. As a result, the regional RFFE discharge estimates were not required.

Nevertheless, the RFFE can be used to assist in verifying the results produced by the XP-RAFTS model. Accordingly, peak 1% AEP discharges were established using the RFFE approach at a selection of locations across the catchment and are summarised in **Table 29**. Also included in **Table 29** are the "raw" XP-RAFTS discharges as well as the "factored" XP-RAFTS discharges at the same locations (i.e., XP-RAFTS discharges factored to match the flood frequency analysis outputs at the Lochiel stream gauge).

The RFFE approach acknowledges that there is uncertainty associated with regional approaches. Accordingly, the approach also provides confidence intervals so that an appreciation of the uncertainty in the discharge estimates developed using this approach can be gained. The confidence limits are also included in **Table 29**.

Table 29 Comparison between XP-RAFTS, FFA and Regional Flood Frequency Estimation 1% AEP discharges

Location	Peak 1% AEP Discharge (m^3/s)				
	Raw XP-RAFTS	Factored XP-RAFTS	Regional Flood Frequency Estimate		
			5% Confidence	Design Discharge	95% Confidence
Pambula River @ Lochiel Stream gauge	552	652	450	1,256	3,545
Pambula River @ Princes Highway	621	733	647	1,900	5,700
Pambula River @ Tasman Sea	1,491	1,759	778	2,228	6,450

As discussed above, the RFFE is a regional approach that does have limitations. Most notably, Chapter 3 of Book 5 of ARR2019 states that:

- The RFFE will not provide a reliable estimate when catchments incorporate a significant urban proportion, contain dams or other water storages, are affected by mining, include agricultural activity or fall outside of the shape and size characteristics of the gauged catchments used to develop the regional relationships.
- All RFFE techniques are subject to uncertainty which is likely to be greater than for at-site flood frequency analysis (such as that as documented in Section 7.2.1) or a well calibrated catchment model (such as the XP-RAFTS model documented in Section 5.2)

- The relative accuracy of the regional flood estimates is likely to be within ±50% of the true value. However, it is possible that the estimation error may exceed the true value by a factor of two or more.

With these limitations in mind, the comparison provided in **Table 29** shows that the raw and factored XP-RAFTS discharges are lower relative to the RFFE approach. However, in all cases the XP-RAFTS peak discharges fall well within the RFFE confidence limits at each location. Therefore, the XP-RAFTS model peak discharges are not unreasonable.

7.5.2 Comparison with Past Studies

There have been minimal past flooding investigations completed within the Pambula River or Yowaka River catchments. However, the 'Bridge Over Pambula River at Pambula' (2004) does include design flood discharge and flood level information for the Pambula River in the vicinity of the Princes Highway, which are reproduced in **Table 30.**

Table 30 Comparison of peak 1% AEP discharges and flood levels

Location	Discharge (m^3/s)			Flood Level (mAHD)	
	Current Study		2004 Study	Current Study	2004 Study
	Raw XP-RAFTS	Factored XP-RAFTS			
Pambula River @ Lochiel	552	652	868	21.25	N/A
Pambula River upstream of Princes Highway	621	733	1026	4.15	4.30

The comparison provided in **Table 30** shows that the current study produces peak 1% AEP discharges and flood levels that are lower than the 2004 study. However, it is noted that the 2004 study utilised a simplified hydrologic approach (involving factoring up the FFA estimates based on the contributing catchment area) that does not account for the significant floodplain storage capacity afforded in the vicinity of Pambula.

Despite the lower design discharges in the vicinity of the Princes Highway, the TUFLOW model produces a peak 1% AEP flood level that is within 0.15 metres of the 2004 study. This indicates that the design flood estimates provided by the computer models developed for the current study are reasonable.

8 IMPACTS OF FLOODING ON THE COMMUNITY

8.1 Overview

Flooding has the potential to cause significant disruption to local communities and, during very large floods, poses a risk to life and may cause damage to buildings and other infrastructure. There are also specific facilities whose occupants may be particularly susceptible to the impacts of flooding (e.g., aged care facilities).

To assist in quantifying the potential impacts that flooding may have on the communities contained within the catchment, the results of the hydraulic modelling were interrogated to prepare:

- Flood hazard mapping (Section 8.2) which quantifies the potential impacts that floodwater may have on vehicles, people and structures/buildings.
- Hydraulic category mapping (Section 8.3) which identifies areas that should be kept free of development to maintain flood function and ensure existing flooding is not increased.
- Flood emergency response categories (Section 8.4) which identifies potential emergency response requirements across the catchment including areas that may become isolated and/or require special treatment by emergency services during future floods.
- Assessment of the potential impacts that flooding may have on vulnerable and critical facilities (Section 8.5).
- Assessment of the impacts that flooding may have on major transportation routes in the catchment (Section 8.6).

8.2 Flood Hazard

Flood hazard defines the potential impact that flooding will have on vehicles, people, and property across different sections of the floodplain. More specifically, it describes the potential for floodwaters to cause damage to property or loss of life / injury (Australian Government, 2014).

For this study, the variation in flood hazard across the catchment was defined using flood hazard vulnerability curves presented in Chapter 7 of Book 6 of 'Australian Rainfall & Runoff' (Ball et al, 2019). The hazard curves are reproduced in **Plate 21** and are also described in **Table 31**.

In past flood studies in the Bega Valley Shire Council LGA (and elsewhere across NSW), hazard was defined based on categories presented in the NSW Government's 'Floodplain Development Manual' (FDM) (2005). This delineated the floodplain into two main categories: low and high. The boundary between the FDM and the new ARR2019 hazard categories do not perfectly align but, in general, the H1 to H3 categorises fall within the low hazard category defined in the FDM and the H4-H6 categories fall with the high hazard category in the FDM.

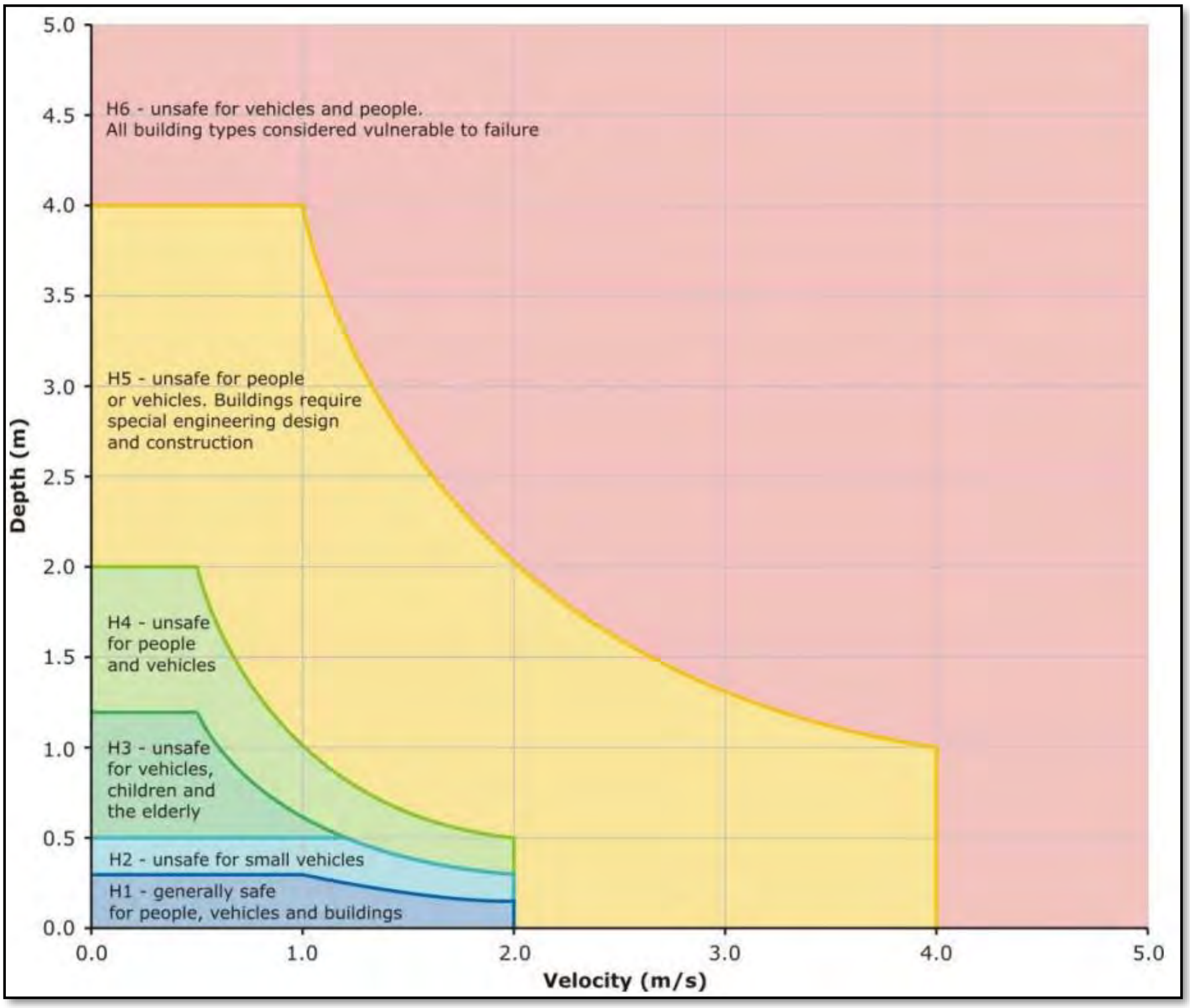


Plate 21 Flood hazard vulnerability curves (Ball et al, 2019)

Table 31 Description of Adopted Flood Hazard Categories (Ball et al, 2019)

Hazard Category	Description
H1	Relatively benign flood conditions. Generally safe for vehicles, people and buildings.
H2	Unsafe for small vehicles
H3	Unsafe for vehicles, children and the elderly
H4	Unsafe for vehicles and people of all ages & levels of mobility
H5	Unsafe for vehicles and people. All building types vulnerable to structural damage. Some less robust building types vulnerable to failure
H6	Unsafe for vehicles and people. All building types considered vulnerable to failure.

As shown in **Plate 21**, the hazard curves assess the potential vulnerability of people, cars and structures based upon the depth and velocity of floodwaters at a particular location. Therefore, peak depth, velocity and velocity-depth product outputs generated by the TUFLOW model were used to map the variation in flood hazard across the catchment based on the hazard criteria shown in **Plate 21** for the 5% AEP, 1% AEP, 0.2% AEP floods as well as the PMF. The resulting hazard category maps are shown in **Figures 34.1** to **37.6**.

