BERRIGAN SHIRE COUNCIL

TOCUMWAL AND BAROOGA FLOOD STUDY

FINAL

FEBRUARY 2025

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February 2025

Project Tocumwal and Barooga Flood Study	**Project Number** **120074**
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Revision History

Revision	Description	Distribution	Authors	Reviewed by	Verified by	Date
0	Stage 2 – Calibration	BSC, DPE	Fabien Joly, Andrew Bova	Erin Askew	Erin Askew	AUG 23
1	Draft Flood Study	BSC, DCCEEW	Fabien Joly Erin Askew	Erin Askew	Erin Askew	OCT 24
2	Draft for Public Exhibition	BSC, DCCEEW	Fabien Joly Erin Askew	Erin Askew	Erin Askew	NOV 24
3	Final	BSC, DCCEEW	Fabien Joly	Erin Askew	Erin Askew	FEB 25

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TOCUMWAL AND BAROOGA FLOOD STUDY

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LIST OF ACRONYMS

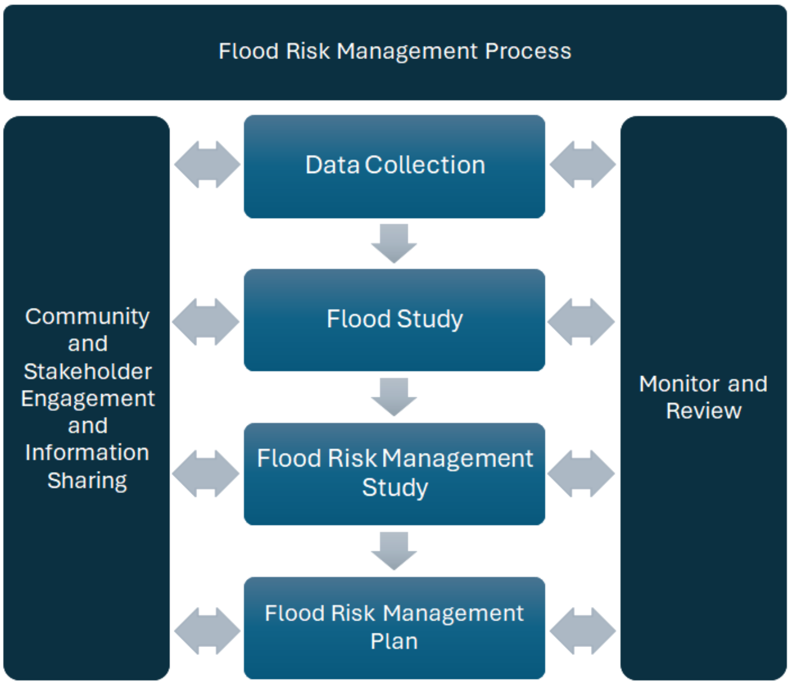
AEP	Annual Exceedance Probability
ARI	Average Recurrence Interval
ALS	Airborne Laser Scanning
ARR	Australian Rainfall and Runoff
BOM	Bureau of Meteorology
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DPE	Department of Planning and Environment (now DCCEEW)
DRM	Direct Rainfall Method
DTM	Digital Terrain Model
GIS	Geographic Information System
GPS	Global Positioning System
IFD	Intensity, Frequency and Duration (Rainfall)
LiDAR	Light Detection and Ranging
LFC	Layered Flow Constriction
mAHD	meters above Australian Height Datum
MDBA	Murray-Darling Basin Authority
OEH	Office of Environment and Heritage (now DCCEEW)
PMF	Probable Maximum Flood
SCIMS	Survey Control Information Management System
TUFLOW	One-dimensional (1D) and two-dimensional (2D) flood and tide simulation software (hydraulic model)
WBNM	Watershed Bounded Network Model (hydrologic model)

FOREWORD

The NSW State Government's Flood Prone Land Policy, contained in the Flood Risk Management Manual (Department of Planning and Environment , 2023) provides a framework to ensure the sustainable use of floodplain environments. The primary objective of the NSW Government's Flood Prone Land Policy is to reduce the impact of flooding and flood liability on individual owners and occupiers of flood prone property, and to reduce private and public losses resulting from floods using ecologically sustainable methods, where possible. At the same time, the Policy recognises the benefits flowing from the use, occupation, and development of flood prone land. The Policy provides a means of ensuring that any new development is compatible with the flood hazard and does not create additional flooding problems in other areas.

Under the Policy, the management of flood liable land remains the responsibility of local government. The State Government subsidises flood mitigation works to alleviate existing problems and provides specialist technical advice to assist Councils in the discharge of their floodplain management responsibilities.

The Policy provides for technical and financial support by the Government through the Flood Risk Management Process:



This document constitutes the first and second stages of the management process for the study area. It presents a compilation of the data collected and has defined flood behaviour and flood risk for the towns of Barooga and Tocumwal.

This study was commissioned under the 2005 NSW Floodplain Development Manual (NSW Government, 2005), however, it is recognised that the 2023 Flood Risk Management Manual (Department of Planning and Environment , 2023) was gazetted while the project was in progress. While the study was undertaken in accordance with the 2005 Manual, there are elements that are consistent to both the 2005 and 2023 Manuals. Where appropriate, the 2023 Manual is referenced where project methodology or outputs are consistent with the new 2023 Manual.

ACKNOWLEDGEMENTS

This study was undertaken by WMAwater Pty Ltd, on behalf of Berrigan Shire Council. Berrigan Shire Council has prepared this document with financial assistance from the NSW Government through its Floodplain Management Program. This document does not necessarily represent the opinions of the NSW Government or the Department of Climate Change, Energy, the Environment and Water.

A number of organisations and individuals have contributed both time and valuable information to this study. The assistance of the following in providing data and/or guidance to the study is gratefully acknowledged:

- Berrigan Shire Floodplain Risk Management Committee
- Residents of the study area
- Berrigan Shire Council
- NSW Department of Climate Change, Energy, the Environment and Water
- Victorian Department of Energy, Environment and Climate Action
- Moira Shire Council
- Goulburn Broken Catchment Management Authority
- Murray Darling Basin Authority
- NSW State Emergency Service

EXECUTIVE SUMMARY

Introduction

Berrigan Shire Council (Council) engaged WMAwater to undertake the Tocumwal and Barooga Flood Study. The objective of this study is to improve understanding of flood behaviour and impacts to better inform management of flood risk in the study area. The study area includes the towns of Tocumwal and Barooga, as well as the intervening reaches of the Murray River. Both local overland flooding and mainstream flooding from the Murray River were investigated in this study.

Background

The towns are located on the banks of the Murray River, downstream of Yarrawonga Weir. The nature of flooding in both Barooga and Tocumwal is dominated by riverine flooding from the Murray River. Flooding along the 30 km stretch of river immediately downstream of Yarrawonga is partially confined to the naturally occurring terraced areas of the Murray River floodplain and within anabranches (such as Barooga Cowal) which are activated during increased flows in the Murray River as well as during local storm events. Around Barooga and Tocumwal and downstream, the river is confined by the naturally occurring localised sandhills as well as a series of constructed levees, including the Barooga and Tocumwal levee system. Flows leave the river through the offtake to Tuppal, Native Dog and Bullatale Creeks.

The towns are affected by two separate flood mechanisms – Murray River flooding and local overland flooding. These generally occur independently of each other due to the storm mechanisms required to produce the relevant flooding and the difference in timing. Large Murray River flood events have occurred in 1867, 1870, 1917, 1974, 1975, 2016 and most recently 2022.

Available Data

As part of the data collection, WMAwater received the previous studies undertaken for the area and for the wider Murray River catchment as well as stormwater infrastructure from Council's database, design drawings and field survey. Topographic information was received from aerial, ground and bathymetric surveys. Gauge data was collected, including rainfall and stream flow data. Information about previous flood events in the area was obtained from Council which included surveyed flood marks, drone photography, service requests and SES assessments.

Community Consultation

At the commencement of the project, the community were informed of the study and provided the opportunity to contribute their observations of flooding within the catchment. A total of 11 responses to a community questionnaire were obtained. A community drop-in session was also held in each of the towns to gather information. Additional information was obtained from residents via these sessions.

Model Development

The models developed to simulate overland flood behaviour in the study area consist of a two-stage process:

1. Hydrologic modelling using WBNM to convert rainfall to runoff
2. Hydraulic modelling using TUFLOW to estimate overland flow distributions, flood depths, levels and velocities.

Both of these models were developed for each of the towns to simulate overland flow flooding. Subcatchments were delineated to trapped low points, stormwater infrastructure or flow paths. Subcatchments were assigned an impervious fraction and a typical catchment lag factor was adopted in the WBNM models.

The TUFLOW hydraulic models cover each of the towns and the catchment in between. The models consist of a 3 m by 3 m regular grid. The best available terrain and structure data was incorporated into the model, along with model adjustments to ensure that hydraulic features (including gutters and channels) were adequately represented. The simulated runoff hydrographs from the WBNM models were applied to the TUFLOW model as inflows.

A TUFLOW hydraulic model was also developed for the Murray River, consisting of a 20 m grid. Topographic features such as embankments were enforced in the model and key structures including bridges were included in the model. Inflows were derived from upstream stream gauge data at Yarrawonga Weir and the findings of studies completed upstream.

Model Calibration

The flood events of 1975, 1993, and 2016 were utilised to undertake calibration of the Murray River model. Gauge data, flood marks, photography and observations were used to calibrate the model. Calibration results are contained in Appendix C.

Flood Frequency Analysis

Flood frequency analysis (FFA) was utilised Murray River Downstream Yarrawonga Weir (#409025) and undertaken for Tocumwal (#409202). The adopted approach typically consisted of obtaining an annual maximum series of flows from the available gauge data, application of low flow censoring, application of high flow censoring (for the 1867, 1870 historic events) and utilising a Log Pearson Type III probability distribution. This resulted in 1% AEP peak flow of 390,000 ML/d at Yarrawonga, and 279,500 ML/day at Tocumwal. The peak flow rates from these analyses were used to derive inflows and validation for the Murray River model.

Design Flood Modelling

Design flood modelling was undertaken in accordance with Australian Rainfall and Runoff (ARR) 2019 guidelines. For the Murray River, the 1958 and 1952 event hydrographs were scaled using the peak flows primarily derived from the FFA. An extreme event representing three times the 1% AEP flowrate was also assessed.

For the local overland models, design rainfalls from the Bureau of Meteorology were adopted in the WBNM models. ARR 2019 requires an ensemble of temporal patterns to be run for each duration and these were simulated in the hydrologic and hydraulic model. The critical storm duration (duration that produces the highest flood level) was determined based on the mean of the 10 temporal patterns for each duration. The storm duration was typically long (approximately 24 hours) for the towns due to the flood storage that dominates the towns. There were very few areas that are conveyance driven, where a shorter storm duration dominates.

The design flood events simulated were the 20%, 10%, 5%, 2%, 1%, 0.5% and 0.2% annual exceedance probability (AEP) events in addition to the PMF (or equivalent extreme) event, for both the Murray River and local overland events.

Design Flood Results

Design flood depths, levels, velocities, hydraulic hazard and hydraulic categories were mapped and are provided in Appendix D for the Murray River, Appendix E for local overland flooding. Flood results were also tabulated and plotted at key road crossings.

Parts of Tocumwal begin to be impacted in the 10% AEP event, at Barooga impacts begin in the 5% AEP event. In the 1% AEP event, the Seppelts Levee just upstream of Barooga is overtopped. Portions of the golf course are inundated, which extends into the Barooga Cowal. Flows break out of the Barooga Cowal and across Berrigan Road. Flows spread from the Barooga Cowal back towards the Murray River, inundating a larger area of Barooga-Tocumwal Road and Mulwala-Barooga Road, as well as the area behind Levee No. 5 (Barooga Levee). Inundation is also shown to occur in Vermont Street, Collie Street, Banker Street, Snell Road and Howard Street and between Nangunia Street and Buchanans Road. Some farmlands along Berrigan Road in Barooga are inundated during this event. In Tocumwal, the Barooga Cowal inundates parts of the golf course and its crossings of Kelly Street, Tuppal Street, Hennessy Street, Deniliquin Street and Brunton Street. Moving west flows spread across the area generally bound by Racecourse Road, Bruce Birrel Drive, Deniliquin Road and the Newell Highway. There is extensive inundation across the northern and southern floodplain downstream of Tocumwal in this event.

Flood emergency response planning was considered for both towns, for both Murray River and local overland flooding, including property inundation, road inundation and emergency response classification.

A preliminary flood planning area was defined for both the Murray River and local overland events and advice was provided considering the new modelling of overland flow affectation of the towns. Flood planning constraint categories were also mapped.

Sensitivity Analysis

A sensitivity analysis (Appendix F) was undertaken for key modelling parameters by varying the adopted values and assessing the change in peak flood levels. Peak flood levels are relatively insensitive to changes throughout the urban areas.

Economic Impacts of Flooding

A flood damage assessment was undertaken to determine the economic impact of flooding. A property database was developed with an estimation of floor levels. Flood damage curves were applied that estimate the cost of damage for a certain depth of inundation. Average annual damages (AAD) were estimated for each of the towns, with separate damage calculations undertaken for the Murray River and local overland events.

At Tocumwal and Barooga, the Murray River impacts lead to an AAD of approximately $2.4M and overland events, an AAD of $2.7M.

1. INTRODUCTION

The Tocumwal and Barooga Flood Study aims to provide information about existing flood risk in the study area (Figure B1); which covers the urbanised townships of Tocumwal and Barooga, as well as the intervening reaches of the Murray River. Tocumwal and Barooga are situated on the banks of the Murray River on the southern border of NSW, within the Berrigan Shire Council (Council) Local Government Area (LGA). Flooding can occur as a result of rising water levels in the Murray River and its local tributaries (riverine), in addition to shorter duration local rainfall events (local overland flow). This study has investigated both mechanisms of flooding.

In 2011, the Murray River Regional Flood Study (Water Technology Pty Ltd, 2011) was completed and delimited the extent of the floodplain using a computer based 2D hydraulic flood model. This study also undertook an extensive review of the hydrological data available and provided a series of recommendations regarding the levee system protecting the southern and northern floodplain from riverine flooding. Whilst informative, the Murray River Regional Flood Study did not comprehensively investigate the impacts of riverine and major overland flow flooding on the townships of Tocumwal and Barooga. In addition, since the completion of the Murray River Regional Flood Study in 2011 there has been a range of significant advancements in the modelling tools available, development of industry guidelines, the availability of considerably more detailed topographic data (i.e. LiDAR data) and reasonably significant flood events in 2016 and 2022, for which recorded flood information is available. Furthermore, there has been an increase in developments and changes within the catchment. As such, Council seeks to use the latest available tools and data to define flood risk in Tocumwal and Barooga, under current catchment conditions.

Council is responsible for managing development of flood prone land under guidance provided in the NSW Flood Risk Management Manual (Department of Planning and Environment , 2023) and previous Floodplain Development Manual (NSW Government, 2005). The flood modelling tools and outputs developed as part of this study can be used by Council to improve the understanding of flood behaviour and impacts, for informed decision-making about land-use planning, for emergency management, and in future studies to assess the effectiveness of potential measures to reduce flood risk. The models have been calibrated using observations from historical floods and subsequently used to estimate the impacts of flooding for a range of standardised “design” flood probabilities. This modelling has been completed in accordance with the guidelines in Australian Rainfall and Runoff Version 4.1 (Ball, et al., 2019).

This study will enable Council to:

- Understand the current flood risk across the catchment
- Provide up to date flood data for all end users
- Enable future development planning
- Assess cumulative impacts of future development
- Assess the effectiveness of potential flood mitigation measures
- Inform emergency management and planning (in collaboration with NSW State Emergency Service)

2. BACKGROUND

2.1. Study Area

The study area is located in the southern Riverina region of NSW, along the Murray River extending from Yarrawonga Weir to approximately 23 km downstream of Tocumwal, near to where the Tuppal and Bullatale Creeks leave the Murray River. This, approximately 75 km, stretch of river extends across the Berrigan Shire LGA, including the townships of Tocumwal and Barooga.

The study focusses on flood affectation within NSW, although Murray River flooding also affects land within Victoria (as the southern bank of the Murray River forms the boundary between the two states in this area). Flooding on the Victorian side of the Murray River is shown for illustrative purposes only and are not ratified by the relevant Victorian Authorities.

The study area is generally rural in nature, with considerable clearing of the land beyond the immediate Murray River floodplain for agricultural purposes, supporting the grazing of livestock and irrigated crops (rice, wheat, barely oats and canola). Low or medium density residential development is present in the townships. The population of the townships of Barooga and Tocumwal is 1752 and 2587, respectively (Australian Bureau of Statistics, 2021). Within the townships, the land use is mostly residential with an airport and railway hub in the town of Tocumwal. Most of the commercial and industrial needs are met in the town of Cobram on the south side of the Murray River (Victoria).

The sensitivity of some crops in the region to inundation, coupled with the relatively flat terrain led to the construction of numerous flood protection levees across the floodplain, including the Seppelts Levee, and town levees at Barooga and Tocumwal. A number of levees also exist on the Victorian floodplain.

At Tocumwal, a single, main levee protects the town itself north of the Murray from riverine flooding. The levee begins near Bushlands Road, south of the town, extending approximately 6.8km to the northwest along the northern bank of the Murray River. At Barooga, a series of levees, originally constructed in the early 1900s, protect the northern floodplain. The system was extended and upgraded following the 1975 flood.

The area is serviced regionally by the Riverina and Newell Highways and Tocumwal Road, Mulwala-Barooga Road, Barooga-Tocumwal Road and Tuppal Road at a more local level. The Murray River can be crossed at Yarrawonga Weir (including Weir Road), Barooga-Cobram Road/Murray Valley Highway at Barooga and Newell Highway/Goulburn Valley Highway at Tocumwal.

Elevations across the study area vary between approximately 120 m AHD to 100 m AHD, moving down the Murray River and immediate floodplain, while locally around the townships, levels from approximately 123 m AHD to 111 m AHD in Barooga and from 115 m AHD to 107 m AHD in Tocumwal.

At Barooga, the Murray River and immediate floodplain sits within approximately a 2 km wide area of lower elevation bounded by high banks, this terraced area generally confines many of the smaller floods. At Tocumwal and downstream this area becomes broader and less defined as the river moves towards the Barmah Millewa Forest.

Within the townships of Barooga and Tocumwal, local rainfall is conveyed through the towns via a drainage system consisting of kerb and gutters, dish drains and a pit and pipe network.

2.1.1. Murray River

The Murray River rises at approximately 1,430 m AHD in the Australian Alps, between Mount Pilot and Forest Hill on the NSW/Victorian border and flows in a westerly direction approximately 2,530 km to enter the Southern Ocean through Lake Alexandrina in South Australia (Gutteridge Haskins & Davey Pty Ltd, Cameron McNamara Pty Ltd, Laurie Montgomerie & Pettit Pty Ltd, 1986). The river is managed by the Murray Darling Basin Authority (MDBA). The Murray River is heavily regulated, with fourteen (14) weirs and three (3) large dams controlling water levels and river flows (Murray Darling Basin Authority, 2020). These controls are designed and built to regulate river flows for irrigation purposes and provide only limited flood mitigation. Hume Dam is located approximately 10 km east of Albury and controls Murray River flows downstream of the dam wall, including through the study area. The dam was constructed over a seventeen (17) year period, commencing in late 1919 and its storage capacity was approximately doubled to 3,000 GL, between 1950 and 1961. Dartmouth Dam, located upstream of Hume Dam was also constructed between 1973 and 1979 with a capacity of 3,800 GL. Flows entering the study area are also controlled by Yarrawonga Weir and water levels in Lake Mulwala.

The Murray River catchment area to key locations is shown in Table 1. There are a number of tributaries that join the Murray River between Hume Dam and Yarrawonga Weir, with the primary ones being the Kiewa River (confluence between Hume Dam and Albury-Wodonga), and the Ovens River (confluence just upstream of Lake Mulwala). There are no significant tributaries joining the Murray within the study area, however, the Tuppal, Native Dog and Bullatale Creeks leave the Murray River and travel to the Edward River system at the downstream end of the study area. In addition, the Mulwala Canal and Yarrawonga Main Channel divert water from Lake Mulwala to service the irrigation areas north and south of the study area, respectively.

Table 1: Murray River Catchment Details

Location	Catchment Area[1] (km^2)	Distance from Hume Dam[2] (km)
Hume Dam (GS #401027)	15,300	0
Albury (GS #409001)	17,200	29
Howlong (GS #409037)	17,900	100
Corowa (GS #409002)	18,800	149
Mulwala/Yarrawonga (GS #409025)	27,300	236
Barooga	-	304
Tocumwal (GS #409202A)	29,008	331
Downstream Extent of Study Area	-	354

1 Catchment areas based on WaterNSW and VIC Department of Energy, Environment and Climate Action gauge station data

2 Measured on GIS using the NSW/Victoria border

2.2. Nature of Flooding

The nature of flooding in both Barooga and Tocumwal is dominated by riverine flooding from the Murray River. Flooding along the 30 km stretch of river immediately downstream of Yarrawonga is partially confined to the naturally occurring terraced areas of the Murray River floodplain and within anabranches (such as Barooga Cowal) which are activated during increased flows in the Murray River as well as during local storm events. Around Barooga and Tocumwal and downstream, the river is confined by the naturally occurring localised sandhills as well as a series of constructed levees, including the Barooga and Tocumwal levee system. Flows leave the river through the offtake to Tuppal, Native Dog and Bullatale Creeks. During Muray River events, both Barooga and Tocumwal are generally unimpacted until the 5% AEP event. Above this flow begins to enter the Barooga Cowal and impact both towns. In Barooga this occurs through the golf course, while in Tocumwal, through Whites Lagoon, south of the cemetery. In the 1% AEP, flooding in Barooga is confined to the natural depressions and some small flowpaths between Buchanans Road and Nangunia Street, as well as around Vermont Street. Flooding also extends from the golf course to Barooga Cemetery. During an event of this size in Tocumwal, flow breaks from the natural depression and adjacent roadways (Hughes Street and Snell Road), travelling north, and spilling into Kelly Street, Deniliquin Street and Brunton Street. Flow also moves from Tuppal Road to the area between Racecourse Road and George Street. In larger events, the impacted areas in Barooga are generally the same, while the extent of impact in Tocumwal is broader.

The towns can also be impacted by intense rainfall events that cause significant runoff in excess of the stormwater network capacity. This is exacerbated by the relatively flat nature of the towns. The ponding of water from local runoff and well as overland flow paths can affect each of the towns.

In Barooga, overland flows impact the southern end of Nangunia Street. Flooding also extends across the northern half of the golf course. Barooga remains mostly unimpacted for all events more frequent than the 5% AEP event.

In Tocumwal, overland flooding occurs even at frequent events, and depths do not vary greatly between the 20% and 1% AEP events. The areas which are most significantly impacted by overland flooding include: populated region between Tocumwal Tourist Park and the Police Station, and widespread areas north of the town surrounding the racecourse.

Several recent reports have considered the integrity of both levee systems, in addition to those on the Victorian floodplain, highlighting a number of locations where failure may occur. The complex nature of the levee systems and locations of potential failure can result in unpredictable flood behaviour.

The two flood mechanisms (riverine and overland flow) typically occur at different times, as a result of different storm mechanisms. Murray River flooding is ultimately controlled by outflows from Hume Dam. While the primary role of Hume Dam is water conservation, it also provides some secondary flood mitigation benefit for downstream areas. Inflows into the dam are driven by rainfall over the 15,000 km^2 upstream catchment. Flood events occur from widespread rainfall sustained over several days or more, resulting from inland low pressure troughs, typically in the winter months.

Outflows from the dam are controlled by Murray Darling Basin Authority (MDBA) and are based on the following priorities (Murray Darling Basin Authority, 2021):

1. Protect the structural integrity and safety of the dam; then
2. Maximise water availability (i.e. fill the storage to at least 99% of capacity prior to any ensuing drawdown to meet downstream needs); and then
3. Limit flood damage to downstream communities and increase benefits to the environment and public amenity.

Given this, the passing of floodwaters from Hume Dam will be dependent on how full the dam is before the flood event occurs. An incoming flood may be entirely captured by the dam, or may be entirely passed by the dam, depending on how much storage is available. The Bureau of Meteorology (BoM) will issue flood forecast information and flood warnings based on forecast rainfall, water levels and dam releases. The travel time of a flood peak from Hume Dam to the study area is provided in Table 2.

Table 2: Typical Flood Peak Travel Times from Hume Dam

Location	Average Travel Time (days)[1]	Historical Range (days) [1]
Mulwala/Yarrawonga	2.7	1 to 8
Tocumwal	4.5	1 to 10
Echuca	11.1	7 to 20

1 Based on Berrigan Shire Local Flood Plan, NSW State Emergency Service (2017)

These travel times typically allow for improved predictions of the flood magnitude and timing. Peaks of major floods generally last a few days, although the river can often remain in flood (above the minor flood level) for several months. It should also be noted that flooding on the Murray River can also be driven by large inflows from the large tributaries flowing from Victoria, which can occur independently to Hume Dam outflows. Flows from these catchments are also considered when the BoM issues flood forecasts and flood warnings.

In contrast, local overland flooding typically occurs from local rainfall storm bursts over the towns, resulting in much shorter warning times. The same storm is unlikely to produce flooding from both mechanisms at the same time, however coincident flooding may occur.

2.3. Levee System

A system of nine deflector levees were designed to protect both Barooga and Tocumwal from Murray River flooding up to approximately the 1% AEP. The levee generally has approximately 600mm of freeboard based on the design flood levels at the time of the levee design. The levee system was originally constructed in the early 1900’s, with upgrades and extensions undertaken following the 1975 flood. A significant rehabilitation program commenced in 2009, with construction between 2013 and 2015. Four major pumps are permanently located at Anzac Avenue, Cemetery Levee, Bruton Street and Dean Street, additional temporary pumps are used during a flood event. The location of these levees is shown on Figure B1. An overview of the levee system is provided in Table 3.

Table 3: Barooga and Tocumwal Levee System

Levee	Length (m)	Material	Construction of Current Levee (some years approx.)
Tocumwal No. 1	10,755	Earth embankment plus 82m or reinforced concrete and 575m of natural sandhills	Ch. 0 – 2,500 – 1986 Ch. 2,500 – 4,100 – 1986 reconstructed 2001 Ch.4,675 – 5,700 – 1982 Ch. 5,700 – 6,800 – 1980 reconstructed 2001 Ch. 6,800 – 7,580 – 1978 Ch. 7,580 – 7,905 – 1979 Ch. 7,905 – 8,435 – 2003 Ch. 8,435 – 9,100 – 1980 reconstructed 2001 Ch. 9,100 – 9,650 – 1979 Ch. 9,650 – 9,800 – 2000 Ch. 9,800 – 10,467 – 1976 Ch. 10,467 – 11,412 – late 1970s
Pinewood Lane	80	Earth embankment	Late 1970s
Cemetery Levee	80	Earth embankment	Late 1970s
Tocumwal No. 2	400	Road embankment	Replaced by Mulwala-Tocumwal Road raising
Tocumwal No. 3	220	Earth embankment	Late 1970s
Tocumwal No. 4	190	Earth embankment	Late 1970s
No .5 (Barooga Levee)	2,120	Earth embankment	1984
Seppelts	970	Earth embankment	1986

A number of other smaller levees and embankments exist for localised protection (such as Quicks levee at the end of Quicks Road, between Levee No.4 and Levee No.5) and do not form part of the levee system protecting the towns.

2.4. Flooding History

The Murray River has a long history of flooding, with major floods occurring in 1867, 1870, 1917, 1931, 1956, 1974, 1975, 1992, 1993 and more recently in 2016 and 2022. Formal records commenced at Tocumwal in 1908. Table 4 provides the top ten ranked major flood events at the Murray River at Tocumwal gauge (#409202), these events generally peaked above 7.0m. In addition to those in Table 4, large Murray River events occurred in 1867 and 1870, both of which are reported in historic newspaper articles, further floods are also reported in 1889, 1894 and 1905.

The Riverine Herald (Tuesday September 17, 1889) states that the 1889 flood levels in Tocumwal were above those from 1870, as did *The Australasian* (Saturday July 29, 1905) of the 1905 flood. *The Australasian* article also notes that the river is now confined by levee banks which have raised water levels.

Due to the occurrence of these events prior to reliable gauges being installed, there is uncertainty regarding the magnitude of the events. These events also occurred prior to the construction of major infrastructure such as Hume Dam and Yarrawonga Weir, and as such, understanding the magnitude of these events in the current day floodplain conditions is difficult to determine.

Table 4: Recorded Murray River Flood Events at the Murray River at Tocumwal Gauge (#409202)

Rank	Month Year	Peak Average Daily Flow ML/d
1	Oct 1975	224,400
2	Oct 1993	196,300[1]
3	Jul 1917	190,800
4	May 1974	183,400
5	Jul 1956	183,200
6	Oct 2016	180,200
7	Jul 1931	162,100
8	Sep 1970	161,700
9	Aug 1955	157,800
10	Nov 2022	174,700

(1) There are a number of variations in this value (176,000 ML/day through to 205,100 ML/day) across the range of available sources. The value has been adopted from the WaterNSW record.

Low pressure troughs across the Murray River catchment can result in sustained rainfall. These troughs rarely produce high daily rainfalls but can bring substantial falls over longer periods. The cumulative effect of these systems can result in catchment flooding. Analysis of the historic record shows that more than half the Murray River catchment annual average rainfall occurs in the months from May to October, with the majority of flood events occurring in these months.

2.5. Social Characteristics

Understanding the social characteristics of the study area can help in shaping the methods used for community engagement and in ensuring appropriate risk management practices which consider the vulnerability of a community are adopted. Census data regarding house tenure and age distribution can also provide an indication of the community's lived experience with recent flood events, and hence an indication of their flood awareness. According to The Flood Preparedness Manual (Australian Institute for Disaster Resilience, 2009), it is also possible, using population census data and other information held by Councils and state agencies, to identify the potential number and location of people in an area (or the proportion of the community's population) with special needs or requiring additional support during floods.

The Flood Preparedness Manual (Australian Institute for Disaster Resilience, 2009) identifies that, in general, people who belong to the following groups may be considered especially susceptible to the hazard posed by flooding:

- **The elderly**, especially those living alone and/or frail, who are often unable to respond quickly or without assistance;
- **Those with low incomes**, including the unemployed and others on pensions, who may lack resources which would give them independence of decision making and action;
- **Single-parent families, large families or families with very young children**, these may be characterised by low adult / child ratios making evacuation difficult;
- **Those lacking access to a motor vehicle** may need additional assistance to evacuate;
- **Newcomers** (i.e. those residents in their communities for only short periods), who are unlikely to appreciate the flood threat and may have difficulty understanding advice about flooding. They may need special attention in terms of threat education and communication of warnings and other information;

- **Members of Culturally and Linguistically Diverse communities**, who need special consideration with respect to the development of preparedness strategies as well as warnings and communications during flood events. Special attention may also be needed if actions which become necessary during floods offend cultural sensitivities;
- **The ill or infirm** who need special consideration with respect to mobility, special needs, medications, support and 'management' to ensure they continue to receive appropriate care and information; and
- **Those whose homes are isolated by floods**, requiring early evacuation, or if evacuation orders are ignored, may need medical evacuation resupply of essential items, or emergency rescue.

Information is available from the 2021 census (http://www.abs.gov.au/) (Australian Bureau of Statistics, 2021) for each of the towns in the study area. Table 5 below shows the 2021 census statistical for the available State Suburbs (SSCs) compared to the NSW average.

Table 5: 2021 Census Data

	NSW	Tocumwal	Barooga
Median age	39	60	47
0 – 14 years	18.2%	13.7%	15.7%
15 - 64 years	64.2%	45.1%	57%
> 65 years	17.7%	41.2%	27.5%
Average people per household	3.1	2.9	2.9
Couple family w/ children	37.9%	61%	52.1%
Couple family w/out children	44.7%	27%	34.5%
One parent family	15.8%	11.2%	12.3%
Own/mortgage property	64%	77.2%	74.4%
Rent property	32.6%	16.8%	21.6%
No motor vehicle at household	9%	3.3%	3.1%
1 motor vehicle at household	37.8%	34.4%	34.4%
2 motor vehicle at household	34.1%	38.5%	40.8%
3 or more motor vehicle at household	17.5%	19%	19.1%
Not stated	1.5%	4.8%	2.5%
Speak only English at home	67.6%	87%	89.8%
Households where a non-English language is spoken	29.5%	3.7%	5.8%
Suffering from long-term health condition	27%	38.9%	34.2%
< $650 gross income per week	16.3%	27.5%	18.4%
>$3000 gross income per week	26.9%	10%	13.7%

The characteristics noted above are considered in the community engagement strategy and when evaluating response modification options, such as flood education, warning, or evacuation systems. Given the high proportion of English-only households, the delivery of community consultation material and flood warnings/ information in English is deemed appropriate. With a significant proportion of residents (higher than the state average) over the age of 65 years, online engagement strategies are not as likely to be as effective as face-to-face or postal communications.

In addition to communication strategies, census data can be used as an indicator of a community's vulnerability regarding flood risk management. Aged residents are more likely to be frail and physically unable to respond as quickly to flood emergencies. Barooga and Tocumwal have a higher proportion compared to the NSW average of people over 65 years of age and those suffering from long-term health conditions. This means there is a higher proportion of people considered to be more vulnerable to flood events and provision of assistance to such residents should be a key consideration when developing flood evacuation systems and the lead time with which warnings are provided. It should also be highlighted that while the proportion of people who own/mortgage their home when compared to the NSW statistic is higher for Barooga and Tocumwal, wages are comparatively lower. While home ownership often indicates greater awareness of the flood risk exposure to their property. The percentage of people who earn more than $3000 per week in Barooga and Tocumwal is 13.7% and 10% respectively, compared to the overall NSW profile of 26.9%. This may potentially indicate lower financial resilience to flooding events among the community.

2.6. Land Use

Land use zoning is defined by the Berrigan Local Environmental Plan (LEP) 2013. The LEP and accompanying Development Control Plan (DCP) set development regulations throughout the Local Government for each land use type and constraint.

The town of Tocumwal is mostly comprised of RU5 – Village with areas of R5 - Large Lot Residential north and east of the town. E4 - General Industrial zoning, is located west of the town. The area south of the town along the Murray River is zoned as C3 – Environmental Management. SP2 – Infrastructure is present both west and east of the town, which encompasses the sewage treatment, airport, and railway infrastructure. The rest of the town and locality is classified as Primary Production.

The centre of Barooga is classified as RU5 – Village with areas north and southeast classified R5 - Large Lot Residential. The western part of the town is part of the RE2 - Private Recreation area with the riparian corridor classified National Parks to the south. E4 – General Industrial zoning is also present to the northeast. Outside of this, to the north and east of the town, the land is zoned as RU1 – Primary Production.

3. AVAILABLE DATA

3.1. Previous Studies

A number of flood studies and assessments have previously been undertaken at Tocumwal and Barooga, as well as across the surrounding floodplain. In addition to these, there are a number of studies available for the Murray River that focus on the entire river system, or more localised reaches of the river upstream or downstream of the current study area. A brief overview of the more significant studies, and those relevant to the current assessment, is provided below.

