WINGECARRIBEE SHIRE COUNCIL

WINGECARRIBEE RIVER FLOOD STUDY UPDATE

FINAL REPORT

FEBRUARY 2022

Level 2, 160 Clarence Street
Sydney, NSW, 2000

Tel: (02) 9299 2855
Fax: (02) 9262 6208
Email: wma@wmawater.com.au
Web: www.wmawater.com.au

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Project Wingecarribee River Flood Study Update	**Project Number** 120019
Client Wingecarribee Shire Council	**Client's Representative** Sha Prodhan
Authors Michael Reeves Michael Ren Rhys Hardwick Jones	**Prepared by** Rhys Hardwick Jones
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EXECUTIVE SUMMARY

This flood study provides information about the existing flood risk in the Wingecarribee River catchment. The study involved development of computer models of the floodplain. The models were used to estimate flood levels and map flood extents for a range of flood sizes, from smaller relatively frequent floods to extreme but very rare floods. The flood modelling tools and spatial mapping from this study can be used by Council for decision-making about land-use planning, testing impacts and assessing risk for future development in the flooding, and to assess the effectiveness of potential measures to reduce flood risk in the future.

This study supersedes a previous flood study of the catchment published by SMEC in 2014. Although Mittagong Creek and the Burradoo local drainage area both flow into the Wingecarribee River, these catchments have been the subject of previous detailed flood studies by Councils and flood risk in those areas has not been mapped as part of this study.

There are few well-documented records of flood levels or extents prior to the construction of the Wingecarribee Dam as part of the Shoalhaven Scheme in 1974. The Wingecarribee Dam impounds a large part of the upper catchment, and therefore significantly reduces flood runoff into the upper Wingecarribee River compared to pre-dam conditions. However significant flooding can still occur, both from catchment areas that do not flow through the dam, and due to releases from the dam itself when its capacity is exceeded.

Aside from the direct effects of the dam on flooding, the construction of the reservoir was accompanied by installation of automatic gauges to measure streamflow in the river at Berrima Weir, Bong Bong Weir (at Cecil Hoskins Reserve), and at Sheepwash Road from the dam outlet. These gauges provide the most definitive history of flood records in the catchment. During the 45-year period of record from these gauges, the March 1978 flood event is the largest that has occurred. Although significant, significantly larger floods than this event can and will occur, and it appears likely that the 1% AEP (1 in 100 chance per year) flood for this catchment is larger than what occurred in 1978. A flood similar in magnitude to 1978 is estimated to have approximately a 1 in 60 to 1 in 90 chance of occurring each year.

In the last decade there have been several minor floods of the Wingecarribee River, including March 2012, August 2015, June 2016 and February 2020, which have affected low-lying land. Events similar to these will occur frequently, and there are several locations in the catchment where existing development, infrastructure or access roads are affected even in these relatively small events, such as Headlam Road at Moss Vale and Railway Road at Burradoo. Communities accessed by these roads can become isolated for several days even in minor floods.

In larger moderate flood events (with around 1 in 10 to 1 in 20 chance of occurring per year), flood impacts are more widespread and damage to rural properties is likely, although there are relatively few direct impacts on homes or other buildings. In floods of this size, additional communities can become isolated such as those accessed via Sproules Lane or Kangaloon Road at Glenquarry, or Iona Park Road, Moss Vale.

In rarer and larger flood events, with a 1 in 100 chance per year for example, there are likely to be more direct impacts and damages to property, including homes. In these more extreme flood events, some lower lying buildings are subject to inundation in and around Berrima, as well as properties with overland flow flooding from local catchment runoff, such as in low lying parts of Sheaffe Street and Price Street, Bowral.

Using the above information, properties subject to potential flood affectation and flood-related development controls have been identified, and Council will include this information on the relevant Section 10.7 planning certificates. Mapping of design flood behaviour is provided in Appendix E, with planning maps that are relevant for development controls as follows:

- Hydraulic classification (floodways, flood storage and flood fringe) for 1% AEP in Figure F27;
- Provisional Flood Planning Area (FPA) in Figure F31; and
- Provisional Flood Risk Precincts (FRP) in Figure F32.

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LIST OF ACRONYMS

AEP	Annual Exceedance Probability
ARI	Average Recurrence Interval
ARR	Australian Rainfall and Runoff
ALS	Airborne Laser Scanning
ARR	Australian Rainfall and Runoff
AWS	Automatic Weather Station
BOM	Bureau of Meteorology
DEM	Digital Elevation Model
DPIE	Department of Planning, Industry and Environment
DRM	Direct Rainfall Method
D/S	Downstream
DTM	Digital Terrain Model
ELVIS	Elevation Information System
EY	Exceedances per Year
FRMS&P	Floodplain Risk Management Study and Plan
GIS	Geographic Information System
GPS	Global Positioning System
IFD	Intensity, Frequency and Duration (Rainfall)
LiDAR	Light Detection and Ranging
LGA	Local Government Area
mAHD	meters above Australian Height Datum
OEH	Office of Environment and Heritage
PMF	Probable Maximum Flood
RAFTS	Runoff Analysis and Flow Training Simulation (hydrologic model)
SCA	Sydney Catchment Authority
SES	State Emergency Services
SRTM	Shuttle Radar Topography Mission
SWMM	Stormwater Management Model – modelling software for stormwater systems
U/S	Upstream
TUFLOW	Two-dimensional Unsteady Flow – a one-dimensional (1D) and two-dimensional (2D) flood and tide simulation software (hydraulic model)
WBNM	Watershed Bounded Network Model (hydrologic model)
WSC	Wingecarribee Shire Council

FOREWORD

The NSW State Government's Flood Prone Land Policy provides a framework to ensure the sustainable use of floodplain environments. The Policy is specifically structured to provide solutions to existing flooding problems in rural and urban areas. In addition, 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 four sequential stages:

1. Flood Study
- Determine the nature and extent of the flood problem.

2. Floodplain Risk Management Study
- Evaluates management options for the floodplain in respect of both existing and proposed development.

3. Floodplain Risk Management Plan
- Involves formal adoption by Council of a plan of management for the floodplain.

4. Implementation of the Plan
- Construction of flood mitigation works to protect existing development, use of Local Environmental Plans to ensure new development is compatible with the flood hazard.

ACKNOWLEDGEMENTS

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

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:

- Wingecarribee Floodplain Risk Management Committee
- Residents of the study area
- Wingecarribee Shire Council
- Department of Planning, Industry and Environment
- State Emergency Service

1. INTRODUCTION

The Wingecarribee River Catchment lies within the Wingecarribee Shire Council (Council) Local Government Area (LGA), approximately 100 km southwest of Sydney. The study area covers the entire Wingecarribee River catchment to Wallaby Rocks, as shown in Figure 1. The catchment area is approximately 225 km^2.

The localities of Bowral, Burradoo, Moss Vale, Berrima and New Berrima lie within (or partially within) the study area.