The hazard maps indicate that during the 1% AEP flood, H5 and H6 hazard conditions are common within and immediately adjacent to each of the main watercourses. Most of the expansive floodplain located south of Pambula and at Greigs Flat would be subject to at least H4 hazard in the 1% AEP flood indicating it would not be safe for people or vehicles.

During the PMF, most watercourses and floodplain areas would be subject to at least H5 hazard. This includes the Princes Highway south of Pambula. This indicates that cars and people would be exposed to a significant flood risk during large floods such as the PMF.

8.3 Hydraulic Categories

The NSW Government's *'Floodplain Development Manual'* (NSW Government, 2005) characterises flood prone areas according to the hydraulic categories presented in **Table 32.** The hydraulic categories provide an indication of the potential for development across different sections of the floodplain to impact on existing flood behaviour and highlights areas that should be retained for the conveyance and storage of floodwaters.

The *'Floodplain Development Manual'* (NSW Government, 2005) does not provide explicit quantitative criteria for defining hydraulic categories. This is because the extent of floodway, flood storage and flood fringe areas are typically specific to a particular catchment.

In line with the floodway definition provided in **Table 32**, floodways were defined, as a minimum, as all areas contained within a major watercourse (i.e., from top of bank to top of bank). Velocity, depth and velocity-depth product results were also reviewed to identify areas where the majority of floodwaters are conveyed outside of the main watercourses. Several iterations were performed, and it was determined that it would not be possible to employ the same criteria to define floodways across the major rivers and the smaller, local creeks. Therefore, separate criteria were adopted to define floodways across the major river systems and local creeks. This resulted in the additional criteria described in **Table 32**. Additional manual delineation of floodways was also completed to ensure continuity of floodways in some areas.

Likewise, a consistent set of criteria could not be established to define flood storage areas across the deeper, major waterways and the shallow and more incised local creek systems. The resulting depth criteria that was adopted to define flood storage areas is summarised in **Table 32**.

All other areas that were predicted to be flooded but were not classified as flood storage or floodway were designated as "flood fringe" areas (areas located outside of floodways where the depth of inundation was less than 0.5 metres).

The resulting hydraulic category maps for the 5% AEP, 1% AEP and 0.2% AEP floods as well as the PMF are shown in **Figures 38.1** to **41.6**.

Table 32 Qualitative and Quantitative Criteria for Hydraulic Categories

Hydraulic Category	Floodplain Development Manual Definition	Adopted Criteria
Floodway	• often aligned with obvious natural channels and drainage depressions • those areas where a significant volume of water flows during floods • they are areas that, even if only partially blocked, would have a significant impact on upstream water levels and/or would divert water from existing flowpaths resulting in the development of new flowpaths. • they are often, but not necessarily, areas with deeper flow or areas where higher velocities occur.	• Minimum top of bank to top of bank (for main stream areas) **AND** Major Rivers: • VxD >= 0.5 m^2/s AND V >= 0.3 m/s **OR** • VxD >= 0.4 m^2/s AND V >= 0.4 m/s Local Creeks: • VxD >= 0.4 m^2/s AND V >= 0.4 m/s **OR** • D >= 0.1 m AND V >= 0.8 m/s
Flood Storage	• those parts of the floodplain that are important for the temporary storage of floodwaters during the passage of a flood • if the capacity of a flood storage area is substantially reduced by, for example, the construction of levees or by landfill, flood levels in nearby areas may rise and the peak discharge downstream may be increased. • substantial reduction of the capacity of a flood storage area can also cause a significant redistribution of flood flows.	• If not FLOODWAY **AND** Major Rivers: • D >= 0.5 m Local Creeks: • D >= 0.2 m
Flood Fringe	• the remaining area of land affected by flooding, after floodway and flood storage areas have been defined. • development (e.g., filling) in flood fringe areas would not have any significant effect on the pattern of flood flows and/or flood levels.	• Remaining areas after FLOODWAY and FLOOD STORAGE are defined

To confirm the suitability of the hydraulic categorisation, verification simulations were completed based upon the 1% AEP flood. The verification was completed by:

- Floodway Verification: obstructions were included across part sections of floodways to confirm that the partial obstructions *"…would have a significant impact on upstream water levels and/or would divert water from existing flowpaths"*

- Flood Storage Verification: All flood storage areas were assigned a high roughness to allow water into the storage areas but prevent conveyance to confirm that these areas are indeed storage areas and not conveyance/floodway areas.
- Flood Fringe Verification: Flood fringe areas were completely filled to confirm that removal of the fringe areas would *"…not have any significant effect on the pattern of flood flows and/or flood levels"*.

The outcomes of the verification are summarised in **Appendix I** and show that the adopted criteria meet the requirements/definitions set out in the *'Floodplain Development Manual'* (2005).

The hydraulic category maps show that floodways are typically contained in close proximity to the main watercourses, particularly across the upper catchment where the channels are incised. However, more extensive floodways are predicted across the more extensive floodplains adjoining Pambula and Griegs Flat. This includes sections of the Princes Highway between Pambula and South Pambula.

As outlined in **Table 32**, flood storage areas are important for the temporary storage of floodwaters and filling these areas has the potential to adversely impact on existing flood behaviour. This was confirmed as part of the hydraulic category verification presented in **Appendix I**, which showed filling all flood storage areas would result in existing 1% AEP flood levels commonly increasing by between 0.1 and 0.2 metres. As a result, filling across the flood storage areas defined as part of this project should be discouraged.

8.4 Flood Emergency Response Precinct Classifications

In an effort to understand the potential emergency response requirements across different sections of the floodplain, Flood Emergency Response Precinct (ERP) classifications were prepared in accordance with the flow chart shown in **Plate 22** (Australian Emergency Management Institute, 2014). The ERP classifications can be used to provide an indication of areas which may be inundated and/or isolated during floods. This information, in turn, can be used to quantify the type of emergency response that may be required across different sections of the floodplain during future floods. This information can be useful in emergency response planning.

Each lot within the catchment was classified based upon the ERP flow chart for the 5% AEP, 1% AEP, and 0.2% AEP floods as well as the PMF. This was completed using the TUFLOW model results, digital elevation model and a road network GIS layer in conjunction with proprietary software that considered the following factors:

- Whether evacuation routes/roadways get "cut off" by the depth of inundation (a 0.15 m depth threshold was used to define a "cut" road).
- Whether evacuation routes continuously rise out of the floodplain.
- Whether properties become inundated.

The resulting ERP classifications for the 5% AEP, 1% AEP and 0.5% AEP floods, as well as the PMF, are provided in **Figures 42.1** to **45.6**.

Figures 42.1 to **45.6** show that the most common ERP classification is “Rising Road Egress”, which indicates that evacuation routes grade up and out of the floodwaters (i.e., most people should be able to safely walk away from the floodwater to higher ground). However, there are several “flooded isolated submerged” areas (i.e., low flood islands) and “flooded isolated elevated” areas, which indicates that evacuation routes are likely to be cut during floods. Most of these areas are located on the floodplain south of Pambula and are not inhabited.

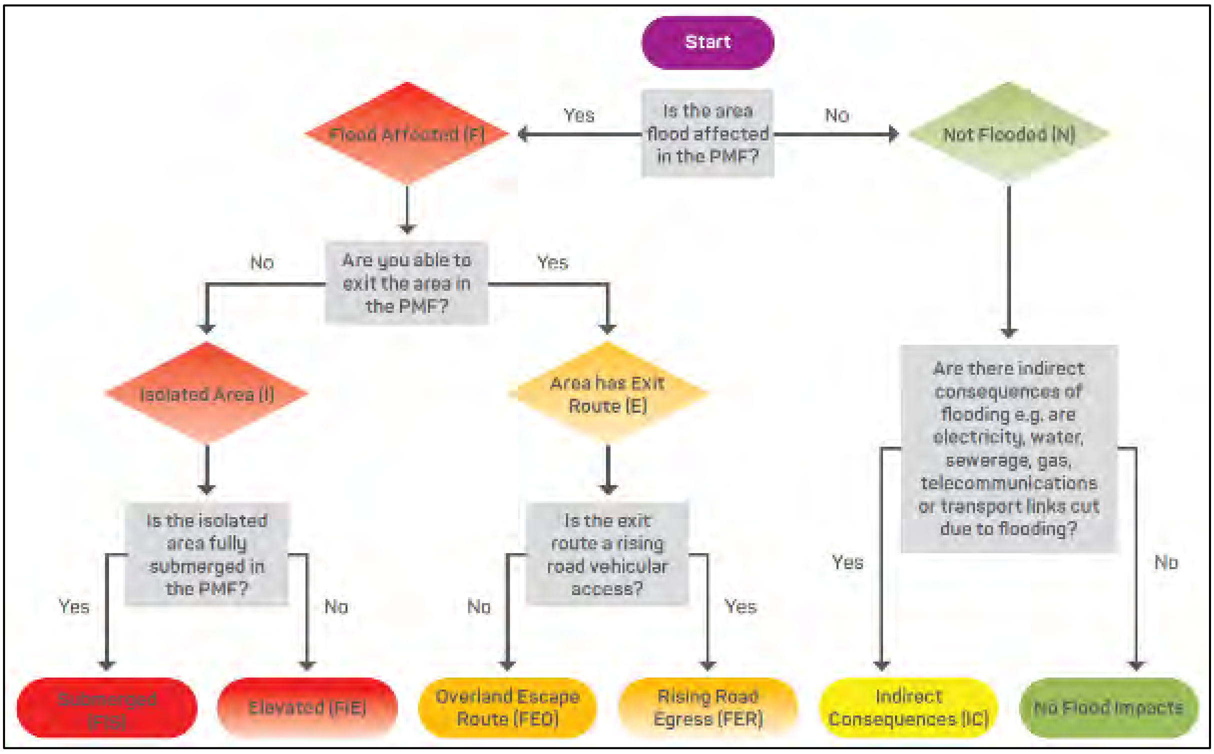


Plate 22 Flow Chart for Determining Flood Emergency Response Classifications (AEMI, 2014).

Multiple properties adjoining Nethercote Road, including those at Greigs Flat, are predicted to be isolated during floods as frequent as the 5% AEP event. Several properties located at Greigs Flat would also be considered “flooded isolated submerged” at the peak of the PMF.

8.5 Impacts on Vulnerable and Critical Facilities

The Pambula River, Pambula Lake and Yowaka River catchment is home to a range of property types and infrastructure. This includes facilities where the occupants may be particularly vulnerable during floods, such as schools and aged care homes. In addition, some facilities may play important roles for emergency response and evacuation purposes during future floods (e.g., police stations). Therefore, it is important to have an understanding of the potential vulnerability of these facilities during a range of floods.