Australian Rainfall and Runoff (ARR) is a national guideline document that can be used for the estimation of design flood characteristics in Australia. Design methodologies applied in these previous studies have generally been obtained using ARR 1977 or ARR 1987, while the current study considers the terminology, methodology and data described in ARR 2019 Version 4.1, the event terminology used in previous reports has been maintained in the following section.

3.1.1. Murray River Flood Plain Management Study, Rural Water Commission of Victoria and the Water Resources Commission of New South Wales

The report for this study (Gutteridge Haskins & Davey Pty Ltd, Cameron McNamara Pty Ltd, Laurie Montgomerie & Pettit Pty Ltd, 1986) considered the Murray River from Lake Hume to the South Australian border. The investigation collated historical flood information, assessed flood magnitude, and prepared indicative 100-year ARI flood maps. The flood maps largely utilised observed flood levels. This previous investigation provided valuable and extensive background information and description of flooding for the current study. The study then identified areas impacted by flooding on the Murray River floodplain between Lake Hume to the South Australian border. The study considered historic flood inundation along with previous and proposed floodplain works to identify impacted areas and prioritise areas for further investigation. The report details the information available for the historic events of 1867, 1870, 1916, 1917, 1931, 1956, 1974 and 1975. The study involved consideration of existing (at the time) floodplain management legislation and collation and analysis of a large flood data set. A review of environmental issues and the effects of floodings was carried out. Flood frequency analysis (FFA) indicated the results outlined in Table 6. The associated flood atlas mapped the 1975 event from Lake Hume to Yarrawonga.

Table 6: Murray River Historic Events and Design Estimates (Gutteridge Haskins & Davey Pty Ltd, Cameron McNamara Pty Ltd, Laurie Montgomerie & Pettit Pty Ltd, 1986) for Yarrawonga and Tocumwal

Year / AEP	Yarrawonga (GS #409025)		Tocumwal (GS#409202A)	
	Flow (ML/day)	Gauge Level[1] (m)	Flow (ML/day)	Gauge Level[2] (m)
1% AEP[2]	390,000	10.825 (U/S) 9.835 (D/S)	340,000[4]	8.07
2% AEP	325,000	8.965 (D/S)	290,000[4]	7.68
5% AEP	238,000	8.265 (D/S)	210,000[4]	7.39
1867	NA	-	NA	-
1870	NA	10.365 (U/S) 9.565 (D/S)	NA	7.57
1916	111,500	-	71,900	-
1917	390,000	9.805 (U/S) 9.005 (D/S)	338,000	7.37
1931	210,000	8.155 (D/S)	162,000	7.19
1955	171,000	-	157,800	-
1956	193,000	7.975 (D/S)	183,000	7.28
1974	204,000	8.005 (D/S)	193,000	7.32
1975	243,000	8.325 (D/S)	249,000	7.57
1981	121,000	-	117,300	-

1 Using a gauge zero level of 115.035 mAHD, as per the report. Design levels based on 1985 rating tables.
2 Using a gauge zero level of 103.830 mAHD.
3 The adopted 1% AEP was the 1917 flood level
4 From GHD (1986) Flood Frequency Analysis
Note: NA is not available (as stated in the report), while - denotes that it is not reported

3.1.2. Cobram Town Levees Study

The study (Camp Scott Furphy Pty Ltd, 1993) investigated the level of flood protection afforded to the town of Cobram. Several potential flood mitigation options were identified to protect the town against a failure of the levee. The study also defined design requirements and standards for the construction of levees. The study estimated the 1 in 100-year event flow and the 1870 flood flow. It also stated that there were two requirements to protect the town of Cobram from a repeat of the largest flood on record: “Upgrading the existing levee system including providing levee protection downstream of the township”, and; “Determine a strategy for diverting upstream breakaways from Cobram”. This study provided a reference point for the 1870 and 1% AEP flows.

3.1.3. Yarrawonga Weir Review of Flood Security

The Australian Dams Alliance (Australian Dams Alliance, 1999) prepared a review of the flood security of Yarrawonga Weir for Goulburn-Murray Water, detailing the expected performance of the weir during significant flood events. Extracts of this report were provided to WMAwater.

The review focussed on the security of the weir structure and potential flooding impacts upstream and downstream of the weir were not considered. The review found that under free flow conditions, the weir is capable of passing 270,000 ML/d at the full supply level (FSL) of 124.9 mAHD and a design discharge of 345,000 ML/d at the design flood level of 125.85 mAHD. A peak discharge of 445,000 ML/d was estimated when the flow reaches the bottom of the raised gates (127.0 mAHD), assuming no outflanking flows. In events larger than this, the structural integrity of the weir and embankment (when overtopped) may be compromised.

3.1.4. Murray River Regional Flood Study Dicks/Seppelts levees to downstream of the Ulupna Creek confluence

This study (Water Technology Pty Ltd, 2011) covers the Murray River from approximately 20 km downstream of Yarrawonga Weir. The study undertook flood frequency analysis (FFA) at the Yarrawonga gauge (GS #409025 downstream of the weir) and Tocumwal gauge (GS #409202A).

Of particular interest to the current study is the analysis of gauge data at the Yarrawonga gauge, including a comparison of estimates of peak flows for significant flood events between 1905 and 1979 to determine a reliable annual maximum series.

The FFA considered peak flows (including censoring of the 1867 and 1870 events) and flood volumes (over a 14 day, 21 day and 28 day period). A 1% AEP peak flow estimate at the Yarrawonga gauge ranged from 269,000 ML/d to 445,000 ML/d depending on the period assessed, censoring of events and probability distribution adopted. The study adopted a 1% AEP peak design flow rate of 387,000 ML/d at Yarrawonga.

A large data collection exercise was also conducted as part of the 2011 study, this included extensive field survey of syphons, road crossings, channel banks, culverts and bridges. The survey was undertaken by SKM in 2008 primarily using RTK GPS and Total Stations. This survey provides a key input to the current model development.

The peak flow to peak volume ratio was used to inform the selection of historic flood hydrographs for design flood events. These design flow hydrographs were used in a MIKEFLOOD hydraulic model covering the study area including the towns of Cobram, Barooga and Tocumwal, that was calibrated using the October 1975 and October 1993 flood events. Design flood inundation maps were produced considering no levee failure and levee failure scenarios. The analysis found that in the event of a NSW levee breach, very extensive increases in flood extents and depths would occur – with flood depths up to 1m. Various structural and non-structural (land use planning and controls, flood warnings and responses) mitigation measures were also assessed with recommendations provided.

3.1.5. Albury City to Greater Hume Murray River Flood Study

The study, herein referred to as the ‘Albury Flood Study’ (GHD, 2012) defined flood behaviour for a 34 km stretch of the Murray River floodplain using flood frequency analysis (FFA) and a TUFLOW hydraulic model. Design flood events ranging from a 5 year ARI to 500 year ARI were defined for the study area, extending from Hume Dam to approximately 20 km downstream of Albury. Stream gauge data was used to conduct a FFA that considered hydrology both pre- and post-construction of Hume and Dartmouth Dams. A 1% AEP flow of 250,000 ML/d was adopted downstream of Hume Dam. This value was consistent with earlier estimates of the 1% AEP flow.

Steady state design flows were input into a TUFLOW model which adopted a 10 m grid and was calibrated to the 1975 flood event and validated against the 1917 flood event. Design flood behaviour was used to produce flood hazard maps, hydraulic category maps and flood profile plans. The flood study did not model the PMF event, as the Murray Darling Basin Authority (MDBA) was undertaking a study in relation to dam break scenarios at the time, which would provide estimates of the PMF event at Albury.

3.1.6. Rural Levee Assessment

The study (Water Technology Pty Ltd, 2013) was designed to improve the state of knowledge, data, and information of the strategic levees along the Goulburn River from Loch Garry to the Murray River and the Murray River from Cobram to Barmah. Survey of the levees was undertaken. An assessment was undertaken to determine where levees are located either within public or privately owned land parcels. In addition, an assessment of the condition of the levee was undertaken, to identify points of weakness, and develop a plan of works and costings to bring the entire levee system to a more consistent level of protection. The study estimated that the total length of Murray River levees with a level of protection below the 1975 event level is 67.5 km. A total of 131 sites and nearly 1km of levee was identified as being at risk of breach. An estimated cost of works was given of approximately $400,000 for Murray River levees, and $2.1 million for Goulburn River levees. In conclusion, it was established that the condition of both levee systems was extremely inconsistent along their lengths, and that if a large flood was to occur, it would be extremely difficult to predict the resulting flood characteristics and behaviour. Further to this, it was determined that the repair and upgrades to the levees required to afford consistent protection would be a significant undertaking.

3.1.7. Yarrawonga Weir Flood Incident Management Plan

The MDBA provided WMAwater with extracts from the Yarrawonga Weir Flood Incident Management Plan (Murray Darling Basin Authority, 2016). The document provides rules to be followed in order to safely route a flood event through Yarrawonga Weir in the case that communications with MDBA are unavailable. The operation of the weir is required to pass floods without damaging the structure, with requirements for flows less than 68,000 ML/d to be passed through the southern structure only. The gate is to be operated incrementally to pass a flood event, with various requirements (such as minimum gate openings, maximum differential gate openings and gate opening order) to ensure the structural integrity of the weir.

3.1.8. Hume to Yarrawonga Hydrodynamic Model

This report (Murray Darling Basin Authority, 2019) outlines the MIKE 1D/2D hydrodynamic model that was developed to assess the 2016 Hume to Yarrawonga Constraints Measure business case that outlined the feasibility and environmental outcomes of increasing operational flows at Doctors Point from 25,000 ML/day to 40,000 ML/day. The business case utilised an existing MIKE11 model developed in 2006. This model was updated and refined to be a 1D/2D linked MIKEFLOOD model based on 2001 LiDAR and 2016/2017 cross section data. While limitations in the terrain data were noted, the model was calibrated to two events with the aim of producing a good fit at the 40,000 ML/day flow rate, which was the primary purpose of the model (simulate a 40,000 ML/day flow). The model was not available to WMAwater, however the cross section data was provided for reaches upstream of the current study area. The report also examined gauge data (including gaugings to evaluate reliability), with some useful commentary provided.

3.1.9. Tocumwal Levee – Levee Owner’s Manual

The Tocumwal levee owner’s manual (NSW Government Public Works Advisory, 2018) was prepared by Public Works Advisory for Berrigan Shire Council in June 2018. The document provides general assistance to the levee owner (Berrigan Shire Council) to operate and maintain the levee. The manual provides an overview of the levee system, including responsibilities, location, construction detail, history, survey of the levee and available design flood information, as well as details of levee drainage structures. The manual outlines how and when the levee should be inspected and identifies current issues, as well as providing a sequence of task as a flood approaches.

Given the number of levees that make up the overall levee system at Tocumwal and Barooga, this document assists in understanding the location and purpose of each element.

3.1.10. South Albury Levee Upgrade – Murray River Flood Study

This report (Water Technology Pty Ltd, 2024) detailed the flood modelling undertaken as part of the South Albury Levee Upgrade project and presents an update of the flood mapping provided in GHD, 2012. The study updated the topography and hydraulic model applied to the stretch of the Murray River from immediately downstream of Hume Dam to 20km downstream of Albury. Extensive validation of the LiDAR was undertaken as a large discrepancy was identified in the LiDAR data applied as part of GHD, 2012. The study identified that the 2020 LiDAR data set provided a more reliable representation of the study area topography. A review of the existing flood frequency analysis at Albury, considering Heywood Bridge (gauge # 409016), Doctors Point (gauge # 409017), and Union Bridge (gauge # 409001) was undertaken. The study attempted to account for the potential influence of upstream storages on events prior to the construction of Hume Dam by applying a linear relationship to pre dam events. It was determined that too much uncertainty existed in this approach and the study adopted the design flows derived in GHD, 2012.

3.1.11. Corowa, Howlong and Mulwala Flood Study

The objective of this study (WMAwater Pty Ltd, 2024) was to improve the understanding of flood behaviour and impacts to better inform management of flood risk in the study area. The study area included the towns of Howlong, Corowa and Mulwala, as well as the intervening reaches of the Murray River. Both local overland flooding and mainstream flooding from the Murray River were investigated. The hydrology for the study area was defined by Flood Frequency Analysis and a WBNM runoff routing model. A set of TUFLOW models were developed to represent flood behaviour for the Murray River and the towns in the study area. The study undertook a comprehensive analysis of historical events through the Flood Frequency Analysis as well as confirming the capacity and performance of Yarrawonga Weir. The study showed that above that capacity, flows can become uncontrolled and bypass the study area for the current study. These outcomes have informed the analysis undertaken in the current study.

3.2. Topographic Data

3.2.1. LiDAR

Light Detection and Ranging (LiDAR) topographic survey of the study area and its immediate surroundings was provided for the study by NSW Government Spatial Services, freely available from Geosciences Australia Elevation Information System (ELVIS, https://elevation.fsdf.org.au/).

LiDAR is aerial survey data that provides a high resolution topographic representation of the ground elevation with approximately 4 survey marks every square metre, covering large areas. LiDAR is captured using laser scanners and GPS devices mounted on small aircrafts. The accuracy of the ground information obtained from LiDAR survey is typically 0.3 m in the vertical (95% confidence interval) and 0.8 m in the horizontal (95% confidence interval).

The accuracy can be adversely affected by the nature and density of vegetation, the presence of steeply varying terrain, the vicinity of buildings and/or the presence of water. The accuracy is typically closer to ± 0.15 m for clear terrain.

A number of datasets were available across the study area:

- 10 m VICmap Elevation data,
- 5 m DEM available across the entire study area derived from photogrammetry (Berrigan, January 2015),
- 2 m DEM available immediately downstream of Mulwala, (Dookie, February 2017),
- 1 m DEM available across the entire study area (Berrigan, April 2012, Wakool, September/October 2015) and over the area immediately downstream of Mulwala (Berrigan, November 2020 and Dookie, November 2020).

The dataset with the most complete coverage of the study area was Wakool 2015 1m data. This is the primary terrain dataset utilised for this study, supplemented by the other datasets where required, including through the northern overland flow model.

The Datasets captured later than 2019 were projected using the GDA2020 datum. For the purpose of consistency with existing GIS data, these DEMs were reprojected in GDA94.

3.2.1.1. LiDAR Verification

The Wakool 2015 LiDAR data was verified against reliable survey points from the NSW Survey Control Information Management System (SCIMS). This data is publicly available through NSW Spatial Information Exchange (SIX, https://six.nsw.gov.au/). SCIMS points were available in both Tocumwal and Barooga.

In NSW these points are typically located within the urban areas of the towns. The following filtering of points was applied in order to obtain a reliable dataset:

- Removal of points marked as “Destroyed”, “Uncertain” or “Not Found” for status
- Removal of points marked as “U” for Vt class (unknown/unreliable survey)
- If the difference between the point and the LiDAR dataset was greater than 1 m

This yielded a total of 77 and 75 reliable points, in Barooga and Tocumwal, respectively. A histogram of the difference in level between the 2015 LiDAR and these SCIMS points is shown in Diagram 1 and Diagram 2. In addition, a comparison is made to the 2012 LiDAR dataset at Tocumwal in Diagram 2.

The histograms show that the differences are primarily within +/-0.2 m, which is considered a reasonable match. There is a slight skew in the 2015 LiDAR, indicating a bias for the LiDAR data to be slightly lower than the survey marks. The average difference is less than -0.2 m. This demonstrates a high quality dataset that is considered reliable for the purposes of flood modelling.

The 2012 LiDAR is shown to be biased slightly higher than the survey marks, with an average variation slightly less than 0.1m.

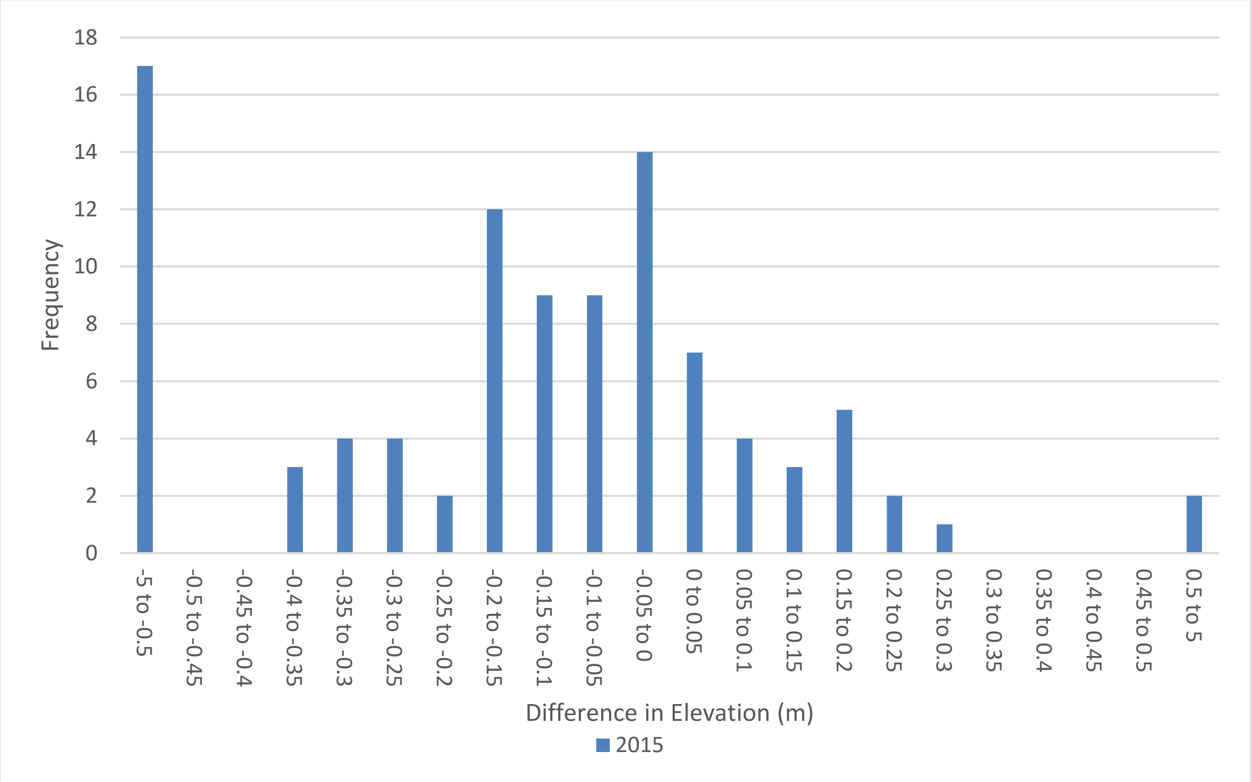


Diagram 1: Histogram of the difference between the 2015 LiDAR dataset and the SCIMS points – Barooga

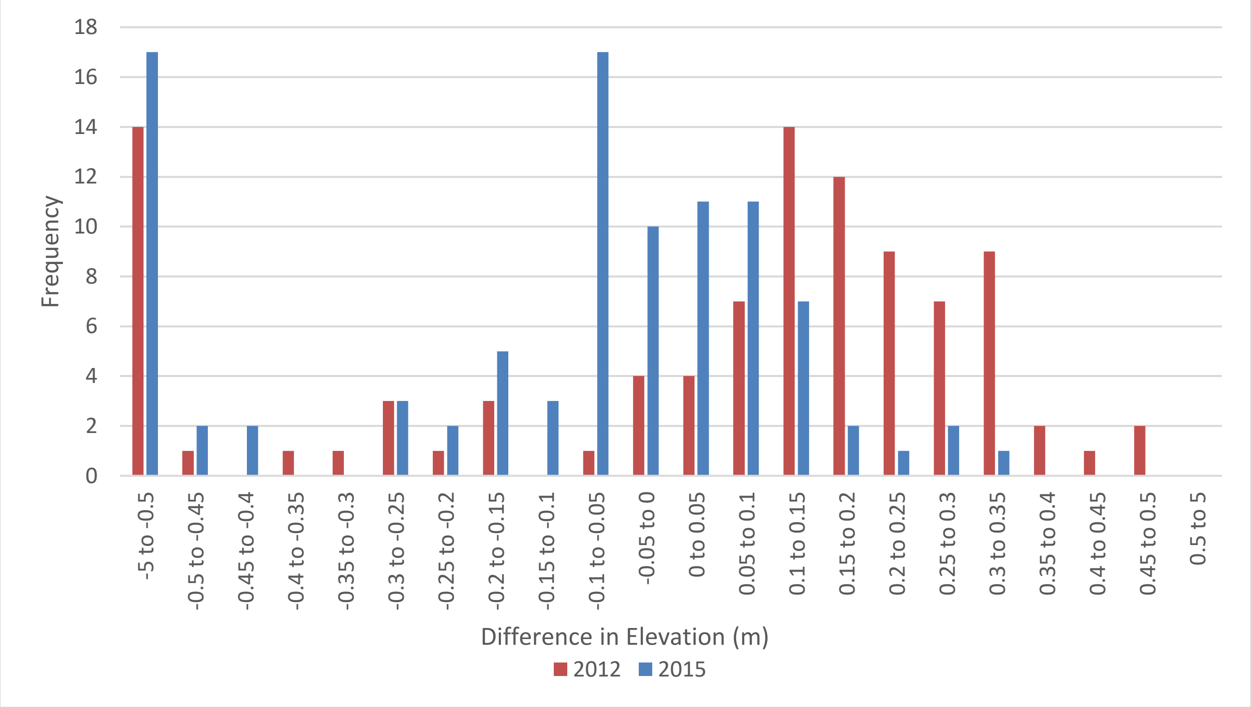


Diagram 2: Histogram of the difference between the 2012 and 2015 LiDAR dataset and the SCIMS points – Tocumwal

3.2.2. Bathymetric Survey

A range of bathymetric survey of the Murray River was provided by Council and the Department of Climate Change, Energy the Environment and Water, containing surveys for various reaches of the Murray River. The most suitable provided data was captured in approximately March 2021 by Hydro-Map through SA Water Hydrographic Unit and was high quality hydrographic survey using a boat mounted CeeScope sounder system with positioning recorded with a Novatel GPS. The data is reported to have a depth accuracy of +/- 3cm and a point density of approximately 800 points per 150m of waterway. The extent of data was from immediately downstream of Yarrawonga Weir to downstream of Moira Lake. The density of points in this dataset allows a digital elevation model (DEM) to be constructed. Initially a TIN was created with the survey points from which a DEM was derived. The survey points (red points), and TIN (green lines) is shown on Diagram 3.

Diagram 3: River bathymetric survey at Goulburn Valley Highway Bridge

3.3. Aerial Imagery

For the purposes of mapping and spatial data and modelling results interpretation, two sources of aerial imagery were utilised: Nearmap and SixMaps. Nearmap provides frequently updated (up to 6 times per year) and high-quality imagery (down to a resolution of approximately 5.8 – 7.5cm per pixel). SIXMaps imagery and data was provided by Berrigan Shire Council.

3.4. Buildings

A buildings layer was obtained from Microsoft that contains over 11 million buildings Australia-wide (https://github.com/microsoft/AustraliaBuildingFootprints). The data is derived from aerial and satellite imagery from 2013 to 2018 for Microsoft's Bing product and is freely available to download and use under the Open Data Commons Open Database License. The building extents are automatically delineated based on learning algorithms.

3.5. Stormwater Infrastructure

Council supplied WMAwater with GIS files of Council's pits and pipes. A summary of the number of pits and pipes within each town, as well as the percentage with useful data attached is shown in Table 7. There are approximately 1,300 pits across the study area, with 49% having elevation data in the form of an invert level or a depth to invert from the surface. There are also approximately 1,300 conduits (pipes and box culverts) in the database, with sizes attributed to all of them, although invert information is available for 48%.

Table 7: Summary of stormwater network data provided

Parameter	
Number of pits	1332
Pits with elevation data	49%
Number of conduits	1293
Conduits with size	100%
Conduits with elevation data	48%

3.6. Hydraulic Structures

Council supplied WMAwater with GIS files of available details for key hydraulic structures including road and kerb, levees, channels, bridges and culverts. Source or date information was not available for this information. Levels were checked against available LiDAR to ensure reasonableness. This information was supplemented with details collected as part of the Murray River Regional Flood Study (Water Technology Pty Ltd, 2011) (refer Section 3.1.4). Photography of some structures was also available.

Details were not available for the bridges at Vernon Street and the northern bridge of the Goulburn Valley Highway. Appropriate assumptions were made for these bridges in the hydraulic model build. These assumptions should be validated when survey information becomes available.

3.7. Levees

The system of levees along the Murray River is quite complex, thus, a variety of sources were used to derive the alignment and crest height of the system. The levee information south of the Murray River was provided by the Victorian Government (consisting of approximately 60 kilometres of levees) as part of the Rural Levee Assessment (Water Technology Pty Ltd, 2013). The levee information north of the river was provided by the Berrigan Shire Council, comprising of approximately 5.8 km of levees. The Rural Levee Assessment includes mark ups of the levee height. Additional surveys were conducted between 2017 and 2019 and provided by Berrigan Shire Council including information for 13.5 km of levee. The LIDAR provided the elevation for the remaining (approximately 4.6 km) levees along the river.

3.8. Floor Level Database

A key outcome of the current study is a flood damages assessment. To complete this aspect of the study, floor level estimates are required to undertake a broad assessment of flood affectation across the suite of design flood events. While the assessment uses floor level data for individual properties, the results are not an indicator of individual flood risk exposure but part of a regional assessment of flood risk exposure to give a feel for the magnitude of the flood problem. The outcomes can also assist in identifying areas which may potentially be inundated more frequently than other areas. For each property, the floor level estimation captured the following descriptors:

- Ground Level (in mAHD);
- An indication of house size (number of storeys);
- Location of the front entrance to the property; and
- Local Environmental Plans (LEP) land use (residential, commercial, industrial, primary production, or public recreation and infrastructure).

The floor level database includes all properties within the towns of Tocumwal and Barooga within the PMF (or equivalent extreme) event. WMAwater used LiDAR data and visual inspection (Google Streetview) to estimate floor levels for all properties within the database. In areas where the dwelling was not visible from Google Streetview, an average height above ground from the surrounding area was applied. This method of determining floor levels is appropriate particularly considering the other uncertainties present in the damages assessment procedure, such as the large variation in building types, their contents, the duration of flooding and other factors and its use as a comparative tool. A summary of the floor level estimates is provided in Table 8 below and properties with estimated floor levels are shown on Figure B35.

Table 8: Floor Level Database

Property Type	No. Included in Damages Assessment	
	Tocumwal	Barooga
Residential	**1,002**	**397**
Non-Residential	**101**	**25**
Total	**1,103**	**422**

3.9. Historic Flood Data

3.9.1. Stream Gauge

Stream gauges are available on the Murray River and its tributaries within and surrounding the study area. Stream gauges are operated by WaterNSW and the Victorian Department of Energy, Environment and Climate Action (DEECA). These gauges record the water level, at a range of intervals, and this information can be converted to flow values using height to flow rating curves. A summary of the available gauge data is provided in Table 9. Available gauges are shown on Figure B31.

Table 9: Summary of Stream Gauge Data Available

Gauge Number	Station Name	Agency	Date Range	Data Resolution	Data Available[1]
401027	Murray River at Hume Dam – Storage Gauge No. 2	WaterNSW	Aug 1969 – Mar 2013	Sub-daily[2]	WL, RF
			Mar 2013 – current	15 min	
409016	Murray River at Downstream Hume Dam (Heywoods)	WaterNSW	Jul 1969 – Aug 2011	Subdaily[2]	WL, Q
			Aug 2011 – current	15 min	
409017	Murray River @ Doctors Point	WaterNSW	Nov 1929 – May 1961	Daily	WL, Q
			May 1961 – Aug 2005	Subdaily[2]	
			Aug 2005 – current	15 min	
409001	Murray River at Albury (Union Bridge)	WaterNSW	Jan 1885 – Jul 1976	Daily	WL, Q[3]
			Jul 1976 – Dec 2011	Subdaily[2]	
			Dec 2011 – current	15 min	
409037	Murray River @ Howlong	WaterNSW	Feb 1967 – Dec 2011	Subdaily[2]	WL
			Dec 2011 – current	15 min	

Gauge Number	Station Name	Agency	Date Range	Data Resolution	Data Available[1]
409002	Murray River at Corowa	WaterNSW	July 1909 – Feb 1967	Daily	WL, Q
			Feb 1967 – current	Subdaily[2]	
			Jan 2012 - current	15 min	
409108	Murray River @ Mulwala OT	WaterNSW	No data available		
409216A	Murray River at U/S Yarrawonga Weir – Storage Gauge	WaterNSW	Nov 2010 – current	Daily	WL
409216	Murray River @ Yarrawonga Weir (Head Gauge)	DEECA	Jun 1992 – Dec 2009	Subdaily[2]	WL, RF
			Dec 2009 – current	15 min	
409025	Murray River Downstream Yarrawonga Weir	WaterNSW	Jan 1938 – Dec 1960	Monthly Max[3]	WL, Q
			Dec 1960 – Apr 2012	Subdaily[2]	
			Apr 2012 – current	15 min	
409202	Murray River at Tocumwal	DEECA	Jan 1908 – Dec 1974	Daily	WL,Q
			Dec 1974 – current	15 min	
402205	Kiewa River @ Bandiana	DEECA	Oct 1965 – Jan 2010	Subdaily[2]	WL, Q
			Jan 2010 – current	15 min	
403248	Indigo Creek @ D/S Creamery Bridge	DEECA	Jun 1999 – Jun 2017	Subdaily[2]	WL, Q
			Jun 2017 – current	15 min	
403246	Gullivers Creek @ Lilliput (Rutherglen Research Stn)	DEECA	Nov 1991 – Jan 1995	Subdaily[2]	WL, Q, RF
409600	Lake Moodemere @ Rutherglen	DEECA	Jul 2010 – current	135 field readings	WL
403247	Black Dog Creek Upstream of Dugays Bridge	DEECA	Aug 1998 – Jun 2017	Subdaily[2]	WL, Q

Gauge Number	Station Name	Agency	Date Range	Data Resolution	Data Available[1]
			Jun 2017 – current	15 min	
403241	Ovens River @ Peechelba	DEECA	Feb 1990 – Mar 2011	Subdaily[2]	WL, Q
			Mar 2011 – current	15 min	
409722	Yarrawonga Main Channel 5km U/S 409700	DEECA	Jul 2014 – current	15 min	WL, Q

1. WL = Water Level, Q = Flow, RF = Rainfall
2. Recording resolution varies, but is generally a reasonably high resolution
3. There is limited flow data at this gauge, only from 1908 to 1952, and currently only records water level
4. Only data from 1960 is available through the WaterNSW online portal. Monthly maximum discharge data was obtained from Pinneena 10.2.

3.9.1.1. Rating Curves

Rating curves define a relationship of height to flow at the gauge location. They are typically constructed by the gauge owner based on collected velocity measurements (gaugings) across different periods. Adjustments are made to the applied rating curve based on recently collected gaugings. This can occur, for example, if there is a change in the floodplain conditions, that causes a change in flood level resulting from a particular flow.

WMAwater, 2024 identified a significant shift in the rating curves at Doctors Point (#409017) and Corowa (#409002) between 1996 and 2016. The shift was most prominent at 100,000 ML/day, where a higher level occurs compared to 1996 conditions. WMAwater, 2024 in consultation with WaterNSW determined that the shift is a result of a change in method for gauging measurement, in addition to re-snagging of the Murray River and densification of floodplain vegetation. The historic rating curves at Tocumwal (#409202) were analysed to determine if a similar shift was evident (Diagram 5). Diagram 5 shows a similar shift and is confirmed by a gauging from 17th November 2022 at 7.345 m with a flow of 169,040 ML/day and another 8th October 2016 at 7.343 m with a flow of 174,548 ML/day. A gauging was collected during the 1993 event, delineated below as a triangle (Δ) at a level of 7.375 m with a flow of 191,771 ML/day, which indicates that by 1993 the height to flow relationship may have already shifted towards the current rating curve position.

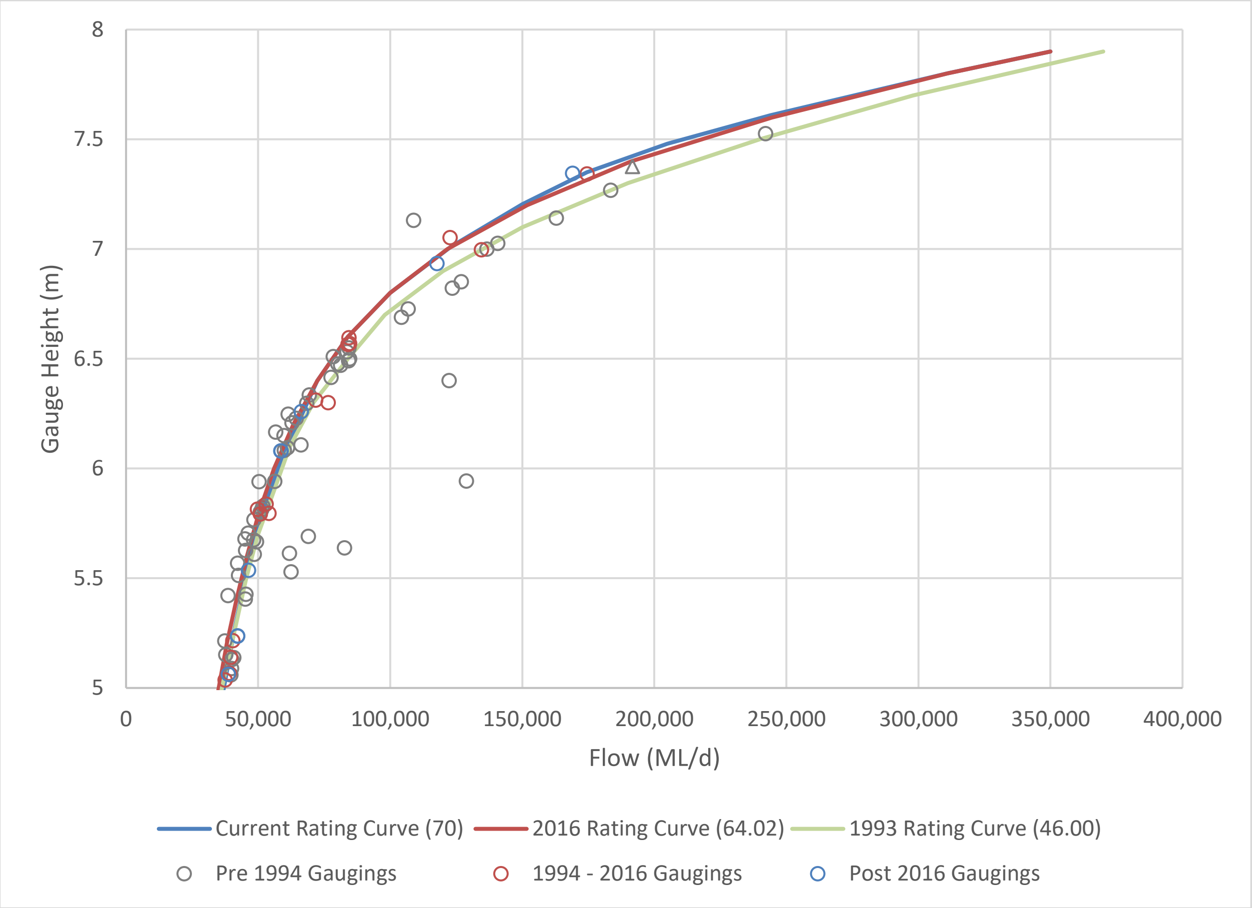


Diagram 4: Tocumwal Gauge Rating Curves and Gaugings

3.9.2. Rainfall Gauge

There are currently eight (8) rainfall gauges operating within and surrounding the study area. These gauges are operated by the Bureau of Meteorology (BoM). Recent, and currently operating gauges in close proximity to the study area are shown in Table 10.