The previous flood study for the catchment was completed by SMEC in 2014 (Reference 1). There is a need to update this study to use the latest Australian Rainfall and Runoff (ARR) guidelines. The previous flood study adopted ARR87 (Reference 2), and since then, the latest guidelines, ARR19 (Reference 3), have been finalised. With an additional 30 years of data and improvements in computing technology, ARR19 presents a significant update to how floods are estimated. These updates include the following:

- Rainfall Intensity-Frequency-Duration (IFD) Data
- Rainfall Temporal Patterns
- Rainfall Losses
- Areal Reduction Factors

1.1. Scope and Objectives

The objective of this study is to review and update the existing flood study using the available data and the current ARR guidelines (Reference 3). The study will define the flood behaviour of the Wingecarribee River, providing information on flood levels, velocities, flows, hydraulic categories and hazard for a full range of design flood events for existing floodplain conditions. This will provide a foundation for development of a robust floodplain risk management plan. Council is responsible for managing flood risk as outlined in the NSW Floodplain Development Manual (Reference 4). This study will enable Council to:

- Understand the current flood risk across the catchment
- Provide up to date flood data as current for all end users
- Enable future development planning
- Control cumulative impacts of future development
- Assess the effectiveness of potential flood mitigation measures

Design flood events to be defined include the 20%, 10%, 5%, 2%, 1% and 0.5% Annual Exceedance Probability (AEP) events and the Probable Maximum Flood (PMF) event across the study area. It involved the following broad tasks:

- Collection of data and information relevant to the study
- Preparation of hydrologic and hydraulic models capable of defining the flood behaviour
- Calibrate the hydrologic and hydraulic models using available data from recent flood events
- Simulate design flood behaviour across the study area for a range of probabilities

- Undertake sensitivity analysis of adopted model parameters
- Interpretation and presentation of model results to describe and categorise flood behaviour and hazard
- Provide information relating to the consequences of flooding, emergency response, land use planning and cumulative flood impacts of development

2. BACKGROUND

2.1. Study Area

The study area consists of the Wingecarribee River catchment, from its headwaters to Wallaby Rocks, just downstream of the Hume Motorway. This portion of the catchment covers approximately 225 km^2. The catchment generally drains from East to West and includes a number of prominent tributaries such as Kellys Creek, Mittagong Creek and Stony Creek, with Cordeaux Creek and Black Springs Creek joining just downstream of the Hume Motorway. Wingecarribee River continues downstream for approximately 20 km (straight line distance) to its confluence with the Wollondilly River near Joadja. The Wollondilly River is a significant source of inflows into Warragamba Dam.

Land use in the catchment is dominated by rural landscapes with cleared land for farming with stands of remnant vegetation. A small portion of the catchment is covered by low to medium density urban development within the localities of Bowral, Burradoo, Moss Vale, Berrima and New Berrima.

The river is controlled in the upper catchment by the Wingecarribee Reservoir, which captures runoff from approximately 40 km^2 of the Wingecarribee River catchment. The Wingecarribee Reservoir forms part of the Shoalhaven Scheme, via which water can be pumped from the Shoalhaven River and stored in the Fitzroy and Wingecarribee Reservoirs before being released into either the Nepean or Wingecarribee Rivers. A number of hydraulic structures control flow downstream of Wingecarribee Reservoir, including Bong Bong Weir, Berrima Weir and bridge structures of Sheepwash Road, Sproules Lane, Argyle Street, Railway Road (and the railway line), Old Hume Highway and Hume Motorway.

2.2. Historical Flooding

The Wingecarribee River catchment has been subject to flooding in the past, with notable events occurring in March 1893, January 1895, August 1922, February 1931, August 1938, May 1943, June 1952, March 1975, March 1978, August 1986, April 1988, August 1990, June 1991, September 1995, August 1998, August 2015, June 2016 and February 2020. Gauging of the Wingecarribee River at Berrima Weir commenced in 1975 after construction of Wingecarribee Reservoir. Since then, the largest event recorded was the March 1978 event, following by the April 1988 and August 1998 events.

A man drowned when his car was swept into Mittagong Creek in Bowral during the June 2016 flood event (Photo 1, Reference 5). The most recent flood event of February 2020, although the largest event since 2016, was a moderate event. Flooding was still observed across the Wingecarribee floodplain, at Bong Bong Common in particular.

Photo 1: Vehicle swept off the road in Bowral in June 2016 flood event (*Source: Reference 5*)

3. AVAILABLE DATA

3.1. Previous Studies

A number of previous studies have been completed within the Wingecarribee River Catchment, including the following:

- Mittagong Rivulet Flood Study (Engineering Department of WSC, 1990)
- Berrima Flood Study (Bewsher, 2000)
- Berrima Floodplain Risk Management Study and Plan (Bewsher, 2002)
- Bowral Flood Study (Bewsher, 2005)
- Bowral Floodplain Risk Management Study and Plan (Bewsher, 2009)
- Burradoo BU2 Catchment Assessment Study (Cardno, 2010)
- Burradoo BU2 Catchment Floodplain Risk Management Study and Plan (Cardno, 2012)
- Wingecarribee River Flood Study (SMEC, 2014)

Apart from SMEC (2014) these studies focused on minor drainage creeks or tributaries and do not take into account direct flooding from the Wingecarribee River. A brief summary of the studies that are relevant for the current investigation are outlined in the following sections.

3.1.1. Mittagong Rivulet Flood Study (Engineering Department of WSC, 1990)

The Mittagong Rivulet Flood Study (Reference 6) was undertaken by Wingecarribee Shire Council (WSC) to enable planning and development in the Bowral urbanised area. A RAFTS hydrologic model and HEC2 hydraulic model were developed for study and calibrated to the 1988 storm event. This study has limited relevance to the current study due to its age and the limited catchment and floodplain area investigated. It is noted that the previous Wingecarribee River Flood Study (SMEC, 2014) undertook a comparison of the 5% AEP and 1% AEP peak flows at the downstream end of Mittagong Rivulet (also known as Mittagong Creek).

3.1.2. Berrima Flood Study (Bewsher Consulting, 2000) and Berrima Floodplain Risk Management Study and Plan (Bewsher, 2002)

The Berrima Flood Study (Reference 7) and subsequent Floodplain Risk Management Study and Plan (FRMS&P, Reference 8) defined the flood behaviour for the township of Berrima, including the 5 year, 10 year, 20 year and 100 year average recurrence interval (ARI) events and an extreme flood event. Peak flows at the Berrima Weir gauge were used to calibrate a HEC-RAS model to the March 1978, April 1988, August 1990 and August 1998 events. A flood frequency analysis (FFA) undertaken at the gauge was used to estimate design flows for the HEC-RAS model to simulate flood levels and velocities. Flood risk precincts and flood damages were assessed for the town and a number of flood risk management measures were proposed including planning controls, public awareness, improved emergency management plans, vegetation management, voluntary purchase of one house, flood proofing of commercial properties and development of a flood warning system.

3.1.3. Bowral Flood Study (Bewsher Consulting, 2005) and Bowral Floodplain Risk Management Study and Plan (Bewsher, 2009)

The Bowral Flood Study (Reference 9) was initially completed in 2004 and updated in 2005 to include the new Bowral Street Bridge when the subsequent FRMS&P was completed. The FRMS&P was updated again in 2009 (Reference 10) to incorporate updated modelling and sensitivity analysis. Flood modelling was undertaken using RAFTS and TUFLOW software to determine the flood behaviour through the town of Bowral. The models were calibrated to the April 1988 and October 1999 flood events and the 5 year, 10 year, 50 year, 100 year ARI and probable maximum flood (PMF) events were simulated. A number of flood risk management options were proposed, including planning controls, public awareness, improved emergency management plans, riparian corridor management, gauging of the catchment, voluntary house raising, flood proofing individual properties and infrastructure feasibility studies for two detention basins, railway culvert amplification and bridge removal.

3.1.4. Burradoo BU2 Catchment Flood Study (Cardno, 2010) and Floodplain Risk Management Study and Plan (Cardno, 2012)

The Burradoo Catchment Flood Study (Reference 11) was completed in 2010 by Cardno. The catchment drains through the suburb of Burradoo and into Mittagong Creek. An XP-RAFTS hydrologic model and a TUFLOW hydraulic model were developed and validated for the June 2007 storm event using community observations. Design flood events investigated in this study were the 5 year, 20 year, 50 year and 100 year ARI and PMF events. Sensitivity analysis was also conducted on model parameters including blockage and a climate change assessment. A subsequent FRMS&P was undertaken (Reference 12) to investigate flood risk mitigation options.