An assessment of whether each facility is predicted to be impacted during floods was completed for the 5% AEP, 1% AEP, 0.5% AEP and PMF events. This included whether the facility was predicted to be impacted during the design flood and, if so, the flood hazard category that could be expected. An assessment of whether access to or from each facility was also completed. The outcomes of this assessment are provided in **Table 33**.

Table 33 Impact of Flooding on Vulernable and Critical Facilities

Facility		5% AEP Flood		1% AEP Flood		0.5% AEP Flood		PMF	
		Max Hazard	Vehicular Access Cut?	Max Hazard	Vehicular Access Cut?	Max Hazard	Vehicular Access Cut?	Max Hazard	Vehicular Access Cut?
Aged Care Facilities	**Imlay House** Merigan St, Pambula NSW 2549	-	-	-	-	-	-	-	-
Hospitals	**Pambula Hospital** Merimbola St, Pambula NSW 2549	-	-	-	-	-	-	-	-
Child Care facilities	**Pambula Pre-School** Dingo St, Pambula NSW 2549	*	-	*	-	*	-	*	-
	Pambula Village Pre-school 37 Toalla St, Pambula NSW 2549	-	-	-	-	-	-	-	-
	Shorebreakers Kindergarten 1-3 Monaro Street, PAMBULA NSW 2549	-	-	-	-	-	-	-	-
Schools	**Pambula Public School** 25 Oregon St, Pambula NSW 2549	-	-	-	-	-	-	-	-
	Lumen Christi Catholic College 388 Pambula Beach Rd., Pambula Beach NSW 2549	-	-	-	-	-	-	-	-
Hotels	**Idlewilde Motor Inn** 46 Bullara St, Pambula NSW 2549	-	-	-	-	-	-	H5	✓
	Colonial Motor Inn 51 Bullara St, Pambula NSW 2549	-	-	-	-	-	-	H5	✓
Caravan Parks	**Discovery Parks - Pambula Beach** 1 Pambula Beach Rd, Pambula Beach NSW 2549	H1	-	H1	-	H1	-	H1	-
	Reflections Holiday Parks Pambula 1 Toallo St, Pambula NSW 2549	-	-	-	-	-	-	-	-

*Southern section of lot is exposed to H3 hazard during 5% AEP, 1% AEP and 0.5% AEP flood event and H5 hazard for the PMF. However, building and car park remain flood free.

The information presented in **Table 33** indicates that most critical and vulnerable facilities located within the catchment are not impacted by flooding during events up to and including the PMF. The only major exception is the Discovery Park caravan park at Pambula Beach where a small section of the park is predicted to be exposed to H1 hazard conditions during each design flood. However, the H1 hazard extends predominately across open space and the H1 designation indicates that it is unlikely to pose a significant hazard to people or vehicles in the area.

It is noted that the Colonial Motor Inn and Idlewilde Motor Inn (both located near the western end of Bullara Street) is predicted to be exposed to H5 hazard during the PMF and access would also be cut. The H5 hazard classification indicates that not only would the area be unsafe for vehicles and people but there is also potential for structural damage to the buildings themselves if they have not been structurally designed withstand the forces of floodwater during the PMF. Although the PMF is a very rare flood, "sheltering in place" is unlikely to be a safe emergency response option of these facilities. It is recommended that discussions are completed with the owners of each facility to highlight the significant hazard that could occur during the PMF and encourage the preparation of a "flood safe plan" that would promote early evacuation of staff and motor inn occupants during very large Pambula River floods.

8.6 Transportation Impacts

There are several major roadways within the catchment which may be required for evacuation or emergency services access during floods. It is important to understand the impacts of flooding on these roads so that appropriate emergency response planning can occur.

An assessment of the locations where roadways are first predicted to be overtopped was completed as part of the Flood Emergency Response Precinct classifications discussed above. The roadway overtopping locations are shown as yellow dots in **Figures 42.1** to **45.6**. The numbering on the yellow dots relates to the road overtopping identifiers included in **Appendix J**. The following information is provided in **Appendix J** for each overtopping location:

- The amount of time from the initial onset of rainfall until access is cut.
- The amount of time the roadway would be cut.
- The peak flood hazard at the overtopping location.

This information is provided for the 5% AEP, 1% AEP, 0.5% AEP floods as well as the PMF.

In terms of the major transportation links that extend through the catchment, the following observations are made:

- Princes Highway is predicted to be cut during the 10% AEP flood. Inundation first commences just south of the Pambula River Bridge. Inundation of the highway would first commence around 7 hours after the initial onset of rainfall and the road would remain cut for a minimum of 5 hours. During the 0.2% AEP flood, access would be cut for more than 7 hours.

- Nethercote Road would be cut during the 10% AEP flood between the Princes Highway and Greigs Flat. Inundation would commence about 5 hours after the initial onset of rainfall and the road would remain cut for at least 7 hours. The road is also predicted to be cut near the Yowaka River bridge crossing as well as near Ruggs Road making it one of the most susceptible major roads to inundation in the catchment. Furthermore, H5 hazard is predicted across parts of the road during floods as frequent as the 5% AEP event which also making it one of the most dangerous roads.
- Mount Darragh Road is predicted to be inundated from local catchment runoff at South Pambula during the 5% AEP flood. The flooding is "flashy" in this area. As a result, limited advanced warning time is available, but the water drains away quite quickly (i.e., in less than 2 hours during more frequent floods). During more severe floods, the road may be cut for up to 4 or 5 hours.
- Back Creek Road is predicted to be cut by floodwaters near Blairlands Road. However, inundation is only predicted during the PMF. As a result, Back Creek Road will remain trafficable during most floods in the catchment and may provide an alternate transportation route if Mount Darragh Road and/or Nethercote Road are cut by floodwaters.

9 SENSITIVITY AND CLIMATE CHANGE ASSESSMENT

9.1 Overview

Computer flood models require the adoption of several parameters that are not necessarily known with a high degree of certainty or are subject to variability. Each of these parameters can impact on the results generated by the model.

As outlined in Section 6, the computer models developed as part of the current study were calibrated using recorded rainfall, stream flow and flood mark information for historic floods. This information confirmed that the models were providing realistic descriptions of flood behaviour at locations where historic flood information was available.

Nevertheless, it is important to understand how any uncertainties and variability in model input parameters may impact on the results produced by the model. Therefore, a sensitivity analysis was undertaken to establish the sensitivity of the results generated by the computer model to changes in model input parameter values. The outcomes of the sensitivity analysis are presented in Section 9.2.

A climate change analysis was also completed to assess how increases in rainfall intensity and sea level rise may impact existing flood estimates. The outcomes of the climate change simulations are summarised in Section 9.3

9.2 Model Parameter Sensitivity

9.2.1 Initial / Storm Loss

An analysis was undertaken for the 5% AEP and 1% AEP storms to assess the sensitivity of the results generated by the TUFLOW model to variations in antecedent wetness conditions (i.e., the dryness or wetness of the catchment prior to the design storm event). A catchment that has been saturated prior to a major storm will have less capacity to absorb rainfall. Therefore, under wet antecedent conditions, there will be less "initial loss" of rainfall and consequently more runoff.

The variation in antecedent wetness conditions was represented by altering the "storm" rainfall loss in the XP-RAFTS model by ±20%. Specifically, the pervious storm losses were changed from the "design" value of 16.8mm to:

- "Wet" catchment: 13.4mm; and,
- "Dry" catchment: 20.2mm.

The modified storm losses were used with the probability neutral loss information on the ARR2019 Data Hub to develop revised "burst losses" for each AEP and storm duration (refer discussion in Section 7.2.2 for further information). The revised burst losses were subsequently applied to the XP-RAFTS model and the updated versions of the model were used to re-simulate each of the 1% AEP and 5% AEP storms in accordance with ARR2019.

The revised discharge hydrographs were then applied to the TUFLOW model and the TUFLOW model was used to re-simulate the 5% AEP and 1% AEP floods with the modified storm losses. Peak water levels were extracted from the results of the modelling and were compared against peak flood levels for "base" design conditions. This allowed water level difference mapping to be prepared showing the magnitude of any change in water levels associated with the change in initial loss values. The difference mapping is presented in **Appendix K**.

Peak 5% AEP and 1% AEP flood level differences were also extracted from the results of the sensitivity simulations at various locations across the catchment and are presented in **Table** 34 and **Table 35**.

The difference mapping shows that changing the storms loss value will cause small, localised changes in 5% AEP and 1% AEP flood levels at isolated locations (most commonly around Greigs Flat). However, the change in levels is less than 0.03 metres at all locations. As a result, it can be concluded that the model results are relatively insensitive to changes in storm initial losses.

9.2.2 Continuing Loss Rate

An analysis was also undertaken to assess the sensitivity of the results generated by the TUFLOW model to variations in the adopted continuing loss rates. Accordingly, the continuing loss rates within the TUFLOW model were changed by ±20% from the "design" values of 1.16 mm/hr to:

- <u>Increased Continuing Loss Rates</u>: 1.39mm/hr.
- <u>Decreased Continuing Loss Rates</u>: 0.93m/hr

The modified continuing loss rates were applied to the XP-RAFTS model and were used to re-simulate each of the 1% AEP and 5% AEP storms in accordance with ARR2019. The revised discharge hydrographs were then applied to the TUFLOW model and the TUFLOW model was used to re-simulate the 5% AEP and 1% AEP floods with the modified continuing loss rates. Flood level difference mapping was prepared to quantify the impact of the changes in loss rates on peak flood levels and is provided in **Appendix K**.

Peak 5% AEP and 1% AEP flood level differences were also extracted from the results of the sensitivity simulations at various locations across the catchment and are presented in **Table** 34 and **Table 35**. A positive difference indicates that the sensitivity simulation levels are higher than the 'base case' levels while a negative difference indicates that the sensitivity levels are lower.

The results of the sensitivity analysis show that the TUFLOW model is relatively insensitive to changes in continuing loss rates. More specifically, altering the continuing loss rates is not predicted to alter 'base' design flood levels by more than 0.1 metres at most locations.

Therefore, it can be concluded that any uncertainties associated with the adopted continuing loss rates are unlikely to have a significant impact on the results generated by the TUFLOW model.