Table 10: Rainfall Gauges

Station	Name	Operating Authority	Opened	Closed
074009	Berrigan Post Office	BOM	1875	2016
074042	Finley Post Office	BOM	1897	-
074081	Mulwala Post Office		1903	-
074088	Oaklands General Store	BOM	1925	-
074106	Tocumwal Airport	BOM	1897	2022
074208	Tuppal (Warragoon)	BOM	1950	-
074255	Berrigan (New Shiloh)	BOM	1994	2013

Station	Name	Operating Authority	Opened	Closed
080109	Cobram (Goulburn Murray)	BOM	1958	-
080065	Yarroweyah	BOM	1890	-
080101	Numurkah	BOM	1968	-
081124	Yarrawonga	BOM	1993	-
080129	Strathmerton	BOM	2003	2015

In addition to the official BoM rainfall stations, private rainfall data was also obtained. In particular, for the recent period to identify potential overland calibration events, this rainfall data is valuable to understand the nature of any localised storm events. This rainfall data was sourced from Weather Underground (www.wunderground.com). A summary of the rainfall stations available in this area is provided in Table 11. A tipping bucket rainfall gauge is also located at Murray River at Yarrawonga Weir (Head Gauge) (#409216), which provides a sub-daily representation of rainfall. The gauge commenced in June 1992.

Table 11: Summary of Private Rainfall Stations around Tocumwal and Barooga

Station Name	Location
IFINLE2	Fullers Road
INEWSOUT1270	Logie Brae Road
INEWSOUT1914	Newell Highway
IBAROO3	Putter Court
INSWTOCU6	Torgannah Road

3.9.3. Floodmarks

The Murray River has experienced many major floods, with the oldest on record in 1870. During some of these flood events, the local communities observed the extent of the floodwaters as well as the flood depth at various location across the floodplain. Local Councils and State Government agencies have kept extensive records of these floodmarks. The Victorian Government through the Victoria Flood Database (https://discover.data.vic.gov.au/dataset/victoria-flood-database) provides a series of recorded floodmarks and extents observed for various events across the southern floodplain of the Murray River, as seen in Table 12.

Table 12: Number of Floodmarks in the Victoria Flood Database

Flood events	Number of floodmarks	Flood events	Number of floodmarks
1906	4	**1975**	191
1909	38	**1978**	1
1917	42	**1981**	10
1956	52	**1993**	15
1970	48	**2016**	134
1974	75		

3.9.4. Flood Photography

During the 2016 flood event, the local community and Council collated images of flooding observed at various locations within the floodplain. Although these photos do not provide an accurate quantification of the flooding in terms of level or depth, they do provide an indication of the extent of flooding and give a sense of the flood behaviour during the flood event. Berrigan Shire Council provided a series of images (~ 40 images) taken during the 2016 event, with an example provided by Diagram 5 and the full set provided in Appendix I.

Diagram 5: Lower River Road - 17th October 2016

3.10. Site Visit

A site visit was conducted in January 2021 and was attended by WMAwater and Council staff. A tour to familiarise the study team with the entire study area was undertaken, including both Barooga and Tocumwal as well as the extensive Murray River levee systems and local overland drainage features.

4. COMMUNITY AND STAKEHOLDER CONSULTATION

One of the central objectives of the Flood Risk Management Process is to actively engage with the community and stakeholders throughout the process to achieve the following key outcomes:

- Inform the community and promote awareness of the study and its objectives and outcomes;
- Identify community concerns in regard to flooding;
- Gather information on flooding 'hotspots' (locations of particular flood risk) and information on past floods (flood marks, observed flood behaviour, photographs) for use in the calibration of flood models in the study area; and
- Seek feedback on study outcomes via Public Exhibition (towards completion of this Study).

"Community" refers to government (both state and local departments), business, industry, and the general public. Consultation with the community is an important element of the Flood Risk Management process facilitating community engagement, building confidence in flood modelling tools, and leading to acceptance and ownership of the overall project.

4.1. Flood Risk Management Committee

The process of managing flood risk in the study area is assisted by the Flood Risk Management Committee. The committee is made up of Councillors, Council Staff from a variety of areas across Council, NSW Government Agencies including DCCEEW and the NSW SES, and community representatives. The Flood Risk Management Committee assists Council by providing a forum for discussion of the differing viewpoints within the study area. In the Data Collection phase, the Committee assists by providing insight into historic flood events (including photos and anecdotes of observed flood behaviour), which, if appropriate, are used to shape the model calibration in the Flood Study phase.

4.2. Community Consultation

As part of the Data Collection stage, a range of community consultation activities were undertaken in the study area to inform the community and invite them to contribute their knowledge and experience. The consultation period ran from the 2nd December 2022 to the 13th January 2023, and comprised the following engagement methods:

- Newsletter and questionnaire, made available as hardcopies in the Council office and at drop in sessions;
- Online questionnaire (via SurveyMonkey); and
- Drop-in Sessions at Tocumwal and Barooga on the 6th December, 4pm – 6pm and 7th December, 10am – 12pm, respectively. These sessions provided a forum for discussion supported by large format mapping.

The consultation activities were advertised via Council's social media.

Approximately 8 people attended in Tocumwal and 2 in Barooga. Many attendees were interested in general information about the studies and specific comments related to:

- the impacts of overland flow,
- lack of street drainage,
- recent flood events and
- flood insurance.

A copy of the newsletter, questionnaire and a selection of promotional articles are provided in Appendix H.

4.2.1. Questionnaire Responses

A total of 11 responses were submitted online. Seven respondents were from Tocumwal, three did not provide a location and one was from a rural property outside the study area, close to Berrigan. Responses came from a mix of urban and rural properties, with more than 60% of respondents having lived and worked in the region for more than 5 years. The majority of responders (57%) had not been directly impacted by flooding at their property but indicated that access route limitations and secondary impacts such as increased insurance premiums had occurred. Of those that were directly impacted by flooding, impacts were to the front or backyard of the property or to the entrance access, rather than over floor flooding, however isolation within the property during an event was noted by one responder. All responders indicated that floodwaters took days to recede or had to be pumped out, from under the house, for example.

Within Tocumwal, a number of responders indicated that road inundation occurs following all rainfall events regardless of the storm size.

From an emergency management perspective, less than 50% of responders indicated that they are prepared for flooding by having an appropriate level of insurance, are aware of their evacuation route or have modified their property (such as house raising). A single respondent indicated that they had an emergency plan in place. Nearly all responders indicated that their preferred method of receiving flood warning information was via emergency SMS, however 40% of responders also indicated that they frequently lost mobile phone reception. Information on road closures, potentially impacted areas (including service suppliers) and comparisons to previous flood events was indicated to be the most important information to receive during flood events.

Approximately two thirds of respondents seek information related to flood risk from Council, rather than from other sources. Council was also indicated by responders to be the most trusted source of information during a flood event, above the NSW SES and other emergency services.

Capital works to improve stormwater capacity, followed by capital works to prevent river inundation and zoning and development controls were considered the most important strategies for managing flooding.

4.3. Public Exhibition

The Draft Tocumwal and Barooga Flood Study was endorsed for public exhibition at the Berrigan Shire Council meeting on the 4th December 2024. The Public Exhibition period extended from 5th December 2024 through to 20th January 2025, during this time the community was invited to provide feedback on the report and its outcomes.

An information page was established on Council's 'Have Your Say' website, providing an overview of the Study and the NSW Government Flood Risk Management Process. A copy of the report was available for download and an information video (approximately 15 minutes in length) was also available for viewing.

Drop-in information sessions were held in both, Tocumwal and Barooga, where residents could attend and discuss the project with Council staff in person. Sessions were held as follows:

- Barooga Library: Tuesday 7th January 2025 12:00pm – 1:30pm
- Tocumwal Library: Thursday 9th January 2025 8:30am – 9:30am
- Tocumwal Library: Wednesday 15th January 2025 12:00pm – 1:30pm

Submissions and feedback were accepted through an electronic form on the 'Have Your Say' website, as well as direct feedback during drop-in information sessions.

The drop-in sessions were well attended with over 20 attendees. The majority of attendees were to the Tocumwal sessions. The key themes of discussion are summarised below:

- Gaining an understanding of the different types of flood event mapping provided in the study, that is, flooding occurring from the Murray River (riverine) and that occurring from a localised rainfall storm (overland).
- Discussion around how the model can be used to understand the consequences of structural levee failure or collapse during a flood event. The current mapping assumes a worst case flood behaviour of levees in New South Wales remaining intact, while overtopping of the crest may occur and a scenario where the lowest sections of New South Wales levees structurally fail or collapse, once their design height is exceeded. The sensitivity of inundation extents has also been assessed. Further assessment of the consequences of levee failure will be undertaken in the future Flood Risk Management Study and Plan.
- Discussion about the various parties responsible for maintaining waterways.
- Recollection of experiences during the flood events that have been used to calibrate the hydraulic models.
- Discussion around the influence of current infrastructure on flood levels in the area covered by the hydraulic model. The hydraulic model can be used to understand these impacts and to test scenarios to improve these impacts. Improvement scenarios will be undertaken in the future Flood Risk Management Study and Plan.
- Localised stormwater issues.
- Climate change, further analysis of potential future climatic scenarios and their consequences would be undertaken in the future Flood Risk Management Study and Plan.
- Discussion of how Hume Dam levels influence flood behaviour.

In addition to feedback received at the drop-in sessions, the study received four (4) electronic submissions. Some submissions suggested locations where floodplain works do not appear to be functioning as intended, such as the Warina Drainage Basin, the pump at Amaroo Dam and the levee bank near Greens Lane. Another sought information on access across the river during flood events.

These submissions are regarding potential flood mitigation measures, including flood response measures, such as access. A Flood Risk Management Study and Plan is the next stage of the NSW Government Flood Risk Management Process. In this separate study, flood risk mitigation measures will be investigated, assessed and recommended.

The final submission was related to how this study may affect house insurance premiums. Flood Studies undertaken in accordance with the NSW Government’s Flood Risk Management Process are not created for or on behalf of insurance companies, they are intended to assist in the management of flood risk and impacts on people and property. Insurance companies may rely on their own risk assessment to identify flood risk.

The outcomes of the Public Exhibition have been considered in finalising the Tocumwal and Barooga Flood Study.

5. HYDROLOGIC MODEL SETUP

5.1. Overview

A hydrologic model is a tool for estimating the timing and amount of runoff that flows from a catchment for a given amount of rainfall. There are several hydrologic modelling techniques and software packages available as described in Australian Rainfall and Runoff (ARR) 2019 Version 4.1 (Ball, et al., 2019), such as Flood Frequency Analysis and rainfall-runoff routing. The terrain, mechanisms and data availability often guide the selected approach.

The study area experiences inundation from the Murray River and from local overland catchments, both these mechanisms require flow to be determined for input to the hydraulic model.

Stream gauges (which measure water level in a stream) are a way of directly measuring flow information but can be expensive to setup and maintain. They also require a long record length (several decades) to be of most use for design flow estimation in the form of a Flood Frequency Analysis. Most of the smaller creeks in NSW are not gauged, and the lack of defined waterways within the overland flow local catchment areas of Tocumwal or Barooga, make these areas unsuitable for streamflow gauges. Only the Murray River has streamflow data that is suitable for Flood Frequency Analysis, and this is documented in Section 8. In the case of local overland flow in Tocumwal and Barooga, using a computer-based hydrologic model is the best practice method for determining how much flow occurs from rainfall information (which is more widely available from rainfall gauges). This type of hydrologic model is referred to as a runoff-routing model.

A range of runoff-routing hydrologic models are available. These models allow the rainfall to vary in both space and time over the catchment and convert rainfall into the runoff generated by each sub-catchment. The generated flow hydrographs then serve as inputs at the boundaries of the hydraulic model, which allow for details about flood levels and velocities to be determined.

The Watershed Bounded Network Model (WBNM), runoff routing model was used to convert rainfall into runoff and determine flows from each sub-catchment. The WBNM model has a relatively simple but well supported method, where the routing behaviour of the catchment is primarily assumed to be correlated with the catchment area. Moreover, WBNM allows for spatial variation of rainfall and application of aerial reduction factor when modelling specific design and historic events. Where flow or other historical data is available, the WBNM model can be calibrated to this data through adjustment of various model parameters including the stream lag factor, storage lag factor, and/or rainfall losses.

A series of hydrological models were established for the area flowing to both Tocumwal and Barooga and used to calculate the flows for each individual sub-catchment for inclusion in the TUFLOW hydraulic model. The hydraulic model development is discussed in Section 6.

The hydrologic parameters adopted for this study were initially based on those recommended in ARR 2019 Version 4.1 and previous experience with modelling of similar catchments. Parameters were adjusted within reasonable limits as part of model calibration.

5.2. Sub-catchment Delineation

Typically, the size of the sub catchments can vary greatly in rural areas, with few hydraulic features to stop/obstruct the flow of water. Topographical variations are the primary delimitation of sub-catchment. However, roads, railways and gutter lines can also be used as a point of separation between sub-catchment regions. The sub-catchments were delineated using the best available LiDAR as well as a preliminary rainfall on grid hydraulic model. This ensured that areas contributing to overland flow paths within the town were delineated, rather than those areas draining directly to the Murray River were not.

The hydrological model covers a catchment area of 524 km^2 or 52,400 Ha. The area has been divided into 976 sub-catchments with an average size of 53 Ha, with the largest being 1825 Ha and the smallest, 0.3 Ha. Larger sub-catchments have been delineated in the broader catchment, while small sub-catchments are defined in the urbanized areas to capture the drainage catchments to the stormwater system. This relatively fine-resolution sub-catchment delineation ensures that where significant overland flow paths exist in the catchment, they are accounted for and incorporated into hydraulic routing in the model. The sub-catchment delineation is shown on Figure B2.

5.3. Hydrologic Model Parameters

WBNM uses a series of parameters to determine the amount of runoff generated by applied rainfalls.
These parameters include:

- The development conditions of the sub-catchment by an imperviousness percentage,
- The soil infiltration via an initial and continuous loss,
- A lag factor which influences the speed of conversion of rainfall into runoff,
- An impervious lag factor which does the same as above but for the developed part of the catchment if any,
- A stream flow routing factor which influences the speed of transfer of runoff from one sub-catchment to another.

WBNM requires a catchment lag parameter and a stream lag factor to be selected which describes the average travel time for runoff from the catchment surface. The lag parameter is applied to pervious surfaces and adjusted to apply to impervious surfaces by multiplication by an impervious lag factor. The WBNM parameters selected are summarised in Table 13.

Table 13: Adopted WBNM Parameters for Calibration and Design

WBNM Parameters	Value
Lag Parameter (C)	1.7
Stream Lag Factor (natural channels)	1.0
Impervious Lag Factor	0.1

The parameter values applied are generally consistent with the recommended values in the WBNM manual (Boyd, et al., 2012) for an ungauged catchment in NSW. There was not sufficient information (including calibration data) to warrant deviating from these values.

5.3.1. Impervious Surface Area

Runoff from impervious surfaces (such as roads, gutters, roofs or concrete surfaces) occurs significantly faster than from pervious surfaces. This disparity results in a faster concentration of flow within the urbanized area of the catchment as well as increased peak flow in some situations. This is accounted for in the hydrologic model through an estimate of the proportion of both impervious and pervious surfaces.

ARR 2019 Version 4.1 (Ball, et al., 2019) methodology recognises that there are significantly different infiltration regimes present across the varying urban surface types and therefore recommends applying varied losses to these different urban surface types in the catchment. These surface types are:

- Effective Impervious Areas – including areas directly connected to the drainage system, such as roads, pavements and some building roofs, and other portions of a catchment area which have a similar response to impervious areas,
- Indirectly Connected Areas – impervious areas which are not directly connected to the drainage system, areas that runoff over a pervious area before entering the drainage system such as roofs that discharge onto a lawn, both the roof and lawn are within this category,
- Pervious areas – such as parks.

'Effective Impervious Area' (EIA), is typically calculated as a percentage of the Total Impervious Area (TIA). Using the literature from Australian studies in ARR 2019 Version 4.1, the ratio of EIA/TIA is typically in the range from 60% to 80%. Given the reasonably large blocks of land and low-density development within the study area, a lower ratio of 60% has been adopted. For these areas the TIA was assumed to be 50% (i.e. 50% of the urban area is impervious). This yields an overall EIA of approximately 30% (60% x 50%). Commercial and industrial areas were assumed to have an EIA of approximately 70%, while road corridors were assumed to be 60% impervious. A summary of the adopted EIA percentages for each land use type is shown in Table 14. An overall EIA percentage was assigned to each sub-catchment based on the land use within the sub-catchment.

Table 14: Land use categories and percent impervious fraction for the WBNM model

Land Use	Effective Impervious Area Percentage (%)	Comment
Road corridor	60	Road corridor includes asphalt plus grassed verges
Industrial / commercial	70	Industrial and commercial properties
Rural residential / farmland / rail corridor	5	Nominal 5% EIA for buildings, sheds, etc.
Suburban residential	30	Larger blocks and low-density development.
Grass / open areas / vegetated areas	0	Applied to undeveloped areas.

The pervious and impervious areas of each sub-catchment was determined by estimating the proportion of the sub-catchment area covered by different surface types (from Google maps and aerial photography supplied by Council).

5.3.2. Rainfall Losses

Methods for modelling the proportion of rainfall that is “lost” to infiltration are outlined in ARR 2019 Version 4.1 (Ball, et al., 2019). The methods are of varying degrees of complexity, with the more complex options only suitable if sufficient data are available. The method most typically used for design flood estimation is to apply an initial and continuing loss to the rainfall. The initial loss represents the wetting of the catchment prior to runoff starting to occur and the continuing loss represents the ongoing infiltration of water into the saturated soils while rainfall continues.

Rainfall losses from a paved or impervious area are considered to consist of only an initial loss (an amount sufficient to wet the pavement and fill minor surface depressions), with the assumption that little to no ongoing infiltration occurs. Losses from grassed and vegetated areas are comprised of an initial loss and a continuing loss.

6. HYDRAULIC MODEL SETUP

6.1. Introduction

Hydraulic modelling of floods is the simulation of how floodwaters move across the terrain. A dynamic hydraulic model can estimate the flood levels, depths, velocities and extents across the floodplain. It also provides information about how the flooding changes over time. The hydraulic model can simulate floodwater both within the river or creek banks, and when it breaks out and flows overland, including flows through structures (such as bridges and culverts), over roads and around buildings.

Two-dimensional (2D) hydraulic modelling is currently the best practice standard for flood modelling. For the type of information required from a flood study, hydraulic models require high resolution information about the topography, which is available for this study from the LiDAR aerial survey. The TUFLOW package (BMT TUFLOW, 2023) was adopted as it meets requirements for best practice and is currently the most widely used model of this type in Australia for riverine flood modelling.

The TUFLOW modelling package includes a finite difference or finite volume numerical model for the solution of the depth averaged shallow water equations in two dimensions. The TUFLOW software has been widely used for a range of similar floodplain projects both internationally and within Australia and is capable of dynamically simulating complex overland flow regimes.

The TUFLOW model version used in this study was 2020-01-AB-iSP-w64 (using the finite volume Heavily Parallelised Computing (HPC) solver). TUFLOW (HPC) can use the Graphical Processing Unit hardware of a computer, which considerably speeds up the hydraulic model run time and allows for an increased model resolution as well as better output quality.

In TUFLOW, the ground topography is represented as a uniform grid with a ground elevation and Manning's 'n' roughness value assigned to each grid cell. The size of grid is determined as a balance between the model result definition required, catchment features and the computer processing time needed to run the simulations. The greater the definition (i.e. the smaller the grid size) the greater the processing time need to run the simulation.

6.2. TUFLOW Hydraulic Model Approach

For this project, four separate hydraulic models were developed –

- one for the Murray River,
- two localised overland flow models, one for each town, Tocumwal (west) and Barooga (east),
- a final model for the overland flow area between the towns (north).

Flooding due to the Murray River for both towns was simulated using the Murray River model. Local overland flooding was simulated in each of the local overland models. The TUFLOW model domains are shown in Figure B3.

6.3. Digital Elevation Model

The Digital Elevation Model (DEM) is a representation of the ground topography. DEMs are created using various sources (LiDAR, photogrammetry, ground survey or hydrographic survey).

The 2D terrain for each of the TUFLOW models was primarily based on the available LiDAR data (Section 3.2.1). The Murray River model relies on the 1 m 2015 LiDAR Wakool data set. The overland flow models, also primarily use the Wakool data set, which was also supplemented as a secondary priority, with the 5 m 2015 Berrigan photogrammetry data set through the northern areas of the model domain, upstream of the Mulwala canal.

The in-bank bathymetry of the Murray River is not represented in the LiDAR data, and as such the available bathymetry data (Section 3.2.2) was used to supplement the LiDAR based DEM for the Murray River bathymetry. The river bathymetry took priority over the LiDAR data. A review of the edges showed good integration of the datasets, and minimal manual editing was required.

Diagram 6 compares the captured LIDAR elevation with the bathymetric survey at Goulburn Valley Highway Bridge. The LIDAR does not capture the channel below the water level, the bathymetric survey supplements this information into the DEM.

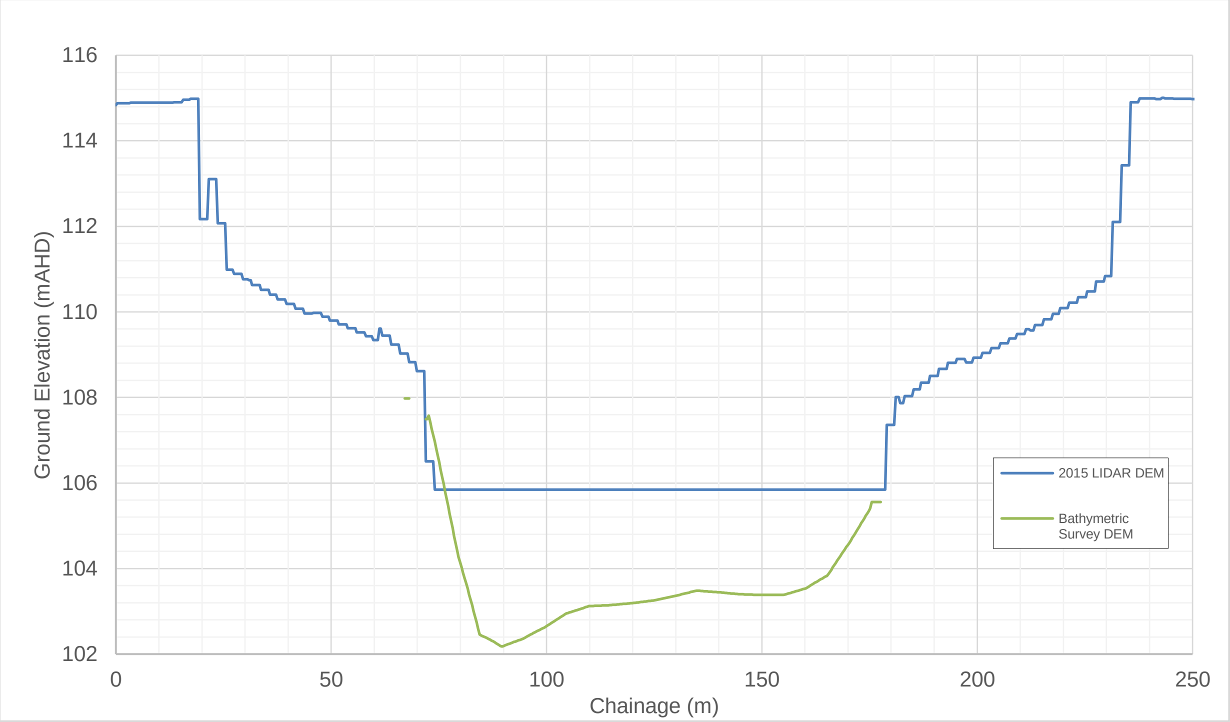


Diagram 6: River Cross Section At Goulburn Valley Highway Bridge

The TUFLOW model DEMs are shown on Figure B4 to Figure B9.

The LiDAR was found to be generally representative of existing conditions and larger creek lines within the study area. Breaklines were used to ensure that the model correctly represents smaller features, such as levees, embankments, smaller drainage lines and channel. These modifications are discussed in the following sections and also shown in the figures listed above.

6.4. Murray River TUFLOW Model Overview

The Murray River (riverine) TUFLOW model 2D domain covers the Murray River floodplain from downstream of Yarrawonga Weir to approximately 23 km downstream of Tocumwal (Figure B17). The boundary is located far enough from Tocumwal and Ulupna Island to avoid any influence of the boundary conditions on the flood levels and behaviour in the key areas of interest. The model covers an area of approximately 570 km^2 with a model grid resolution of 20 m, this resolution provides an appropriate balance between providing suitable representation of the river conveyance and floodplain interactions and workable computational run-times.

6.5. Overland Flow TUFLOW Models Overview

Three local overland flow TUFLOW models were established to cover the overland flow through and between the urban areas of Tocumwal and Barooga. A preliminary rainfall on grid hydraulic model identified Dry Creek (6km north-east of Barooga), and the Lalalty channel (3.5km north of Tocumwal), as the two main conveyors of overland flow in a local storm event. The three domains cover the following areas:

- North model – south of Berrigan to 4 kilometres downstream the Mulwala canal,
- East model – from the Mulwala-Barooga Road in Boomanoomana to the Berrigan Road,
- West model – from Dry Creek at the Coldwell Road and the Mulwala canal to the Murray River and Racecourse Road/Tocumwal N 6 channel to the west.

Where the model domains overlap the results from the West model take precedence. A model grid resolution of 3 m was used.

6.6. TUFLOW Model Extent and Resolution Summary

Table 15: TUFLOW Model Summary

TUFLOW Model	Areas Covered	Grid Resolution
Riverine	Murray River from downstream Yarrawonga Weir to 23km downstream of Tocumwal	20m
North	Overland flow, south of Berrigan to 4 kilometres downstream the Mulwala canal	3m
East	Overland flow from the Mulwala-Barooga Road in Boomanoomana to the Berrigan Road	3m
West	Overland flow from Dry Creek at the Coldwell Road and the Mulwala canal to the Murray River and Racecourse Road/Tocumwal N 6 channel to the west.	3m

6.7. Hydraulic Roughness

The hydraulic efficiency of the flow paths within the TUFLOW model is represented (in part) by the hydraulic roughness or friction factor formulated as Manning's 'n' coefficients. This factor describes the net influence of bed roughness and incorporates the effects of vegetation and other features (channel sinuosity, bedform and shape) which may affect the hydraulic performance of the particular flow path.

The Manning's 'n' values have been defined across the study area based upon the land use, which was visually inspected using the available aerial imagery, industry guidance (Babister, et al., 2012) and past experience in similar floodplain environments. The cadastre and Local Environmental Plan (LEP) zoning was also used as a guide. Each land use category was assigned a Mannings 'n' value, as outlined in Table 16. The spatial distribution of these categories is shown on Figure B10 to Figure B12 for the Murray River, and on Figure B13 to Figure B15 for the local overland flow models.

Table 16: Mannings coeffient for the hydraulic model

Soil type	Manning's 'n' Coefficient
Murray River and major anabranches	0.035
Overbank/Riparian corridor	0.075
Pasture	0.045
Lots	0.06
Roads	0.02
Park/Golf Course	0.04

These values are within typical values and were adjusted during the calibration stage.

6.8. Hydraulic Structures

6.8.1. Levees and Channels

There are a number of levees, roads, embankments and channels throughout the model domains that were included as breaklines. These breaklines ensure that the crest (overtopping level) or invert level of the embankment or channel is accurately represented in the TUFLOW model where:

- these form an obstruction to flow,
- where flow paths cross over the embankment or
- where conveyance is crucial to the movement of a flood.

Embankments and channels were located on both the northern and southern floodplains and were derived from a range of sources including Council survey, previous reports and 1m LIDAR. Validation of dimensions, particularly for levees was undertaken by comparing available data sources. In some locations where there are large culverts or bridge structures, the LiDAR typically shows an interpolated ground surface under the road. Depending on the way each structure is modelled, these can require modification to represent the road correctly in the 2D domain (where the structure is modelled in 1D), or to represent the opening correctly (where the structure is modelled in 2D). A total of 84 km of levees, embankments and channels were included in the TUFLOW models. Included levees and channels are shown on Figure B16 to Figure B23.

6.8.2. Bridges

The key model parameters for modelling of hydraulic structures such as culverts and bridges are the assumed energy losses at the structure (from turbulence, expansion/contraction of flow etc.) and blockage of the structure waterway area by the structure and debris.

Schematisation of structures depended on whether they were represented in the 1D or 2D domain. Culverts were generally modelled as 1D features embedded in the 2D model, since the majority of culverts have dimensions smaller than the grid resolution. Bridge modelling was generally undertaken in the 2D domain using a 2D layered flow constriction shape. The bridges, including bridges along parts of the highway and railway, have been surveyed as part of (Water Technology Pty Ltd, 2011). Survey details include deck levels along the bridge (top and underside), surrounding ground levels and pier details. These details, in conjunction with current best practice guidance, were used to determine energy losses at the structures for input into the TUFLOW model. Diagram 7 is an example of a bridge on the Murray River floodplain in the study area.

Diagram 7: Bridge located over a small waterway 1.8km to the south of the Murray River (Goulburn Valley Highway – Bridge 3 (Victoria))

Details were not available for the Murray River bridges at Barooga-Cobram Road, Goulburn Valley Highway and the railway bridge at Tocumwal; engineering judgment, using available data for other bridges was utilised to determine the energy loss and geometry parameters. This included using LiDAR levels to determine the top of the deck and assumed deck thickness of 0.5m.

For culverts, losses were adjusted based on whether they are connected to the 1D or 2D domain, up to a maximum entrance loss of K=0.5 and a maximum exit loss of K=1.0. Bridge details are provided below in Table 17.

Table 17: Parameter Values for Hydraulic Losses at Structures

Structure	Loss Parameter K (as a factor of dynamic head $V^2/2g$)	Blockage[(1)]
Bridge (below deck obvert)	0.05 – 0.37 (depending on pier size)	0%
Bridge deck	1.56	100%
Bridge handrails (where present)	0.0 - 0.05	0% - 10%

Note (1): This blockage is due to the estimated ratio of waterway area that is obstructed by the piers at each structure, and not an allowance for potential debris blockage at these locations.

6.8.3. Pit and Pipe Network

The pits and pipes network details were available for the towns of Barooga and Tocumwal. Pit and pipe systems assist in drainage during smaller rainfall events. However, are inadequate to accommodate major flood events.

The stormwater drainage network was modelled in TUFLOW as a 1D network dynamically linked to the 2D overland flow domain. The pits enable the transfer of flows from the 2D domain to the 1D pipes below the ground. The pipes carry flows to the outlet where it discharges to the 2D domain or has a boundary condition, with many pipes connected to the river with floodgates, which prevent backflow in elevated river conditions. This stormwater network includes conduits such as concrete lined channels, pipes and box culverts, and stormwater pits, including inlet pits and junction manholes.

The schematisation of the stormwater network was undertaken using the pit and pipe GIS layers supplied by Council which was supplemented with assumed data from WMAwater. Pipe inverts were adjusted where there was a conflict with joined systems, or to achieve a negative grade. LiDAR, available pipe diameters and 0.15m cover were assumed when adjustments were made. Figure B24 to Figure B28 show the location of major drainage features and hydraulic structures included as 1D or 2D elements in the TUFLOW model.

Culverts with a size of 300 mm width/diameter and greater were included in the local overland flow TUFLOW models as 1D elements. Information on road crossing structures was not available across the overland flow model domain and therefore 1.2m diameter culverts were assumed at road crossings.

A summary of the pit and pipe network included in each local TUFLOW model is presented in Table 18.

Table 18: Summary of stormwater elements in the local overland flow TUFLOW models

Network Element	
No. Pits (inlets, junctions and outlets)	954
No. Pipes	1,177

6.8.4. Roads, Kerb, and Gutter

During a flood event, roads often act as an obstruction to flowpath as they are typically raised above the floodplain. Those roads can stop and redirect floodwater in the same way as informal levees. The locations of the road centrelines were added to the riverine and overland flood models. Centrelines derived from the 1m LiDAR effectively enforced the crest of the roads in the model DEM to ensure that these potential obstructions are appropriately represented.

In the overland flood models, kerbs and gutters are the main conveyor of floodwater specifically in the towns of Tocumwal and Barooga. Kerbs and gutters channelise the water toward the downstream ends of the towns. The overland model grid size is too coarse to accurately model those features. A set of break lines was added to the model where kerb and gutters exist, based on a review of aerial images and Google Streetview, this enforced the kerb and gutter location by lowering the DEM by 100mm.

6.8.5. Building Representation

The buildings are a major obstruction in the floodplain to overland flowpaths. They can lead to localised increased flood levels, blocked flowpath and create hazard as flow moves around the building.

Buildings and other significant features likely to obstruct flow were incorporated into the model. Buildings were based on building footprints defined from Microsoft’s building layer (Section 3.4). These types of features were modelled as impermeable obstructions to flow and thus were assumed to have no flood storage capacity. While this is not necessarily realistic (as flow can enter buildings), it is an appropriate method that simulates the obstruction that buildings can impose on floodwaters and the resulting flow distribution around buildings.

Building delineation was validated in key overland flow areas using Google Street View photographs and aerial photography supplied by Council. The building polygons were slightly reduced when the distance between two buildings was lower than the adopted cell size (3m) to retain flowpaths between adjacent buildings.

6.9. Boundary Conditions

6.9.1. Inflows

The inflow boundary defines how much floodwater enters the model domain. The Murray River TUFLOW model uses recorded flows for the calibration events and the results from the FFA at Yarrawonga combined with the outcomes from WMAwater, 2023 as an inflow.

For sub-catchments within the local overland flow TUFLOW model domains, local runoff hydrographs were extracted from the WBNM model (see Section 5) for both calibration and design. These were applied at the concentration point of each sub-catchment (downstream end) within the 2D domain of the hydraulic model. These inflow locations typically correspond with gutters, stormwater inlet pits, drainage reserves or open watercourses features which have typically been constructed to receive intra-lot drainage and sheet runoff flows from local upstream catchment areas.

Inflow locations are shown on Figure B24 to Figure B28.

6.9.2. Downstream Boundaries

The downstream boundary defines how much water can leave the model domain. A HQ (height flow) boundary was utilised for the Murray River at the downstream end of the TUFLOW model. The boundary allows flow to exit the model at a constant rate. This boundary is located a substantial distance from the study area boundary to ensure it does not influence the results.

A HQ (height flow) boundary is applied along the southern floodplain. The outflow from this boundary is dependent on water level and topography, which is converted to flow using a rating curve in which the topographic gradient is assumed to equal the water level gradient (i.e. uniform flow). This boundary type allows water to flow out of the model at a proportional rate compared to water levels. The adopted slope (gradient) value for this HQ boundary was 0.01.