3.1.5. Wingecarribee River Flood Study (SMEC, 2014)

The Wingecarribee River Flood Study (Reference 1) was completed by SMEC in 2014. It is the most recent study completed within the catchment and also the most relevant to the current study. The flood study focussed on mainstream flooding from the Wingecarribee River, from just downstream of the Wingecarribee Reservoir to Wallaby Rocks. A WBNM hydrologic model was developed and calibrated to the August 1998 and August 1990 events, with the March 2012 event serving as a validation. The Bong Bong Weir gauge and Berrima Weir gauge were the primary calibration sources and the upper catchment and lower catchment (separated by Bong Bong Weir) had different calibrated parameters. A TUFLOW hydraulic model was also developed, which combined inflows from the WBNM model and direct rainfall within the 2D model domain to simulate flood behaviour. The model was based on a 10 m grid with nested 1D elements such as the Wingecarribee River channel, tributaries and hydraulic structures. Model parameters were again calibrated for the upper and lower catchment to match the gauge hydrographs and several recorded flood marks for the same flood events. Design flood events for the 20%, 10%, 5%, 2%, 1% and 0.5% AEP and PMF were also simulated using ARR87 methodologies. Flood depths, levels and velocities were simulated across the study area as well as flood hazard and hydraulic categories. A sensitivity analysis was undertaken on the adopted model parameters. The WBNM and TUFLOW models for this study were available and were reviewed, with the outcomes presented in Section 3.2.

3.2. Flood Models

The hydrologic and hydraulic models from the Wingecarribee River Flood Study (Reference 1) were obtained and reviewed. The adopted hydrology for the study combined a WBNM model and direct rainfall within the TUFLOW domain. The WBNM model consists of 43 catchments covering the Wingecarribee River catchment from its headwaters to Wallaby Rocks. The upper catchment used a C value of 1.4, while the lower catchment used a C value between 1.4 and 1.6 (varies by subcatchment). The flow-path routing parameter was between 0.8 and 1.4. The Wingecarribee Reservoir was included in the model (as a stage-storage-discharge relationship). The dam was assumed full at the start of the simulation. For the design flood events, an initial loss of 15 mm was adopted for the upper catchment, and 10 mm for the lower catchment. A continuing loss of 1.2 mm/hr was adopted for the upper catchment and 0.5 mm/hr for the lower catchment.

The TUFLOW model was developed using version 2012-05-AD-iDP-w64. The model adopts a 10 m grid with breaklines to define embankments, creeks and key structures such as weirs. Large hydraulic structures are incorporated in the 2D domain while smaller culverts are 1D elements. Surface roughness and infiltration layers are also defined within the model domain. Large tributary inflows are sourced from the WBNM model while direct rainfall is applied within the 2D domain. A stage-discharge relationship is defined for the downstream boundary at Wallaby Rocks.

Council also provided other models to WMAwater including the following:

- Burradoo BU2 Flood Study (Reference 11) RAFTS model.
- East Bowral SWMM model, used as inflow for a portion of the Bowral Flood Study (Reference 10).
- Berrima Flood Study (Reference 7) HEC-RAS model.

3.3. Aerial Survey

According to the 2014 Flood Study completed by SMEC (Reference 1), Light Detection and Ranging (LiDAR) provided the main topographic data, which covered most of the area within the TUFLOW model extent. The LiDAR data was acquired from a fixed wing aircraft on 1 April 2010 by AAM Pty Ltd. The dataset contains thinned ground points with intensity as GRD files, 1m Digital Terrain Model (DTM) grids as ESRI ASCII files, and 0.5m contours as ESRI shape files. The horizontal datum for the data is GDA94 MGA Zone 56 and the vertical datum is local AHD. The vertical accuracy is reported within ± 0.15m Standard Error (1 sigma), and the horizontal accuracy is ± 0.55m Standard Error (1 sigma). Ground data was been compared to 290 reference points on open clear ground obtained by field survey. The average difference is within ±0.03m.

The Elevation Information System (ELVIS, www.elevation.fsdf.org.au) was also consulted to view the available data from government services. NSW Spatial Services holds LiDAR data covering approximately the upper half of the Wingecarribee catchment as a 1 m Digital Elevation Model (DEM) from the Burragorang, Moss Vale and Kiama datasets. These datasets are primarily dated May 2014, with some tiles being from 2016. In the lower half of the catchment, 2 m LiDAR DEMs are available from the Burragorang and Moss Vale datasets, dated May 2018. Shuttle Radar Topographic Mission (SRTM) data is also available from Geoscience Australia through ELVIS, covering the whole catchment with a coarse grid of approximately 30 m resolution. The coverage of this data from ELVIS can be seen in Figure 2.

3.4. Hydraulic Structure Survey

A field survey of hydraulic structures was undertaken by Richard Cox Surveyors Pty Ltd as part of the 2014 Flood Study (Reference 1). The survey data included site inspection photos and sketches of 37 structures along the Wingecarribee River and its tributaries. Additional electronic files of the structures surveyed were provided with elevation values. The location of these structures is shown in Figure 3.

The summary of the surveyed structures is as follows:

- **Bridges**
  The survey included height, span, deck thickness, guardrail height, and pier sizes of 11 bridges including Sheepwash Road Bridge just downstream of Wingecarribee Dam, Sproules Lane Bridge in Glenquarry, Railway Bridge and Railway Road Bridge west of Burradoo. Additional bridges over the Wingecarribee River that were incorporated in the 2014 TUFLOW model are Berrima Bridge on the Old Hume Highway and Bong Bong Bridge on Moss Vale Road, upstream of Bong Bong Weir. A drawing of the Bong Bong Bridge designed by Department of Main Roads NSW in 1973 was also provided by Council.
- **Culverts**
  Shape, size and cover of the culvert was collected in the survey. The invert levels at the upstream and downstream ends of the structure were also included.
- **Weirs**
  2 key weirs across the Wingecarribee River were surveyed - Bong Bong Weir and Berrima Weir. Width, height and crest elevation of the weir was collected in the survey.
- **Basin**
  The survey included a basin in “Sutherland Park” along a tributary of the Wingecarribee River, east of Burradoo.

WMAwater identified a number of other structures that were considered to be important to accurately simulate flood behaviour. WMAwater staff undertook a field inspection of these structures on 14th and 18th September 2020 and measured (or estimated, where measuring was not practical) the size of the structure and depth of cover. A photo of the structure was also taken and GPS coordinates recorded. This provides adequate information to include the structure in the hydraulic model. Invert levels can be estimated by using LiDAR levels of the road surface (typically quite accurate) and the depth of cover. A total of 27 structures were surveyed including 15 pipes, 11 box culverts and 1 bridge. There were some additional structures, particularly along the railway line running parallel to the Illawarra Highway, that were inaccessible and their details are unknown. The location of the 2014 survey, 2020 WMAwater survey and inaccessible structures can be seen in Figure 3.

3.5. Flood Mark Survey

Flood marks were surveyed as part of the 2014 Flood Study (Reference 1) by Richard Cox Surveyors Pty Ltd. A limited number of reliable recorded flood heights exist for historical events that were utilised in the previous study. A total of 15 flood marks were surveyed from the 1988 (1), 1990 (1), 1997 (1), 1998 (5) 2007 (2), 2009 (1), 2010 (1) and 2012 (3) flood events. The descriptions and photos of the marks were also available in the survey data from the study. The SMEC Wingecarribee River Flood Study (Reference 1) also indicates that two flood marks from the Berrima Flood Study (Reference 7) were also used for the 1990 event.