Table 34 Peak 5% AEP Sensitivity Simulation Flood Level Differences at Various Locations across the Catchment

Location		Water Level Differences (m)									
		Lower Storm Losses	Higher Storm Losses	Lower Continuing Losses	Higher Continuing Losses	Lower Manning's "n"	Higher Manning's "n"	No Blockage	Complete Blockage	ISLW Tide	ARR1987
Pambula River	Chalk Hills Road	0.01	-0.01	0.04	-0.02	-0.22	0.20	0.00	0.00	0.00	0.18
	Wolumla Peak Road	0.00	-0.01	0.05	-0.03	-0.35	0.26	-0.03	-0.12	-0.01	0.31
	Princes Highway	0.00	0.00	0.01	0.00	0.03	-0.02	-0.04	0.03	0.00	0.03
	Upstream of Yowaka River confluence	0.01	-0.01	0.05	-0.02	-0.17	0.18	0.00	0.00	-0.08	-0.21
	Downstream of Pambula Lake	0.01	-0.01	0.04	-0.01	-0.08	0.11	0.00	0.00	-0.12	-0.14
	Ocean outlet	0.02	0.01	0.04	0.00	0.12	0.00	0.00	0.01	-0.01	0.03
Yowaka River	Back Creek Road	0.01	-0.01	0.05	-0.02	-0.20	0.19	-0.08	-0.08	0.00	0.10
	Nethercote Road	0.01	-0.01	0.05	-0.02	-0.23	0.26	-0.17	-0.17	0.00	0.08
	Pipeclay Creek confluence	0.01	-0.02	0.08	-0.03	-0.33	0.32	-0.01	-0.01	0.00	-0.03
	Princes Highway	0.01	-0.01	0.06	-0.03	-0.21	0.20	-0.08	-0.08	-0.02	-0.12
	Upstream of Pambula River confluence	0.01	-0.01	0.05	-0.02	-0.17	0.18	0.00	0.00	-0.08	-0.21
Other Watercourses	Centipede Creek @ Nethercote Road	0.00	0.00	0.02	-0.01	-0.03	0.03	0.00	0.35	0.00	0.03
	Old Hut Creek @ Nethercote Road	0.00	0.00	0.03	-0.01	-0.14	0.19	-0.07	-0.07	0.00	0.07
	Back Creek @ Back Creek Road	0.00	-0.01	0.04	0.00	-0.01	0.01	0.00	2.86	0.00	0.33
	Back Creek @ Mount Darragh Road	0.03	-0.01	0.04	-0.03	-0.23	0.24	-0.01	2.02	0.01	0.31
	Burtons Creek @ Mount Darragh Road	0.00	-0.01	0.03	-0.02	-0.17	0.16	-0.08	-0.08	0.00	0.18
	Seven Mile Creek @ Mount Darragh Road	0.00	0.00	0.03	0.00	-0.17	0.15	-0.10	-0.10	0.00	0.15
	Chalk Hills Creek Upstream of Pambula River	0.01	-0.01	0.06	-0.03	-0.32	0.31	0.00	0.00	0.00	0.30

Table 35 Peak 1% AEP Sensitivity Simulation Flood Level Differences at Various Locations across the Catchment

Location		Water Level Differences (m)									
		Lower Storm Losses	Higher Storm Losses	Lower Continuing Losses	Higher Continuing Losses	Lower Manning's "n"	Higher Manning's "n"	No Blockage	Complete Blockage	ISLW Tide	ARR1987
Pambula River	Chalk Hills Road	0.00	0.00	0.03	-0.02	-0.21	0.22	0.00	0.00	0.00	0.70
	Wolumla Peak Road	0.02	0.01	0.03	-0.03	-0.34	0.30	-0.03	-0.18	0.03	1.18
	Princes Highway	0.00	0.00	0.01	0.00	0.05	0.05	-0.03	0.02	-0.01	0.10
	Upstream of Yowaka River confluence	0.00	0.00	0.02	-0.02	-0.08	0.15	0.00	0.00	-0.51	0.09
	Downstream of Pambula Lake	0.00	0.00	0.02	-0.01	0.00	0.10	0.00	0.00	-0.65	0.06
	Ocean outlet	0.00	0.00	0.00	0.00	0.52	0.00	0.00	0.00	-1.32	-0.20
Yowaka River	Back Creek Road	0.00	0.00	0.02	-0.03	-0.16	0.17	-0.10	-0.10	0.00	0.49
	Nethercote Road	0.00	0.00	0.03	-0.03	-0.24	0.31	-0.14	-0.14	0.00	0.58
	Pipeclay Creek confluence	0.00	-0.01	0.04	-0.05	-0.34	0.35	-0.01	-0.01	-0.02	0.65
	Princes Highway	0.00	0.00	0.03	-0.03	-0.15	0.18	-0.08	-0.08	-0.22	0.32
	Upstream of Pambula River confluence	0.00	0.00	0.02	-0.02	-0.06	0.15	0.00	0.00	-0.52	0.10
Other Watercourses	Centipede Creek @ Nethercote Road	0.00	0.00	0.01	-0.01	-0.03	0.03	0.00	0.32	0.00	0.23
	Old Hut Creek @ Nethercote Road	0.00	-0.01	0.02	-0.02	-0.17	0.24	-0.13	-0.13	0.00	0.69
	Back Creek @ Back Creek Road	0.00	0.00	0.00	-0.03	0.01	0.00	0.00	2.61	0.00	0.59
	Back Creek @ Mount Darragh Road	0.01	0.00	0.02	-0.01	-0.19	0.26	-0.02	1.10	0.02	0.99
	Burtons Creek @ Mount Darragh Road	0.00	0.00	0.02	-0.02	-0.17	0.18	-0.10	-0.10	0.00	0.60
	Seven Mile Creek @ Mount Darragh Road	0.00	0.00	0.03	-0.02	-0.19	0.19	-0.13	-0.13	0.00	0.58
	Chalk Hills Creek Upstream of Pambula River	0.00	0.00	0.03	-0.04	-0.32	0.36	0.00	0.00	0.00	1.13

9.2.3 Manning's "n"

Manning's "n" roughness coefficients are used to describe the resistance to flow afforded by different land uses and surfaces across the catchment. However, they can be subject to variability (e.g., vegetation density in the summer would typically be higher than the winter leading to higher Manning's "n" values). Therefore, additional analyses were completed to quantify the impact that any uncertainties associated with Manning's "n" roughness values may have on predicted design flood behaviour.

The TUFLOW model was updated to reflect a 20% increase and a 20% decrease in the adopted Manning's "n" values and additional 5% AEP and 1% AEP simulations were completed with the modified "n" values (no changes to hydrology were completed as part of this assessment). Peak flood levels were extracted from the results of the modelling and were used to prepare flood level difference mapping, which is presented in **Appendix K**.

Peak 5% AEP and 1% AEP flood level differences were also extracted from the results of the sensitivity simulations at various locations across the catchment and are presented in **Table** 34 and **Table 35**.

The difference mapping shows that changing the Manning's "n' values by ±20% will alter 5% AEP and 1% AEP flood level across most of the catchment. The flood level differences are most commonly contained between 0.1 and 0.2 metres. However, flood level differences of more than 0.3 metres are predicted along parts of the Pambula River and Yowaka River. The most significant changes are predicted to occur in more heavily vegetated areas where the absolute change in Manning's' "n" value is greatest.

Although reducing Manning's "n" is generally predicted to reduce flood levels across the catchment, it will also increase the speed at which floodwaters move downstream. This reduction in travel time is predicted to result in flood levels increasing in the Pambula River between the ocean entrance and Pambula Lake.

Overall, the results of the sensitivity simulations show that the model results in some areas can be quite sensitive to changes in Manning's "n" values.

9.2.4 Hydraulic Structure Blockage

As discussed in Section 6.2.3, blockage factors were applied to all bridges, culverts and stormwater inlets as part of the design flood simulations. However, as it is not known which structures will be subject to what percentage of blockage during any particular flood, additional TUFLOW simulations were completed to determine the impact that alternate blockage scenarios would have on flood behaviour. Specifically, additional simulations were undertaken with complete blockage of all stormwater inlets, bridges and culverts.

Peak flood levels were extracted from the results of the "complete blockage" and "no blockage" modelling and were compared to the "design blockage" flood level results to prepare flood level difference mapping, which is presented in **Appendix K**.

Peak 5% AEP and 1% AEP flood level differences were also extracted from the results of the sensitivity simulations at various locations across the catchment and are presented in **Table** 34 and **Table 35**.

The difference maps show that removing blockage will generate some small, localised reductions in flood levels in the vicinity of bridges and culverts. The changes are not particularly significant as many of the hydraulic structure had relatively low blockage factors applied as part of the base flood simulations. The most extensive reductions in flood levels are predicted upstream of the Princes Highway south of Pambula where the combined impact of the roadway embankment and four separate hydraulic structures is more significant.

Complete blockage will cause some more significant changes to 5% AEP and 1% AEP flood levels. Design flood levels are predicted to increase by over 2.5 metres at some locations and are driven by the significantly elevated embankments at some locations (most notable, in the steeper, upper sections of the catchment such as Back Creek Road). Blockage of the Princes Highway bridge crossing of the Yowaka River is also predicted to have a significant impact, with flood level increases extending well upstream and into the Greigs Flat area.

The results of the blockage sensitivity analysis show that the model results are sensitive to variations in blockage in the immediate vicinity of major hydraulic structures, particularly if complete blockage of structures occurs. This outcome emphasises the need to ensure key drainage infrastructure and bridges and culverts are well maintained (i.e., debris is removed on a regular basis).

9.2.5 Ocean Level

The Pambula River and Yowaka River catchment drains into the Tasman Sea which forms the downstream boundary of the hydraulic model. As discussed in Section 7.3.1, the "base" simulations adopted a design flood envelope which considered the potential interaction of both catchment runoff and elevated ocean levels. However, if the prevailing sea level at the time of a local catchment flood was different, it has the potential to impact on results across the downstream sections of the catchment.

Therefore, the enveloped flood level results for the 1% AEP flood (which included a peak 1% AEP tide level of 2.55mHAD) were compared against the 1% AEP flood level results with a ISWL tide only (i.e., a "low" tide level of -0.82 mAHD at the time of peak catchment outflow). Difference mapping was prepared to show the impact of the different tide levels on peak flood levels and the resulting mapping is presented in **Appendix K**.

Peak 5% AEP and 1% AEP flood level differences were also extracted from the results of the sensitivity simulations at various locations across the catchment and are presented in **Table** 34 and **Table 35**.

The difference mapping shows that the adopted sea level can have a significant impact on flood levels across the downstream sections of the study area. More specifically, 1% AEP flood levels are predicted to reduce by well over 0.5 metres between the ocean and the Pambula River/Yowaka River confluence and by around 0.4 metres across the floodplain south of Pambula.

It is noted that increases in 1% AEP flood levels are predicted upstream of the Princes Highway south of Pambula. This outcome is associated with the lower water levels east of the highway resulting in higher velocities and greater afflux through the Princes Highway culverts and bridge.

Therefore, the outcomes of the sensitivity simulations show that the flood level results across the lower, eastern sections of the catchment are sensitive to the adopted sea level boundary conditions. However, flood level impacts across the upstream sections of the catchment are predicted to be negligible.