The overland model uses a constant water level in the Murray River equivalent to a non flood condition. It was assumed that levee pipes were blocked, essentially assuming no flow could leave the overland system. This allows the dissociation of the riverine and overland mechanism in this study. For each of the local overland flow models, stage-discharge boundaries were applied at all locations where water could exit the model domain. These are primarily where water can flow to the north and west. This is typically in the order of 0.001 for overland flows to the north and west.

The locations of the boundary conditions are shown on Figure B16

6.9.3. Initial Water Levels

Initial water levels define the water present at the start of the model simulation and often represent the average water level outside of a period of flooding.

The riverine model was used with a series of steady inflows ranging between 50 and 300 m^3/s. The stabilised water level grid was then extracted and used in the calibration and design events. The calibration model uses the initial water level grid that provides the closest water level recorded at the Tocumwal gauge at the beginning of the flood event. The design events use the highest of the calibration initial water level grids.

An initial water level to the road level is assumed within Dry Creek, east of Barooga in the overland flow models.

7. MODEL CALIBRATION

7.1. Objective

The aim of the calibration process is to ensure the modelling system can replicate historical flood behaviour. There are assumptions in the modelling inputs, such as the effect of vegetation on flow and the amount of infiltration into the soil, which can be adjusted to improve the match between observed and modelled flood levels. A good match to historical flood behaviour provides confidence that the modelling methodology and schematisation can accurately represent the important flood processes in the catchment. If the modelling system can replicate flood behaviour which has occurred in the past (historical flood) then it can be more confidently used to estimate flood behaviour that will occur in the future by the estimation of design flood events. Design flood behaviour can go on to be used for planning purposes, assessment of flood mitigation options, infrastructure design and emergency management.

A number of factors can prevent a comprehensive calibration of both the hydrologic and hydraulic models, these include, limited stream gauge data, limited rainfall records and particularly pluviometer records, and unknown catchment changes. Comprehensive information that provides a perfect representation of these factors is often not available and industry best practice provides guidance on how to proceed in these circumstances; this approach has been applied to this study.

The choice of calibration events for flood modelling depends on a combination of the severity of the flood event and the quality of the data available. Ideally, data is available from streamflow and rainfall gauges in addition to records of flood marks or inundation extent. There are two streamflow gauges in the study area, Murray River Downstream Yarrawonga Weir (#409025) and Murray River at Tocumwal (#409202). The gauge at Yarrawonga is used to inform the TUFLOW model inflow, while the gauge at Tocumwal provides a point of comparison in the calibration process.

There are two different flood mechanisms that affect the study area. Flooding from the Murray River is simulated in the Murray River model while overland inundation is simulated in the local overland flow models. Due to the availability of stream gauge data, there is more information available regarding large flood events for the Murray River than for the local overland events. These events are discussed below.

7.1. Murray River Flood Events

Three Murray River flood events were selected to be modelled as part of this flood study. These events are summarised in Table 19. All of the events selected were within the top 10 events at all of the relevant gauges. Consideration was given to the November 2022 event, which occurred during the study however given its size is similar (slightly smaller) to the October 2016 and there is less available data for the more recent event within the study area, the October 2016 provided greater information for model calibration. In addition, the October 2016 event has been assessed as part of studies in surrounding areas.

Table 19: Summary of Murray River Flood Events Modelled

Event	Doctors Point (409017)		Yarrawonga (409025)		Tocumwal (409202)	
	Peak Flow[1] (ML/d)	Rank[2]	Peak Flow[1] (ML/d)	Rank[2]	Peak Flow[1] (ML/d)	Rank[2]
Oct 1975	200,600	1	242,600	1	224,400	1
Oct 1993	76,400	23[3]	213,300	2	196,300[4]	2
Oct 2016	99,900	7	182,800	7	180,200	5

1. Peak flow in megalitres per day, to the nearest 100
2. Event/year rank based on post Hume Dam gauge data
3. October 1993 was an Oven River dominated event, its rank in the Ovens River record is number #1
4. There are a number of variations in this value (176,000 ML/day through to 202,000 ML/day) across the range of available sources. The value has been adopted from the WaterNSW record downloaded in 2021.

The October 1993 event differs from October 1975 and October 2016, in that the primary flow contribution was from the Ovens River, rather than the Murray River and Hume Dam. For the record at Doctors Point (#409017) the October 1993 event was ranked 23rd, while for the Ovens River at Peechelba (#403241), the 1993 event is ranked 1st. This impacts on the flood hydrograph approaching the study area, most notably the 1993 event is a much shorter event with a steep sharp rise and fall. The 1993 event was above 100,000 ML/day for just 5 days compared to 10 days for both 1975 and 2016.

7.2. Local Overland Flood Events

Limited local rainfall events were identified through the data collection phase and community consultation, while specific dates were not mentioned, community responses indicated issues with local overland flooding. In order to identify a suitable local storm event for calibration of the local overland flow models a review of the available data at the Tocumwal Airport rainfall gauge (#74106) was undertaken (Table 20).

Table 20: Highest Daily Rainfalls – Tocumwal Airport (#74106)

Month/Year	Total Rainfall (mm)	Month/Year	Total Rainfall (mm)	Month/Year	Total Rainfall (mm)
Mar 1950	122.7	**Jan 1974**	64.6	**Jan 1956**	57.2
May 1918	98.3	**Dec 1948**	64	**May 1974**	57
Feb 1955	95.3	**Jun 1913**	62.2	**Feb 1946**	55.6
Mar 2012	84.6	**Oct 1974**	62.2	**Feb 2011**	55
Jan 1954	76.7	**Jan 1941**	59.9	**Mar 1973**	54.6
Oct 1963	73.7	**Feb 2012**	59.7	**Mar 2020**	54.4
Apr 1970	73.2	**Dec 2017**	58.6		
Nov 1912	70.1	**Sep 1916**	57.9		

The majority of rainfall gauges are daily rainfall gauges. The first gauge recording sub-daily rainfall (0.2mm tipping bucket reported at 2 hourly increments) information, was installed in 1992 at Yarrawonga. The typical storm duration for a flood producing event within overland flow catchments is less than a 24 hour duration and is more likely between 3 – 9 hours, making sub daily data crucial to calibration of the modelling tools. As shown in Table 20 significant rainfall events have occurred 1950, 1918, 1955 and 2012.

A small number of daily rainfall records are available for these earlier events but there is no detailed sub-daily information to inform the rainfall temporal pattern (how rainfall falls over time) and duration.

Rainfall sourced from Weather Underground (Section 3.9.1.1) can provide sub-daily information if gauges were operating during storm events. This data source is relatively recent and therefore a review identified that the only available event is March 2020. Five local gauges captured this storm event. While there is little specific information known about the impacts of this local storm event, comparison can be made to the general comments from the community consultation.

Figure B29 shows a cumulative rainfall plot of the available data. Over the 24 hour period between 7:55am 4th March 2020 and 7:55am 5th March 2020, the Weather Underground gauges recorded between 50.04mm and 77.73mm, with two burst occurring between 8am and 1pm (4th March 2020) and 11pm (4th March) and 8am, the following day. Figure B31 shows the rainfall depth grid constructed from the available rainfall information, indicating that the March 2020 event was localised over the study area with lower rainfalls occurring to the east near Mulwala. For shorter durations (< 6 hours) four of the five gauges recorded the equivalent AEP of less than a 0.5 EY, which is considered to be fairly frequent. The INSWTOCU6 gauge recorded slightly less frequent (0.2 EY) rainfall for the same period. For the long durations, approaching 24 hours the equivalent AEP was between 0.2 EY and a 10% AEP, again the INSWTOCU6 gauge recorded the slightly less frequent rainfall. The gauge burst intensities are shown on Figure B30 in comparison to the intensity-frequency-duration (IFD) design rainfall data for Tocumwal.

As all the temporal distributions display a very similar pattern, the INSWTOCU6 gauge provided the temporal distribution of rainfall across the event.

7.3. Methodology

7.3.1. Murray River Model Calibration

The Murray River TUFLOW model calibration was undertaken for three large historic events. Recorded flows were applied at the Murray River upstream boundary based on recorded data at Murray River Downstream Yarrawonga Weir (#409025).

The modelled flood results were then compared to the observed data. This primarily consisted of the stream gauge at Murray River at Tocumwal (#409202), although this was supplemented with additional flood data available for each event. The model parameters were adjusted until a reasonable fit was obtained to the observed data. This primarily consisted of altering the Mannings ‘n’ values. It is noted that the model was not altered for historic conditions as there is no reliable information available to reproduce historic conditions.

7.3.2. Local Overland Flow Model Calibration

The approach to calibration for the local overland flow models was a joint calibration process of both the WBNM hydrologic models and TUFLOW hydraulic models. Rainfall loss parameters in the WBNM model and the Mannings 'n' roughness values in TUFLOW were adjusted until a reasonable match to the anecdotal remarks was achieved.

7.4. Murray River

7.4.1. 1975 Event

The Murray River 1975 flood event is the highest flood on recent records, reaching 7.44m at the Tocumwal gauge (#409202). The anecdotal reports indicate that three levees collapsed during the event: Brentnall's (Seppelts), Cleaves and Dixons Bend. (Water Technology Pty Ltd, 2011) estimated the event as being a 5.88% AEP event.

The event was simulated using the recorded flows at Murray River Downstream Yarrawonga Weir (#409025) for the period 1st August 1975 to 17th November 1975. The flood peak occurred on the 31st October at the Tocumwal gauge.

The inflow hydrographs are shown in Diagram 8.

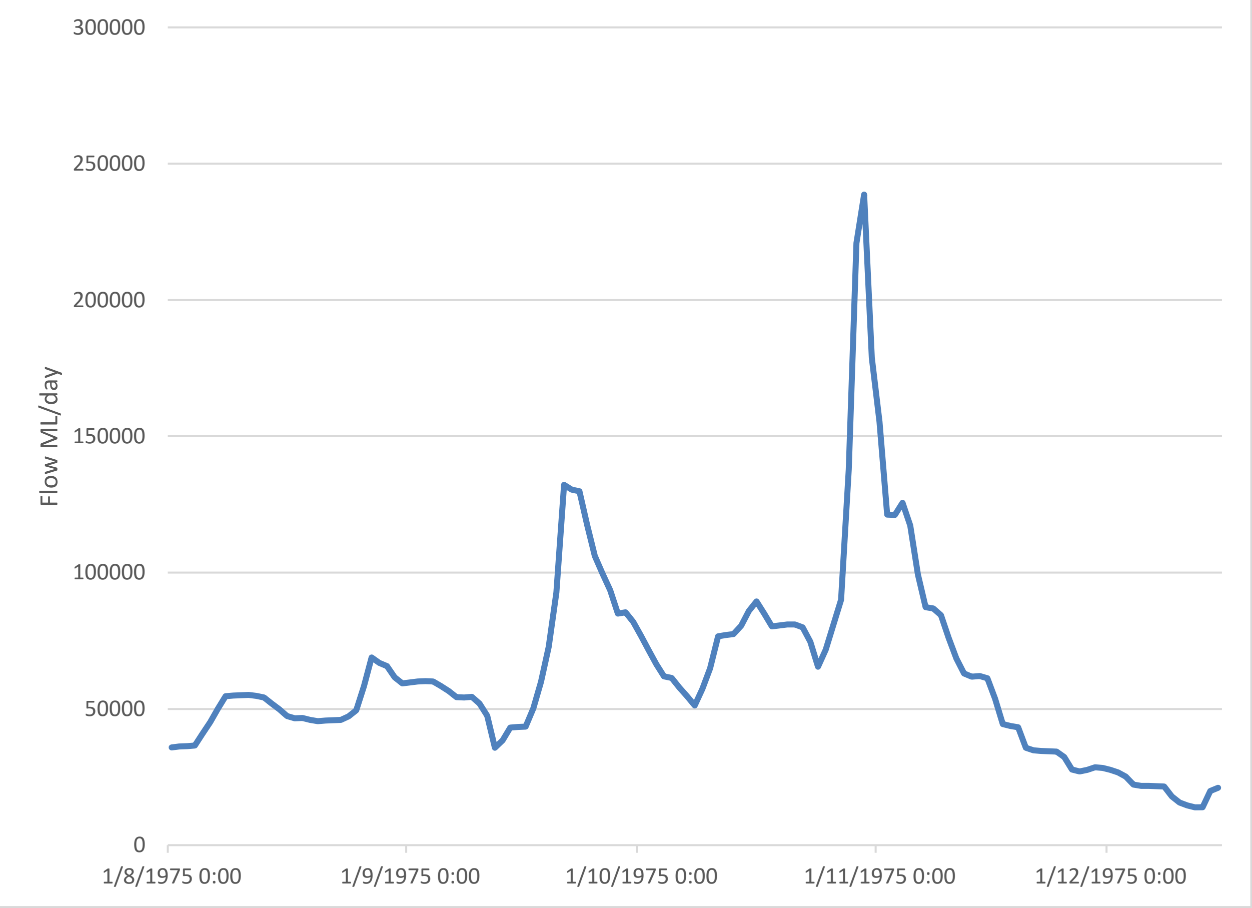


Diagram 8: Inflow hydrographs for the 1975 flood event

The results of the TUFLOW model calibration to the gauge data is shown on Figure C22 and Figure C23. The model reproduces the shape and general timing of the event well. The model is slightly delayed compared to the record, but overall reproduces the event well. Recorded peak flood levels are reproduced by the model to within 0.15m.

The modelled peak flow is very close to the recorded flow at the gauge (within 1.8%). The modelled hydrograph matches the shape of the main hydrograph peak and falling limb well, with a slight delay. The model tends to overestimate the peak flow and volume of the earlier smaller peak at around 125,000 ML/day.

A summary of the calibration to peak gauge levels and flows is shown in Table 21.

Table 21: Comparison of peak levels and flows at the gauges for the Murray River 1975 event

Gauge	Variable	Gauge	Modelled	Difference (% for flow)
Tocumwal	Water Level (m)	7.44	7.62	0.18
	Flow (ML/d)	224,400	220,400	-4,000 (-1.8%)

Note: Levels rounded to the nearest centimetre and flows rounded to the nearest 100 ML/d

Flood marks for the 1975 event were available from the Victorian Flood Database, these have been compared with the flood model results. A visual comparison of the modelled 1975 flood depth and the Victorian Flood Database flood marks is provided on Figure C1 to Figure C8. Of the 184 flood marks, 89% are within +/-0.2m, with an overall average variance of -0.03m. The absolute range is -0.38m to 1.08m. The flood mark with a variance of 1.08m is surrounded by at least six flood marks with a variance of less than 0.1m. Given that the 1.08m variance flood mark is derived from the same source and its proximity to much better matched levels, it suggests it is likely a reporting error from the original flood mark source. The -0.38m variance flood mark on the other hand is adjacent to another floodmark with a variance of -0.34m, located downstream of Ulupna Island. This is more likely to be a result of the model not likely reproducing the flow distribution between the various channels in this region near to the downstream boundary. This could be improved in the future with additional survey data on the southern (Victorian) floodplain.

7.4.2. 1993 Event

The Murray River 1993 flood event is the 7th highest flood in recent records, reaching 7.33m at the Tocumwal gauge (#409202). The anecdotal reports indicate that the flood event remained within the levees with no overflows occurring. (Water Technology Pty Ltd, 2011) estimated the event as being a 11.11% AEP event.

The event was simulated using the recorded flows at Murray River Downstream Yarrawonga Weir (#409025) for the period 9th July 1993 to 29th October 1993. The flood peak occurred on the 8th October at the Tocumwal gauge.

The inflow hydrographs are shown in Diagram 9.

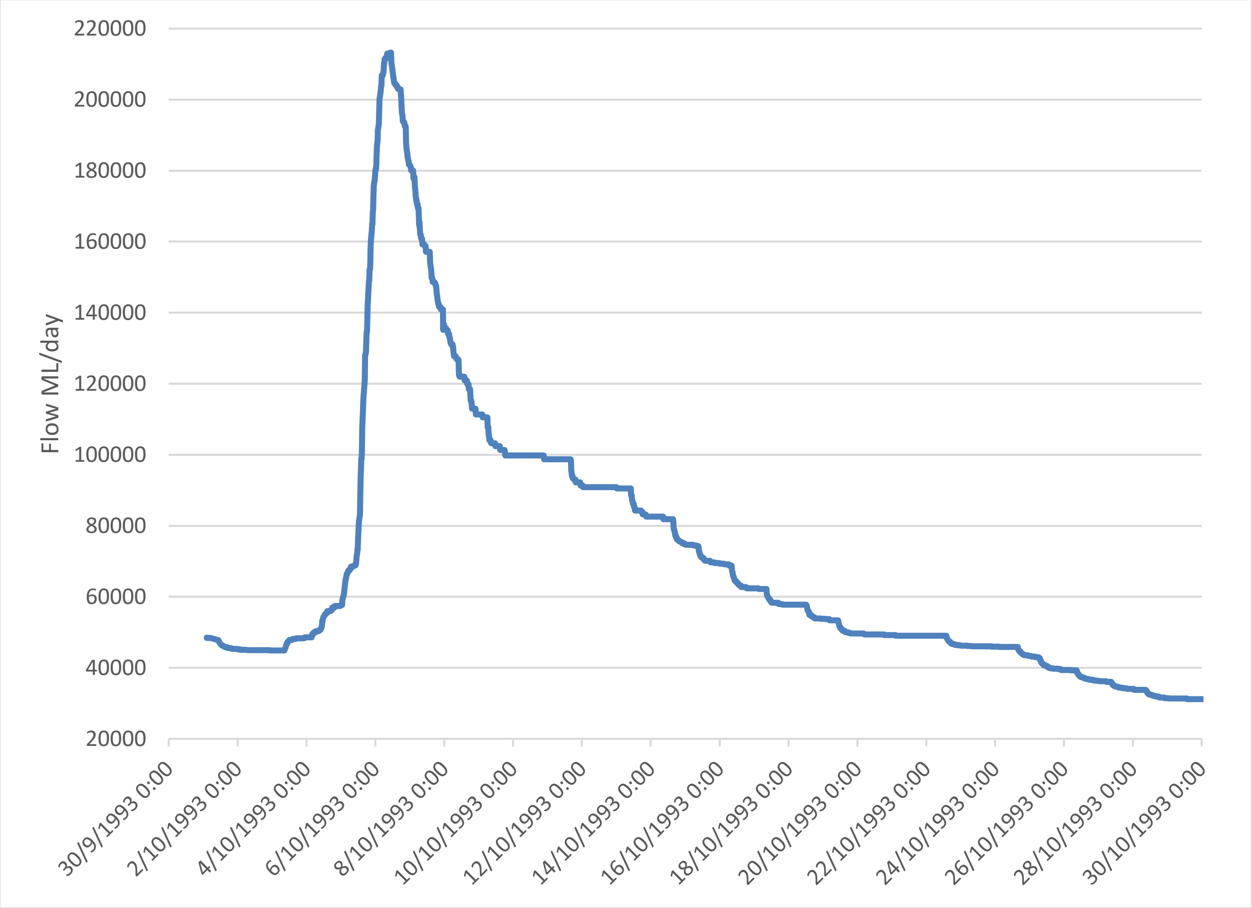


Diagram 9: Inflow hydrographs for the 1993 flood event

The results of the TUFLOW model calibration to the gauge data is shown on Figure C24 and Figure C25. The model reproduces the shape and timing of the event well. Recorded peak flood levels are reproduced by the model within -0.05m.

The modelled peak flow is reasonably close to the recorded flow at the gauge (within 6.8%). The modelled hydrograph matches the shape of the main hydrograph peak and falling limb well. As noted, there is some uncertainty around the recorded peak flow, with estimates ranging from 176,000 to 205,100 ML/day. There is also a flow gauging at 7.375m of 191,000 ML/day which also suggests that a lower flowrate may be reasonable.

A summary of the calibration to peak gauge levels and flows is shown in Table 22

Table 22: Comparison of peak levels and flows at the gauges for the Murray River 1993 event

Gauge	Variable	Gauge	Modelled	Difference (% for flow)
Tocumwal	Water Level (m)	7.37	7.31	-0.06
	Flow (ML/d)	196,300	183,000	-13,300 (-6.8%)

Note: Levels rounded to the nearest centimetre and flows rounded to the nearest 100 ML/d

Flood marks for the 1993 event were available from the Victorian Flood Database, these have been compared with the flood model results. A visual comparison of the modelled 1993 flood depth and the Victorian Flood Database flood marks is provided on Figure C9 to Figure C13. Of the 15 flood marks, the overall average variance of -0.28. The absolute range is -0.97m to 0.13m.

The flood mark with a variance of -0.97m is again located in the vicinity of Ulupna Island. It is not surrounded by any other flood marks for validation but is likely a result of the models' representation of the complex flow distribution in this area. This could be improved in the future with additional survey data on the southern (Victorian) floodplain.

7.4.3. 2016 Event

The Murray River 2016 flood event is the fifth highest flood on recent records, reaching 7.35m at the Tocumwal gauge (#409202). This was a similar size to the 1993 event, although with a lower peak inflow (178,100 ML/day compared to 196,300 ML/day for the 1993 event). The preceding peak in 2016 flood peaked at 89,500 ML/day in comparison to 61,600 ML/day in 1993.

The event was simulated using the recorded flows at Murray River Downstream Yarrawonga Weir (#409025) for the period 24th August 2016 to 13th December 2016. The flood peak occurred on the 9th October at the Tocumwal gauge.

The inflow hydrographs are shown in Diagram 10.

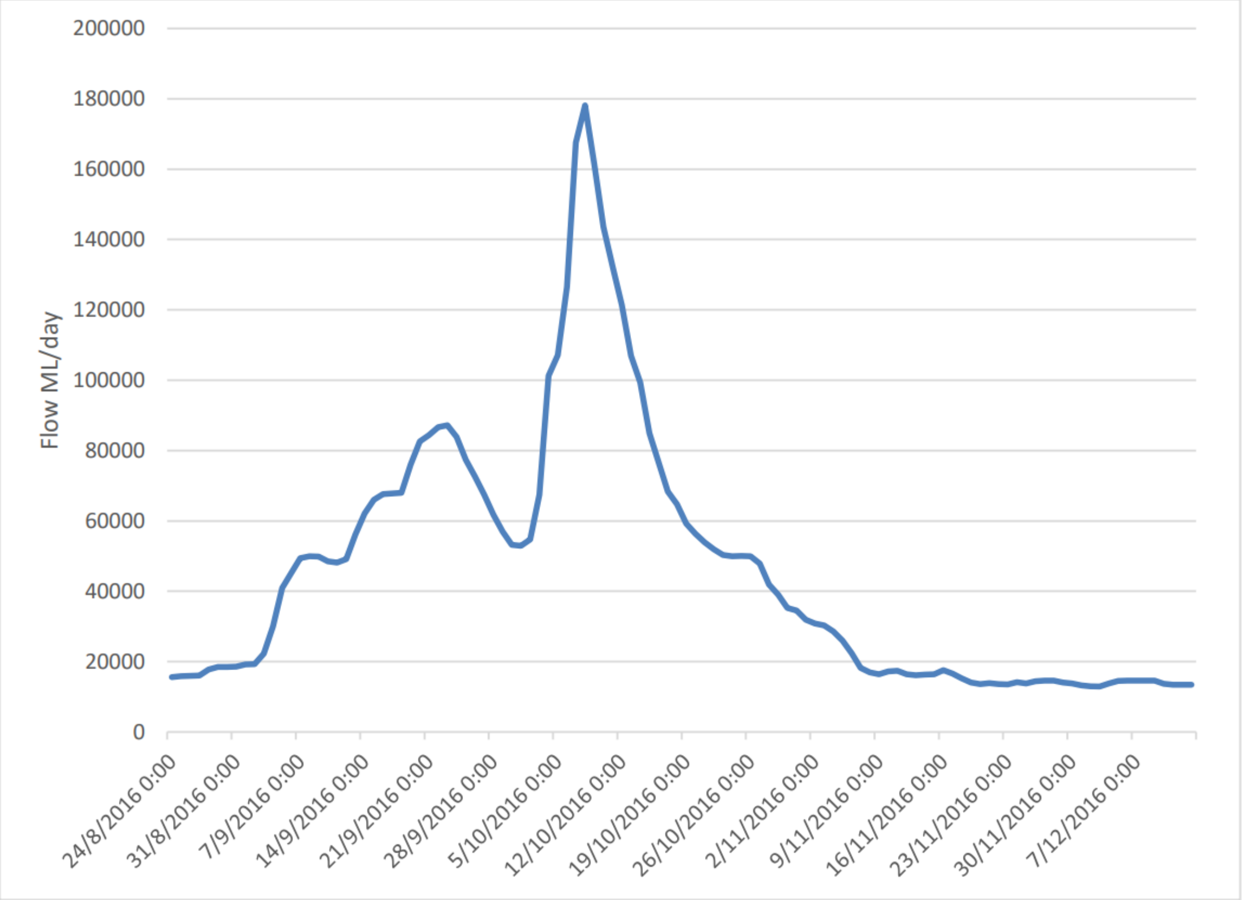


Diagram 10: Inflow hydrographs for the 2016 flood event

The results of the TUFLOW model calibration to the gauge data is shown in on Figure C26 and Figure C27. The model reproduces the shape and general timing of the event well. The model is slightly delayed compared to the record, but overall reproduces the event well. Recorded peak flood levels are reproduced by the model within 0.07m.

The modelled peak flow is close to the recorded flow at the gauge (within 4.2%). The modelled hydrograph matches the shape of the earlier and main hydrograph peak and falling limb well, with a slight delay.

A summary of the calibration to peak gauge levels and flows is shown in Table 23

Table 23: Comparison of peak levels and flows at the gauges for the Murray River 2016 event

Gauge	Variable	Gauge	Modelled	Difference (% for flow)
Tocumwal	Water Level (m)	7.35	7.30	-0.05
	Flow (ML/d)	180,200	172,600	-7,600 (-4.2%)

Note: Levels rounded to the nearest centimetre and flows rounded to the nearest 100 ML/d

Flood marks for the 2016 event were available from the Victorian Flood Database, these have been compared with the flood model results. A visual comparison of the modelled 2016 flood depth and the Victorian Flood Database flood marks is provided on Figure B14 to Figure B21. Of the 133 flood marks, 44% are within +/-0.2m, with an overall average variance of -0.04m. The absolute range is -2.40m to 2.04m.

Both flood marks at the extremes of the range (-2.4m and 2.04m variances) are indicated as being of low reliability. Other flood marks showing significant variation are again located in the vicinity of Ulupna Island, where complex flow distribution exists across many floodplain channels.

Berigan Shire Council provided a series of photographs along the Lower River Road. The images have been compared to the flood model result for the 2016 flood event. The photos (Diagram 11 and Diagram 13) taken 17th October, eight days after the peak, show the floodwater coming from the river overtopping low points along the Lower River Road. It is difficult to estimate the depth of water at the time of photography but is estimated at 0.1m to 0.2m deep based on flood depth markers shown and vehicles driving through the water. On the 17th October river levels at the Tocumwal gauge had dropped 0.8m from the peak, at an average of 0.1m per day. The modelled peak flood depth at both locations is close to 1m (Diagram 12 and Diagram 14), considering the recorded drop in river levels at the time of the photography, the flood depth estimated from the photographs is considered reasonable.

Diagram 11: Flood depth indicator at Lower River Road, 2016 (10 kilometre West of Tocumwal) Taken 17th October 2016 10:45am

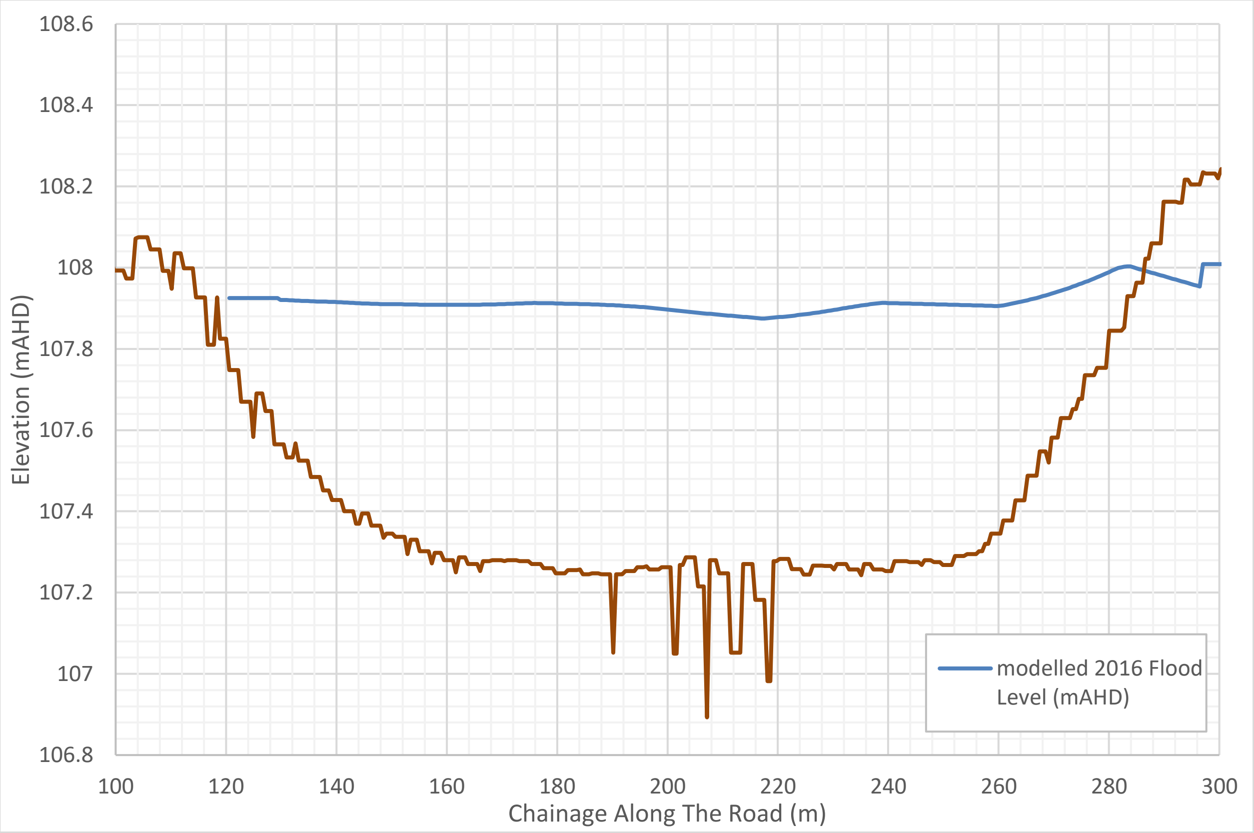


Diagram 12: Lower River Road profile at Flood depth indicator (10 kilometre West of Tocumwal)

Diagram 13: Vehicle driving along Lower River Road, 2016 (8 kilometre West of Tocumwal) Taken 17th October 2016 10:59am

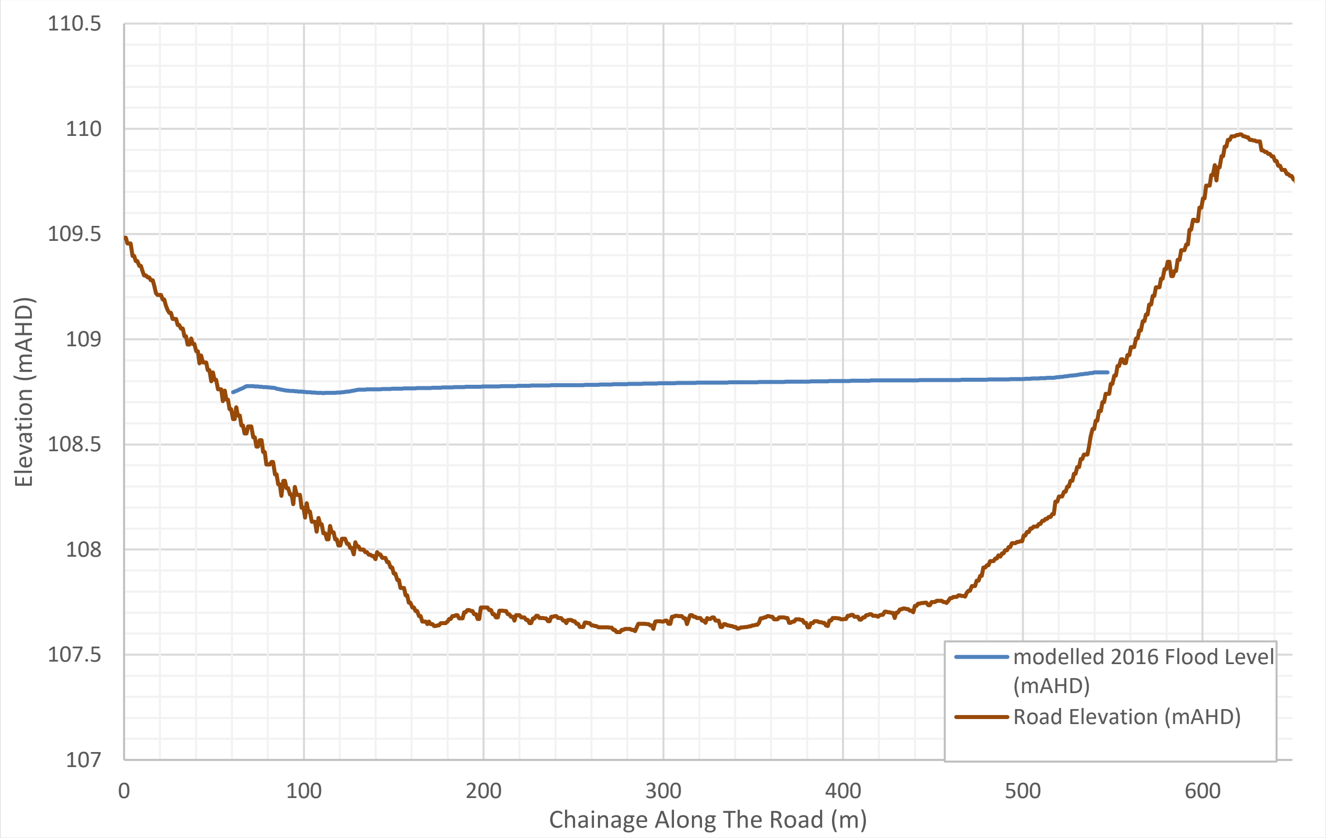


Diagram 14: Lower River Road profile (8 kilometre West of Tocumwal)

7.5. Local Overland Flow

The March 2020 storm event over the study area was modelled in the WBNM hydrologic model using the INSWTOCU6 private rainfall gauge temporal pattern and rainfall depths derived from available information (Figure B31). The resulting runoff was used as inflows into the TUFLOW hydraulic models to simulate flood behaviour. The resulting flood depths and extents were compared to the available information collected as part of the community consultation (Section 4.2.1.

Figures C28 and C29 provide a comparison of the anecdotal commentary with the modelled peak flood depth and extent for the March 2020 event.

The results indicate a reasonable match to the anecdotal information, much of the commentary related to a general description of the flood behaviour, such as flooded in the road or backyard. Good correlation can be seen at Hill Street and Keogh Drive, Tocumwal and near the intersection of Yarrawonga Road and the Riverina Highway, to the south of Berrigan.