From the community consultation responses for this study (see Section 4.2), one resident located on Wingecarribee Street in Berrima identified that a number of flood marks existed on their property. This resident was contacted by WMAwater staff and subsequently a site inspection was undertaken on 30th June 2020. Flood depths and extents for a number of events were taken. Flood levels were estimated based on available LiDAR data. A summary of the collected flood marks is provided in Table 1, and locations are shown on Figure 6.

Table 1: Surveyed Flood Marks from Historical Flood Events

ID	Event	Source	Mark Location	Mark Description	Level (mAHD)	Confidence / Accuracy
FM16	June 1964	Bewsher, 2000	Jellore St, Berrima	Mark on nursery shed door jam	646.63	Good
FM17	1975	Bewsher, 2000	Cnr Wingecarribee St / Old Hume Hwy, Berrima	1 inch below patio level of rear southern units	649.3	
FM18	1978	Bewsher, 2000	Cnr Wingecarribee St / Old Hume Hwy, Berrima	1 foot lower than the 1975 event	649.0	
FM54	1978	WMAwater, 2020	Wingecarribee St, Berrima	Reached doorstep in 1970's (assumed 1978)	646.7	Low
FM53	1978	WMAwater, 2020	Wingecarribee St, Berrima	Approximate depth 2 foot at tree in 1970's, largest flood observed (assumed 1978)	647.7	Low
FM20	March 1978	Bewsher, 2000	Jellore St, Berrima	Mark on nursery shed door jam	646.73	Good
FM49	March 1978	Bewsher, 2000	Lot 10 Wingecarribee St, Berrima	Mark on top of shed	648.422	Seems low
FM21	1982	Bewsher, 2000	Lot 10 DP758098 Sutton St, Berrima	Base of small deciduous tree	646.4	Doubtful due to date
FM19	April 1988	Bewsher, 2000	Jellore St, Berrima	Mark on nursery shed door jam	646.21	Good
FM22	April 1988	Bewsher, 2000	Lot 13 Wingecarribee St, Berrima	Mark inside orange shed	645.6	Good
FM23	April 1988	Bewsher, 2000	Lot 3 Jellore St, Berrima	Ground level at base of large tree in NE of backyard	646.73	Doubtful
FM24	April 1988	Bewsher, 2000	Lot 6-8 Wingecarribee St, Berrima	1 inch below top of rear gate post on lot 8 boundary fence	646.3	Good
FM25	April 1988	Bewsher, 2000	Jellore St, Berrima	Ground level at large tree next to two star posts in backyard	647.24	Doubtful
FM26	April 1988	Bewsher, 2000	15-17 Market Pl, Berrima	Ground level at base of metal gate at top of rear garden stairs	647.61	Good
FM27	April 1988	Bewsher, 2000	Lot 1 and 2 Cnr Argyle St / Villiers St, Berrima	Backyard fore place, cross bar rod	647.6	Good
FM28	April 1988	Bewsher, 2000	Cnr Wingecarribee St / Old Hume Hwy	0.67m below restaurant verandah	648.61	Good
FM38	1988	SMEC, 2014	Town Bridge, Berrima	Depth Marker	647.35	Good
FM50	1988	WMAwater, 2020	Wingecarribee St, Berrima	Just below metal cap on fence post (1.2m depth) in late 1980's (assumed 1988)	646.0	Good
FM55	1988	WMAwater, 2020	Wingecarribee St, Berrima	Halfway up shed in 1980's (assumed 1988), estimated 1.3m deep	645.8	Low
FM35	1990	SMEC, 2014	180 Sproules Ln, Bowral	Position along fence – depth above ground	658	Low
FM29	August 1990	Bewsher, 2000	Lot 2 Jellore St, Berrima	Ground level at corner post of vegetable garden	645.81	Doubtful

ID	Event	Source	Mark Location	Mark Description	Level (mAHD)	Confidence / Accuracy
FM30	1990	Bewsher, 2000	15-17 Market Pl, Berrima	Rear garden stairs top of riser immediately up from handrail mid pole position	646.2	Satisfactory
FM31	1995	Bewsher, 2000	Lot 3 Wingecarribee St, Berrima	Ground level at base of tree in backyard	646.33	Uncertain
FM32	1996	Bewsher, 2000	Lot 10 DP80581 (End of Wingecarribee St, Berrima)	Near arena	645.64	Uncertain
FM33	1996	Bewsher, 2000	Lot 10 DP758098 Sutton St, Berrima	Near sandstone wall	644.18	Uncertain
FM36	1997	SMEC, 2014	180 Sproules Ln, Bowral	Ground	657.7	Low
FM56	1998	Bewsher, 2000	Oxley St, Berrima	Berrima Flood Study Cross Section 4	645.51	Uncertain
FM57	1998	Bewsher, 2000	Jellore St, Berrima	Berrima Flood Study Cross Section 7	646.51	Uncertain
FM58	1998	Bewsher, 2000	Downstream of Berrima Bridge	Berrima Flood Study Cross Section 8	646.88	Uncertain
FM59	1998	Bewsher, 2000	Upstream of Berrima Bridge	Berrima Flood Study Cross Section 9	647.03	Uncertain
FM60	1998	Bewsher, 2000	Bend at Wingecarribee St, Berrima	Berrima Flood Study Cross Section 12	648.57	Uncertain
FM61	1998	Bewsher, 2000	Bend at Schotts Ln, Berrima	Berrima Flood Study Cross Section 13	648.8	Uncertain
FM34	1998	SMEC, 2014	3 Victor Cr, Moss Vale	Estimate water level at stump from photo	658.1	Low
FM45	1998	SMEC, 2014	154 Headlam Rd, Moss Vale	Estimate water level at post from photo	653.3	Good
FM40	1998	SMEC, 2014	6 Oldbury Rd, Berrima	Approximate indication of water level at tree by resident	647.1	Low
FM39	1998	SMEC, 2014	180 Sproules Ln, Bowral	At fence line	658.2	Low
FM48	1998	SMEC, 2014	Town Bridge, Berrima	Depth marker	646.93	Good
FM37	June 2007	SMEC, 2014	388 Headlam Rd, Moss Vale	Estimate water level at fence from photo	660.3	Low
FM44	2007	SMEC, 2014	180 Sproules Ln, Bowral	Not precise	658	Low
FM51	2009	WMAwater, 2020	Wingecarribee St, Berrima	Approximate 2009 extent	645.7	Low
FM47	Dec 2009 / 2010 (?)	SMEC, 2014	40C Church Rd, Moss Vale	Water level at tree	660.25	Low
FM46	November 2010	SMEC, 2014	47 Eridge Park Rd, Burradoo	Estimate of water level by resident	653.8	Low
FM43	2012	SMEC, 2014	40C Church Rd, Moss Vale	Water level at shed	660.58	Low
FM42	March 2012	SMEC, 2014	388 Headlam Rd, Moss Vale	Estimate water level at fence from photo	660.9	Good
FM41	2012	SMEC, 2014	6 Oldbury St, Berrima	Water level on ground	644.35	Good
FM52	March 2012	WMAwater, 2020	Wingecarribee St, Berrima	Approximate 8 March 2012 flood extent	643.8	Low

3.6. GIS Files

Geographical Information System (GIS) information was provided by Council, including the following:

- A study area extent for the current Flood Study
- Local Environmental Plan (LEP) zoning
- Cadastre
- Road corridors and road alignments
- River and stormwater catchments
- Major rivers, drainage lines and water bodies
- Wetland locations
- Stormwater infrastructure including facilities, easements, pits and conduits

The stormwater conduits layer contains a conduit type, size, invert level and location. In the dataset there are 6,840 conduits, of which approximately 65% are within the Wingecarribee River Catchment. In this subset of the data, there are approximately 3,500 pipes, 250 box culverts, 400 open channels. There are invert levels for approximately 45% of the conduits. The majority of these stormwater systems are relatively small. Only the larger drainage systems are relevant to the study and require inclusion in the flood models.