9.2.6 Timing of Pambula River and Yowaka River Flows

The design flood simulations assumed that each design storm was "static" across the whole catchment. However, "real" storms often move across the catchment with respect to time. This can alter the distribution of rainfall across different parts of the catchment, which can impact on the timing of peak flows from difference parts of the catchment. Therefore, additional 1% AEP sensitivity simulation were completed by adjusting the timing of flows from the Yowaka River catchment. Two scenarios were completed (also refer **Plate 23**):

- Yowaka River flows were delayed by 40 minutes to maximise flood levels
- Yowaka River flows were delayed by 9.5 hours to minimise flood levels

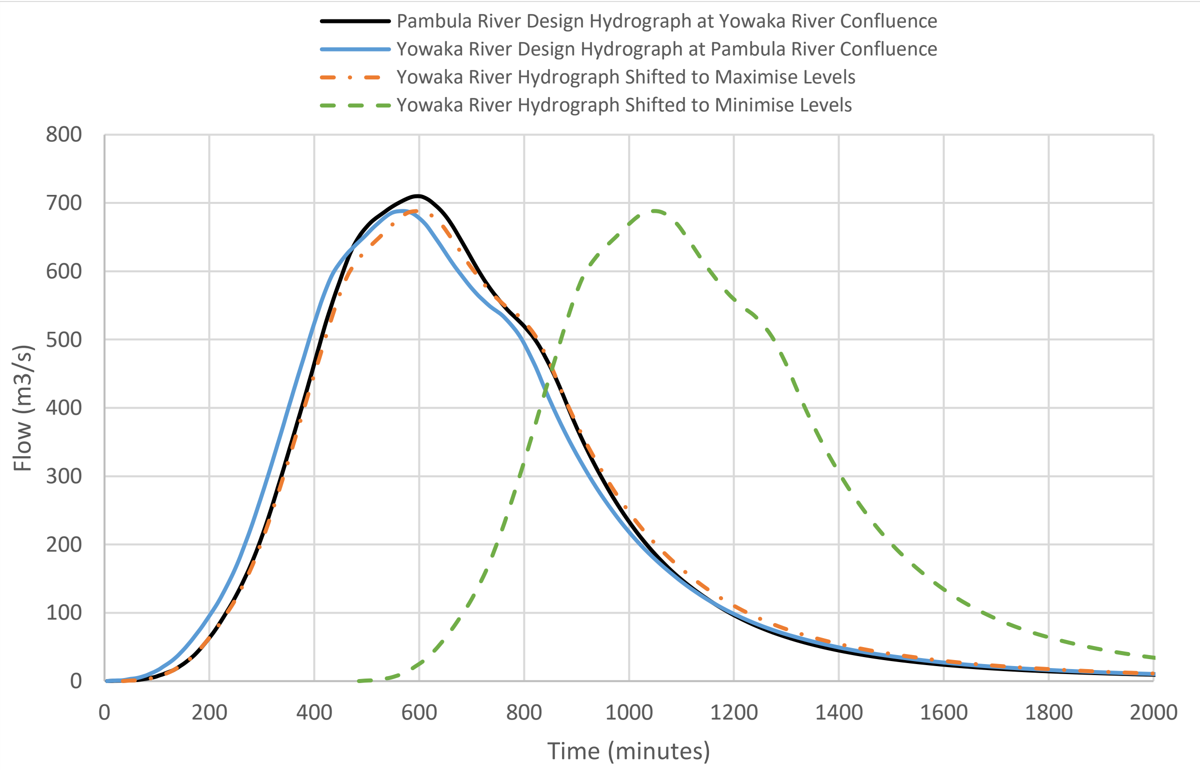


Plate 23 Hydrographs adopted to test sensitivity of timing of Yowaka River flows

The TUFLOW model was used to re-simulate the 1% AEP flood with the revised Yowaka River flows. Flood level difference mapping was prepared to quantify the impacts of the timing of flows and is presented in **Appendix K**. However, it was noted that there were negligible flood level increases in the first sensitivity simulation, therefore, the difference maps were not included. This is associated with the characteristics of the Pambula River and Yowaka River being very similar. As a result, the time of peak catchment outflow for the “base” simulations are very similar for both catchment and there was little opportunity to better align the timing of the peak outflows (refer **Plate 23**).

However, the difference mapping shows that if the timing of the Yowaka River and Pambula River catchments was significantly offset, it does have the potential to reduce 1% AEP flood levels along the Yowaka River by more than 0.2 metres and along the Pambula River by 0.05-0.10 metres. Therefore, the flood level results along the Yowaka River and Pambula River are sensitive to the timing of flows in the Pambula River and Yowaka River.

9.2.7 Australian Rainfall & Runoff 1987

The current study was prepared based on *‘Australian Rainfall and Runoff – A Guide to Flood Estimation’* (Ball et al, 2019) (ARR2019). However, most flood studies across the Bega Valley LGA over the past 30 years were prepared in accordance with the 1987 version of Australian Rainfall and Runoff (ARR1987). ARR2019 takes advantage of more thorough hydrologic procedures as well as an additional 30 years of rainfall information and should provide improved design flood estimates across the catchment. Nevertheless, it was considered important to understand how results produced based upon ARR2019 may differ from those generated using ARR1987. Therefore, an additional sensitivity assessment was completed to confirm the impact that the revised hydrologic procedures may have on design flood behaviour across the study area.

The ARR1987 design storms were first applied to the XP-RAFTS hydrologic model. Peak ARR1987 discharges were extracted for each subcatchment and are summarised in **Appendix L**. The ARR2019 discharges are also included for comparison.

The peak discharge information presented in **Appendix L** shows that ARR1987 produces higher peak design discharge estimates relative to ARR2019. The ARR1987 discharges are typically 40 to 70% higher that the ARR2019 discharges.

The ARR1987 1% AEP and 5% AEP hydrographs were applied to the TUFLOW model and the TUFLOW model was used to simulate flood behaviour with the modified hydrology. Difference mapping was prepared to show the impacts of the modified hydrology and is presented in **Appendix K**.

Peak 5% AEP and 1% AEP flood level differences were also extracted from the results of the sensitivity simulations at various locations across the catchment and are presented in **Table** 34 and **Table 35**.

The difference mapping presented in **Appendix K** also shows the ARR1987 is predicted to produce higher flood levels across most of the catchment relative to ARR2019. During the 5% AEP flood, the ARR1987 levels are typically a minimum of 0.1 metres higher than ARR2019. During the 1% AEP flood, the ARR1987 levels are typically a minimum of 0.3 metres higher than ARR2019.

It was noted that the ARR1987 flood levels are lower along the very downstream reaches of the Pambula River during each design flood. This is because the time of peak tide was arranged to coincide with the peak ARR2019 catchment outflow, not the peak ARR1987 outflow. As a result, the ARR1987 flood levels are typically lower across those sections of the catchment that are more tide-dominated.

Accordingly, there are some notable difference between flood behaviour defined under ARR1987 versus ARR2019. However, ARR2019 takes advantage of a greater amount of historic rainfall information and employs that latest available research in deriving the design flood estimates. Therefore, it is considered that the flood estimates defined under ARR2019 are reasonable and improve upon the flood estimates provided by ARR1987.

9.3 Climate Change Analysis

Climate change refers to a significant and lasting change in weather patterns arising from both natural and human induced processes. The former Office of Environment and Heritage's *'Practical Consideration of Climate Change'* states that climate change is expected to have adverse impacts on sea levels and rainfall intensities in the future.

Although there is considerable uncertainty associated with the impact that climate change may have on rainfall, it was considered important to provide an assessment of the potential impact that climate change may have on the current flood risk across the study area and the suitability of freeboard when establishing the flood planning level (refer Section 10.2.1).

The climate change assessment considered the potential impacts associated with:

- Increased sea level
- Increased rainfall intensity
- Increased rainfall intensity and increased sea level

The outcomes of the climate change simulations are provided below.

9.3.1 Increases in Sea Level

The 'NSW Coastal Planning Guideline: Adapting to Sea Level Rise' (Department of Planning, 2010) provides guidance on the expected impacts that climate change may have on sea levels. The former '*NSW Sea Level Rise Policy Statement*' (Department of Environment and Climate Change, 2009) states that ocean level increases of 0.4 metres could be expected by 2050 and a 0.9 metre increase could occur by 2100. This document has since been repealed and the NSW Government recommends that local Councils determine their own sea level rise projections based on their local conditions (NSW Department of Environment and Heritage, 2012).

The Bega Valley Shire Council has adopted a sea level rise policy (dated 2013) that is consistent with the former NSW Government's Sea Level Rise Policy. That is, a 0.4 metre increase in sea level by 2050 and a 0.9 metre increase in sea level by 2100. The sea level rise projections were incorporated as part of the following revised design flood simulations:

- Highest high-water solstice spring (HHWSS) tide with 0.4 m increase in sea level
- HHWSS tide with 0.9 m increase in sea level
- 1% AEP flood with 0.4 m increase in sea level (included full envelope of tidal and catchment runoff simulations as documented in Section 7.3.1)
- 1% AEP flood with 0.9 m increase in sea level

In addition, there is potential for sea level rise to change the tidal dynamics around the river entrance, thereby, leading to a change in erosion/deposition of bed material and an increase in river entrance bed elevations. More specifically, there is potential for the entrance bed elevation to increase proportionally with sea level rise. Therefore, each of the above sea level rise scenarios was also run with the following increases in river entrance elevations:

- 0.4 m increase in sea level = 0.4 m increase in river entrance elevation
- 0.9 m increase in sea level = 0.6 m increase in river entrance elevation

Peak floodwater depths were extracted across the tidally influenced sections of the catchment and are presented in:

- *HHWSS tide with 0.4 m increase in sea level*:
  - Existing river entrance conditions: **Figures 46.1** to **46.3**
  - River entrance elevation increase by 0.4m: **Figures 47.1** to **47.3**
- *HHWSS tide with 0.9 m increase in sea level*:
  - Existing river entrance conditions: **Figures 48.1** to **48.3**
  - River entrance elevation increase by 0.9m: **Figures 49.1** to **49.3**
- *1% AEP flood with 0.4 m increase in sea level*:
  - Existing river entrance conditions: **Figures 50.1** to **50.3**
  - River entrance elevation increase by 0.4m: **Figures 51.1** to **51.3**
- *1% AEP flood with 0.9 m increase in sea level*:
  - Existing river entrance conditions: **Figures 52.1** to **52.3**
  - River entrance elevation increase by 0.9m: **Figures 53.1** to **53.3**

In all figures, inundation extents for existing climate conditions are superimposed so that the impact of the sea level (and ocean entrance) increases can be visualised.