7.6. Calibration Parameters for Overland Models

There is very little ‘calibration’ of hydraulic model parameters (such as Mannings ‘n’), due to the nature of flooding and the uncertainties regarding the available calibration information. The most important features are the terrain (in which high quality LiDAR data is being used) and hydraulic structures (which have been included in the model). As such, ‘calibration’ typically involves consideration of the WBNM hydrologic model and representation of the storm.

Initial and continuing losses derived from the ARR Data Hub (probability neutral initial loss and NSW factored continuing loss) for an event equivalent to the size of the March 2020 storm. An initial loss of 18mm and a continuing loss of 0.72mm/hour were adopted. The adopted initial and continuing loss values do not necessarily represent a ‘calibrated’ value, but rather a typical value that is justifiable given a reasonable match to anecdotal information.

The use of the WBNM model to simulate rainfall runoff and the TUFLOW hydraulic model to represent design flood events is considered reasonable.

8. FLOOD FREQUENCY ANALYSIS

8.1. Overview

Flood frequency analysis (FFA) uses recorded and related flood data to identify an underlying probability model of flood peaks, which enables the magnitude of flood flows for different annual exceedance probabilities (5%, 1% AEP etc.) to be estimated. This is achieved by establishing a series from the flood record, in this case an Annual Maximum Series (AMS), which represents a homogenous flood record, then fitting a probability distribution to the data and using the resulting curve to estimate the peak design flows.

Typically, flood frequency is the most robust method for estimating design flows of a particular annual exceedance probability as it inherently accounts for many assumptions which are required in rainfall-runoff modelling of design flood events; additionally, it allows for a confidence limit to be assigned to the estimate. The reliability of the flood frequency approach depends largely upon the length and quality of the observed record and accuracy of the rating curve, particularly at high flows where limited gauging measurements exist and the relationship changes from in bank to overland flow. The influence of climatic periods or the construction of large structures, such as dams or weirs, which modify the natural frequency of flood events can also reduce the homogeneity of the gauge record.

Most flood records are relatively short, compared to the design events for which a magnitude is required, introducing uncertainty. The application of Bayesian approaches however assists in reducing the uncertainty related to shorter record lengths.

The key locations to understand the magnitude of flood flows for different annual exceedance probabilities for the study area are at Murray River Downstream Yarrawonga Weir (#409025) and Murray River at Tocumwal (#409202). The gauge at Yarrawonga is located at the upstream limit of the study area and can inform model inflows, while the Tocumwal gauge can provide validation of the model performance within the study area.

Flood events on the Murray River downstream of Hume Dam are derived from a combination of factors including outflows from Hume Dam, flow contributions from the Keiwa and Ovens Rivers, offtakes and diversions as well as operations of Yarrawonga Weir. A number of large flood events (including the largest on record) have also occurred prior to the construction of both Hume Dam (constructed between 1919 and 1936) and Yarrawonga Weir (constructed between 1935 and 1939) and estimates of these events under current conditions are associated with some uncertainty. In addition, the capacity of the Hume Dam storage was approximately doubled between 1950 and 1961. Considering the study area in isolation may neglect the influence of these factors and it is important to consider these aspects of the flood record. WMAwater, 2024 which considered the stretch of the Murray River from upstream of Howlong to Yarrawonga Weir undertook a comprehensive review of these aspects and has provided a basis for the assessment undertaken as part of the current study. The following sections summarise this assessment.

8.2. Albury to Yarrawonga Weir

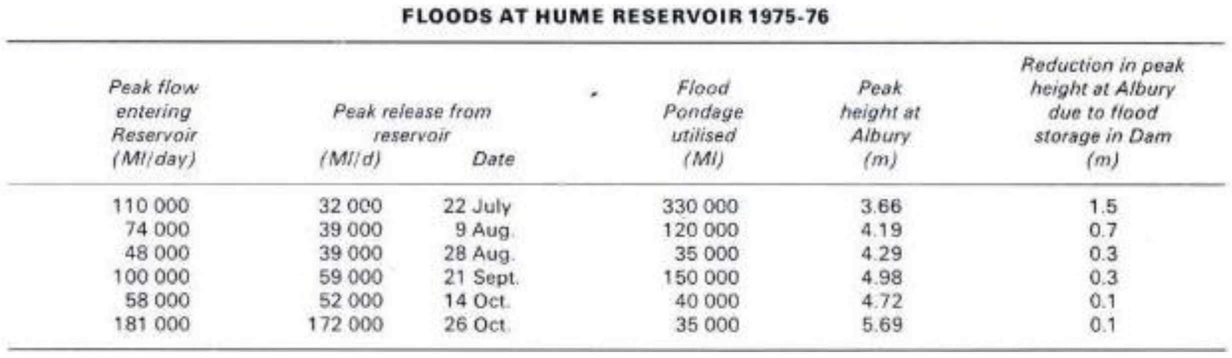
A stream gauge commenced at Doctors Point (#409017) towards the end of 1929 and is currently operational. It is located downstream of the Murray River and Kiewa River confluence, essentially recording flows from the Hume Dam and Kiewa River. The flood record at Doctors Point can be supplemented with Murray River at Albury (Union Bridge #409001), which includes the large events in 1867, 1870 and 1917 and allows for a continuous record from 1887 to 2022 to be constructed.

A stream gauge commenced at Corowa (#409002) located at the John Foord Bridge, midway through 1909, and is currently operational. A continuous record from 1909 to 2022 can be constructed. Level and flow estimates of the 1867 and 1870 events are available from a range of previous reports.

A stream gauge commenced at Yarrawonga (#409025) located downstream of the weir, in 1938, and is currently operational. Water Technology, 2011 obtained additional flood records for Yarrawonga from the Victorian State Rivers and Water Supply Commission (SR&WSC). Two datasets were obtained, labelled SR&WSC-A and SR&WSC-B. This additional data allowed a continuous record from 1905 to 2022 to be constructed. Floods at Yarrawonga can also be generated by the Ovens River independently of the Murray River.

Hume Dam is located 8 km upstream of the Doctors Point gauge and affects flooding downstream, as it can store floodwaters arriving at the dam. In order to construct a homogeneous data set, the likely influence of the dam needs to be understood. In general, dams have a greater ability to attenuate smaller flood events than larger flood events. The larger flood events typically occur in wet years when dams may be close to full supply level (FSL) and the flood may be passed downstream with little attenuation. An example of this is the 1975 flood at Hume Dam – the largest flood since the dam's construction. In their 1975-76 annual report, the River Murray Commission indicated that from July to December 1975, Hume Dam remained full (River Murray Commission 1977). There were several flood events in this period, as shown in Table 24. The dam was able to attenuate some of the earlier floods, however, by October the capacity of the dam to attenuate flood peaks was significantly less. The last flood event in October 1975 had an estimated peak inflow of 181,000 ML/d and a peak release of 172,000 ML/d. This represents just a 5% reduction in peak flow.

Table 24: Floods at Hume Reservoir 1975-76 (*Source: River Murray Commission 1977*)



FLOODS AT HUME RESERVOIR 1975-76

Peak flow entering Reservoir (Ml/day)	*Peak release from reservoir (Ml/d)*	*Date*	*Flood Pondage utilised (Ml)*	*Peak height at Albury (m)*	*Reduction in peak height at Albury due to flood storage in Dam (m)*
110 000	32 000	22 July	330 000	3.66	1.5
74 000	39 000	9 Aug.	120 000	4.19	0.7
48 000	39 000	28 Aug.	35 000	4.29	0.3
100 000	59 000	21 Sept.	150 000	4.98	0.3
58 000	52 000	14 Oct.	40 000	4.72	0.1
181 000	172 000	26 Oct.	35 000	5.69	0.1

Given the uncertainty in the influence of the dam on smaller events, WMAwater, 2024 constructed an AMS for Doctors Point and Corowa for the post dam period, 1929 – 2022. Hume Dam has some impact on flows arriving at Yarrawonga, however, this is not as prominent in the study area due to the distance between Hume Dam and the Yarrawonga gauge and the contribution from the Ovens River. An AMS from 1905 – 2022 was constructed at Yarrawonga. The adopted AMS for Doctors Point, Corowa and Yarrawonga are provided in WMAwater, 2024.

Low flows which may be a result of dam releases rather than naturally occurring flood events can unduly influence the fit of the probability distribution. WMAwater, 2024 applied a low flow censor at 30,000ML/day to all Murray River gauges and notes that this improved the fit for rarer events and tighter confidence limits.

The three largest events on record, are the 1867, 1870 and 1917 events, which occurred prior to the construction of Hume Dam, have variable flow estimates available from a range of previous reports. The incorporation of these events into the FFA is considered important, as these large events significantly affect the fit of the curve at the upper end. It is uncertain, however, the affect that Hume Dam would have on these flows. Converting these flows to a ‘post-dam’ flow is problematic, as it would heavily depend on the initial water level in the dam and the operation of the dam. WMAwater, 2024 included these events as events above a censored threshold of 200,000 ML/day at Doctors Point and 198,200 ML/day at Corowa. At Yarrawonga the 1867 and 1870 events were included above the 1917 flow of 340,000 ML/day.

Estimates of the 1917 event at Yarrawonga are variable. WMAwater, 2024 utilised the established TUFLOW model to support the adopted flow of 340,000 ML/day. This was also based on considering a coincident flow rate in the Ovens River of 69,583 ML/day rather than the annual peak of 108,600 ML/day which occurred at a different time of year.

A probability distribution (Log Pearson III) was fit to the AMS and the adopted design flow estimates are provided in Table 25.

Table 25: Adopted Design Peak Flows (ML/d)

AEP	**Adopted Peak Flow (ML/d)**		
	Doctors Point	**Corowa**	**Yarrawonga**
20%	83,000	75,000	131,000
10%	122,000	114,000	189,000
5%	162,000	155,000	249,000
2%	215,000	213,000	330,000
1%	250,000	250,000	390,000
0.5%	290,000	300,000	450,000
0.2%	340,000	360,000	530,000

8.3. Tocumwal

The stream gauge at Tocumwal (#409202) commenced in early 1908 and is currently operational. Mean daily flow was available for the period from 1908 to 1974 and instantaneous daily maximum data was available for the period 1974 to 2023. This allowed an AMS to be constructed from 1908 to 2023. Estimates of the peak level for the 1870 (7.57m) event are available from NSW State Emergency Service, March 2017.

Table 26: Annual Maximum Series – Tocumwal Gauge (#409202)

Year	Flow (ML/day)	Year	Flow (ML/day)	Year	Flow (ML/day)	Year	Flow (ML/day)
1908	31,800	**1937**	16,500	**1966**	41,100	**1995**	6,700
1909	125,000	**1938**	14,600	**1967**	15,700	**1996**	140,500
1910	49,800	**1939**	107,000	**1968**	41,100	**1997**	13,500
1911	41,000	**1940**	13,500	**1969**	46,700	**1998**	70,900
1912	70,000	**1941**	17,900	**1970**	162,000	**1999**	17,500
1913	30,300	**1942**	66,800	**1971**	76,100	**2000**	87,600
1914	8,350	**1943**	36,100	**1972**	19,700	**2001**	14,400
1915	66,600	**1944**	9,870	**1973**	127,000	**2002**	15,800
1916	71,900	**1945**	15,900	**1974**	183,000	**2003**	39,700
1917	191,000	**1946**	95,200	**1975**	224,400	**2004**	31,900
1918	65,900	**1947**	55,400	**1976**	21,900	**2005**	28,300
1919	23,300	**1948**	55,400	**1977**	12,300	**2006**	11,100
1920	76,400	**1949**	57,600	**1978**	49,800	**2007**	10,200
1921	125,000	**1950**	42,700	**1979**	47,300	**2008**	7,900
1922	32,400	**1951**	75,400	**1980**	21,100	**2009**	10,600
1923	73,400	**1952**	114,000	**1981**	116,000	**2010**	93,000
1924	125,000	**1953**	75,200	**1982**	15,400	**2011**	49,000
1925	48,700	**1954**	38,200	**1983**	53,500	**2012**	59,300
1926	64,600	**1955**	158,000	**1984**	60,200	**2013**	43,300
1927	39,400	**1956**	183,000	**1985**	35,900	**2014**	21,900
1928	56,400	**1957**	15,900	**1986**	73,000	**2015**	16,600
1929	34,200	**1958**	113,000	**1987**	21,800	**2016**	180,200
1930	54,300	**1959**	24,800	**1988**	34,100	**2017**	29,200
1931	162,000	**1960**	89,600	**1989**	57,700	**2018**	18,300
1932	88,900	**1961**	17,900	**1990**	91,600	**2019**	15,500
1933	45,900	**1962**	17,800	**1991**	68,600	**2020**	21,100
1934	75,200	**1963**	27,100	**1992**	131,100	**2021**	9,000
1935	55,200	**1964**	95,400	**1993**	196,300	**2022**	155,600
1936	82,100	**1965**	25,800	**1994**	21,400	**2023**	53,800

WMAwater, 2024 demonstrated that Yarrawonga Weir has a finite capacity (approximately 343,000 ML/day) and once flows exceed this, the weir is outflanked, and flows are uncontrolled with the hydraulic model showing a portion exiting the system through Mulwala (at approximately 370,000 ML/day) and travelling to the north of Mulwala Canal.

In addition, Water Technology 2011 identified that once levee overtopping occurs at Cobram, significant flow moves across the southern (Victorian) floodplain. In both these cases flow effectively bypasses the streamflow gauge at Tocumwal. As a result, flows for events above approximately the 2% AEP (330,000 ML/day at Yarrawonga) are considered to be unreliable.

The Bayesian maximum likelihood approach has been adopted to fit the Log Pearson III probability distribution to the AMS. This was undertaken using the TUFLOW FLIKE software (version 5.0.251.0) developed by Kuczera (1999) as recommended in ARR 2019 Version 4.1 (Ball, et al., 2019). Peak event flows at Tocumwal are generally slightly lower than at Yarrawonga due to flow diversions into the northern and southern floodplains, which bypass the Tocumwal gauge and the attenuation of peak flows in this reach. A low flow censoring threshold of 25,800 ML/day, slightly lower than the 30,000 ML/day adopted at Yarrawonga, was therefore adopted at Tocumwal. The 1867 and 1870 event were included above a censored threshold of 250,000 ML/day. A range of thresholds between 175,000 and 275,000 ML/day were tested, based on recorded levels and flows for other large events. The 250,000 ML/day was found to provide the best fit. Regional priors derived from the gauge at Yarrawonga were also applied to improve the result.

Table 27: Tocumwal Design Peak Flows (ML/d) with LPIII Distributions

AEP	Peak Flow (ML/day)
20%	99,800
10%	141,100
5%	182,900
2%	238,100
1%	279,500
0.5%	320,400
0.2%	373,000

Note: Flows rounded to the nearest 100 ML/d

The FFA results at Tocumwal are comparable to estimates provided in Water Technology 2011, however given the uncertainties in the gauge record related to flow bypassing through Mulwala and Cobram, the results are considered to be unreliable and have not been utilised in this study. Instead, the more reliable flows derived from the FFA from the upstream system, coupled with the results of the TUFLOW modelling from WMAwater, 2024 have been utilised in this study.

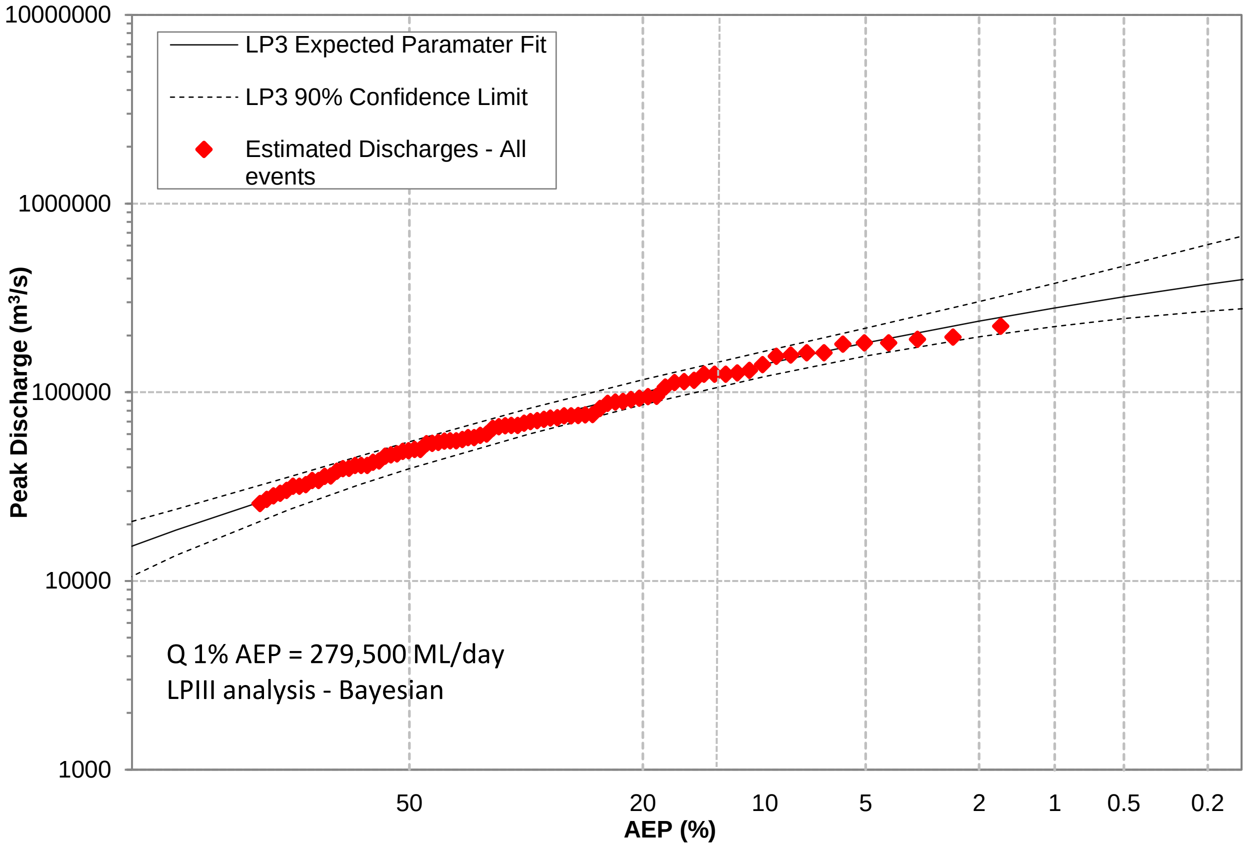


Diagram 15: Flood Frequency Analysis – Murray River at Tocumwal (#409202)

9. DESIGN FLOOD MODELLING

Following model calibration (Section 7) the established models have been used to determine design flood behaviour in the study area. The following sections outline the approach and outcomes of the assessment for both the Murray River and local overland flow catchments.

9.1. Murray River

The Murray River design flood events were simulated by developing a design flood hydrograph for each event. The flood hydrograph consists of two main components – the peak flow and the hydrograph shape. Flood hydrographs were input into the TUFLOW model for the Murray River. The 20%, 10%, 5%, 2%, 1%, 0.5%, 0.2% AEP and PMF (or equivalent extreme) events were simulated. The development of the design flood hydrographs is detailed in the following sections.

9.1.1. Design Peak Flows

WMAwater, 2024 demonstrated that Yarrawonga Weir has a finite capacity (approximately 343,000 ML/day) and once flows exceed this, the weir is outflanked, and flows are uncontrolled with the hydraulic model showing a portion exiting the system through Mulwala and travelling to the north of Mulwala Canal. In addition, Water Technology 2011 identified that significant flow moves across the southern (Victorian) floodplain. In both these cases flow effectively bypasses the study area. Design peak flows for the 20% AEP to 0.2% AEP events were derived utilising the flows from the FFA (Section 8) at Murray River Downstream Yarrawonga Weir (#409025), in combination with a review of the modelled flows from WMAwater, 2024 for both the flow downstream of the weir and flow bypassing the weir.

The adopted flows are considered to be representative of flows that would pass through Yarrawonga Weir and enter the study area. Noting that during large events it is likely that some flow will leave the Murray River at Mulwala and Cobram, and bypasses the study area. This behaviour is demonstrated in the annual maximum series of events at Tocumwal with a flattening as the frequency reduces.

A summary of the adopted peak design flows for the Murray River is provided in Table 28.

Table 28: Adopted Peak Design Inflows for the Murray River TUFLOW Model

AEP	Murray River at Downstream Yarrawonga Weir
	Flow (ML/d)
20%	126,400
10%	183,600
5%	242,900
2%	323,000
1%	381,200
0.5%	407,800[1]
0.2%	438,000[1]
PMF (or Equivalent Extreme)	1,143,600[2]

(1) FFA flow adjusted based on findings of WMAwater,2024

(2) Extreme event estimate based on three times 1% AEP flow

9.1.2. Design Hydrograph Shape

In selecting a historic hydrograph for design flood event modelling, consideration should be given to its representation of typical flood events for that system, and the flood volume. The Murray River in and surrounding the study area is part of a large complex system where the peak flow, in addition to the hydrograph shape and duration will change which parts of the floodplain become activated during a flood event, as well as whether flow exits the immediate floodplain to travel through other parts of the system, such as the Edward River system. For example, a short sharp peaky event with a relatively large peak flow could inundate less floodplain than a long sustained flood event at a lower peak flow, which ultimately has a greater volume. Considering this observed behaviour, the Murray River Regional Flood Study (Water Technology Pty Ltd, 2011) undertook a flood frequency analysis of both peak flow and flood volume at Yarrawonga (#409025) and Tocumwal (#409202) to determine design flood events, on the assumption that peak flow and flood volume of the same frequency will result in an event of an equivalent frequency. The 2011 study then compared the ratio of peak flow to flood volume for historical events to the results of both flood frequency analysis AT Yarrawonga (#409025) to determine the appropriate flood hydrograph shape for design events (Diagram 16). The 2016 event has been added to Diagram 16 for comparison.

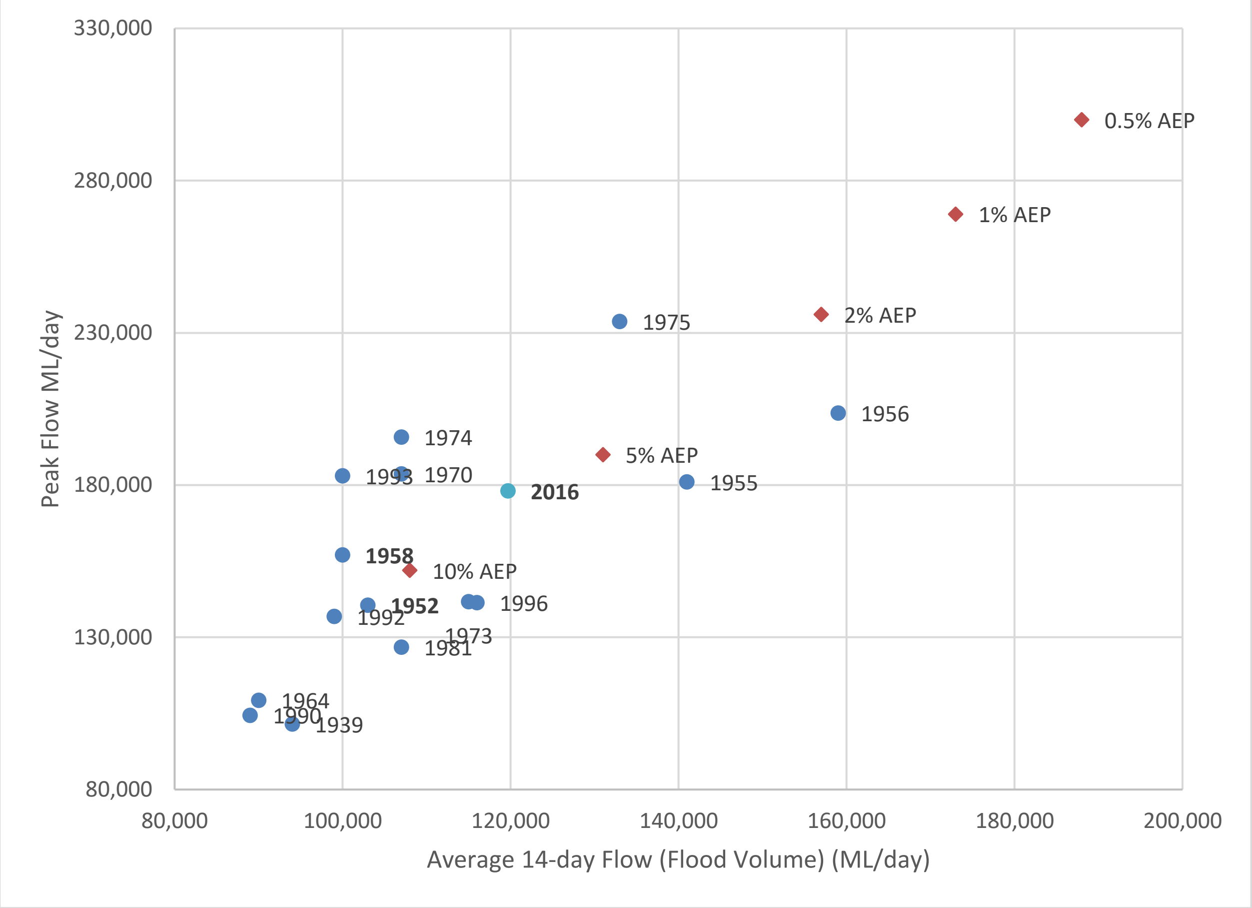


Diagram 16: Yarrawonga (#409025) – Ratio of Flood Peak Flow to Average 14-day Volume – Historical and Design (partially reproduced from (Water Technology Pty Ltd, 2011)

The Murray River Regional Flood Study identified that the ratio of peak flow to flood volume for the 1958 and 1952 events most closely represented the ratio for the design events and adopted the 1952 event hydrograph shape for the 10% and 5% AEP events and the 1958 event hydrograph shape for the larger events. WMAwater, 2024 adopted the 2016 hydrograph shape for the study area upstream of Yarrawonga. Diagram 16 shows that the 2016 event also provides a reasonable representation of the flood peak to volume ratio.

At Tocumwal, the 1958 event contains a smaller initial peak, followed soon after by a larger peak, while the 2016 event, contains a relatively less pronounced earlier peak. Given this and to allow comparison to the earlier assessment the approach from (Water Technology Pty Ltd, 2011) was adopted and the 1952 event hydrograph shape was applied for the 10% and 5% AEP events and the 1958 event hydrograph shape for the larger events.

The 1952 and 1958 flood hydrographs for the Murray River were scaled to match the peak flows discussed in Section 9.1.1, for the 20% AEP to 0.2% AEP events. The resulting hydrographs can be seen in Diagram 17. These hydrographs are as applied at the TUFLOW model boundary downstream of Yarrawonga Weir.

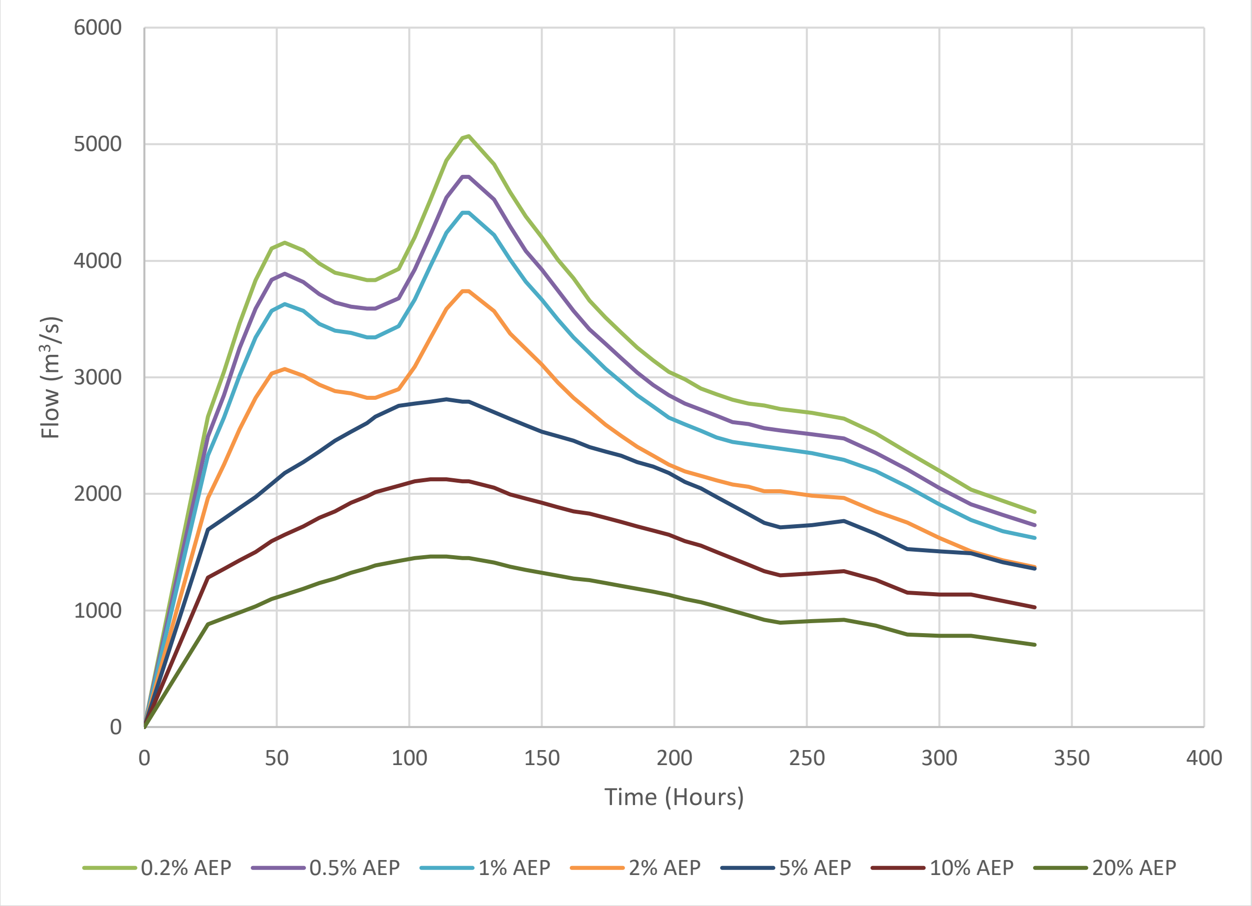


Diagram 17: Murray River Design Flood Hydrographs for the 20% AEP to 0.2% AEP Events

9.1.3. PMF (or Equivalent Extreme) Event

The Probable Maximum Precipitation (PMP) is 'the greatest depth of precipitation for a given duration meteorologically possible...' (Bureau of Meteorology, 2003). In large complex systems, such as the Murray River there are a range of methods available to determine the magnitude of the design flows.

Flooding in the study area is driven by flow passing through Lake Mulwala and Yarrawonga Weir, which is ultimately driven by flows released from Hume Dam and the contributing catchments of the Kiewa and Ovens Rivers. WMAwater, 2024 considered the work of Assessment of Hydrologic Risk for Hume Dam (Nanakumar, et al., 2011) which determined a PMF with PMP rainfall, pre-burst and maximum temporal pattern, 0 mm and 1 mm/h initial and continuing losses, and reservoirs initially at FSL. This approach was adopted in WMAwater, 2024 as no more recent assessments were available for use. An approximate peak flow of 1,287,000 ML/d from Hume was adopted Dam plus 200,000 ML/d for the contributing catchments between the dam and Albury and approximately 1,000,000 ML/d for the Ovens River system. The resulting flow at Yarrawonga was 2,487,000 ML/d.

WMAwater, 2024 also demonstrated that Yarrawonga Weir has a finite capacity (approximately 343,000 ML/day) and once flows exceed this, the weir is outflanked, and flows are uncontrolled with the hydraulic model showing a portion exiting the system through Mulwala and travelling to the north of Mulwala Canal.

Table 29: Breakout Flows though Mulwala (Partially from WMAwater, 2024)

Event (AEP)	Approach Yarrawonga Flow[1] (ML/day)	Mulwala Breakout (ML/day)	Flow at Downstream Model Boundary[2] (ML/day)
2%	336,400	-	329,400
1%	398,400	10,500 (3%)	380,600
0.5%	449,700	38,700 (9%)	408,300
0.2%	537,600	94,600 (18%)	441,800
PMF	2,033,800	641,400 (32%)	834,800

(1) Magnitude of flows approaching Lake Mulwala, does not account for attenuation through the lake and weir.
(2) Extracted from WMAwater, 2024 model

An alternative approach for determining the PMF in systems of this nature is to adopt an equivalent extreme event which is representative of three times the 1% AEP peak flow. This would result in an extreme event flow rate of 1,143,600 ML/day (381,200 ML/day x 3) and 30% higher than the modelled flowrate from WMAwater, 2024.

WMAwater, 2024 indicated that flows in excess of approximately 343,000 ML/day outflank the weir with some flows exiting the system. At the scale of the PMF or equivalent extreme event flowrate there is some uncertainty in this modelled behaviour and therefore the current study has adopted 1,143,600 ML/day as a conservative estimate of the extreme event.

The design flood hydrograph is based on a scaled up 1958 event, consistent with the other large events.

9.1.4. Treatment of Levees

Levees are typically designed for a particular level of protection, with a freeboard added to achieve the crest height. The freeboard aims to provide certainty that protection is provided for the selected design event. In reality as levees age the ability of the levee to remain structural sound, to the crest height diminishes due to settlement, trees, burrowing animals and other structural defects. In order to understand the range of impacts resulting from potential failure of the levees, the levees are assumed to fail once the design heigh is exceeded. Failure in this case is represented as a 100m section of levee that is reduced to half its design height. Failure locations are shown on Diagram 18 and were selected as the lowest point relative to the flood gradient along each levee.

Design flood mapping is produced by an envelope of levee failure and no failure cases.

Diagram 18: Modelled Levee Failure Locations

9.2. Local Overland Flow Catchments

ARR 2019 Version 4.1 guidelines (Ball, et al., 2019) for design flood modelling were adopted for this study, including the use of ARR 2019 Version 4.1 design information for the 20%, 10%, 5%, 2%, 1%, 0.5%, 0.2% AEP events. The PMF flows were derived using the Bureau of Meteorology's Generalised Short Duration Method (GSDM, (Bureau of Meteorology, 2003)) to estimate the probable maximum precipitation (PMP) over the local overland flow catchments. It was assumed that all levee drainage structures were blocked, and overland drainage could not occur. This assumption effectively implements an elevated Murray River water level.

A range of standardised inputs are available for determining design flood behaviour from the ARR Data Hub (Babister, et al., 2016). The design flood inputs and parameters that were used and the critical pattern duration selection method for the local overland flow models are outlined in the following sections.

9.2.1. Design Rainfall Data

The design rainfall intensity-frequency-duration (IFD 2016) data were obtained from the BoM online design rainfall tool for the catchment centroid and are provided in Table 30. IFD 2016 data was also sourced for each sub catchment for use in the WBNM hydrologic model.