Several GIS layers were also provided as part of the 2014 Flood Study (Reference 1) data package, including:

- Bridges
- Buildings
- Soils
- Vegetation communities

These datasets are for the entire Wingecarribee Shire Council, and are assumed to be from Council's GIS database. The bridges layer contains details of 27 bridges within the Wingecarribee River Catchment. A length, width and deck area are provided along with some brief construction details for each bridge. The buildings layer contains polygons of buildings which WMAwater spot-checked against the latest available aerial imagery. Most of the buildings were reasonably matched with their locations on the aerial imagery, although some buildings had no corresponding delineation in the GIS layer, most likely due to their recent development.

3.7. Gauge Data

Rainfall and streamflow gauges are available for the Wingecarribee River catchment, as shown in Figure 4 and described in the following sections.

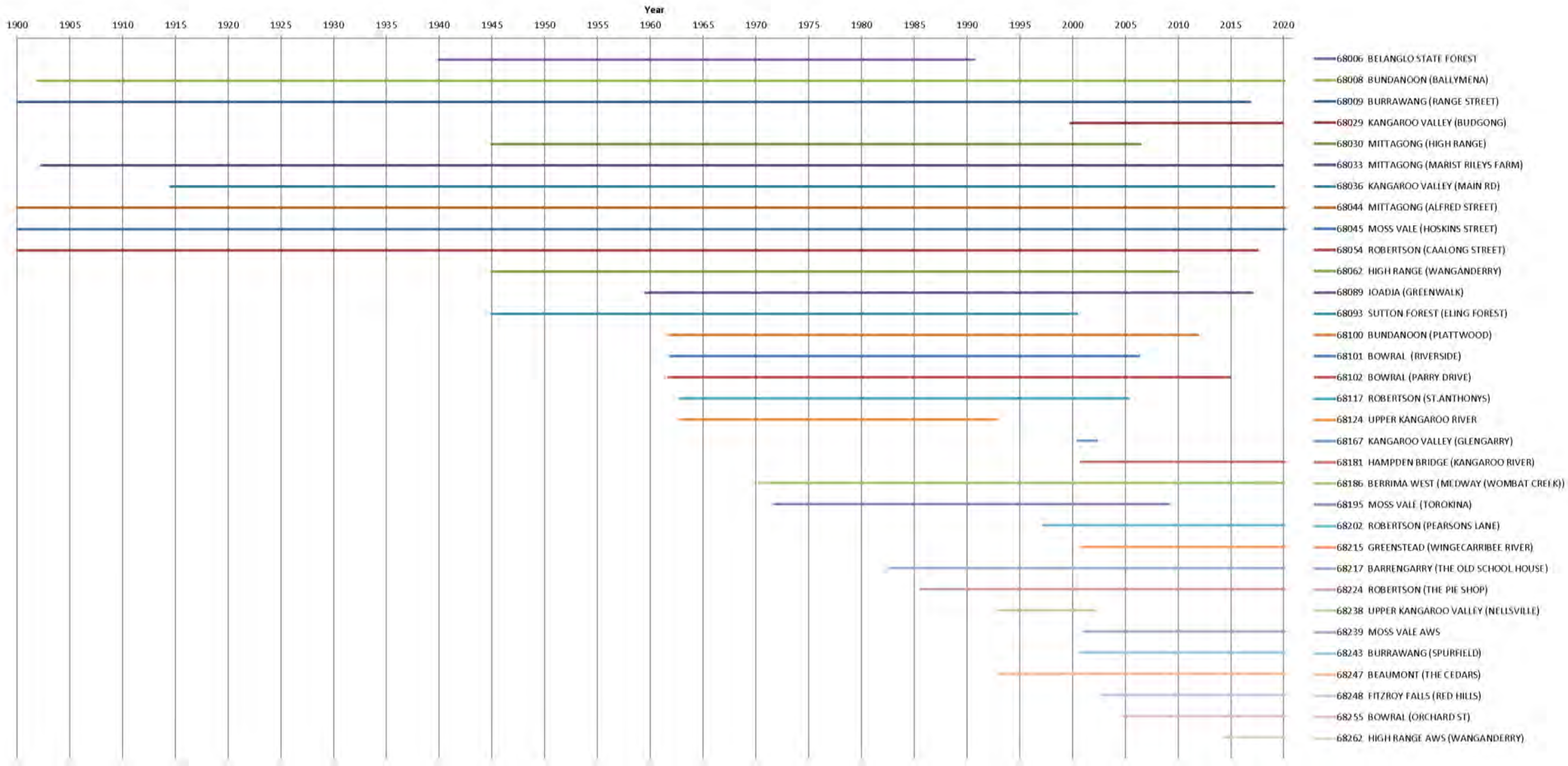
3.7.1. Daily Rainfall

There are 33 Bureau of Meteorology (BoM) daily rainfall gauges within 30 km of Moss Vale (near the centre of the catchment) that have recent data relevant to the study. There were an additional 37 gauges within 30 km of Moss Vale that did not have recent data and were not considered relevant for the current study. These gauges are summarised in Table 2 and Diagram 1, with their locations shown in Figure 4.

Table 2: Daily Rainfall Gauges

Gauge Number	Gauge Name	Length of Record (years)	Completeness (%)
68006	BELANGLO STATE FOREST	50.8	98.3
68008	BUNDANOON (BALLYMENA)	118.2	91.5
68009	BURRAWANG (RANGE STREET)	126.0	60.1
68029	KANGAROO VALLEY (BUDGONG)	20.1	97.5
68030	MITTAGONG (HIGH RANGE)	61.6	97.2
68033	MITTAGONG (MARIST RILEYS FARM)	117.8	69.1
68036	KANGAROO VALLEY (MAIN RD)	104.7	90.3
68044	MITTAGONG (ALFRED STREET)	134.3	87.1
68045	MOSS VALE (HOSKINS STREET)	149.6	97.2
68054	ROBERTSON (CAALONG STREET)	127.5	81.8
68062	HIGH RANGE (WANGANDERRY)	65.2	98.5
68089	JOADJA (GREENWALK)	57.6	93.8
68093	SUTTON FOREST (ELING FOREST)	55.5	91.1
68100	BUNDANOON (PLATTWOOD)	50.2	98.9
68101	BOWRAL (RIVERSIDE)	44.5	80.6
68102	BOWRAL (PARRY DRIVE)	53.3	98.6
68117	ROBERTSON (ST.ANTHONYS)	42.6	99.5
68124	UPPER KANGAROO RIVER	30.1	96.7
68167	KANGAROO VALLEY (GLENGARRY)	1.8	92.1
68181	HAMPDEN BRIDGE (KANGAROO RIVER)	19.3	98.1
68186	BERRIMA WEST (MEDWAY (WOMBAT CREEK))	49.9	97.4
68195	MOSS VALE (TOROKINA)	37.5	98.4
68202	ROBERTSON (PEARSONS LANE)	22.8	95.1
68215	GREENSTEAD (WINGECARRIBEE RIVER)	19.3	93.1
68217	BARRENGARRY (THE OLD SCHOOL HOUSE)	37.4	91.9
68224	ROBERTSON (THE PIE SHOP)	34.6	78.4
68238	UPPER KANGAROO VALLEY (NELLSVILLE)	9.3	86.0
68239	MOSS VALE AWS	19.1	98.2
68243	BURRAWANG (SPURFIELD)	19.3	99.6
68247	BEAUMONT (THE CEDARS)	27.3	99.2
68248	FITZROY FALLS (RED HILLS)	17.4	95.8
68255	BOWRAL (ORCHARD ST)	15.4	99.4
68262	HIGH RANGE AWS (WANGANDERRY)	5.8	99.0

Diagram 1: Available daily rainfall gauge records for Wingecarribee River catchment



3.7.2. Sub-Daily Rainfall

There are 4 BoM pluviograph stations (with sub-daily data) in the vicinity of the study area – two located at the very top of the catchment in Robertson, one to the south of the catchment and one in Bowral. Automatic Weather Station (AWS) data is also available for Moss Vale and another station to the north-west of the catchment. The gauges are listed in Table 3 and the locations are shown in Figure 4.