Flood level difference mapping was also prepared to quantify the impacts of sea level rise across the catchment on existing flood levels. The difference mapping was prepared by subtracting the peak flood levels from each climate change simulation from "existing" peak flood levels. The difference mapping is presented in **Appendix M**.

The difference mapping and floodwater depth mapping shows that increases in sea level will increase existing flood levels and extents for areas located primarily downstream/east of the Princes Highway. The magnitude of the increases is more significant during the HHWSS simulations as the sea level rise impacts are not "drowned out" by catchment runoff. Nevertheless, flood levels during the 1% AEP flood are still predicted to increase by up to 0.74 metres in Pambula Lake and up to 0.2 metres near the Princes Highway bridge crossing of the Pambula River.

Overall, the outcomes of the climate change simulations show that increases in sea level have the potential to increase the severity of flooding across the lower-lying, eastern sections of the catchment.

9.3.2 Increases in Rainfall Intensity

To gain an understanding of what impact increases in rainfall intensity may have on existing flood behaviour, the results of the 0.5% AEP and 0.2% AEP floods were compared to the results from the 1% AEP flood. The 0.5% AEP rainfall reflects a 18% increase relative to current 1% AEP rainfall intensities, while the 0.2% AEP rainfall reflects a 41% increase relative to current 1% AEP rainfall intensities.

Information provided on the ARR2019 Data Hub indicates that these rainfall increases are higher than current best estimates of rainfall intensity increases for the 2090 planning horizon based on Representative Concentration Pathway (RCP) 8.5 conditions (rainfall intensity increases for RCP8.5 and 2090 conditions are currently estimated to be 16.3%, as shown in **Plate 24**). However, it should be noted that climate change is unlikely to "stop" in 2090 so the adopted rainfall increases still provide useful information in understanding the potential impacts of climate change including what may happen beyond 2090.

	RCP 4.5	RCP6	RCP 8.5
2030	0.648 (3.2%)	0.687 (3.4%)	0.811 (4.0%)
2040	0.878 (4.4%)	0.827 (4.1%)	1.084 (5.4%)
2050	1.081 (5.4%)	1.013 (5.1%)	1.446 (7.3%)
2060	1.251 (6.3%)	1.229 (6.2%)	1.862 (9.5%)
2070	1.381 (7.0%)	1.460 (7.4%)	2.298 (11.9%)
2080	1.465 (7.4%)	1.691 (8.6%)	2.719 (14.2%)
2090	1.496 (7.6%)	1.906 (9.7%)	3.090 (16.3%)

Plate 24 Interim Climate Change Rainfall Intensity Increases (Ball et all, 2019)

Peak floodwater depths for both scenarios are presented in **Figures 54.1** to **54.6** and **Figures 55.1** to **55.6**. The 1% AEP inundation extent for current climate conditions is superimposed for comparison.

Flood level difference mapping was prepared to quantify the impacts that a 18% and 41% increase in rainfall would have on current 1% AEP flood level estimates. The difference mapping was prepared by subtracting the peak 1% AEP flood levels from the 0.5% and 0.2% AEP flood levels. The difference mapping is presented in **Appendix M**.

The difference mapping shows that rainfall increases will increase 1% AEP flood level estimates throughout the catchment, although the most notable increases are concentrated along defined watercourses. A 18% increase in rainfall is commonly predicted to increase 1% AEP flood levels by up to 0.2 metres. A 41% increase in rainfall is predicted to increase existing 1% AEP flood levels by more than 0.3 metres at many locations.

Accordingly, the outcomes of the assessment show that increases in rainfall associated with climate change have the potential to produce a notable increase in the severity of flooding across all sections of the catchment.

9.3.3 Increases in Rainfall Intensity and Increases in Sea Level

In order to gain an understanding of the combined impacts that rainfall intensity and sea level increases may have on existing flood behaviour, additional climate change simulations were completed. Four separate "combined" scenarios were considered and peak floodwater depths were extracted from the results of each combined scenario and are presented in the following figures:

- *1% AEP flood with 18% increase in rainfall intensity and 0.4 metre increase in sea level*:
  - Existing river entrance conditions: **Figures 56.1** to **56.3**
  - River entrance elevation increase by 0.4m: **Figures 57.1** to **57.3**
- *1% AEP flood with 41% increase in rainfall intensity and 0.9 metre increase in sea level:*
  - Existing river entrance conditions: **Figures 58.1** to **58.3**
  - River entrance elevation increase by 0.9m: **Figures 59.1** to **59.3**

Peak flood level difference mapping was also prepared and is presented in **Appendix M**.

The results of the simulations show that sea level rise and rainfall intensity increases will result in the 1% AEP flood level increasing throughout the catchment. In the narrow, incised, upper sections of the catchment, the flood level increases are identical to the rainfall increase only scenarios (i.e., these areas are not influenced by increases in ocean level).

However, in areas contained within the lower catchment (i.e., between the sea and roughly the Princes Highway), the combined impacts of rainfall increase, and sea level increase are more pronounced. The 0.4m increase in sea level plus 18% increase in rainfall intensity is predicted to elevate current 1% AEP flood levels by more than 0.3 metres at multiple locations while the 0.9m increase in sea level plus 41% increase in rainfall intensity is predicted to increase current 1% AEP flood level by more than 0.5 metres across large areas and by more than 0.7 metres between the Pambula River/Yowaka River confluence and the Tasman Sea.

A review of the simulation results incorporating the elevated river entrance showed no significant differences relative to the simulation results based on current river conditions. This mirrors the results documented in Section 9.3.1 and shows that the results are not sensitive to changes in the river entrance bed elevations.

Accordingly, the results of the climate change simulations indicate that should both rainfall intensity and sea level increases occur in the future, it would produce a notable increase in flood risk across all sections of the catchment. However, the area of the catchment located east of the Princes Highway would be most significantly impacted.

10 Flood Planning Information

10.1 Overview

Appropriate land use planning is one of the most effective measures available to manage the future risk as well as the ongoing/continuing flood risk. A full review of land use planning including appropriate zoning, policies and planning/building controls is typically undertaken as part of the floodplain risk management study.

Nevertheless, *'Australian Disaster Resilience Handbook 7 Managing the Floodplain: A Guide to Best Practice in Flood Risk Management in Australia'* (ADR Handbook 7) (AIDR, 2017) recommends using the best available information at any point in time to manage the flood risk. Therefore, if a flood study is available that contains relevant information (such as this one), there is no need to wait for the floodplain risk management study before this flood information is used to inform land-use planning. Accordingly, the following chapter outlines the process that was employed to develop flood planning category constraint mapping to assist in informing future land-use planning decisions.

In addition, the results of the flood study can be used to define the flood planning area (i.e., the area within which flood-related development controls apply). Defining the flood planning area will help to identify areas with a higher flood exposure/risk and, should new development or re-development occur, will help ensure appropriate controls are implemented such that the flood exposure/risk is appropriately managed.

10.2 Flood Planning Area

10.2.1 Flood Planning Level

Flood Planning Levels (FPLs) are an important tool in the management of flood risk and are derived by adding a freeboard to the "planning" flood. The FPLs can then be combined with topographic information to establish the Flood Planning Area (FPA). The FPL and FPA can then be used to assist in managing the existing and future flood risk by:

- Setting design levels for mitigation works (e.g., levees); and
- Identifying land where flood-related development controls apply to ensure that new development is undertaken in such a way as to minimise the potential for flood impacts on people and property.

Bega Valley Shire Council has defined the FPL as the level of the 1:100 ARI (i.e., 1% AEP) flood event plus 0.5 metre freeboard in the Bega Valley Shire Council Local Environmental Plan 2013.

Discussions with Council planners indicates that Council is interested in incorporating climate change into the definition of the FPL. As a result, the peak flood levels from the 1% AEP flood with 0.9 metre increase in water level were used as the basis for the FPL.

As part of the current study, Council also wished to confirm the suitability of adopting a 0.5 metre freeboard across the Pambula River, Pambula Lake and Yowaka River catchment. Freeboard is used to account for uncertainties when deriving the 1% AEP flood levels. More specifically, freeboard is used to account for the following uncertainties:

- Model parameter uncertainty (e.g., roughness, blockage of culverts/bridges, rainfall/flows); and,
- "Local" factors that can't be explicitly represented in the computer modelling (e.g., wave action or small flow paths less than the model grid size).

A discussion on each of these components is presented below.

Model Parameter Uncertainty

The potential impacts of model parameter uncertainty can be quantified by reviewing the results of the sensitivity simulations presented in Section 9. More specifically, statistical analyses were completed based upon the results of the various 1% AEP sensitivity simulations to assign "confidence limits" to the peak 1% AEP flood level estimates.

In order to reliably define confidence limits to the 1% AEP results, it would be necessary to undertake thousands (potentially tens of thousands) of simulations to reflect the numerous combinations of potential parameter estimates and provide a sufficiently large population to enable meaningful statistical analysis. Unfortunately, the long simulation times only permit a limited number of parameter scenarios to be investigated.

In instances where a sufficiently large "population" of results is not available, it is still possible to derive confidence limits using the Student's t-test (Zhang, 2013). This approach involves interrogating peak flood level estimates from all 1% AEP simulations (i.e., base and sensitivity) at each TUFLOW grid cell. This information is used to calculate a mean water level and standard deviation at each grid cell. This information can then be combined with the number of degrees of freedom (i.e., number of different 1% AEP simulations minus 1) and a "t-table" to develop 99% confidence limit estimates at each TUFLOW grid cell.

The resulting "99% Confidence Limit" grid is shown in **Plate 25**. Lighter colours indicate small confidence limits (i.e., more confidence in results) and darker colours indicate higher confidence limits (i.e., less confidence in results). It is noted that the Student's t-test assumes that the population of results is "normally" distributed with the majority of the parameters and results located in close proximity to the mean. However, the sensitivity analysis typically adopts parameter values that are at the extremes of realistic ranges. As a result, the population of water level results is unlikely to be normally distributed and the calculated confidence limits are, therefore, likely to be conservative.

The confidence interval grid provided in **Plate 25** shows that across the majority of the study area, the confidence interval is better than 0.2 metres. That is, there is 99% confidence that the "true" 1% AEP flood level is contained within ±0.2 metres of the "base" 1% AEP simulations documented in Section 7 across most of the catchment.

However, some localised areas are subject to greater uncertainty (i.e., larger confidence limits). This includes Greigs Flat as well as the very lower reaches of the Pambula River near the river where the confidence limits approach 0.25 metres. The lower confidence near the river entrance is primarily driven by the uncertainty in ocean tide levels while the lower confidence around Greigs Flat is associated with the thick vegetation adjoining the narrow floodplain opening immediately downstream of the flat.