Table 30: Rainfall IFD Data at the Overland Model Centroid (IFD 2016)

Annual Exceedance Probability (AEP) Rainfall in mm						
Duration	**50% #**	**20% ***	**10%**	**5%**	**2%**	**1%**
1 min	1.82	2.59	3.12	3.65	4.37	4.93
2 min	3.05	4.37	5.33	6.31	7.62	8.65
3 min	4.16	5.93	7.21	8.51	10.2	11.6
4 min	5.12	7.3	8.84	10.4	12.5	14.1
5 min	5.97	8.49	10.3	12	14.4	16.3
10 min	9.05	12.8	15.4	18	21.5	24.3
15 min	11.1	15.7	18.9	22.1	26.4	29.7
30 min	14.7	20.8	25.2	29.5	35.4	40
1 hour	18.4	26.2	31.7	37.2	44.7	50.7
2 hour	22.6	31.9	38.5	45.2	54.3	61.6
3 hour	25.4	35.6	42.9	50.2	60.2	68.2
6 hour	30.9	43.1	51.5	60	71.6	80.8
12 hour	37.8	52.3	62.3	72.3	86.1	96.9
24 hour	45.5	63.3	75.8	88.3	105	119
48 hour	53.2	75.1	91	107	129	147
72 hour	57.1	81.3	99.4	118	144	164
96 hour	59.6	85.1	104	125	153	175
120 hour	61.2	87.4	107	129	157	181
144 hour	62.4	88.8	109	130	159	184

Note:

 # The 50% AEP IFD does not correspond to the 2 year Average Recurrence Interval (ARI) IFD, rather it corresponds to the 1.44 ARI.

** The 20% AEP IFD does not correspond to the 5 year Average Recurrence Interval (ARI) IFD, rather it corresponds to the 4.48 ARI.*

Design rainfalls for the PMP were derived using the BoM's GSDM (Bureau of Meteorology 2003). The GSDM is valid for durations up to 3 hours. The GSDM parameters for each of the towns are shown in Table 31.

Table 31: GSDM parameters

Parameter	
Terrain	Smooth
Elevation Adjustment Factor	1
Moisture Adjustment Factor	0.61
Spatial Distribution	All

9.2.2. Design Temporal Patterns

Temporal patterns describe how rainfall falls over time and are often used in hydrograph estimation. Previously in ARR 1987 guidelines (Pilgrim DH (Editor in Chief), 1987), a single burst temporal pattern has been adopted for each rainfall event duration. However, ARR 2019 Version 4.1 (Ball, et al., 2019) discusses the potential inaccuracies with adopting a single temporal pattern, and recommends an approach where an ensemble of different temporal patterns are investigated.

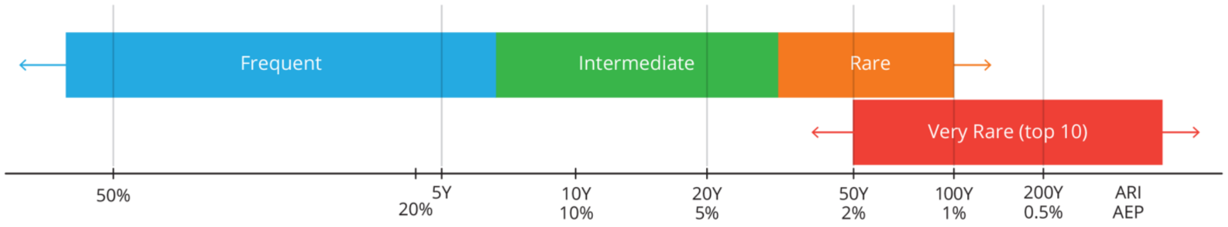
Temporal patterns for this study were obtained from ARR 2019 Version 4.1 and accessed from the ARR Data Hub (Babister, et al., 2016).

There are a wide variety of temporal patterns possible for rainfall events of similar magnitude. This variation in temporal pattern can result in significant effects on the estimated design peak flow. As such, the recommended methodology is to consider an ensemble of design rainfall events and determine the median catchment response from this ensemble.

As hydrologic modelling has advanced, it is becoming increasingly important to use realistic temporal patterns. The ARR 1987 temporal patterns only provided a pattern of the most intense burst within a storm, whereas the ARR 2019 Version 4.1 temporal patterns look at the entirety of the storm including pre-burst rainfall, the burst and post-burst rainfall. There can be significant variability in the burst loading distribution (i.e. depending on where 50% of the burst rainfall occurs an event can be defined as front, middle or back loaded). The ARR 2019 Version 4.1 method divides Australia into 12 temporal pattern regions, with Berrigan Shire Council falling within the Murray Basin region.

ARR 2019 Version 4.1 provides 30 temporal patterns for each duration which are sub-divided into three temporal pattern bins based on the frequency of the events. Diagram 19 shows the three categories of bins (frequent, intermediate and rare) and corresponding AEP groups. The "very rare" bin is in the experimental stage and was not used in this flood study. There are ten temporal patterns for each AEP/duration in ARR 2019 Version 4.1 that have been utilised in this study for the 20% AEP to 0.2% AEP events.

Diagram 19: Temporal Pattern Bins



The method employed to estimate the PMP utilises a single temporal pattern (Bureau of Meteorology, 2003).

9.2.3. Design Rainfall Losses

Methods for modelling the proportion of rainfall that is “lost” to infiltration are outlined in ARR 2019 Version 4.1 (Ball, et al., 2019). The methods are of varying degrees of complexity, with the more complex options only suitable if sufficient data are available. The method most typically used for design flood estimation is to apply an initial and continuing loss to the rainfall. The initial loss represents the wetting of the catchment prior to runoff starting to occur and the continuing loss represents the ongoing infiltration of water into the saturated soils while rainfall continues.

The initial losses adopted for the calibration event was 18mm for the March 2020 event and based on the ARR Data Hub Probability Neutral Initial Loss for an equivalent size event. This was applied due to the lack of available data to calibrate the overland models. As such, for design flood modelling, the probability neutral burst initial losses from the ARR Data Hub (Babister, et al., 2016) were adopted, in line with recent advice from the NSW Government (WMAwater Pty Ltd, 2019). These initial losses were sourced from the ARR Data Hub at the centroid of the catchment. The initial losses vary with storm duration and AEP however, are generally in the range of 5 mm to 25 mm across the full range of AEPs and durations. The probability neutral burst initial losses at the centroid of the overland flood models are provided in Table 32.

Table 32: ARR 2019 Version 4.1 Probability Neutral Burst Initial Loss

Storm Duration (min)	Event (AEP) Depth (mm)					
	50%	20%	10%	5%	2%	1%
60	11.6	7.8	8.9	8.5	8.2	6.4
90	11.9	8.3	9.5	9.5	9.4	6.5
120	13.3	8.9	9.9	9.7	9.4	5.7
180	13.3	9.7	10.7	10.2	8.8	4.5
360	13	8.8	8.6	7.9	9	3
720	18.3	13	12.7	10.9	12.1	3.2
1080	18.6	13.6	14.4	12	12.4	3.9
1440	21.6	16.4	16.5	14.2	14.9	4.4
2160	24.7	19	18.6	15.8	16.7	6.3
2880	27.7	22.4	21.7	23.1	19.9	9.5
4320	29.6	25.7	25.8	26.5	22.3	10.4

For design continuing losses, the ARR Data Hub loss is 1.6 mm/h. Recent advice provided by the NSW Government (WMAwater Pty Ltd, 2019) indicates that these losses should be factored by 0.4 for NSW catchments. This results in continuing losses of 0.64 mm/h. These continuing losses were adopted for the calibration event also, as discussed in Section 7.5.

The PMP event adopted an initial loss of 1 mm and continuing loss of 0 mm/h.

9.2.4. Areal Reduction Factor Parameters

Areal Reduction Factors (ARF) account for the fact that larger catchments are less likely to experience high intensity storms across the whole catchment simultaneously. The ARF simply influences the average rainfall depth across the catchment, it does not account for variability in the spatial pattern over the catchment. The following equation and Input parameters were obtained from the ARR Data Hub and are outlined in Table 33 below.

$$ARF = Min\left\{1, \left[1 - a\left(Area^{b} - c\log_{10}Duration\right)Duration^{-d} + eArea^{f}\,Duration^{g}\left(0.3 + \log_{10}AEP\right) + h10^{iArea\frac{Duration}{1440}}\left(0.3 + \log_{10}AEP\right)\right]\right\}$$

Table 33: ARF Input Parameters for the Central Region

Zone	a	b	c	d	e	f	g	h	i
Southern Semi-arid	0.254	0.247	0.403	0.351	0.0013	0.302	0.058	0.0	0.0

The ARF varies with AEP and duration and the resulting matrix of ARFs for the design storms are shown in Table 34.

Table 34: Areal Reduction Factors for the Design Storm Events

Storm Duration (min)	Event (AEP) ARF (%)					
	50%	20%	10%	5%	2%	1%
60	0.71	0.69	0.67	0.66	0.64	0.62
90	0.75	0.73	0.71	0.69	0.67	0.65
120	0.78	0.75	0.73	0.71	0.69	0.67
180	0.81	0.78	0.76	0.74	0.71	0.69
270	0.84	0.82	0.8	0.78	0.76	0.74
360	0.86	0.84	0.83	0.82	0.81	0.79
540	0.88	0.87	0.86	0.86	0.85	0.84
720	0.89	0.88	0.88	0.87	0.86	0.86
1080	0.91	0.91	0.9	0.9	0.89	0.88

9.3. Critical Duration

The critical storm is the temporal pattern and duration that best represents the flood behaviour (e.g. flow, level) for a specific design magnitude. It is generally related to the catchment size, as flow takes longer to concentrate at the outlet from a larger catchment, as well as other considerations like land use, shape, stream characteristics, etc. Peak flow is often used as an indicator to determine the representative temporal pattern, however in overland catchments peak flow can be less representative and peak flood level is a more suitable indicator.

In accordance with ARR 2019 Version 4.1 (Ball, et al., 2019) the critical duration is the storm duration that produces the highest mean flow or level at a point of interest (where the mean is calculated from the ensemble of ten temporal patterns for that duration).

Where there are multiple locations of interest with different contributing catchment sizes, there can be multiple critical durations that need to be considered. This approach requires the ensemble of temporal patterns to be run in both the hydrologic and hydraulic models. This approach was adopted due to the complex nature of the shallow overland flow paths through overland flow models which means that flows at any point in the hydrologic model may not represent the actual flows arriving at that point due to hydraulic controls and cross-catchment flows. The floodplain also exhibits large areas of flood storage, which are driven by volume rather than flow.

Once the critical duration is established, it is usually desirable to select a representative design storm temporal pattern that reproduces this behaviour for all points of interest. This representative storm can then be used for determining design flood behaviour and for future modelling to inform floodplain management decisions. This is typically the storm that produces the next highest flow (or level) above the average (from the ensemble of temporal patterns) for the critical duration. In most cases, however, a representative storm does not necessarily need to be of the same duration as the critical duration, and there may be a number of storms that can represent the critical duration behaviour, potentially at multiple locations and even where the critical duration varies.

Adopting a range of critical durations across a catchment can complicate future analysis and the use of modelling tools if multiple storms need to be simulated to obtain the design flood behaviour for a particular event. Thus, it is preferable to adopt a single representative storm (or as few as required) that is similar to the critical duration behaviour across the entire catchment for each event where possible.

To select the representative storm for each AEP for each of the models, the WBNM hydrologic models were run for durations from 2 hours to 48 hours, with the ensemble of temporal patterns for the 20% AEP, 5% AEP and 1% AEP events (representative of each temporal pattern bin). Each of these storms was then simulated in the TUFLOW model. For each duration, a grid of the mean peak level at each grid cell was calculated for the 10 temporal patterns. A maximum envelope grid was then calculated taking the highest mean peak level for each grid cell for all durations. This shows the critical duration mean peak level at all flooded cells across the study area. The source of the peak mean level for each grid cell was mapped to show the variation in critical duration across the catchment (Figure B32 to B34).

The critical duration is dominated by the 360 minute, 540 minute, 1080 minute and 1800 minute storms. There are significant storage dominated areas throughout the models. These areas, being driven primarily by runoff volume, require a long storm duration to fill them. Through a comparison of the peak flood level grid for each storm with the critical duration mean peak level across the entire study area, a representative storm was selected for each AEP event simulated.

A similar, but simplified approach was undertaken for the PMF event, whereby a single storm was run for durations from 15 minutes to 3 hours. The results indicated that the 180 minute (3 hour) storm was critical across the majority of the model domain. For the purpose of this study, the 180 minute (3 hour) storm was selected as being representative of flooding across the study area.

The selected storms were considered representative for all design events within that temporal pattern bin (Diagram 19). The selected storms were adopted for modelling of the design flood events and processing of flood results. The adopted representative design storms for Howlong are summarised in Table 35.

Table 35: Adopted Representative Design Storms

Temporal Pattern Bin	Events	Duration (mins)	Temporal Pattern ID
Frequent	20% AEP	1800	4170
Intermediate	10% AEP 5% AEP	1800	4164
Rare	2% AEP 1% AEP 0.5% AEP 0.2% AEP	1800	2498
N/A	PMP	180	GSDM GSDM

10. DESIGN FLOOD RESULTS

The 20%, 10%, 5%, 2%, 1%, 0.5% and 0.2% AEP and PMF (or Equivalent Extreme) events were simulated using the adopted Murray River hydrographs for the Murray River model. For the local overland flow flood behaviour, the adopted representative storms were run in the WBNM hydrologic model and the resulting flows were input into the TUFLOW hydraulic model to simulate flood behaviour for the local overland flow catchments. The results for the design flood events are presented in the following appendices:

- Appendix D: Murray River
- Appendix E: Overland Flow

In each appendix, the following maps are provided:

- Peak flood depths and levels in Figure 1 to Figure 24;
- Peak flood velocities in Figure 25 to Figure 48;
- Hydraulic hazard in Figure 49 to Figure 57;
- Hydraulic categories in Figure 58 to Figure 66.

These results are available in electronic GIS and tabular format. The digital data should be used in preference to the figures in this report as they provide more detail. The figures are intended to provide an overview of the results and should not be relied upon for detailed information at individual properties. Property-level affectation should be confirmed by comparing the estimated design flood level(s) for the property with detailed ground survey undertaken by a registered surveyor.

Additional results are presented in the following tables and graphs:

- Peak flood depths and hazard at road crossings in provided in Table 39 and Table 40;
- Peak water level profile for the Murray River in Figure B40.

A discussion of these results is provided in the following sections.

10.1. Summary of Results

10.1.1. Murray River

The flood behaviour for the Murray River can be seen in the peak flood depth / level maps (Figure D1 to D24) and peak velocity maps (Figure D25 to D45). A graph of the peak water level profile along the Murray River is provided in Figure B40. The description of the flood behaviour in each of the design events is provided in below.

- In the 20% AEP event, due to the natural topography and the extensive levee systems, the flood waters are generally contained within the Murray River channel from Yarrawonga to downstream of the Ulupna Island.
- In the 10% AEP event, flood water begins to break out at Murray Riverside Village and near Whites Lagoon in Tocumwal with flood depths up to 1m. In Barooga, a small breakout begins to the north of the golf course. Overall the floodwater is still largely contained within Murray River and it immediate floodplain. Mainstream inundation due to other water bodies including Lalalty Channel, Tuppal Creek and Tocumwal Channel is also observed.

- In the 5% AEP event, flood waters begin to spill into the southern floodplain upstream of Barooga and more extensively into the golf courses at Barooga and Tocumwal. Extensive inundation also spills into the southern and northern floodplains downstream of Tocumwal, surrounding Ulupna Island. A small break out just upstream of Levee No. 5 (Barooga Levee) inundates Barooga-Tocumwal Road during this event. Within Barooga, water begins to pond in the Barooga Cowal as flow enters the urban stormwater system from the river breakouts, mainly near Lawson Drive.
- In the 2% AEP event, backwater extends into the Barooga Cowal with a larger proportion of the Barooga-Tocumwal Road flooded (from the breakout upstream of Levee No. 5 (Barooga Levee). Flows break into the southern floodplain downstream of Barooga and Cobram. Some roads including Vermont Street, Collie Street, Buchanans Road and Snell Road in Barooga are flooded.
- In the 1% AEP event, the Seppelts Levee just upstream of Barooga is overtopped in two locations. Portions of the Barooga golf course are inundated, which extends into the Barooga Cowal. Flows break out of the Barooga Cowal and across Berrigan Road. Flows spread from the Barooga Cowal back towards the Murray River, inundating a larger area of Barooga-Tocumwal Road and Mulwala-Barooga Road, as well as the area behind Levee No. 5 (Barooga Levee). Inundation is also shown to occur in Vermont Street, Collie Street, Banker Street, Snell Road and Howard Street and between Nangunia Street and Buchanans Road. Some farmlands along Berrigan Road in Barooga are inundated during this event. In Tocumwal, the Barooga Cowal inundates parts of the golf course and its crossings of Kelly Street, Tuppal Street, Hennessy Street, Deniliquin Street and Brunton Street. Moving west flows spread across the area generally bound by Racecourse Road, Bruce Birrel Drive, Deniliquin Road and the Newell Highway. There is extensive inundation across the northern and southern floodplain downstream of Tocumwal in this event.
- As the event size increases to the 0.5% AEP, generally the same areas are impacted in Barooga with a slightly broader extent and higher depths of inundation. In Tocumwal a much larger area becomes inundated from river overtopping and backwater from the downstream floodplain inundation.
- In the 0.2% AEP, generally the same areas are impacted in both Barooga and Tocumwal, with slightly deeper inundation.
- In the PMF (or equivalent extreme) event, most of the study area is flooded except for some of the area situated on higher ground.

10.1.2. Local Overland Flow

During a local storm event flow accumulates in localised depressions and channels. In storm events as frequent as the 20% AEP flood waters begin to collect against floodplain features such as roads and levees and localised impacts occur within both Tocumwal and Barooga.

10.1.2.1. Barooga

The Barooga Cowal starts filling up in the 20% AEP event along with the local depression areas. Some properties and roads in the town lying along the flow path running between Buchanans Road to Vermont Street are flooded. Additionally, properties on Barinya Street, Banker Street, Arramagong Street, Gunnamarra Street and Snell Road are inundated as well. Open regions lying along Berrigan Road, north of the town are flooded as well. As the event size increases up to the 0.2% AEP, the flooded area remains the same with some widening in the flood extent and increase in the depth of the inundation. Flooding in localised depressions join to form broader flow paths. In the PMF event, dwellings along Nangunia Street are flooded. Properties lying along the flow path through the town are flooded with depths greater than 1m.

10.1.2.2. Tocumwal

In the 20% AEP event, the flow path between Golf Links Drive and Henessey Street is joined by the Barroga Cowal. Road surfaces including Bruton Street, Charlotte Street, Anthony Avenue, Hill Street, Deniliquin Street are inundated. Properties on Falkiner Street, Hutsons Street, Deniliquin Street, Viceconte Court, Bruton Street, George Street, Henessey Street and Racecourse Road are flooded. Flood water fills up in the part of the town lying to the north which travel south towards Hill Street in larger events, resulting in flooding of the properties lying between George Street and Hills Street. In the 1% AEP event, properties along Nugget Fuller Drive are flooded as well. Generally, as event size increases up to the 0.2% AEP event, the flood extent widens, and flood depths increase with the same regions being impacted as in the 20% AEP event. In the PMF event, the flood extent expands to include a huge proportion of the town.

10.2. Gauge Results

Design flood modelling results at the Tocumwal gauge are provided in Table 36.

Table 36: Design Flood Modelling Results at Tocumwal Gauge

Event	Modelled Flow (ML/D)	Modelled Level (MAHD)	Modelled Stage (m)
20% AEP	125,300	110.76	6.93
10% AEP	181,000	111.21	7.38
5% AEP	229,500	111.50	7.67
2% AEP	267,000	111.59	7.76
1% AEP	284,600	111.60	7.77
0.5% AEP	292,700	111.61	7.78
0.2% AEP	303,600	111.61	7.78
Extreme	589,900	111.64	7.81

At Tocumwal as the frequency of a flood reduces and flow spreads further across both the northern and southern floodplains, the change in depth between events is not significant. A significant volume of water moves into the southern Victorian floodplain above approximately a 1% AEP. This limited scale in flood levels is also observed in the flood record.

Table 37: Comparison to Previous Study Results – Tocumwal

Event	Berrigan Shire Local Flood Plan (2017)	Murray River Flood Plain Management Study (1986)	Modelled Stage (m)
5% AEP	NA	7.39	7.67
2% AEP	7.66	7.68	7.76
1% AEP	8.05/8.14	8.07	7.77

Peak flood levels tend to be lower for events at and above the 1% AEP than previously reported studies (Table 37), however this is consistent with the findings of WMAwater, 2024. WMAwater, 2024 identified that flow can outflank Yarrawonga Weir and flow is likely to exit the system through Mulwala. For comparison previously reported levels for the 1% AEP downstream of Yarrawonga Weir were in the order of 9.8m (Gutteridge Haskins & Davey Pty Ltd, Cameron McNamara Pty Ltd, Laurie Montgomerie & Pettit Pty Ltd, 1986) (URS, 2009), whereas WMAwater, 2024 estimated a level of 9.3m. Previously modelling has not taken into consideration the flow exiting the system through Mulwala or represented the lake and weir with a 2D hydraulic model. The 2D representation allowed validation of the lake and weir behaviour.

10.3. Levees

10.3.1. Levee Performance

Figure B41A to Figure B41G provide the modelled levee crest height in comparison to design flood levels. The following provides a summary of the levee performance during flood events, assuming that they are structurally intact.

Tocumwal Levee Number 1

The levee runs along the northern portion of the Murray River within Tocumwal and just downstream of the town centre along Groutt Lagoon. The levee is not overtopped even in the PMF(or equivalent extreme) event. In the 2% AEP event, although the levee is not overtopped, the flood water begins to go around the levee at its eastern end to join the flow path through the town. Once the flood water fills up within the town, its banks up against the levee. Water also banks up near the portion of the levee downstream of the town.

Tocumwal Pinewood Lane Levee

This levee sits next to Pinewood Lane, approximately 400m east of the end of No. 1 Levee and is not overtopped in any of the modelled events.

Tocumwal Cemetery Levee

This levee is adjacent to Barooga Road and is not overtopped in any of the modelled events.

Tocumwal Levee Number 3 and 4

These levees are located upstream of Tocumwal and are not overtopped in any of the modelled events.

Barooga Levee (Levee Number 5)

This levee is located downstream of Barooga and is not overtopped in any of the modelled events.

Seppelts Levee

The levee is located upstream of the town of Barooga. Small sections of the levee are overtopped in the 1% AEP event. As the event size increases, a larger proportion of the levee is overtopped. The overtopping of the levee begins when the level upstream of the levee exceeds 117.13 m AHD. The corresponding level at the upstream gauge (#409025) during a 1% AEP event is 124.44 mAHD.

10.3.2. Levee Failure

An extensive system of levees exists across both the northern and southern rural floodplains, in addition to urban levees at Cobram, Barooga and Tocumwal. Many reports have indicated the structural integrity of parts of the levee system are either compromised or unknown. As a result failure of portions of the levee system can result in unpredictable flood behaviour. To understand the likely sensitivity of flood levels and extents of inundation to a potential levee failure, a range of scenarios have been assessed. Tocumwal Levee No. 1 has been assessed as two levees with the division at the area of natural high ground to the east of Grout Lagoon.

Each levee has been individually removed from the TUFLOW model to understand the area which the levee protects. The results have been presented in Table 38.

Table 38: Areas Protected by NSW Floodplain Levees

Levee	Location	Area Protected	Maps
Tocumwal Levee #1 (Western)	Just downstream of Tocumwal	Prevents inundation of Tocumwal and the floodplain to the north and west in events as frequent as the 5% AEP.	Figures G1 to G5
Tocumwal Levee #1 (Eastern)	Just downstream of Tocumwal	Prevents inundation of the floodplain to the northwest of Tocumwal in events as frequent as the 5% AEP.	Figures G6 to G10
Tocumwal Levee #2	Just upstream of Tocumwal	Prevents inundation of central Tocumwal as well as Barooga Cowal in events as frequent as the 5% AEP. In the 1% AEP the protected area extends further to the west of Tocumwal.	Figures G11 to G15
Tocumwal Levee #3	~3km upstream of Tocumwal	Provides some protection to Tocumwal in the 1% AEP event, by the 0.2% AEP the removal of this levee has minimal impact on Tocumwal.	Figures G16 to G20
Tocumwal Levee #4	~5km upstream of Tocumwal	Provides protection to Tocumwal and the Barooga Cowal in events as frequent as the 5% AEP. In the 1% AEP event areas both up and downstream of Tocumwal are also protected by this levee.	Figures G21 to G25

Levee	Location	Area Protected	Maps
Levee #5 (Barooga Levee)	Between Barooga and Tocumwal	Provides protection to broad floodplain area to the north and west of Tocumwal as well as the town of Tocumwal in events as frequent as the 5% AEP event. Increases flood levels in the Barooga Cowal in larger events.	Figures G26 to G30
Seppelts Levee	~5km upstream of Barooga	Prevents flow entering the Barooga Cowal in events as frequent as a 5% AEP event. At a 1% AEP event, prevents inundation of the floodplain between Barooga and Tocumwal as well as the town of Tocumwal.	Figures G31 to G35

Figures G36 to G40, show the impacts of removal of all town levees currently defined in the TUFLOW model, in a 5% AEP event, large areas of both the northern (between Barooga and Tocumwal) and southern floodplains become inundated. Inundation extends for almost 10km to the north of Tocumwal, and to areas which under existing conditions remains flood free in the 5% AEP event. As the events become larger, the extent of inundation does not significantly increase, but the depths of inundation increase, in the 0.2% AEP event increases in depth of up to 1m are shown to occur.

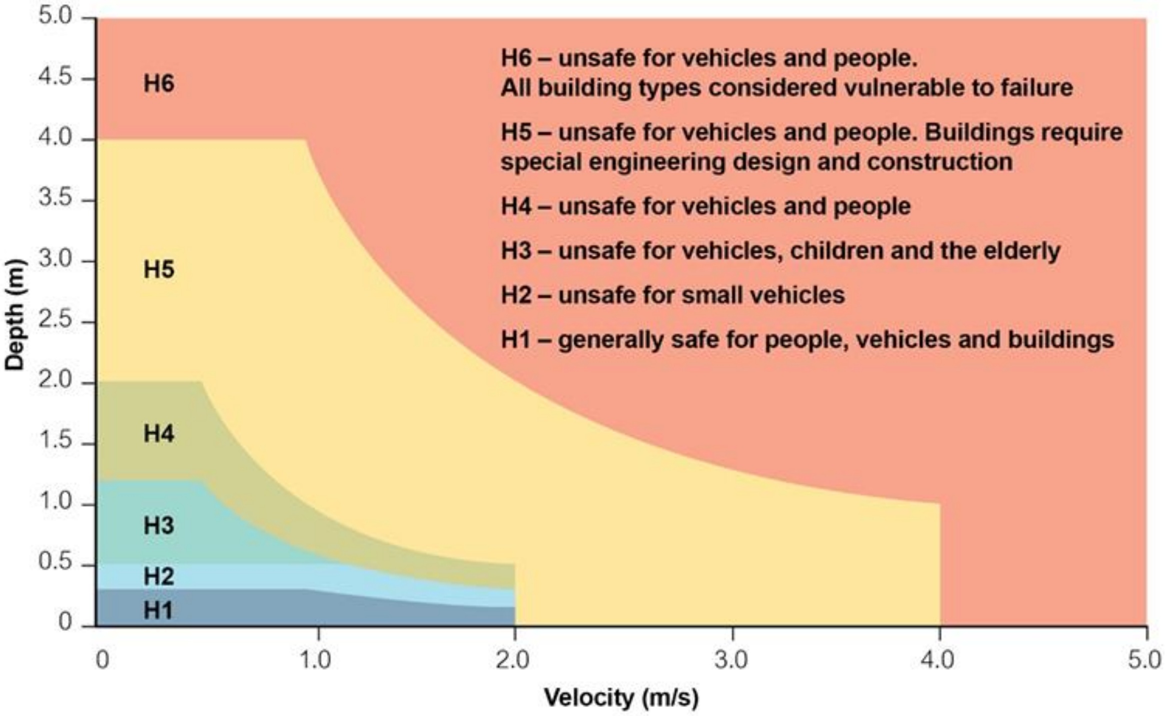
The design flood mapping presents an envelope of a scenario where levees remain completely intact (but can be overtopped) and a scenario where town levees are assumed to fail once the design heigh is exceeded. The method of failure is described in Section 9.1.4. Figure G41 to Figure G45 shows the change in these two scenarios. The most significant impact occurs in the 1% AEP event and larger when the Seppelts Levee is assumed to fail. This is mainly due to the significant benefits afforded to floodplain inundation from the Seppelts Levee.

10.4. Hydraulic Hazard Categorisation

Hazard classification plays an important role in informing floodplain risk management. It reflects the likely impact of flooding on development and people, providing a measure of potential risk to life and property damage, from a flood event. Hydraulic hazard is typically determined by considering the depth and velocity of floodwaters. In recent years, there have been a number of developments in the classification of hazards. Research has been undertaken to assess the hazard to people, vehicles and buildings based on flood depth, velocity and velocity depth product. Hydraulic hazard categories have been determined for the study area in accordance with the NSW Flood Risk Management Manual (Department of Planning and Environment , 2023) and its accompanying guideline FB03 – Flood Hazard (Department of Planning and Environment, 2023). FB03 provides a best practice approach for understanding of the potential vulnerabilities as a result of hydraulic hazard of flood water.

The accompanying guideline FB03 contains information relating to the categorisation of flood hazard. A summary of this categorisation is provided in Diagram 20.

Diagram 20: General flood hazard vulnerability curves



This classification provides distinction of the practical vulnerabilities of hazard categories, identifying the following 6 classes of hazard:

- H1 – Generally safe for vehicles, people and buildings;
- H2 – Unsafe for small vehicles;
- H3 – Unsafe for vehicles, children and the elderly;
- H4 – Unsafe for people and vehicles;
- H5 – Unsafe for people and vehicles. Buildings require special engineering design and construction; and
- H6 – Unsafe for people and vehicles. All building types considered vulnerable to failure.

It should be noted that these classifications are based on the physical flood behaviour in design flood events and do not account for other hazards that may exist (such as, road surface failure, loss of access) or the variability in real storm events.

Figure D49 to Figure D57 present the hazard classifications for the Murray River based on the H1 to H6 delineations for the 5% AEP, 1% AEP, and PMF (or equivalent extreme) events respectively. Figure E49 to Figure E57 provides the hazard classification for the overland flow areas.

10.4.1. Murray River

The majority of the immediate Murray River floodplain is classified as H5 and H6 in the 5% and 1% AEP events. This indicates that the flood water presents hazard constraints to people, vehicles, as well as buildings being vulnerable to structural failure. During the 1% AEP downstream of Tocumwal, the broader floodplain is impacted by hazard categories H1 to H3, with some small areas of higher classifications. Hazard categories H2 and H3 indicate constraints for small vehicles and vulnerable persons through these areas. Higher hazard classifications occur through Ulupna Creek (H6), the downstream areas of Ulupna Island (H4 and H6), between Bullatale Creek and the Murray River (H4 and H5), Bullatale Creek (H5), Native Dog Creek (H4/H5). During the PMF (or equivalent extreme), large areas of the floodplain are also classified as H4 and H5.

At Tocumwal, during the 1% AEP event, the tail end of the Barooga Cowal is classified as H5, but the majority of residential areas are classified as H3 and less. A similar pattern occurs at Barooga, with limited hazard constraints across the residential areas.

10.4.2. Local Overland Flow

During a local storm event which results in overland flow, very few areas are classified above H3 in the 1% AEP event. Those areas with higher hazard classification are floodplain depressions. The same is true within both Barooga and Tocumwal.

During the PMF while there is a greater extent of areas experiencing up to H3, the higher hazard categories are isolated generally to the floodplain depressions.

10.5. Hydraulic Categorisation

Hydraulic categorisation involves mapping the floodplain to indicate which areas are most important for the conveyance of floodwaters and the temporary storage of floodwaters. This can help in planning decisions about which parts of the floodplain are suitable for development, and which areas need to be left as-is to ensure that flooding impacts are not worsened compared to existing conditions.

The Flood Risk Management Manual (Department of Planning and Environment , 2023) defines three hydraulic categories which can be applied to different areas of the floodplain depending on the flood function:

- Floodways;
- Flood Storage; and
- Flood Fringe

Floodways are generally areas which convey a significant portion of water during floods and are particularly sensitive to changes that impact flow conveyance. They often align with naturally defined channels. Flood storage areas are located outside of floodways and generally store a significant proportion of the volume of water.

Flood behaviour in these areas is sensitive to changes that impact on the storage of water during a flood. Flood fringe areas are within the extent of flooding for a particular event but are outside floodway and flood storage areas. The flood fringe is not sensitive to changes in either flow conveyance or storage.

There is no quantitative definition of these three categories or accepted approach to differentiate between the various classifications. The delineation of these areas is somewhat subjective based on knowledge of an area and flood behaviour, hydraulic modelling and previous experience in categorising flood function. A number of approaches, such as that of Howells et al (2003), rely on combinations of velocity and depth criteria to define the floodway.

For this study, hydraulic categories were defined by the following criteria and is considered to be a reasonable representation of the flood function of this catchment:

- Floodway is defined as areas where:
    - the peak value of velocity multiplied by depth (V x D) > 0.05 m^2/s, **AND** peak velocity > 0.2 m/s, **OR**
    - peak velocity > 0.1 m/s **AND** peak depth > 0.4 m;

  The remainder of the floodplain is either Flood Storage or Flood Fringe;
- Flood Storage comprises areas outside the floodway where peak depth > 0.5 m; and
- Flood Fringe comprises areas outside the Floodway where peak depth < 0.5 m.

In the local overland flow models, the above criteria did not produce a continuous floodway in some defined channels and creeks. The flood function based on the indicator method above were used to inform where defined significant flow paths were located. These flow paths were digitised and categorised as floodways.

In the riverine model for the Murray River, the floodway from the indicator method above was generalised and tested in the hydraulic model with an encroachment analysis. The encroachment analysis showed that the parameters used in the indicator method were appropriate, however minor adjustments to the floodway was made in order to achieve a maximum increase in peak flood level of approximately 0.1 m. This encroachment analysis was undertaken for the 1% AEP event.

The hydraulic categories defined in this study are considered to be ‘preliminary’ and subject to review and refinement in a subsequent Flood Risk Management Study.

10.5.1. Murray River

Figure D58 to Figure D66 presents the preliminary hydraulic categorisation of the Murray River in the 5%, 1% AEP and Extreme riverine events. In the 1% AEP event, the Murray River and its immediate floodplain is categorised as a floodway, in addition to the Barooga Cowal and the floodplain areas downstream of Tocumwal. Through Tocumwal the Barooga Cowal continues to be classified as floodway and areas of flood storage occur around Racecourse Road and Short Street.

In Barooga, the Barooga Cowal depression is classified as floodway as well as the area between Vermont Street and Collie Street. Flood storage also occurs between Nangunia Street and Buchanans Road.