Table 3: BoM Sub-Daily Rainfall Stations

Gauge Number	Gauge Name	Resolution
068054	ROBERTSON (CAALONG STREET)	6 minute
068102	BOWRAL (PARRY DRIVE)	6 minute
068117	ROBERTSON (ST.ANTHONYS)	6 minute
068195	MOSS VALE (TOROKINA)	6 minute
068239	MOSS VALE AWS	1 minute
068262	HIGH RANGE AWS (WANGANDERRY)	1 minute

WaterNSW provided sub-daily rainfall data for 10 gauges within and adjacent to the catchment. This data was provided in 6 minute intervals from 1981 onwards. 6 of the gauges are currently still in operation. These gauges are listed in Table 4 and are shown in Figure 4.

Table 4: WaterNSW Sub-Daily Rainfall Stations

Gauge Number	Gauge Name
568054	Mittagong Maguires Crossing
568070	East Kangaloon
568081	Wildes Meadow
568082	Colyers Ck
568093	Glen Mavis
568098	Mittagong (Kia-Ora)
568113	Wingecarribee Dam
568165	Moss Vale (Berrima Junction)
568183	Burrawang (Amgrow)
568184	Robertson (Crowes)

3.7.3. Streamflow

There are 4 streamflow gauges within the study area that are currently in operation. There is one located upstream of the Wingecarribee Reservoir (212274) and 3 located downstream. The downstream gauges are located immediately downstream of Wingecarribee Dam at Sheepwash Road (212275), near Moss Vale at Bong Bong Weir (212031) and near Berrima at Berrima Weir (212272). These gauges are located at the upstream, midpoint and downstream locations of the study area. Recorded water levels, flows, gaugings and rating curves for these gauges were provided by WaterNSW. The gauges are listed in Table 5 and locations are shown on Figure 4.

Table 5: Streamgauge Data

Gauge Number	Gauge Name	Start Date
212274	CAALANG CK AT MAUGERS	November 1986
212275	WINGECARRIBEE RIVER AT SHEEPWASH BRIDGE	October 1986
212031	WINGECARRIBEE RIVER AT BONG BONG WEIR	June 1989
212272	WINGECARRIBEE RIVER AT BERRIMA	August 1975

3.8. Wingecarribee Reservoir and Dam Operations

Wingecarribee Reservoir historic storage levels were obtained from WaterNSW. Gauge data at Glenquarry Cut (212212), on the northern side of the reservoir, is available from 1984 to the present. Water level and quality data is also available at the dam wall (420112) from February 2015 to June 2019. A daily water level record was also provided by WaterNSW from 1975 to the present. All of the datasets had some missing or erroneous data, so the information from all of these sources was synthesised to generate a complete daily record of water levels in the reservoir from 1975 to the present.

Bathymetric survey of the reservoir undertaken in 2011 by AWT Survey Pty Ltd was provided by WaterNSW. CAD files were provided that were analysed in a CAD program to extract volume information about the reservoir. This aligned with a stage-storage-area table that was provided by WaterNSW up to the full supply level (FSL) of 677.52 mAHD. A separate stage-storage-area table was provided by WaterNSW that also provided discharge information for dam release flows above FSL. This is assumed to be the spillway and/or gate capacity at levels above FSL. No other information regarding the operation of gates and release strategies were provided. While this curve did not match the stage-storage-area curve from the survey data for levels below FSL, a composite curve was developed utilising the survey data below FSL, and the stage-storage-area-discharge curve above FSL. The adopted stage-storage and stage-discharge curves can be seen in Figure 5.

Design drawings of dam outlet structures were also provided. Details of these outlet structures is useful to understand at what reservoir levels water can be released, both to the Wingecarribee River and Nepean River (via Glenquarry Cut). An incomplete dam break modelling report (Reference 13) was also provided by WaterNSW. MIKE FLOOD modelling was undertaken to assess sunny day, 1 in 500 year and PMF failure with three failure mechanisms. Basic flood behaviour was tabulated and is useful to understand the influence of dam failure on downstream flood behaviour. Characteristic PMF flow hydrographs into and out of the dam were also provided, assumed to be from the same study.

3.9. Field Inspection

A field inspection was undertaken by WMAwater staff on the 16th March 2020. General catchment conditions were observed along the Wingecarribee River, from the Wingecarribee

Reservoir to Berrima, including the towns of Moss Vale and Burradoo. A sample of photographs taken of the catchment are shown in Photo 2 to Photo 4.

Photo 2: Bong Bong Weir from Headlam Road, Moss Vale

Photo 3: Railway Bridge and Railway Road crossing the Wingecarribee River

Photo 4: Old Hume Highway Bridge over Wingecarribee River at Berrima

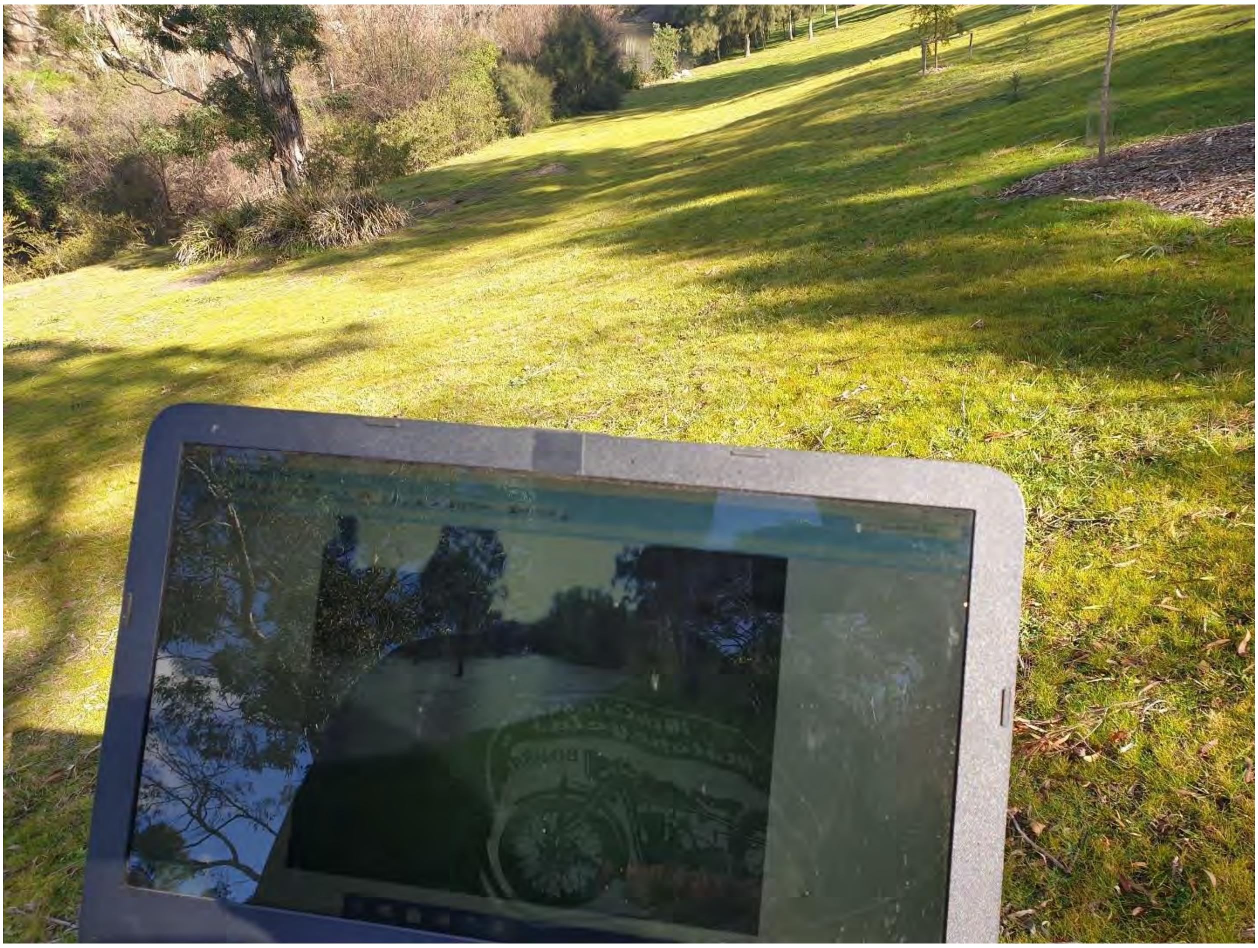
Following receipt of community survey responses, WMAwater staff conducted a site visit to a property in Berrima on 30th June 2020, as they indicated a number of flood marks existed on their property. Flood depths and extents for a number of events were taken. These locations are shown in Photo 5 to Photo 8, and estimated flood levels are included in the summary of flood marks in Section 3.5.