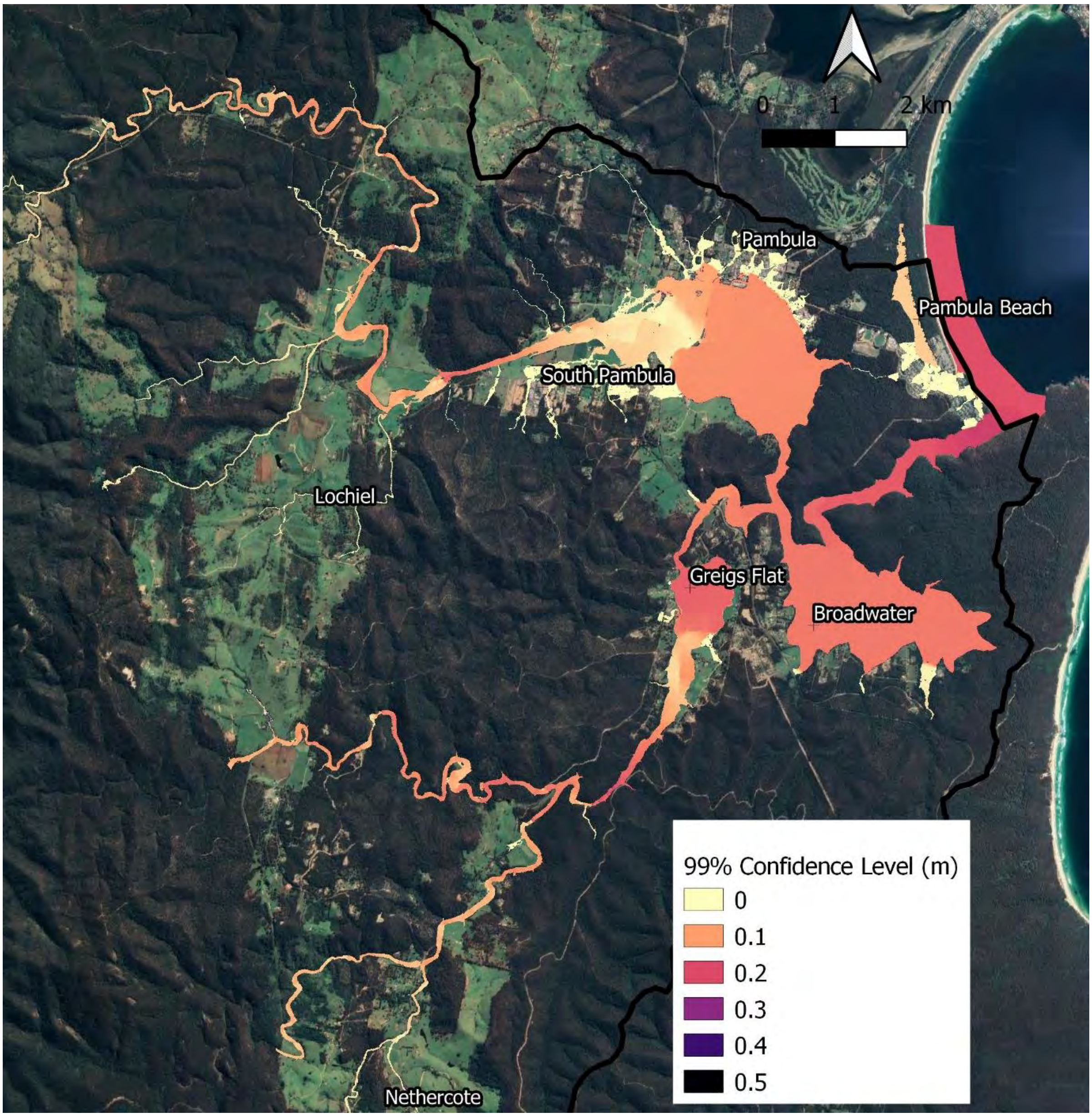


Plate 25 99% Confidence Level Grid

Therefore, modelling uncertainty is not predicted to exceed 0.25 metres at any location.

Local Factors

Unfortunately, the uncertainty associated with the remaining factors (i.e., wave action and local factors that cannot be represented in the model) cannot be as readily quantified. However, if a 0.5 metre freeboard is adopted it would provide a 0.25 metres allowance for these local factors (as outlined above, the other 0.25 metres is required to account for modelling uncertainty). A 0.25 metre allowance is considered sufficient to cater for these factors as cars/boats will most likely be travelling at low speed and generating relatively small waves (refer **Plate 26**).

Therefore, adoption of a 0.5 metre freebaord should be sufficient to account for uncertainty in the 1% AEP flood level estimates. That is, there does not appear to be suitable justification to vary the 0.5 metre freeboard defined in the LEP for this catchment.

Plate 26 Example of cars driving through flood waters and generating waves

Therefore, the 0.5 metre freeboard was added to the 1% AEP with 0.9m increase in sea level water level results to produce a Flood Planning Level (FPL) grid. The FPL grid was then extended laterally until it intersected higher ground to form the FPA. The resulting flood planning area is shown in **Figures 60.1** to **60.6**. Also included on **Figures 60.1** to **60.6** are flood planning level contours.

10.3 Flood Planning Constraint Categories

Flood planning category constraint mapping was prepared based on guidance provided in the *'Australian Disaster Resilience Guideline 7-5: Flood Information to Support Land-use Planning'* (AIDR 2017). This guideline delineates flood liable land into one of four major "constraint" categories (with several subcategories) based upon key flooding considerations such as flood hazard, flood function and emergency response. The resulting categories can serve to inform land use planning activities. The guideline notes that the categorisation is intended to support community/precinct scale decisions where flow paths and flood extents can be readily defined and was not developed to support change of land use or development at the lot/site scale.

The flood planning constraint categories (FPCC) are summarised in **Table 36**. **Table 36** also summarises how the categories are defined along with the associated planning implication/considerations. In general, a FPCC categorisation of "1" implies a more flood constrained section of land relative to FPCC category "2", and so on.

Table 36 Flood Planning Constraint Categories (AIDR, 2017)

FPCC	Sub-Category	Constraint	Implications	Consideration
1	A	Flow conveyance and storage areas in the DFE	Development or changes to topography within flow conveyance areas and flood storages areas affect flood behaviour, which will alter flow depth or velocity in other areas of the floodplain. Changes can negatively affect the existing community and other property	The majority of developments and uses have adverse impacts on flood behaviour. Consider limiting uses and development to those compatible with maintaining flood function
	B	H6 hazard in the DFE	Hazardous conditions considered unsafe for vehicles and people. All building types are considered vulnerable to structural failure	The majority of developments and uses are vulnerable to failure in this flood hazard category. Consider limiting developments and uses to those that are compatible with flood hazard H6
2	A	Flow conveyance area in events larger than the DFE	Flow conveyance areas may develop during an event larger than the DFE. People and buildings in these areas may be affected by flowing and dangerous floodwaters	Consider compatibility of developments and users with rare flood flows in this area
	B	H5 hazard in the DFE	Hazardous conditions are considered unsafe for vehicles and people, and all buildings are vulnerable to structural damage	Many uses and developments will be vulnerable to flood hazard. Consider limiting new uses to those compatible with flood hazard H5. Consider treatments such as filling (where this will not affect flood behaviour) to reduce the hazard to a level that allows standard development conditions to be applied. Alternatively, consider a requirement for special development conditions
	C	Isolated and submerged areas (low flood island or low trapped perimeter in 1%AEP event)	Area becomes isolated by floodwater or impassable terrain, with loss of evacuation route to the community evacuation location. The area will become fully submerged with no flood-free land in an extreme event, with ramifications for those who have not evacuated and are unable to be rescued	Consequences of isolation and inundation can be severe. Consider the consequences of: • evacuation difficulty or inundation of the area on the development and its users, which may include limitations on land use, or on land use that has occupants who are more vulnerable to disruption and loss • the development on emergency management planning for the existing community, including the need for additional treatments • the development on community flood recovery • disruption or loss of the development on the users and wider community
	D	Isolated but not submerged areas (high flood island or high trapped perimeter in 1%AEP event)	Area becomes isolated by floodwater or impassable terrain, with loss of an evacuation route to a community evacuation location. The area has some land elevated above the extreme flood level. Those not evacuated may be isolated with limited or no services, and will need rescue or resupply until floods recede and roads are passable	Some developments and their users may be vulnerable to disruption or loss. Consider: • the consequences of disruption or loss of the development on the users and the wider community • limiting land use, or land use that has occupants who are more vulnerable to disruption and loss • additional emergency management treatment requirements • issues associated with the level of support required during a flood, particularly for long-duration flood events • potential for loss of services
	E	H6 hazard in events rarer than the DFE	Hazardous conditions may develop in an event rarer than the DFE, which may have implications for the development and its occupants	Consider the need for additional development conditions to reduce the effect of flooding on the development and its occupants

FPCC	Sub-Category	Constraint	Implications	Consideration
3	-	Outside FPCC 2 but generally below the DFE plus freeboard	Hazardous conditions may exist creating issues for vehicles and people. Structural damage to buildings that meet building standards unlikely because of flooding	Standard land-use and development controls aimed at reducing damage and the exposure of the development to flooding in the DFE are likely to be suitable. Consider the need for additional conditions for emergency response facilities, key community infrastructure and vulnerable users
4	-	Outside of FPCC 3 but within the PMF extent	Emergency response may rely on key community facilities such as emergency hospitals, emergency management headquarters and evacuation centres operating during an event. Recovery may rely on key utility services being able to be readily re-established after an event	Consider the need for conditions for emergency response facilities, key community infrastructure and land uses with vulnerable users

The FPCC use a “Defined Flood Event” (DFE), which is analogous to the “planning flood” (i.e., 1% AEP event). It also requires consideration of flood impacts in events rarer than the DFE. The 0.2% AEP event was selected for this purpose.

The information contained in **Table 36** was used with the flood modelling outputs (most notably the flood hazard, hydraulic category and emergency response mapping) to prepare the FPCC map shown in **Figures 61.1** to **61.6**. Also included on **Figures 61.1** to **61.6** are the current land use zones to gain an appreciation of how the current zoning align with the FPCC.

The FPCC categories presented in **Figures 61.1** to **61.6** show that current land use zones are broadly compatible with the level of flood exposure. More specifically, the more highly constrained land (i.e., FPCC 1) typically coincides with areas of open space (e.g., zones E1-E5, W1), which is considered to be a compatible land use.

FPCC 1 and 2 does extend through some industrial zoned land in South Pambula. Fortunately, much of the FPCC 1 area does not include existing development. It is recommended that any future industrial development in this area is kept clear of FPCC 1 and 2 and any development falling within FPCC 3 is implemented with appropriate development controls to ensure it is compatible with the flood risk.