10.5.2. Local Overland Flow

Figure E58 to Figure E66 presents the preliminary hydraulic categorisation of the Overland Flow in the 5%, 1% AEP and PMF events. In the 1% AEP event floodplain depressions are classified as floodways with the majority of other inundated areas classified as flood fringe. During this flooding mechanism, in Tocumwal, the Barooga Cowal is a combination of floodway and flood storage, while the area around Racecourse Road is also classified as flood storage. The remaining inundated areas are classified as flood fringe. Within Barooga, flood storage occurs along Snell Road and through the Cowal depression.

10.6. Flood Emergency Response Planning

10.6.1. Flood Emergency Response Classification for Communities

The Flood Risk Management Manual (Department of Planning and Environment , 2023) requires flood studies to address the management of continuing flood risk to both existing and future development areas. As continuing flood risk varies across the floodplain, so does the type and scale of the emergency response problem and therefore the information necessary for effective Emergency Response Planning (ERP). Classification provides an indication of the vulnerability of the community in flood emergency response, a basis for understanding the varying nature, seriousness, and scale of these issues, with a particular emphasis on isolation, across the floodplain. As well as providing the type and scale of information needed by the NSW SES to assist in ERP.

The Flood Emergency Response Classification for Communities (FERCC) for the study area was undertaken in accordance with the NSW Flood Risk Management Manual (Department of Planning and Environment , 2023) and its accompanying guideline EM01 – Support for Emergency Management Planning (Department of Planning and Environment, 2023). FERCCs consider flood affected communities as those in which the normal functioning of services is altered, either directly or indirectly, and results in the need for external assistance. This impact relates directly to the operational issues of evacuation, resupply and rescue, which is coordinated by the SES.

The FERCC for the study area were defined using the Murray River PMF (or equivalent extreme) flood event with existing development within the study area and can be seen on Figure B50 and Figure B51. The classification has been undertaken on a precinct basis rather than lot-by-lot and is targeted at highlighting those areas which may require evacuation or assistance during a flood event. However, these classifications may vary depending on local flood characteristics and resultant flood behaviour. These categories are described in Diagram 21 below.

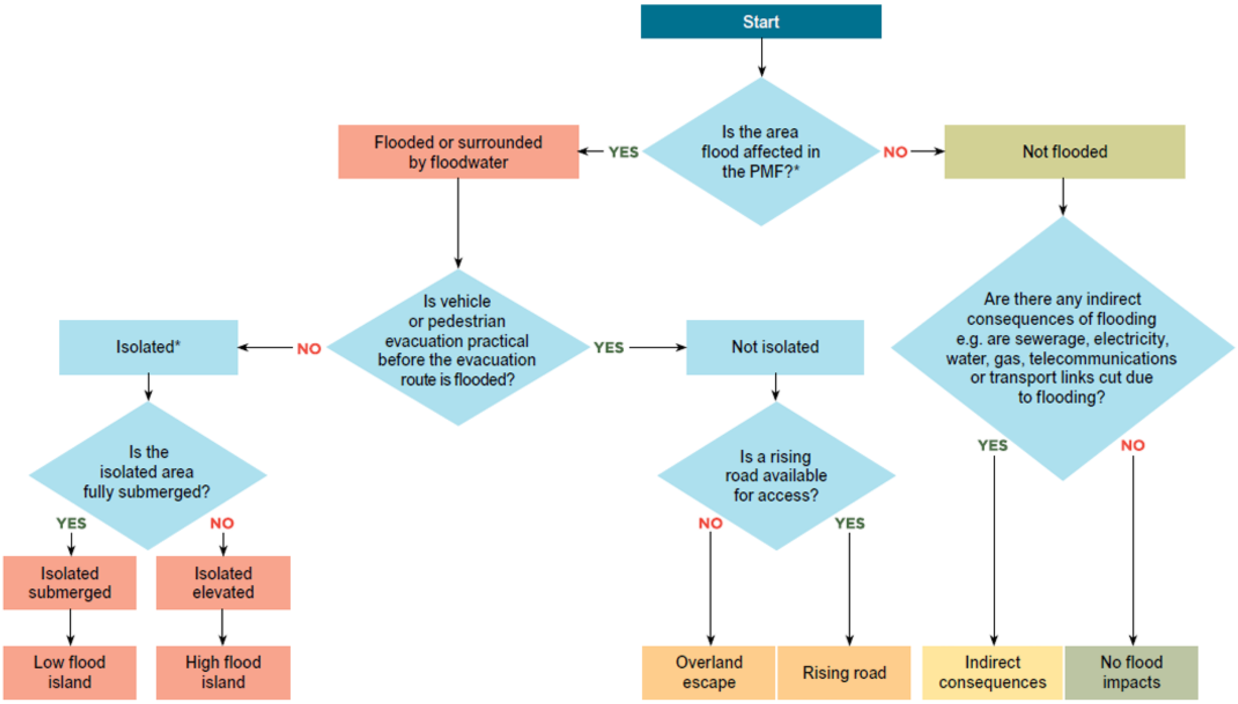


Diagram 21: Flow Chart for Determining Flood Emergency Response Classifications (Department of Planning and Environment, 2023)

The FERCC for Barooga and Tocumwal was undertaken with consideration of the PMF event. At Tocumwal the town is surrounded by floodwater with many areas inundated, almost the entire town is classified as flood affected, isolated and submerged (FIS/Low Flood Island).

Barooga is also surrounded by floodwater, however a number of areas remain elevated above the PMF event. These areas are flood affected areas that are isolated and elevated (FIE/High Flood Island) and are located along Snell Road, Banker Street, Collie Street, Wirunia Street and the intersection of Buchanans Road and Hughes Street. The majority of the remaining area is classified as flood affected, isolated and submerged (FIS/Low Flood Island).

10.6.2. Murray River

10.6.2.1. Property Inundation

At Tocumwal and Barooga, property floor levels are generally not impacted until the 2% AEP event from Murray River inundation. Most properties are either not flooded over floor or flooded in the PMF (or equivalent extreme) event. At Barooga there are a small number of properties impacted in the 5% AEP event.

Figure B36 and Figure B38 provide mapping of the property floor level database intersected with the design flood information to provide an understanding of potential property impacts in the study area.

10.6.2.2. Road Inundation

Road inundation was assessed for major crossings of the Murray River as well as impacted roads across the floodplain. This information is important to understand potential access constraints and isolation times in an emergency planning context. The analysis draws on the information presented in Figure D1 to Figure D24 (Section 10.1.1) for flood depth and Figure D49 to Figure D57 for hydraulic hazard (Section 10.4.1) for the locations shown on Figure B41.

The majority of roads have flood immunity up to and including the 2% AEP. Frequently impacted roads include:

- Amaroo Avenue,
- Hughes Street,
- Barooga-Tocumwal Road (ID 45),
- Newell Highway (ID52),
- Tuppal Road (ID 55 and 56),
- Lower River Road (ID 57).

Hydraulic hazard categorisation provides an understanding of when it is unsafe for vehicle and pedestrian access on roads, for example hydraulic hazard category H2, is considered unsafe for small vehicles, H3 is considered unsafe for all vehicles and vulnerable persons and H4 is considered unsafe for all people. For the roads that are impacted in the 5% AEP, the hazard classification is H3 and above and therefore considered unsafe for all vehicles.

A summary of peak flood depths and hazard categorisation at these road crossings is provided in Table 39.

Table 39: Design Flood Depths for Murray River Impacted Roads

Map ID	Road	Hydraulic Hazard			Depth of Inundation (m)							
		5% AEP	1% AEP	PMF	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP	PMF
28	MULWALA-BAROOGA ROAD		H2	H3					0.46	0.53	0.61	1.08
29	STOCK ROUTE ROAD		H4	H4					1.26	1.28	1.31	1.54
30	MULWALA-BAROOGA ROAD		H3	H4					0.65	0.70	0.76	1.11
31	MULWALA-BAROOGA ROAD		H4	H4					1.20	1.23	1.27	1.54
32	MULWALA-BAROOGA ROAD		H5	H5					2.09	2.12	2.16	2.41
33	MULWALA-BAROOGA ROAD		H2	H3					0.34	0.37	0.39	0.63
34	HUGHES STREET		H4	H5					1.74	1.79	1.86	2.25
35	HUGHES STREET		H4	H4					1.38	1.41	1.45	1.74
36	AMAROO AVENUE	H3	H5	H5			0.58	1.61	2.27	2.33	2.41	2.87
37	NANGUNIA STREET		H4	H4				0.61	1.28	1.33	1.41	1.86
38	HUGHES STREET	H2	H5	H5			0.49	1.51	2.18	2.23	2.31	2.77
39	KAMAROOKA STREET		H3	H3					0.50	0.56	0.64	1.10
40	SNELL ROAD		H4	H5				0.01	1.41	1.43	1.47	1.91
41	KAMAROOKA STREET		H4	H5				0.36	2.00	2.01	2.05	2.42
42	SNELL ROAD		H4	H5				0.12	1.81	1.82	1.85	2.13
43	BAROOGA-TOCUMWAL ROAD		H3	H3					0.60	0.57	0.62	1.11
44	BAROOGA-TOCUMWAL ROAD		H4	H5				1.16	1.55	1.56	1.58	2.02
45	BAROOGA-TOCUMWAL ROAD	H4	H4	H4			1.53	1.79	1.86	1.88	1.89	2.00
46	BAROOGA-TOCUMWAL ROAD		H4	H5					1.07	1.53	1.56	2.21
47	BAROOGA-TOCUMWAL ROAD		H2	H5					0.44	0.91	0.92	1.66
48	BAROOGA ROAD			H1						0.04	0.05	0.11
49	JERILDERIE STREET		H1	H4					0.05	0.85	0.86	1.11
50	BRUTON STREET		H2	H4					0.30	0.94	0.95	1.42
51	NEWELL HIGHWAY		H3	H5					0.74	1.30	1.31	1.72
52	NEWELL HIGHWAY			H6						2.58	2.59	3.19

		Hydraulic Hazard			Depth of Inundation (m)							
Map ID	**Road**	**5% AEP**	**1% AEP**	**PMF**	**20% AEP**	**10% AEP**	**5% AEP**	**2% AEP**	**1% AEP**	**0.5% AEP**	**0.2% AEP**	**PMF**
53	NEWELL HIGHWAY			H4						0.75	0.76	1.27
54	TUPPAL ROAD		H3	H5					0.55	1.55	1.56	2.05
55	TUPPAL ROAD			H3								0.92
56	TUPPAL ROAD			H2								0.47
57	LOWER RIVER ROAD											
58	MULWALA-BAROOGA ROAD		H3	H4					0.61	0.68	0.75	1.23
59	SNELL ROAD		H5	H5				0.05	2.19	2.20	2.22	2.49
60	BERRIGAN ROAD		H1	H2					0.09	0.11	0.12	0.40
61	BERRIGAN ROAD		H2	H4					0.35	0.39	0.42	1.09
62	BERRIGAN ROAD			H2								0.44
63	BERRIGAN ROAD			H2							0.01	0.38
64	BERRIGAN ROAD			H3								0.99
65	PEPPERTREE ROAD			H3								1.16
66	PEPPERTREE ROAD			H5						0.87	1.01	2.13
67	PEPPERTREE ROAD		H2	H5					0.49	1.81	1.85	3.04
68	WOOLSHED ROAD			H4						1.16	1.19	1.95
69	WOOLSHED ROAD			H4						0.70	0.74	1.62
70	WOOLSHED ROAD			H4						0.65	0.68	1.64
71	WOOLSHED ROAD			H3								1.15
72	THE ROCKS ROAD			H3						0.24	0.29	1.18
73	RACECOURSE ROAD			H3						0.04	0.05	0.75
74	MURRAY STREET		H1	H4					0.26	0.84	0.85	1.32
75	HONNIBALL DRIVE		H3	H4					0.56	1.20	1.21	1.70
76	MURRAY STREET		H1	H4					0.27	0.82	0.83	1.27
77	BAROOGA-TOCUMWAL ROAD			H2								0.36
1	SHERWINS ROAD											

Map ID	Road	Hydraulic Hazard			Depth of Inundation (m)							
		5% AEP	1% AEP	PMF	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP	PMF
2	BERRIGAN ROAD											
3	BERRIGAN ROAD											
4	COBRAM ROAD											
5	COBRAM ROAD											
6	COBRAM ROAD											
7	COBRAM ROAD											
8	COBRAM ROAD											
9	COBRAM ROAD											
10	BERRIGAN ROAD											
11	COBRAM ROAD											
12	SANDHILLS ROAD											
13	BOXWOOD ROAD											
14	PINEY ROAD											
15	PINEY ROAD											
16	PINEY ROAD											
17	MARDENOORA ROAD											
18	COLDWELLS ROAD			H3								0.74
19	WOMBOIN ROAD			H5								1.77
20	MULWALA-BAROOGA ROAD		H1	H5					0.20	0.49	0.73	2.21
21	BACK BAROOGA ROAD			H5								2.15
22	BACK BAROOGA ROAD			H5								3.33
23	ENNALS ROAD			H6								5.27
24	STILLARDS ROAD			H6								6.39
25	KENNEDYS ROAD			H6								4.52
26	KENNEDYS ROAD			H6								4.44
27	COLDWELLS ROAD			H6								3.58

10.6.3. Local Overland Flows

10.6.3.1. Property Inundation

At Tocumwal, overland flow flooding impacts isolated areas within the town, resulting in over floor flooding around Hutsons Road, Adamas Street, Kelly Street, Cobram Street, George Street, Moore Street and Hill Street. Very few properties are impacted in the 2% AEP event, with the majority of those impacted, not impacted until the PMF.

At Barooga, property impacts begin to occur in the 20% AEP along Hughes Street. Other impacted streets include Snell Road, Buchanans Road, and Banker Street.

Figure B37 and Figure B39 provide mapping of the property floor level database intersected with the design flood information to provide an understanding of potential property impacts in the study area.

10.6.3.2. Road Inundation

Road inundation was assessed for roads across the floodplain in a local storm event. The analysis draws on the information presented in Figure E1 to Figure E24 (Section 10.1.2) for flood depth and Figure E49 to Figure E57 for hydraulic hazard (Section 10.4.2) for the locations shown on Figure B42.

The majority of roads have flood immunity up to and including the 5% AEP. Frequently impacted roads include:

- Amaroo Avenue,
- Hughes Street,
- Kamrooka Street,
- Snell Road,
- Barooga-Tocumwal Road (ID 45 and 77),
- Mulwala-Barooga Road (ID 58)
- Peppertree Road,
- Woolshed Road,
- The Rocks Road
- Racecourse Road,
- Sherwin Road,
- Berrigan Road,
- Cobram Road
- Sandhills Road,
- Boxwood Road.

Hydraulic hazard categorisation provides an understanding of when it is unsafe for vehicle and pedestrian access on roads, for example hydraulic hazard category H2, is considered unsafe for small vehicles, H3 is considered unsafe for all vehicles and vulnerable persons and H4 is considered unsafe for all people.

In the 5% AEP event, the hazard classification is at H3 and above for Hughes Street, Amaroo Avenue, Newell Highway (ID 52), Sandhills Road, Stillards Road and Kennedy’s Road.

A summary of peak flood depths and hazard categorisation at these road crossings is provided in Table 40.

Table 40: Design Flood Depths for Overland Flow Impacted Roads

Map ID	Road	Hydraulic Hazard			Depth of Inundation (m)							
		5% AEP	1% AEP	PMF Event	20% AEP event	5% AEP	1% AEP	2% AEP event	1% AEP event	5% AEP	1% AEP	PMF Event
28	MULWALA-BAROOGA ROAD		H1	H1						0.01	0.03	0.21
29	STOCK ROUTE ROAD		H1	H3					0.03	0.13	0.25	1.10
30	MULWALA-BAROOGA ROAD			H2								0.37
31	MULWALA-BAROOGA ROAD			H3								0.61
32	MULWALA-BAROOGA ROAD			H3								0.66
33	MULWALA-BAROOGA ROAD			H1								0.11
34	HUGHES STREET			H3							0.04	0.59
35	HUGHES STREET		H1	H2					0.03	0.04	0.04	0.47
36	AMAROO AVENUE	H3	H3	H4	0.51	0.65	0.76	0.85	0.87	0.91	1.03	1.54
37	NANGUNIA STREET		H1	H3				0.02	0.04	0.08	0.19	0.71
38	HUGHES STREET	H3	H3	H4	0.62	0.76	0.87	0.96	0.98	1.02	1.14	1.65
39	KAMAROOKA STREET			H1								0.27
40	SNELL ROAD			H3								1.01
41	KAMAROOKA STREET	H2	H2	H4	0.09	0.24	0.32	0.37	0.43	0.52	0.66	1.83
42	SNELL ROAD	H1	H2	H4	0.00	0.13	0.21	0.27	0.33	0.41	0.55	1.73
43	BAROOGA-TOCUMWAL ROAD			H1								0.01
44	BAROOGA-TOCUMWAL ROAD		H1	H3				0.11	0.14	0.17	0.24	0.67
45	BAROOGA-TOCUMWAL ROAD	H1	H1	H2		0.06	0.11	0.13	0.17	0.20	0.23	0.49
46	BAROOGA-TOCUMWAL ROAD			H2								0.38
47	BAROOGA-TOCUMWAL ROAD			H1								0.12
48	BAROOGA ROAD											
49	JERILDERIE STREET			H1								0.13
50	BRUTON STREET			H1								0.29
51	NEWELL HIGHWAY		H1	H3					0.07	0.17	0.27	0.58
52	NEWELL HIGHWAY	H5	H5	H6	0.72	1.16	1.48	1.83	2.08	2.23	2.32	2.95

			Hydraulic Hazard				Depth of Inundation (m)					
Map ID	Road	5% AEP	1% AEP	PMF Event	20% AEP event	5% AEP	1% AEP	2% AEP event	1% AEP event	5% AEP	1% AEP	PMF Event
53	NEWELL HIGHWAY											
54	TUPPAL ROAD			H1						0.08	0.09	0.16
55	TUPPAL ROAD											
56	TUPPAL ROAD											
57	LOWER RIVER ROAD											
58	MULWALA-BAROOGA ROAD	H1	H1	H1				0.01	0.18	0.22	0.23	0.26
59	SNELL ROAD	H1	H3	H4	0.10	0.18	0.30	0.47	0.57	0.66	0.80	1.97
60	BERRIGAN ROAD		H1	H1					0.03	0.04	0.04	0.12
61	BERRIGAN ROAD		H1	H1					0.02	0.02	0.02	0.07
62	BERRIGAN ROAD		H1	H1								0.05
63	BERRIGAN ROAD		H1	H1						0.02	0.01	0.10
64	BERRIGAN ROAD		H1	H1					0.01	0.03	0.04	0.10
65	PEPPERTREE ROAD	H1	H1	H3		0.01	0.04	0.08	0.11	0.17	0.16	0.57
66	PEPPERTREE ROAD	H2	H3	H3	0.24	0.35	0.45	0.47	0.51	0.60	0.59	1.02
67	PEPPERTREE ROAD		H1	H3				0.01	0.02	0.02	0.02	0.67
68	WOOLSHED ROAD		H1	H2				0.03	0.08	0.11	0.15	0.40
69	WOOLSHED ROAD	H1	H1	H1	0.01	0.01	0.02	0.02	0.02	0.04	0.08	0.30
70	WOOLSHED ROAD	H1	H1	H3			0.08	0.16	0.24	0.28	0.33	0.70
71	WOOLSHED ROAD	H1	H2	H2	0.23	0.26	0.29	0.30	0.31	0.32	0.33	0.43
72	THE ROCKS ROAD	H1	H1	H1						0.02	0.05	0.20
73	RACECOURSE ROAD	H1	H1	H1			0.01	0.06	0.07	0.08	0.09	0.19
74	MURRAY STREET	H1	H1	H2							0.04	0.35
75	HONNIBALL DRIVE	H1	H1	H2	0.01	0.01	0.05	0.08	0.11	0.12	0.14	0.37
76	MURRAY STREET		H1	H2				0.01	0.02	0.02	0.05	0.33
77	BAROOGA-TOCUMWAL ROAD	H1	H1	H2			0.01	0.01	0.05	0.09	0.12	0.32
1	SHERWINS ROAD		H1	H4				0.07	0.17	0.26	0.40	1.28

		Hydraulic Hazard										
Map ID	Road	5% AEP	1% AEP	PMF Event	20% AEP event	5% AEP	1% AEP	2% AEP event	1% AEP event	5% AEP	1% AEP	PMF Event
							Depth of Inundation (m)					
2	BERRIGAN ROAD	H1	H1	H1	0.04	0.05	0.06	0.07	0.07	0.08	0.08	0.22
3	BERRIGAN ROAD	H1	H1	H2	0.16	0.18	0.19	0.21	0.21	0.22	0.23	0.46
4	COBRAM ROAD	H1	H1	H3			0.04	0.08	0.12	0.14	0.16	0.64
5	COBRAM ROAD	H1	H1	H3			0.02	0.05	0.08	0.09	0.11	0.65
6	COBRAM ROAD		H1	H2					0.14	0.20	0.23	0.31
7	COBRAM ROAD		H1	H2					0.12	0.17	0.20	0.38
8	COBRAM ROAD		H1	H3					0.12	0.22	0.26	0.66
9	COBRAM ROAD	H1	H1	H2	0.01	0.06	0.09	0.16	0.22	0.25	0.29	0.43
10	BERRIGAN ROAD	H1	H1	H3	0.07	0.10	0.14	0.18	0.20	0.23	0.26	0.58
11	COBRAM ROAD	H1	H2	H3	0.22	0.26	0.28	0.31	0.32	0.33	0.33	0.57
12	SANDHILLS ROAD	H3	H3	H4	0.93	0.94	0.96	0.99	1.02	1.03	1.05	1.25
13	BOXWOOD ROAD	H1	H1	H2	0.12	0.13	0.14	0.16	0.18	0.19	0.21	0.44
14	PINEY ROAD	H1	H1	H3	0.16	0.17	0.19	0.21	0.25	0.28	0.33	0.60
15	PINEY ROAD		H3	H3				0.31	0.79	0.85	0.91	1.18
16	PINEY ROAD	H2	H2	H3			0.32	0.42	0.47	0.53	0.59	0.87
17	MARDENOORA ROAD	H1	H1	H3	0.18	0.21	0.22	0.23	0.28	0.39	0.51	1.01
18	COLDWELLS ROAD	H1	H1	H2	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.16
19	WOMBOIN ROAD	H1	H1	H3	0.17	0.20	0.23	0.26	0.27	0.28	0.30	0.72
20	MULWALA-BAROOGA ROAD		H1	H1							0.01	0.05
21	BACK BAROOGA ROAD	H1	H1	H2		0.01	0.04	0.08	0.12	0.15	0.19	0.34
22	BACK BAROOGA ROAD		H1	H2				0.01	0.03	0.04	0.06	0.46
23	ENNALS ROAD	H2	H3	H5	0.21	0.37	0.49	0.59	0.69	0.75	0.82	1.62
24	STILLARDS ROAD	H5	H5	H5	1.97	2.13	2.25	2.36	2.47	2.55	2.63	3.64
25	KENNEDYS ROAD	H3	H3	H5	0.29	0.45	0.58	0.70	0.83	0.91	1.01	2.02
26	KENNEDYS ROAD	H1	H1	H4	0.01	0.02	0.05	0.12	0.24	0.32	0.41	1.44
27	COLDWELLS ROAD	H2	H3	H5	0.02	0.18	0.30	0.41	0.50	0.56	0.62	1.29

10.7. Preliminary Flood Planning Area

10.7.1. Background

Land use planning is an effective means of minimising flood risk and damages from flooding. Land use planning for flooding can be achieved through the use of:

- A Flood Planning Area (FPA), which identifies land that is subject to flood related development controls; and
- A Flood Planning Level (FPL), which identifies the minimum floor level applied to development proposals within the FPA.

Defining FPAs and FPLs in urban areas can be complicated by the variability of flow conditions between mainstream and local overland flow. Traditional approaches developed for riverine or "mainstream" flow areas often cannot be applied in overland flow areas. Additionally, defining the area of flood affectation due to overland flow (which by its nature includes shallow flow) involves determining at which point flow is significant enough to be classified as "flooding" rather than just a drainage or local runoff issue. In some areas of overland flow, the difference in peak flood level between events of varying magnitude can be so minor that applying the typical freeboard can result in a FPL greater than the PMF level. Further to this the relatively small increases in depth for Murray River flooding in larger events and the complex levee system, also limit the use of traditional approaches to the development of the Flood Planning Area.

The FPA should include properties where development would result in impacts on flood behaviour in the surrounding area and in areas of high hazard where there is a risk to safety or life. The FPL is determined in addition to this with the purpose of decreasing the likelihood of damage such as over-floor flooding of buildings.

The Flood Risk Management Manual (NSW Department of Planning and Environment 2023) identifies that the FPL is generally be based on the 1% AEP event plus an appropriate freeboard (typically 0.5 m). However, it also recognises that different freeboards may be deemed appropriate due to local conditions provided adequate justification is provided.

The freeboard can be considered as a compulsory 'safety factor' used to provide reasonable certainty that the reduced flood risk exposure provided by selection of a particular flood as the basis of an FPL, is actually provided given the following factors:

- Uncertainty in estimating flood levels, this results from the degree of uncertainty associated with each element used in determining design flood levels, such as model inputs, parameter assumptions, etc;
- Differences in water level because of local factors, such as local water surge due to localised blockages or vehicles moving through flood water;
- Increases due to wave action as a result of vehicles moving through flood waters or the influences of wind.

Further consideration of flood planning areas and levels is typically undertaken as part of the Flood Risk Management Study to determine what should be included in the Flood Risk Management Plan and as such, the FPA derived as part of this study is considered to be preliminary. This is particularly important for areas where a varied approach may be required, for example where the application of the 0.5m freeboard encompasses the entire study area. Alternative approaches may want to consider an increase in flow rather than level to define the Flood Planning Area.

10.7.2. Methodology

The methodology used for defining the flood planning divides the flood area between "mainstream" and "overland" flooding areas as follows:

- Mainstream flooding: For the purpose of this study, it is assumed that mainstream flooding is due to the Murray River only. While there are a number of flow paths and creeks within the towns that drain reasonably large catchments (and may be traditionally considered "mainstream" flooding) these are not included for the mainstream FPA. Further discussion is provided below. For the Murray River, a traditional approach was adopted of adding freeboard to the flood surface and the extent is then "stretched" to intersect with the land. The FPA for the Murray River was defined as the 1% AEP peak flood level plus 0.5 m freeboard, with the level extended perpendicular to the flow direction. In some locations this level was below the crest of the existing levees. The extent was clipped to floodplain features such as road which would in reality would obstruct the flood extent.

- Overland flooding: Overland flooding for the purpose of the FPA is defined as those areas modelled in the local overland flow model. It is noted that these areas include some significant creeks, however, these areas were not treated the same way as the "mainstream" FPA described above. The addition of freeboard and stretching in these areas generally produces an over-estimate of the land subject to flood risk. This is because the stretching extends across land in a way that would not actually occur even with significant additional flow from a much larger storm event. It may even extend beyond the modelled PMF extent. It is therefore appropriate to not apply freeboard for the purpose of defining the FPA for overland flooding. The addition of freeboard on any flood surface encompasses a significant portion of the towns. As such, the 0.2% AEP event was adopted as a proxy for the 1% AEP event with a 'freeboard' added to account for uncertainties. Utilising an actual event results in a more reasonable flood extent than 'stretching' a hypothetical flood surface.

The resultant extent of the preliminary mainstream Murray River FPA can be seen in Figure B43 and the preliminary overland FPA on Figure B44. For Tocumwal and Barooga, the combined riverine and overland FPA are shown on Figure B45 and Figure B46.

10.8. Advice on Land-Use Planning Considering Flooding

It is considered good practice (and a requirement of the Environmental Planning and Assessment Act 1979) to permit land use and development that is compatible with the nature of flooding in a particular area. For example, it is wise to limit use and development of land that is classified as floodway, since these are areas of conveyance and not only pose significant risks to humans, but any development in these areas can alter flood risks to other areas.

10.8.1. Existing Flood Planning Controls Review

Berrigan Shire Council implements flood-related planning controls in the study area via the Berrigan Local Environmental Plan (LEP) 2013 and the Berrigan Development Control Plan (DCP) 2014. The LEP specifies that land is subject to flood-related restrictions if it is within the flood planning area for any type of development (Clause 5.21). The LEP was prepared under the Standard Instrument LEP program and incorporates the revised flood clause introduced as part of the NSW Government's Flood Prone Land Package that commences on 14 July 2021. The Flood Prone Land Package also included a second optional clause 'Special Flood Consideration' which provides Councils the mechanism to apply development controls to land outside the FPA but within the PMF. This clause is specific to land with a significant risk to life, sensitive, vulnerable or critical uses, or land with hazardous materials or industry. Berrigan Shire Council has not adopted this clause. The LEP outlines the overall objectives and nature of these restrictions and the DCP supports the implementation of the LEP objectives, providing specific guidance for design and assessment of proposed developments. Section 11 of the DCP specifies flood-related development controls that apply to land affected by flooding. The DCP controls appear to focus on mainstream Murray River flooding only.

A high-level review of the existing Berrigan Shire DCP has been undertaken as part of this study and the outcomes are included in Table 41.

Table 41: Berrigan Shire DCP Recommendations

Aspect	Comment
Flood Risk Precinct Matrix Approach	The DCP adopts a matrix approach, with controls and performance criteria varying based on the type of development (such as residential, recreational uses and flood control works) and the flood risk precinct (Low Hazard Flood Storage, High Hazard Flood Storage, Low Hazard Floodway, High Hazard Floodway). This general approach, which aligns controls with the level of hazard and inherent vulnerabilities of different development types, is considered generally consistent with current best practice. Refinements to the number of development types, to allow for variable degrees of vulnerability (such as aged care) and the risk precincts could be made to further align with best practice.
Flood Risk Precincts	Update and expand flood risk precinct definitions to match the ARR 2019 hazard (H1 – H6) and flood function categories. This will also allow more refinement in the applied controls based on the specific vulnerabilities and constraints within a particular hazard or flood function category. The current precincts utilise a high and low hazard, which do not align with ARR 2019 or Flood Risk Management Guideline FB03 (Department of Planning and Environment, 2023). The current precincts do not provide controls for areas of flood fringe.

Aspect	Comment
	The use of flood risk precincts is common across NSW. This approach to categorising the flooding provides some breakdown of flood risk however, does not clearly combine common constraints as the flood planning constraint category (FPCC) approach, which is outlined in Section 10.8.2, does. While the flood risk precinct approach is considered appropriate, the FPCC approach provides further detail and considers a range of flood related development constraints and should be considered for implementation.
Controls	The flood-related development controls specified in the DCP could be broken downs to cover minimum floor levels, building components (flood compatible materials), structural soundness (to ensure buildings can withstand flood forces), flood impacts (not making flooding worse for neighbouring properties) and consideration of safety for people, vehicles and the environment. Many of these controls exist and are appropriate for Murray River flooding, revision would be required to ensure suitability for overland flow flooding.
PMF	The DCP notes the difficulties in determining the extent of the PMF. Terminology could be updated to reference the Equivalent Extreme event for Murray River flooding and PMF event for overland flooding and appropriate controls applied to these areas. This would also allow for the application of LEP Clause 5.22 (currently not adopted) which provides considerations of flood risk up to the PMF (or Equivalent Extreme) event, particularly for sensitive and hazardous uses.
Terminology	Update reference to outdated documents, including Floodplain Development Manual 2005, Section 6.2 of the LEP to Flood Risk Management Manual 2023, ARR 2019 and Section 5.21 of the LEP. Replace ARI with AEP in accordance with ARR 2019. AEP is considered best practice terminology. Update definition of Flood Prone Land, currently DCP refers to Flood Prone Land as land identified as flood planning area. Flood Prone Land is the floodplain or flood affected land, which includes the extent of the PMF (or Equivalent Extreme Event) Update other definitions to align with the Flood Risk Management Manual 2023.
DCP/LEP	Changes to the NSW Government planning framework in relation to flooding saw the introduction of Clauses 5.21 and 5.22 (currently not adopted), as well as the removal of a flood planning level definition from LEPs. The DCP currently refers to Clause 6.2 in the LEP (rather than Clause 5.21) and refers to flood planning mapping associated with the LEP.
Objectives	Update objectives to align with LEP and Environmental and Planning Assessment Act 1979.
Nature of Flooding	The nature of flooding column provided specific metrics to describe the flood behaviour, the refined flood risk precinct definition should be used to ensure consistency.
Flooding Implications	The flooding implications column could be updated based on the relevant constraints for the refined flood risk precincts.

Aspect	Comment
Flood Planning Level	LEP has been updated with the introduction of Clause 5.21 to exclude the definition of the FPL. The DCP currently contains a definition of the FPL of 1% AEP plus 500mm. It is assumed that this applies only to Murray River flooding and considerations should be given to including a definition for a separate overland flow FPL. The typically flat terrain and the scale of flood behaviour in overland flooding mean a 500mm freeboard may not be appropriate for overland flow flooding.
Flood Planning Area	The FPA is typically the land at or below the flood planning level, where the flood planning level is typically the 1% AEP event plus a freeboard. The current DCP specifies that the freeboard is 500 mm. With the relatively flat terrain and limited scale in flooding, a 500 mm freeboard may not be appropriate and may result in an FPA that extends beyond the PMF. The DCP provides a definition for the flood planning area but does not present the flood planning area or risk precinct mapping. The DCP refers to mapping in the LEP, changes to the NSW Government planning framework in relation to flooding has removed the FPA overlay from the LEP. Ensure map is available on Council's website if separate from the DCP, flood planning area to be updated based on results from this flood study.
Minimum Floor Level	A matrix approach is used to specify minimum floor levels per development type and flood risk precinct. The freeboard (where applicable), however, is set at 500 mm. A variable freeboard is recommended for overland flow flooding and may depend on the flood risk precinct and development type. This should be updated to the PMF for overland flow flooding.
Flood Proofing	The DCP refers to the use of flood compatible materials, this could be expanded with consideration of flood compatible electrical components, structural soundness and storage of hazardous materials are included in the DCP.
Flood Impacts	The DCP should review which precincts require the consideration of flood impacts, based on the flooding constraints for the precinct. For example, currently Low Hazard, Flood Storage, does not require the consideration of flood impacts, however development within flood storage areas may result in a change in flood behaviour elsewhere and should be considered.
Evacuation	Evacuation requirements should be reviewed in line with the constraints for each refined precinct up to the PMF (or Equivalent Extreme) event. Evacuation requirements in the DCP should be updated to require consideration of overland flow flooding in which sufficient warning time may not be available, including where shelter in place may be appropriate.
Fencing	Fencing and landform requirements are typically prescribed to prevent boundary and internal fences from obstructing natural path of overland flow. There are no prescriptive controls for fencing.
Carparking	The DCP does not specify controls for carparking areas, including basement carparks.
Special Flood Considerations	The LEP currently does not include the *Special Flood Considerations* clause. Changes to the NSW Government planning framework in relation to flooding allows Council the opportunity to include a second clause within their LEPs which applies to land between the FPA and the PMF extent and considers sensitive and hazardous uses in addition to those uses which may have evacuation constraints.