Photo 5: Flooding approximately 2 foot deep at this tree in 1970's (largest flood observed)

Photo 6: Flooding reached halfway up this shed in 1980's

Photo 7: Flooding reached just below metal cap on this fence post in late 1980's

Photo 8: Approximate March 2012 flood extent from photograph



3.10. Aerial Imagery

Aerial imagery was obtained from Nearmap, dated April 25, 2020. This dataset has been used for the mapping provided in this report.

4. COMMUNITY CONSULTATION

4.1. Information Brochure and Survey

An information brochure and survey were distributed as a hard copy to a number of residents located within the Wingecarribee River floodplain. The purpose of the survey was to identify flooding that residents had experienced, problems with flooding and to collate as much historical flood data as possible. This information can be seen in APPENDIX B. The survey was also able to be filled out electronically online. A media release was also issued and posted on the Wingecarribee Shire Council website to alert the community to the commencement of the study. A project website was also developed (https://wrfs.wmawater.com.au/) to be a central hub of information for all residents regarding the Flood Study.

4.2. Community Responses

A total of 899 surveys were sent via post to residents, as well as the survey being available to other residents through the project website (both as a download to print a hard copy and to fill out electronically). Approximately 20 surveys were not successfully delivered to the resident. A total of 85 surveys were completed (approximately 10%). A summary of the responses to each question is contained in APPENDIX B. The results of the community survey are summarised for each question in.

Most respondents provided their address and contact details. Respondents had lived or worked at their current address for between 1 and 46 years, with the average being 15 years. Respondents had generally lived in the area (not necessarily at the current address) for a longer period of time, up to 77 years with an average of 21 years. Approximately half of the respondents stated they had not observed or experienced flooding. Of the remaining respondents, approximately three quarters had observed flooding, while one quarter had their property affected by flooding, with the majority of these being residential properties. On most of these properties, only the land was affected. Only one respondent indicated that their building had been affected by flooding above floor level. 6 respondents had experienced damage to buildings by flooding.

6 respondents had been isolated or evacuated due to flooding. 9 respondents were able to provide photos or know of a specific flood level that they could identify. Community photographs of flooding are contained in APPENDIX C. One resident stated that a number of flood marks existed on their property in Berrima. This resident was contacted by WMAwater and a site visit was conducted on 30th June 2020. During the site visit a number of photographs were taken and measurements of depths were taken for flood events including 1970's and 1980's as well as the 2009 and 2012 floods. From the community responses, it appears that the 2012, 2014 and 2016 flood events are the most memorable of recent times within the community.

4.3. Public Exhibition

A draft version of this report was placed on public exhibition from 1 October 2021 to 12 November 2021 to invite comment from the community. Public notices were placed in the local newspaper and on Council's website, and residents affected by the study were directly notified by Council. A copy of the report was available for inspection at Council's Offices in Moss Vale, and via download from the website. Instructions for making formal written submissions were provided to those wishing to comment on the study.

Five written submissions were received. A compilation of the submissions is included in Appendix I, with a summary below.

Four of the submissions were from residents in close proximity to each other on Eridge Park Road Burradoo, in the vicinity of Sutherland Park Drive and Tirrikee Lane. Each of the homes referred to in the submissions are relatively new developments, having been completed and occupied generally in 2020/2021, subsequent to the commencement of this study in March 2020. The properties are located on the south-eastern side of Eridge Park Road (i.e. the side closer to the Wingecarribee River). While these residences are generally outside the mainstream Flood Planning Area (see Section 10.7.3), there are overland flow paths associated with drainage of local upstream catchment areas from the other side of Eridge park Road (the earlier developed parts of Burradoo). The development of these properties included the construction of formalised overland flow drainage channels either around or through the properties. Each of these properties is zoned R5 "Large Lot Residential," and is on the boundary of this zoning area under the current Wingecarribee Local Environment Plan. The area between these properties and the Wingecarribee River is currently zoned as E3 "Environmental Management," but the area has been identified in various strategic planning documents by Council as a possible future location for additional residential development. The four submissions from this area raised the following concerns:

- Some residents identified that the local overland flow drainage channels in and around the properties carry water in them during heavy rainfall events. Pictures were provided from December 2020 and May 2021. The pictures appear to show these overland flow channels functioning as expected, with water contained in the channels and not intruding into the gardens of the residents.
- Pictures were also provided of water in the Wingecarribee River several hundred metres away from the property boundary, as well as within small tributary creeks or drainage channels on the undeveloped land between the properties and the river. The residents expressed confusion as to why they have seen water in these locations during several rainfall events in the last couple of years, when during the purchase process they "…were advised that 300 meters down from [our] lot that there is a 1 in 100-year flood zone. We have seen this flood now 3 times since we have lived here." The events referred to were not 1 in 100 AEP events. The Wingecarribee River and surrounding streams will frequently carry water when it rains, not just during rarer flood events of 1 in 100 AEP magnitude. It is to be expected that surface water will be visible in drainage channels when it rains in these locations, even during relatively frequent low-intensity rainfall events. These events do not appear to have affected the properties of the

residents who made the submissions.

- Residents raised that the study did not take into account potential impacts of any future subdivision or development on the E3 zoned land between them and the Wingecarribee River. Such an investigation is outside the scope of this study. This type of assessment is normally required to be undertaken by the proponent of any development during the Planning Proposal stage (for rezoning) and during the development design stage (as part of the relevant development applications). Council's LEP and DCP contain flood-related development controls that would apply to this area, as for any other area, including requirements for the development to ensure there are no adverse flood impacts on neighbouring land.
- Some residents raised questions about the potential impacts of releases from the Wingecarribee Reservoir on flows in the river. These releases are taken into account in the design flood modelling for this study, as discussed in detail in Sections 3.8, 6.6 and 9.8 of this report.