There are also some FPCC 1 and 2 areas that extend through residentially zoned land in Pambula. However, these areas are currently undeveloped and align with natural waterways and drainage depressions. Again, future development in these flood constrained areas should be discouraged. In general, other areas of Pambula are most commonly impacted by FPCC 3 and 4. Future development in these areas could be considered (subject to appropriate development controls). However, sensitive/vulnerable developments (e.g., aged care facilities, childcare centres) should ideally be located outside of the floodplain.

10.4 Impacts of Future Development

Although the Pambula River, Pambula Lake and Yowaka River catchment comprises small pockets of urban development (e.g., Pambula, South Pambula and Pambula Beach), the majority of the catchment comprises large areas of National Parks and state forest that comprise a negligible urban footprint. However, there are some sections of the catchment that have the potential to be developed in the future based upon current land use zonings defined in the Bega Valley Local Environmental Plan (LEP) 2013.

This future development has the potential to alter existing flood behaviour which may impact on the existing flood risk across the catchment. Accordingly, additional computer flood simulations were completed to quantify the potential impacts that future development may have on the existing flood risk across the catchment.

Those areas that are currently undeveloped but are likely to be developed in the future (based upon current LEP zoning) were first identified. This was completed by reviewing land use zoning information relative to contemporary aerial imagery.

Bega Valley Shire Council strategic planners were also consulted to identify areas that have the potential to be rezoned in the future to promote further urban development. This consultation yielded no significant additional areas for consideration as part of the assessment.

As the future “make up” of these areas is not known, assumptions were made regarding the likely land use composition. This information was used to calculate weighted average impervious and pervious “n” values for each land use, and these were used to update the XP-RAFTS hydrologic model (refer **Table 37**). Average impervious and pervious “n” values for current/existing conditions are also provided in **Table 37** so that the magnitude of the changes for each LEP zone can be understood. The comparison shows that the adopted future impervious percentages are higher than current impervious percentages (reflecting an increase in hard surfaces and reduced potential for infiltration) while pervious “n” values are lower (reflecting a lower effective roughness and more rapid response to rainfall).

Only land that falls within the LEP zones identified in **Table 37** were updated as part of the assessment. Land falling within LEP zones not included in **Table 37** were left unchanged from the “existing” flood assessment. This includes public recreation areas as well as all National Parks and environmental conservation/management areas. Therefore, negligible future development was assumed across the upper/western catchment areas.

The most notable areas that are currently undeveloped, but the current zoning may permit future development include:

- IN1 area located north of Mount Darragh Road at South Pambula
- IN1 area located south of Pambula Beach Road and east of McPherson Cct
- R2 area located south of George Street at South Pambula

The updated impervious proportions and pervious “n” values were applied to a new “ultimate catchment development” version of the XP-RAFTS model. The updated model was used to re-simulate the 5% AEP, 1% AEP and 0.2% AEP and PMP storms under potential future catchment development conditions. Peak discharges extracted from the results of the revised hydrologic assessment are presented in **Appendix N**. Peak 5% AEP, 1% AEP and 0.2% AEP and PMF discharges for current catchment development conditions are also included in **Appendix N** for comparison.

Table 37 Adopted land use information for future development assessment

LEP Zone	Average Impervious (%)		Average Pervious "n"	
	Current	Adopted Future	Current	Adopted Future
B1 - Neighbourhood Centre	0	80	0.035	0.025
B2 - Local Centre	27	80	0.043	0.025
B4 - Mixed Use	24	80	0.052	0.025
B5 - Business Development	11	90	0.065	0.020
IN1 - General Industrial	8	90	0.055	0.020
IN2 - Light Industrial	9	80	0.068	0.025
R2 - Low Density Residential	24	40	0.051	0.035
R3 - Medium Density Residential	29	70	0.048	0.030
R5 - Large Lot Residential	14	20	0.058	0.050
RU4 - Primary Production Small Lots	2	20	0.067	0.050
SP1 - Special Activities	8	50	0.058	0.045
SP2 - Infrastructure	20	50	0.058	0.045
SP3 - Tourist	20	50	0.052	0.045

The discharge comparison indicates that future catchment development is predicted to generate very localised increases in peak design discharges at some locations (although discharges across most of the catchment are predicted to largely remain unaltered). The increases most commonly occur downstream of areas where there is potential for more significant intensification of development (i.e., Pambula and South Pambula). The most significant increase in discharges is predicted north of Mount Darragh Road at South Pambula where increases of 2 to 3 m^3/s are common during each design flood (equating to an increase of about 10% above current discharges during most design floods).

Although localised increases in local catchment runoff are predicted, only minimal changes in discharges are predicted along the main rivers (i.e., Pambula and Yowaka Rivers). Interestingly, small reductions in design discharges (i.e., typically 1-2 m^3/s) are predicted for the Pambula River near Pambula and South Pambula which appears to be associated with the more rapid rainfall response from the "developed" catchments allowing local catchment runoff to "escape" into the river and out to sea before flow from the upper catchment arrives.

To quantify the impact that the changes in design discharges are predicted to have on future flood behaviour, the hydrographs generated by the future catchment conditions XP-RAFTS model were subsequently applied to the TUFLOW model. In addition to updates to hydrology to reflect intensification of development, two different topographic scenarios were represented in the TUFLOW model to maintain flood function (ensure floodways and flood storage areas are preserved as a minimum):

- Existing topography is maintained.
- Existing topography is maintained except for 1% AEP flood fringe areas which were elevated to the flood planning level.

The updated TUFLOW model was used to re-simulate the 5% AEP, 1% AEP and 0.2% AEP floods as well as the PMF (with and without filling). Flood level difference mapping was also prepared to quantify the impact that future catchment development is predicted to have on “existing” design flood levels across the catchment. The difference mapping is presented in **Appendix N**.

The difference mapping shows future development with no topographic changes is predicted to generate small increases in flood level at localised locations across the lower sections of the catchment during floods up to and including the 1% AEP event. The most extensive changes in flood level are predicted to occur at South Pambula which is zoned for industrial and residential development. However, the flood level increases are not predicted to exceed 0.02 metres in this area. The biggest increase in flood level is predicted to be ~0.1 metres during the 5% AEP flood and occurs in the wetland area to the west of the Discovery Parks caravan park at Pambula Peak. Negligible flood level impacts are predicted during the 0.2% AEP flood and PMF.

Inclusion of filling is not predicted to change the magnitude or extent of the flood level impacts during the 5% AEP and 1% AEP floods (which helps to provide evidence that the 1% AEP flood fringe areas were suitably delineated). However, inclusion of filling is predicted to have more significant impacts during the 0.2% AEP flood and PMF at South Pambula. Flood level increases of more than 0.5 metres are predicted at some locations. Therefore, care will need to be exercised if earthworks are completed to support the development of this area in the future to ensure flood impacts are minimised during events larger than the 1% AEP flood.

Therefore, the outcomes of the assessment shows that future development may have small localised adverse impacts on flood behaviour (i.e., increases in flood discharges and levels). However, flooding across the broader catchment is not predicted to be significantly impacted. Care will need to be exercised if filling is proposed as part of any future development to ensure flood function is maintained and existing flood behaviour is not exacerbated.

11 CONCLUSION

This report documents the outcomes of investigations completed to quantify flood behaviour across the Pambula River, Pamula Lake and Yowaka River catchment. It provides information on design flood discharges, levels, depths and velocities as well as hydraulic and flood hazard categories for a range of design floods.

Flood behaviour across the catchment was defined using two computer models that were developed specifically for the study:

- A hydrologic model of the catchment was developed using the XP-RAFTS software. The hydrologic model was used to simulate the transformation of rainfall into runoff and generate discharge hydrographs at various locations across the catchment.
- A hydraulic computer model of the river system and floodplain was developed using the TUFLOW software. TUFLOW is a two-dimensional hydraulic software package that takes the discharges hydrographs produced by the hydrologic model and simulates how that flow would move and be distributed across the catchment. It can be used to produce a range of important flood information including floodwater depths and velocities.

The XP-RAFTS and TUFLOW models were calibrated using historic rainfall and stream flow records along with surveyed flood marks and reported descriptions of flood behaviour that were provided by the community. The floods that were selected for calibration include events that occurred in 1971, 1985, 2011, 2012 and 2016. The outcomes of the calibration showed that the computer models were producing reliable reproductions of each historic flood.

The calibrated models were used to simulate the design 10%, 5%, 2%, 1%, 0.5% and 0.2% AEP floods based upon the 2019 version of Australian Rainfall and Runoff (Geoscience Australia). The Probable Maximum Flood (PMF) was also simulated. The following conclusions can be drawn from the results of the investigation:

- Flooding across much of the upper catchment is mostly contained near the main watercourses owing to the "incised" nature of the floodplain in these areas. More extensive inundation is predicted across parts of the lower catchment where wider floodplains combined with major topographic "constrictions" combine to create a series of "bathtubs". The most significant "bathtubs" are located south of Pambula as well as at Griegs Flat.
- Flooding across the catchment can occur from a variety of different storm and rainfall durations. The worst-case flooding typically occurs as a result of rainfall of at least 12 hours in duration.
- The catchment is traversed by several important transportation routes. The results of the flood simulations show that Nethercote Road and the Princes Highway are predicted to be cut by floodwaters in events as frequent as the 10% AEP flood. Blockage of major bridges and culverts can also result in more frequent overtopping of

major roadways which highlights the importance of routine maintenance on this infrastructure, particularly immediately after a flood.

- While most properties and facilities are located outside of the floodplain, some properties have a greater flood exposure. In particular, the Colonial Motor Inn and Idlewilde Motor Inn at Pambula are predicted to be exposed to a significant hazard during the PMF and access would also be cut. It is recommended that discussions are completed with the owners of each facility to highlight the significant hazard that could occur during the PMF and encourage the preparation of a “flood safe plan” that would promote early evacuation of staff and occupants during very large Pambula River floods.
- The results of additional climate change simulations indicate that should both rainfall intensity and sea level continue to increase as projected, it would produce a notable increase in flood risk across all sections of the catchment. However, the area of the catchment located east of the Princes Highway would be most significantly impacted (as this area can be impacted by both sea level rise and increases in rainfall intensity).
- Flood planning category constraint mapping prepared as part of the study suggests that the land use zones defined in the Bega Valley Local Environmental Plan (LEP) 2013 are broadly compatible with the flood risk. However, there are vacant parcels of land that at South Pambula that are zoned for industrial and residential uses that are more significantly constrained by flooding. Therefore, care will need to be exercised if these areas are developed in the future to ensure the development is compatible with the flood hazard and floodway and flood storage areas are preserved.

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