Aspect	Comment
	This inclusion empowers Council to apply controls that ensure the developers of such facilities appropriately consider and plan for the full range of flood risk at the site, so as to reduce potential property damages and minimise the risk to life in future flood events. This would also require a map of the area to which this clause applies to be available in Council’s DCP.
Future Climate	The DCP does not consider climate change. The DCP should be updated to incorporate climate change in two ways. Firstly, climate change should be considered as part of flood impact assessments, where climate change impacts should be modelled to manage risk of future climate change. Secondly, development controls should be integrated with consideration of climate change. It is recommended that Council includes climate change in flood-related development controls considering best available climate change data to combat future increased rainfall intensity.

10.8.2. Flood Planning Constraint Categories

The Flood Risk Management Manual (Department of Planning and Environment , 2023) and its supporting guideline FB01 – Understanding and Managing Flood Risk (Department of Planning and Environment, 2023) recommends using Flood Planning Constraint Categories (FPCC) to better inform land use planning activities. These categories condense the wealth of flood information produced in a flood study and classify the floodplain into areas with similar degrees of constraint. These FPCCs can be used in high level assessments of land use planning to inform and support decisions for strategic planning. For detailed land use planning activities, it is recommended that the flood behaviour across the range of flood events be considered, depending on the level of constraint. For detailed land use planning activities, it is recommended that the flood behaviour across the range of flood events be considered, depending on the level of constraint.

The Flood Risk Management Manual and its supporting guideline, recommends the use of four constraint categories. It is recommended that isolation potential also be considered for the high constraint category. This could include areas classified as low flood island or high flood island, refer to Section 10.6). Isolation has not been considered in the preliminary FPCCs defined for the study area.

In land use planning for greenfield areas, it is assumed that any development would be accompanied by new roads and access routes which may change the isolation potential of the land. In areas that are already developed, the isolation potential has been defined using Flood Emergency Response Classifications (see Section 10.6), and land use planning activities should consider these in addition to the preliminary FPCCs.

The constraints defined by Flood Risk Management Manual and its supporting guideline have been adapted to suit the study area and are outlined in Table 42. The associated FPCC map can be found on Figure B47, Figure B48 and Figure B49.

Table 42: Flood Planning Constraint Categories

FPCC	Constraints	Implications	Considerations
FPCC 1	Floodway and flood storage areas in the 1% AEP event H6 hazard in the 1% AEP event	Any development is likely to affect flood behaviour in the 1% AEP event and cause negative impacts on the existing community and other property. Hazardous conditions considered unsafe for vehicles and people, all types of buildings considered vulnerable to structural failure.	Majority of developments and uses have adverse impacts on flood behaviour or are vulnerable. Consider limiting uses and developments to those that are compatible with flood function and hazard.
FPCC 2	Floodway in the 0.2% AEP event H5 flood hazard in the 1% AEP event H6 flood hazard in the 0.2% AEP event	People and buildings in these areas may be affected by dangerous floodwaters in rarer events. Hazardous conditions considered unsafe for vehicles and people, and all buildings vulnerable to structural damage. Hazardous conditions develop in rare events which may have implications for the development and its occupants.	Many uses and developments will be vulnerable. Consider limiting new uses to those compatible with flood function and hazard (including rarer flood flows) or consider treatments to reduce the hazard (such as filling). Consider the need for additional development control conditions to reduce the effect of flooding on the development and its occupants.
FPCC 3	Within the FPA	Hazardous conditions may exist creating issues for vehicles and people. Structural damage to buildings that meet building standards is unlikely.	Standard land use and development controls aimed at reducing damage and the exposure of the development to flooding are likely to be suitable. Consider additional conditions for emergency response facilities, key community infrastructure and land uses with vulnerable users.
FPCC 4	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.

11. SENSITIVITY ANALYSIS

11.1. Overview

A number of sensitivity analyses were undertaken to establish the potential variation in design flood levels and flows that may occur if different parameter assumptions were made. These sensitivity scenarios are summarised in Table 43.

Table 43: Overview of Sensitivity Analyses

<table>
<tr><th rowspan="3">Parameter</th><th rowspan="3">Flood Mechanism</th><th rowspan="3">Tested Conditions</th><th colspan="12">Impact (m) 1% AEP</th></tr>
<tr><th colspan="6">Maximum</th><th colspan="6">Average</th></tr>
<tr><th colspan="3">-20%</th><th colspan="3">+20%</th><th colspan="3">-20%</th><th colspan="3">+20%</th></tr>
<tr><td>Mannings ‘n’ roughness</td><td>Overland</td><td>+/- 20%</td><td colspan="3">-2.26</td><td colspan="3">0.66</td><td colspan="3">0.00</td><td colspan="3">0.00</td></tr>
<tr><td></td><td>Riverine</td><td>+/- 20%</td><td colspan="3">0.03</td><td colspan="3">2.34</td><td colspan="3">-0.08</td><td colspan="3">0.08</td></tr>
<tr><td>Catchment Lag (C)</td><td>Overland</td><td>+/- 20%</td><td colspan="3">0.34</td><td colspan="3">0.14</td><td colspan="3">0.00</td><td colspan="3">0.00</td></tr>
<tr><td>Rainfall Loss IL and CL)</td><td>Overland</td><td>+/- 20%</td><td colspan="3">0.68</td><td colspan="3">0.02</td><td colspan="3">0.00</td><td colspan="3">0.00</td></tr>
<tr><td rowspan="2">Representative Storm</td><td rowspan="2">Overland</td><td rowspan="2">Minimum and Maximum Temporal Pattern from Ensemble</td><th colspan="3">Min TP</th><th colspan="3">Max TP</th><th colspan="3">Min TP</th><th colspan="3">Max TP</th></tr>
<tr><td colspan="3">0.67</td><td colspan="3">1.38</td><td colspan="3">-0.23</td><td colspan="3">0.02</td></tr>
<tr><td rowspan="2">Blockage</td><td rowspan="2">Overland</td><td rowspan="2">50% and Floodgates open</td><th colspan="3">50%</th><th colspan="3">Open</th><th colspan="3">50%</th><th colspan="3">Open</th></tr>
<tr><td colspan="3"></td><td colspan="3"></td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td rowspan="2"></td><td rowspan="2">Riverine</td><td rowspan="2">25%/50%/75%</td><th colspan="2">25%</th><th colspan="2">50%</th><th colspan="2">75%</th><th colspan="2">25%</th><th colspan="2">50%</th><th colspan="2">75%</th></tr>
<tr><td colspan="2">2.1</td><td colspan="2">2.96</td><td colspan="2">3.95</td><td colspan="2">0.00</td><td colspan="2">0.01</td><td colspan="2">0.05</td></tr>
<tr><td rowspan="2">Levee Flood Gates</td><td rowspan="2">Riverine</td><td rowspan="2">Open/50% Blocked</td><th colspan="3">Open</th><th colspan="3">50%</th><th colspan="3">Open</th><th colspan="3">50%</th></tr>
<tr><td colspan="3">0.00</td><td colspan="3">2.24</td><td colspan="3">0.00</td><td colspan="3">0.00</td></tr>
<tr><td rowspan="2">Downstream boundary condition (slope)</td><td rowspan="2">Riverine</td><td rowspan="2">0.1%/0.01%</td><th colspan="3">0.1%</th><th colspan="3">0.01%</th><th colspan="3">0.1%</th><th colspan="3">0.01%</th></tr>
<tr><td colspan="3">0.73</td><td colspan="3">1.36</td><td colspan="3">0.00</td><td colspan="3">0.03</td></tr>
<tr><td rowspan="2">Climate Change (for the 1% AEP event)</td><td rowspan="2">Overland</td><td rowspan="2">0.5% AEP (2050) / 0.2% AEP (2100)</td><th colspan="3">2050</th><th colspan="3">2100</th><th colspan="3">2050</th><th colspan="3">2100</th></tr>
<tr><td colspan="3">1.87</td><td colspan="3">1.89</td><td colspan="3">0.07</td><td colspan="3">0.10</td></tr>
<tr><td></td><td>Riverine</td><td></td><td colspan="3">2.26</td><td colspan="3">2.39</td><td colspan="3">0.04</td><td colspan="3">0.08</td></tr>
</table>

The change in flood level across the study area for each scenario compared to the adopted design 5%, 1% AEP and PMF (or equivalent extreme) flood events are provided in Appendix F.

11.2. Mannings 'n' Roughness

The adopted Mannings 'n' roughness coefficients for the design flood events are shown in Table 16. For sensitivity analyses, the Mannings 'n' roughness coefficient was increased and decreased by 20% for all land types across the study area. The changes in peak flood levels with decreasing and increasing the Mannings 'n' roughness values for the 5%, 1% AEP and PMF events are shown on Figure F1, Figure F2, Figure F9, Figure F10, Figure F17, Figure F18, Figure F28 and Figure F29.

For the riverine event in the Murray River, the results indicate that decreasing the surface roughness results in lower peak flood levels across most of the river. Flood levels decrease through the Barooga Cowal by up to 0.5m in the 1% AEP. Areas surrounding the Barooga Cowal through Tocumwal and Barooga are also shown to be no longer flooded.

Conversely, in the riverine event, increasing the surface roughness results in higher peak flood levels across the Murray River floodplain. Flood levels are increased through the Barooga Cowal by up to 0.5m and an increased extent of inundation is observed to the north of Barooga and west of Tocumwal.

The overland flow model has been shown to be relatively insensitive to changes in Mannings 'n' roughness coefficients, changes fall into the range of +/-0.1m for both the increase and decrease scenario and are localised to depression areas for the 5% and 1% AEP event. In the PMF event the changes are more widespread but generally remain in the +/- 0.1m range.

11.1. Catchment Lag

Catchment lag factor (termed 'C' in the WBNM model) delays and attenuates runoff response to rainfall. The 'C' lag factor of 1.6 was adopted as it is the recommended default value for an ungauged catchment in NSW. The adopted lag factor was increased and decreased by approximately 20% (1.9 and 1.3, respectively) for this sensitivity analysis.

The changes in peak flood levels for the overland model with decreasing and increasing the catchment lag values for the 5%, 1% AEP and PMF events are shown on Figure F3, Figure F4, Figure F11, Figure F12, Figure F19 and Figure F20.

The model results are relatively insensitive to changes in the catchment lag parameter, with levels generally changing by less than 20 mm and small isolated areas, generally in catchment depressions by +/-0.1m. These changes are consistent with a slight increase or decrease in the speed of flows through the catchment.

11.2. Rainfall Losses

Rainfall losses were adopted from the ARR Data Hub (see Section 9.2.3). Initial losses were taken from the ARR Data Hub's probability neutral burst initial losses, which vary based on the AEP and duration of the storm. The continuing loss adopted was 0.64 mm/h, based on the factored ARR Data Hub loss values. A sensitivity analysis was undertaken for both initial loss and continuing loss, where both were adjusted by +/- 20%.

The changes in peak flood levels for the overland model with decreasing and increasing the rainfall losses for the 5%, 1% AEP and PMF events are shown on Figure F5, Figure F6, Figure F13 and Figure F14, Figure F21 and Figure F22.

Both the increase and reduction in losses has minimal impact, <0.1m flood level difference in both the 5% and 1% AEP events, which is most evident in depression channels and floodplain storages due to the slight increase in runoff. During the PMF there is negligible change in levels, this can be attributed to the proportionally small value of losses compared to PMP rainfall.

11.3. Representative Storm Pattern

The representative storm aims to produce the medium catchment response and is derived from a range of critical durations and an ensemble of 10 temporal patterns.

A comparison was made between the selected representative storm and the smallest and largest result from the temporal pattern ensemble. This allows the possible range in flood levels to be understood. The changes in peak flood levels for the overland model with the minimum and maximum temporal pattern results for the 5% and 1% AEP events are shown on Figure F7, Figure F8, Figure F15, and Figure F16.

The results indicate that the absolute range of flood levels, that is from minimum to maximum temporal pattern result is generally around 0.1m and 0.2m, for the 5% and 1% AEP event, respectively. For both events, the range is greater across floodplain depressions, up to 0.5m in the 5% AEP and up to 0.6m in the 1% AEP event.

11.4. Structure Blockage

Sensitivity of the adopted blockage factors of hydraulic structures for the design events were assessed for the riverine model. This consisted of adjusting the assumed blockage at the bridge structures to 25%, 50% and 75% for the 1% AEP event. Additionally, sensitivity in the overland flow model assumed blockage at structures of 50% as well as a scenario where the levee flood gates were assumed to be open to allow for free draining.

The changes in peak flood level are shown on Figure F23, Figure F24, Figure F25, Figure F36 and Figure F37. At Tocumwal with a blockage of 25% applied to Goulburn Valley Highway and railway bridge, flood levels increase through the town by up to 0.3m and the extent of inundation increases to the north and west of town.

Increases of up to 0.1m also occur along the southern floodplain. There are small areas of flood level reductions up to 0.1m downstream of the bridge. At Barooga, the increased blockage to the Barooga-Cobram Road bridge results in a small area of increased flood levels of up to 0.1m in the Barooga Cowal.

Increasing the blockage to 50% results in similar absolute changes in flood level but extends the area of impact at Tocumwal, both within the town and across the southern floodplain. At Barooga, levels increase by less than 0.1m but the area impacted is more extensive to the northwest of town and on the southern floodplain.

At a blockage of 75%, flood levels increase by more than 0.5m through Tocumwal and the extent of inundation increases to the northwest. On the southern floodplain levels increase by up to 0.5m. At Barooga, the extent of impacted area also increases with flood levels increasing by up to 0.2m.

Within the overland flow model domain with application of a 50% blockage to floodplain culverts local flood levels are shown to increase by up to 0.2m at Melrose Lane, Mardenoora Road, Winters Road and Berrigan Road, with an increase of greater than 0.5m at Sherwins Road.

In the scenario where the levee gates remain open to allow free drainage of overland flows, flood levels are reduced locally by up to 0.1m

11.5. Levee Flood Gates

Levee flood gates are designed to prevent river floodwaters entering the protected area during events. For design conditions the levee floodgates are assumed to be closed. The tested scenario considered the levee gates open and with a 50% blockage applied. The changes in peak flood level are shown on Figures F26 and Figure F27 for the 1% AEP event. The most significant impact occurs at Tocumwal where flood levels are increased within and to the northwest of the town by up to 0.3m and the extend of inundation is larger for the 50% blockage scenario.

11.6. Downstream Boundary Conditions

For the design flood events, floodplain breakout areas are applied as a stage-discharge relationship with an adopted slope of 1%. The stage-discharge relationship is determined within the TUFLOW software based on the specified slope. To test the sensitivity of this stage-discharge relationship, the slope was reduced to 0.1% and 0.01%.

The change in peak flood level due to decreasing the boundary is shown on Figure F30 and Figure F31. Decreasing the slope results in less water being able to exit the model.

The most sensitive area is across the southern floodplain where levels increase by up to 0.3m and the extent of inundation is greater. At Barooga the increased level on the southern floodplain results in an increase of up to 0.1m through the Barooga Cowal. At Tocumwal, the increase is up to 0.2m, through the sensitive north west area.

On the northern floodplain at the downstream limit of the model levels also increase by greater than 0.5m, against the downstream boundary and reduce to an increase of less than 0.1m within a few kilometres of the boundary.

11.7. Climate Change

Climate change is expected to increase sea levels and rainfall intensities. It is typical practice in catchment flood studies under the NSW Floodplain Management Program to model scenarios incorporating the effects of these impacts from climate change to understand the potential future changes in flood behaviour.

Various projections of the likely increases to sea levels are available, however, receiving waters of the Murray River are not influenced by the ocean in the study area. Any increase in design flood rainfall intensities will increase the frequency, depth and extent of inundation across the catchment. The primary driver for this change is under a warmer climate, the atmosphere can hold more water, and hence more rainfall can occur in any given storm event. The design rainfall information currently provided by the BoM is based on historical climate data and does not currently include any allowance for likely increases to rainfall intensity in the future. ARR 2019 Version 4.1 (Ball et al 2019) provides some guidance about consideration of the impacts of climate change on design rainfall intensities. It suggests assuming that rainfall intensities can be assumed to scale up by 7 - 8% per degree of average surface warming.

Projected increases to evaporation under a warmer climate are also an important consideration because increased evaporation would lead to generally drier catchment conditions, resulting in lower runoff from rainfall. Mean annual rainfall is projected to decrease, which will also result in generally dryer catchment conditions and potentially lower average dam storage levels. This may be a significant factor for the Murray River catchment.

The current NSW State Government’s advice recommends sensitivity analysis on flood modelling should be undertaken to develop an understanding of the effect of various levels of change in the hydrologic regime on the study area (NSW Department of Planning and Environment 2023).

To understand potential changes to flood behaviour due to increased intensity of rainfall, the 0.5% AEP and 0.2% AEP events were compared with the 1% AEP event, as suggested in the NSW Flood Risk Management Manual (NSW Department of Planning and Environment 2023). These events provide an indication of how 1% AEP flood levels would change if the rainfall intensity increased to the point that it matches either the current 0.5% AEP (7% increase in flows) or 0.2% AEP (16% increase in flows). The change in peak flood levels, comparing the 0.5% AEP event and 0.2% AEP with the 1% AEP event can be seen in Figure F32 to Figure F35.

ARR 2019 Version 4.2 has recently released further advice on how the impacts of climate change should be assessed. The application of these guidelines should be reviewed in future studies to ensure that an understanding of the potential impacts of climate change are understood.

In comparison to the 1% AEP event, the 0.5% AEP flood levels for the Murray River are higher by approximately 0.2m at Barooga, while at Tocumwal increases of up to 0.3m occur. Across the Murray River floodplain, flood levels increase by up to 0.2m. To the north of both Barooga and Tocumwal, the extent of inundation increases in the larger event.

Similarly, the 0.2% AEP flood levels for the Murray River are higher than the 1% AEP levels by more than 0.2m. Increases through Barooga and Tocumwal are up to 0.5m and the extent of inundation is greater.

These results indicate that the Murray River may be highly sensitive to climate change, although the long duration storms required to produce flooding in the Murray River catchment, in addition to the overall drier conditions may result in runoff increases that are not as high as those expected for the local catchments.

For the areas impacted by overland flow in local storm events, in comparison to the 1% AEP, the increases in flood level are generally up to 0.1m and 0.2m, for the 0.5% and 0.2% AEP events, respectively. In both scenarios there are greater increases in localised depressions and against channel and road obstructions where flows are shown to pond.

12. ECONOMIC IMPACTS OF FLOODING

12.1. Background

The economic impact of flooding can be estimated through the calculation of flood damages. While flood damage calculations do not include all impacts associated with flooding, they do, however, provide a basis for assessing the economic loss of flooding and also provide a non-subjective means of assessing the merit of flood mitigation works such as retarding basins, levees, drainage enhancement etc. The quantification of flood damages is an important part of the floodplain risk management process. By quantifying flood damage for a range of design events, appropriate cost-effective management measures can be analysed in terms of their benefits (reduction in damages) versus the cost of implementation. The cost of damage and the degree of disruption to the community caused by flooding depends upon many factors including:

- The magnitude (depth, velocity and duration) of the flood,
- Land use and susceptibility to damages,
- Awareness of the community to flooding,
- Effective warning time,
- The availability of an evacuation plan or damage minimisation program,
- Physical factors such as failure of services (sewerage), flood borne debris, sedimentation, and
- The types of assets and infrastructure affected.

The estimation of flood damages tends to focus on the physical impact of damages on the human environment, but there is also a need to consider the ecological cost and benefits associated with flooding. Flood damages can be defined as being tangible or intangible. Tangible damages are those for which a monetary value can be easily assigned (for example damage to buildings, infrastructure, furnishings, goods or stock), while intangible damages are those to which a monetary value cannot easily be attributed (for example social costs such as increased levels of mental stress, loss of sentimental items, inconvenience to people, injury or loss of life). Types of flood damages are shown in Table 44.

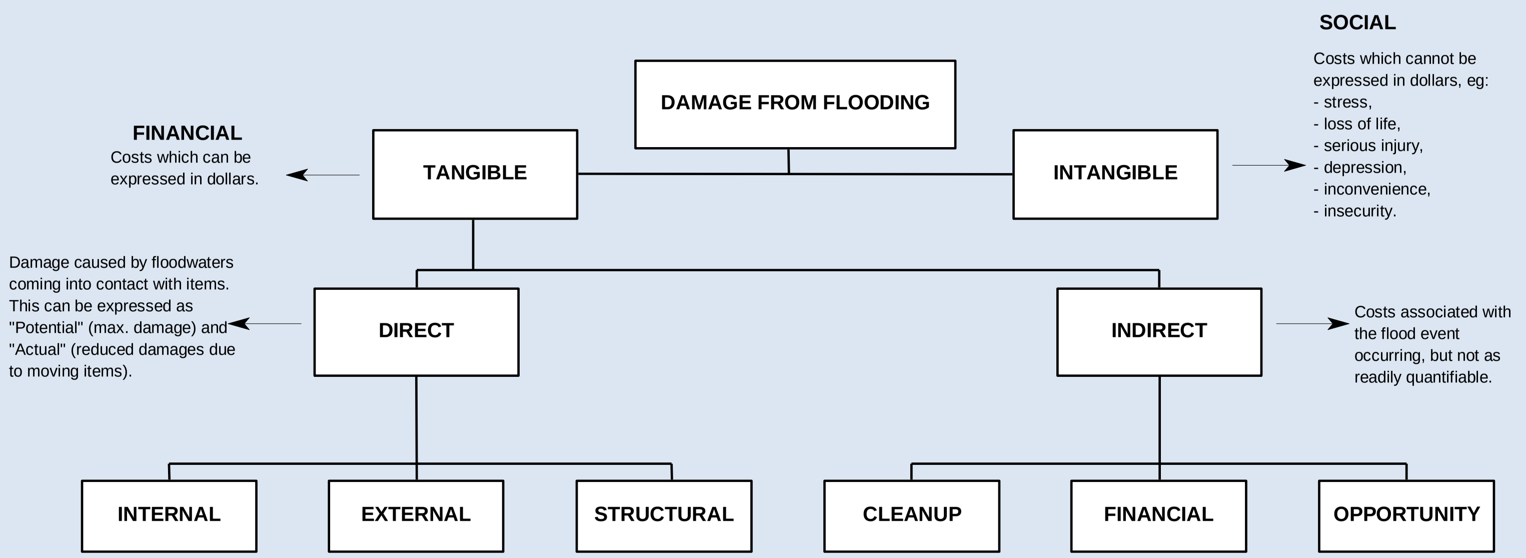
The assessment of flood damages not only quantifies potential costs due to flooding but also identifies when properties are likely to become flood affected by either flooding on the property or by over floor flooding, as shown in Figure B36 and Figure B37.

The total likely damages in any given flood event are difficult to quantify precisely, given the variable nature of flooding and the property and content values of houses affected. Design flood damages are estimated to obtain an indication of the magnitude of the flood problem and compare the economic effectiveness of proposed mitigation options. Understanding the total damages prevented over the life of a mitigation option in relation to current damages, or to an alternative option, can assist in the decision-making process.

Estimation of flood damage has focussed on residential and community buildings in the study area using guidelines issued by the NSW Government (Department of Planning and Environment , 2023) and recognised damage assessment methodologies. The most common approach to present flood damage data is in the form of flood-damage curves for a range of property types, i.e. residential, commercial, public property, public utilities etc. These relate flood damage to depth of flooding above a threshold level (usually floor level). The estimation of damage is based upon a flood level relative to the floor level of a property. These damage curves are then factored 6.26% (according to the consumer price index) to adjust the damages from its initial estimates (in 2022) to current day dollars. Additionally, these damages are varied for different regions in the state. The study area is located within the Central Land Division and requires a regional cost adjustment factor of an additional 10%.

The assumed parameters and flood damage curve assumptions are outlined in the following sections.

Table 44: Flood Damages Categories (including damage and losses from permanent inundation)



	INTERNAL	EXTERNAL	STRUCTURAL	CLEANUP	FINANCIAL	OPPORTUNITY
RESIDENTIAL	Contents of Buildings: Clothes, Carpets, Furniture, Valuables, Fittings, Appliances	External Items: Vehicles, Laundries, Caravans, Sheds, Tools, Gardens, Fences	Physical Damage to Buildings: Gyprock, Cupboards, Scour of Footings, Houses becoming buoyant (floating off footings)	Clean Carpets, Walls, Clothes; Re-instate Furniture; Remove Mud and Debris	Loss of wages, Living costs (temporary accomodation and food), Time to repair/replace damaged items	Not Applicable
RURAL	Contents of Buildings: Clothes, Carpets, Furniture, Valuables, Fittings, Appliances	External Items: Vehicles, Sheds (stables/barns), Machinery, Tools, Fences, Feed storage, Saddles, Crops &/or Stock, Irrigation Systems	Physical Damage to Structures: Damage to Homestead, Sheds, Access tracks, Protection levees	Clean Homestead and Out-buildings; Remove Debris; Dispose of affected crops &/or stock	Loss of Farm Production and Income, Re-instatement of Pastures, Supplementary feeding of stock (by hand or outside agistment), Stock movement/ transport, Living costs (temporary accomodation and food)	Sowing or harvesting of Crops, Sale of Stock (at depreciated value or dependent on market influences)
COMMERCIAL	Contents of Buildings: Products, Stock, Fittings, Tools, Machinery, Raw Materials	External Items: Vehicles, Machinery, Display, Raw Materials/Stockpiles, Fences	Physical Damage to Buildings	Dispose of damaged products, stock, materials; Cleaning and Re-instatement	Loss of Productivity and Income, Bank Interest Charges	Loss of existing &/or Potential Trade
PUBLIC AUTHORITIES	Contents of Public Buildings and Facilities	Public Property and Facilities: Parks, Signs, Machinery, Equipment	Physical Damage to Infrastructure: Electricity, Water, Telephone, Gas, Road & Rail Transport Links	Remove Mud & Debris from Facilities, Public & Private Property Repairs (temporary & permanent)	Disruption of Services, Community Service Relief Grants	Provision of Public Service

12.2. Residential Flood Damages

Tangible flood damages are comprised of two basic categories; direct and indirect damages. Direct damages are caused by floodwaters wetting goods and possessions thereby damaging them and resulting in either costs to replace or repair or in a reduction to their value. Direct damages are further classified as either internal (damage to the contents of a building including carpets, furniture), structural (referring to the structural fabric of a building such as foundations, walls, floors, windows) or external (damage to all items outside the building such as cars, garages). Indirect damages are the additional financial losses caused by the flood for example the cost of temporary accommodation, loss of wages by employees etc.

Given the variability of flooding, property and content values, the total likely damages figure in any given flood event is useful to get a feel for the magnitude of the flood problem, however it is of little value for absolute economic evaluation. Flood damages estimates are also useful when studying the economic effectiveness of proposed mitigation options. Understanding the total damages prevented over the life of the option in relation to current damages, or to an alternative option, can assist in the decision-making process.

In order to quantify the damages caused by inundation for existing development, the floor level database was used (see Section 3.8) in conjunction with modelled flood level information to calculate damages. The flood damages assessment was undertaken for existing development in accordance with current NSW Government guidelines (Department of Planning and Environment , 2023). The damages were calculated using a number of height-damage curves which relate the depth of water above the floor with tangible damages. Each component of tangible damages is allocated a maximum value and a maximum depth at which this value occurs. Any flood depths greater than this allocated value do not incur additional damages as it is assumed that, by this level, all potential damages have already occurred.

12.2.1. Direct Internal Damages

Internal damages were assumed to follow the default damages of $550 per square metre (in 2022 dollars) adopted in the guideline (Department of Planning and Environment , 2023) for residential properties. The actual damage to contents in an event can be reduced by actions taken during the warning time available in response to a flood threat. These actions may include raising goods and furniture, moving valuable items to the kitchen benchtop, onto tables, or up to the second storey, and taking some valuables as part of evacuation, if possible. The default value of 0.9 for the actual to potential damage ratio in the guideline (Department of Planning and Environment , 2023) was adopted for this study area.

12.2.1.1. Direct Structural Damages

Structural damages were assumed to follow the default damages relationships to the dwelling size and number of storeys adopted in the guideline (Department of Planning and Environment , 2023). Damage per m^2 is assumed to be $2,280 for single storey houses and $2,620 for double storey houses and $2,730 for units and $2,620 for townhouses. As the dwelling size has not been obtained, all houses were assumed to have the default size of 220 m^2 and units and townhouses were assumed to be 100 m^2 and 160 m^2, respectively. In floods larger than the 1% AEP event there is the possibility that some buildings may collapse or have to be demolished. The cost of these damages have not been included in the analysis.

12.2.1.2. Direct External Damages

The default external damages of $17,000 (in 2022 dollars) in the guideline (Department of Planning and Environment , 2023) were adopted. This fixed external damage value was applied when the flood depth above ground level exceeded 300 mm or was above the habitable floor level.

12.2.1.3. Indirect Damages

Indirect damages were assumed to follow the default damage relationship in the guideline (Department of Planning and Environment , 2023). That is, for residential clean-up costs of $4,500 (in 2022 dollars) and relocations costs of $441 per week (in 2022 dollars) will apply if over floor inundation exists. Non-residential indirect costs, which cover clean-up costs and loss of trading are 30% of the direct damages.

12.2.2. Non-residential Buildings

12.2.2.1. Commercial Properties and Public Buildings

Damage curves for commercial, industrial, and public buildings were adopted from the guideline (Department of Planning and Environment , 2023). Direct damages (accounting for structural and contents damage) to these buildings are based on the value classification of the building as well as the floor area.

Commercial and industrial buildings are classified as low to medium, medium/default, and medium to high. The low to medium damage curves are factored by 0.6 of the default and medium to high damage curves are factored by 1.5. Commercial and industrial buildings were used the medium/default damage curve as no further information on these buildings had been provided. As no information on floor area of each commercial and industrial building was provided, the default area of 418 m^2 was adopted. Actual to potential damage ratio was assumed to be 0.9.

Public buildings were classified as low/default and medium to high categories. The low/default damage curves for public buildings were assumed to be 40% of the medium/default commercial damage curve, whereas medium to high public buildings damage curve were assumed to be the same as the medium/default commercial damage curve.

12.2.3. Intangible Damages

Intangible damages were assumed to follow the default damage relationship in the guideline (NSW Department of Planning and Environment 2023). These intangible damages cover social and wellbeing impacts of flooding to the community. These intangible damages have been incorporated in this assessment and were found to contribute only a small portion of the total flood damages (<10%).

12.3. Estimated Flood Damages

An estimation of the number of properties impacted, number of properties with above floor flooding and total damage costs for each modelled flood event was undertaken for each of the model areas. Properties estimated to be flooded above floor due to Murray River inundation can be seen on Figure B36 and Figure B38. Properties estimated to be flooded above floor due to local overland flow flooding can be seen in Figure B37 and Figure B39 .

A typical measure used to estimate flood damages over a range of flood events is the Annual Average Damage (AAD). AAD represents the equivalent average damages that would be experienced by the community on an annual basis, by taking into account the probability of a flood occurrence over the long term. The AAD value is determined by multiplying the damages that can occur in a given flood by the probability of that flood actually occurring in a given year, and then summing across a range of floods. This method allows smaller floods, which occur more frequently to be given a greater weighting than the larger catastrophic floods that only occur rarely. The AAD for the existing case then provides a benchmark by which to assess the merit of flood management options.

A summary of the flood damages is provided in Table 45 and Table 46 The damages associated with the Murray River event and overland flow event have been presented separately. Residential damages and the total damages (which include residential, commercial and public buildings, along with infrastructure damages) are provided separately. The total number of properties affected is also presented in these tables. The number of lots affected indicates that the flood level was higher than the ground level near the building on the property and the number of lots affected above floor indicates that the flood level was higher than the floor level.

Tocumwal and Barooga are affected in Murray River events. The number of properties affected increases from 11 to 378 from the 5% AEP to 0.5% AEP. This indicates that there are few residential properties that become inundated up to the 2% AEP (78). In the PMF event, the number of affected properties is substantially higher (918). The AAD due to Murray River flooding in the study area is approximately $1.5M, or $1,400 per flood affected property in the PMF event.

Overland flow events in the study area typically have a gradual increase in the number of properties affected with increasing flood magnitude. Most of the flood damage (52%) is caused by more frequent events, such as the 20% AEP. The AAD due to overland flow is more than the Murray River, due to the relatively high numbers of impacted properties in the frequent events, and is approximately $2.7M, or $3,800 per flood affected property in the PMF.

Table 45: Summary of Estimated Murray River Flood Damages

Flood Event		No. Lots Affected	No. Lots Flooded Above Floor Level	Total Damages for Event	Average Damage Per Flood Affected Property	% of AAD
Residential	20% AEP	0	0	0	0	0%
	10% AEP	0	0	0	0	0%
	5% AEP	25	10	$1,516,867	$60,674	2%
	2% AEP	94	56	$10,311,286	$109,694	9%
	1% AEP	470	246	$43,761,977	$93,110	14%
	0.5% AEP	935	827	$175,958,161	$188,190	27%
	0.2% AEP	952	852	$180,864,120	$189,983	27%
	PMF	1,067	1,013	$244,935,285	$229,555	21%
	Average Annual Damages			**$1,993,914**	**$1,868**	
Total	20% AEP	0	0	$0	$0	0%
	10% AEP	0	0	$0	$0	0%
	5% AEP	25	10	$1,668,554	$66,742	2%
	2% AEP	105	64	$11,543,429	$109,937	8%
	1% AEP	518	281	$53,266,840	$102,830	14%
	0.5% AEP	1051	935	$210,336,815	$200,015	27%
	0.2% AEP	1069	962	$216,142,494	$202,082	27%
	PMF	1194	1138	$297,944,027	$249,439	22%
	Average Annual Damages			$2,374,189	**$1,988**	

Table 46: Summary of Estimated Overland Flow Flood Damages

Flood Event		No. Lots Affected	No. Lots Flooded Above Floor Level	Total Damages for Event	Average Damage Per Flood Affected Property	% of AAD
Residential	20% AEP	88	22	$3,112,886	$35,374	52%
	10% AEP	104	31	$4,687,174	$45,069	16%
	5% AEP	143	36	$5,985,659	$41,858	11%
	2% AEP	194	57	$7,922,051	$40,835	9%
	1% AEP	228	70	$9,845,837	$43,184	4%
	0.5% AEP	251	89	$12,282,478	$48,934	2%
	0.2% AEP	297	112	$15,528,162	$52,283	2%
	PMF	664	427	$65,335,676	$98,397	3%
	Average Annual Damages			$**2,376,929**	$3,580	
Total	20% AEP	94	23	$3,509,772	$37,338	52%
	10% AEP	112	34	$5,254,674	$46,917	16%
	5% AEP	152	43	$6,791,730	$44,682	11%
	2% AEP	205	65	$9,060,097	$44,195	9%
	1% AEP	240	78	$11,331,028	$47,212	4%
	0.5% AEP	265	100	$14,293,089	$53,936	2%
	0.2% AEP	316	124	$18,233,847	$57,702	2%
	PMF	722	467	$77,508,014	$107,351	4%
	Average Annual Damages			$ 2,691,138	**$3,727**	

The estimation of tangible flood damages is a high-level exercise, intended to capture the catchment-scale flood damages. It can provide a good indication of the average flood damage across a catchment. The accuracy of the results at individual properties can be affected by vagaries such as the variability in the flood level across the property, the location of the sampled flood level for the property, whether the floor level is consistent or varies through the building. This variability tends to average out across the catchment, particularly if many properties are considered.

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