The other submission was from a resident in Berrima, who is the owner of a small plot of land adjacent to the river which has been identified as flood prone in this and previous flood studies of the area. The submission makes various assertions about the inaccuracy of this and previous flood studies, primarily relating to the impact of riparian trees on flood levels, and suggests that design flood levels should be much lower than those estimated. The submission does not provide sufficient evidence that the methodology of this study has inadequately taken into account localised factors affecting flooding at Berrima, and no action was taken to revise the modelling methodology in this area.

5. FLOOD FREQUENCY ANALYSIS

The Flood Frequency Analysis (FFA) for this study involved two stages: The first stage was to establish a homogenous flood record using gauged data and information about events that occurred prior to the gauged record. From this data, an Annual Maximum Series (AMS) was developed, that is, a list of peak flows for each available year. The second stage involved fitting a probability distribution to the data and using the resulting curve to estimate the peak design flows. This process was undertaken in accordance with ARR19 (Reference 3) and the results were used to understand the relative magnitude of historic flood events and in the validation of design flood parameters in the hydrologic model.

The streamflow gauges on Wingecarribee River at Bong Bong Weir (212031) and Berrima Weir (212272) were used for the FFA.

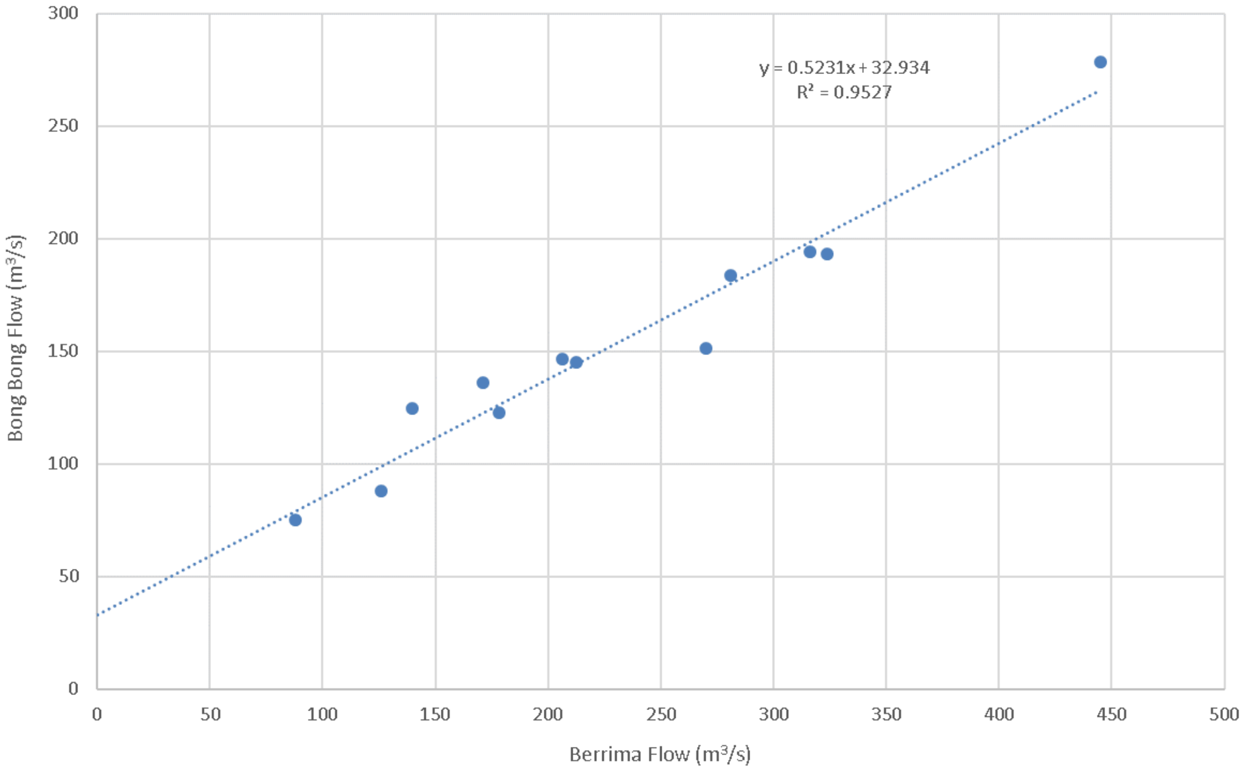
5.1. Bong Bong Weir AMS

The gauge at Bong Bong Weir (212031) commenced in June 1989, with water level recorded every 15 minutes. The record is partially incomplete, with various periods of missing data, as well as being shorter than the record from the downstream Berrima Weir gauge (212272), which was established in August 1975.

The data from each of the gauges was compared to determine whether the peak flow in each year had been captured. An analysis was undertaken to see whether there is sufficient correlation in flows from specific events between the two gauges to derive representative flows at Bong Bong Weir from Berrima Weir where data was missing. By plotting corresponding peak flows for both gauges (see Section 5.2 for details on the Berrima Weir AMS) a reasonable correlation was observed for flows above 50 m^3/s. Flows below this can skew the correlation as they can be more heavily influenced local storm features and local runoff rather than being representative of larger flood events that are of interest for this study. This linear correlation is shown in Diagram 2. Using this correlation, missing years from the Bong Bong Weir AMS were derived from Berrima Weir flows.

The base data is referred to as the gauge AMS, and the extended data set derived from correlation is referred to as the augmented AMS.

Diagram 2: Annual peak flow correlation (above 50 m^3/s) – Bong Bong Weir vs Berrima Weir



Due to minimal development and changes within the catchment, the augmented AMS record is considered to be homogeneous, although the degree of influence from Wingecarribee Dam is uncertain since there have been very few events with significant outflows from the dam. An analysis of flows recorded at Sheepwash Bridge (212275), immediately downstream of Wingecarribee Dam, indicate that since 1986 (commencement of the Sheepwash gauge operation) the largest dam releases occurred in 1990 with peak flows of approximately 26 m^3/s (less than 15% of the peak flow at Bong Bong Weir). This peak flow was released after the flood peak had passed at Bong Bong Weir and due to the attenuation of flows from the Sheepwash Road to Bong Bong Weir, these dam releases are not assumed to have a significant influence on peak flows at Bong Bong Weir.

This lack of influence on peak flows appears to be the case for all other historical releases from the dam apart from the 1978 event. Although the dam releases for that event were not measured (since they were prior to the commencement of the Sheepwash Bridge gauge), the water level data from within the reservoir indicates that this is the only time in the dam's history that water level has been above FSL by any significant amount (0.2 m above FSL). The results from the hydrologic model calibration for the 1978 event indicated a shortfall of approximately 100 m^3/s to 150 m^3/s in the modelling that may have been due to the effect of the dam releases. Details of the calibration to the 1978 event, considering the possible effect of the dam are provided in Section 8. Given the uncertainty about the dam influence in 1978, this event was censored from the AMS, and for the purposes of FFA it was specified that this event was at least the flow without the dam influence, but could have been higher with even higher dam releases. This reduces the influence of this single event on the fit at the rarer end of the distribution. A summary of the adopted AMS is contained in Table 6. A record of 44 years was obtained by this method.

Table 6: Derivation of AMS (m^3/s) for Bong Bong Weir (212031)

Year	Gauge AMS[1]	Augmented AMS[2]	WBNM Flow without Dam[3]	Final AMS
1976		120.1		**120.1**
1977				*
1978			400.8	**Higher than 400.8 (using Bayesian censoring)**
1979		35.9		35.9
1980		36.3		36.3
1981		43.7		**43.7**
1982		36.2		36.2
1983		48.2		**48.2**
1984		109.6		**109.6**
1985		63.6		**63.6**
1986		189.0		**189.0**
1987		91.9		**91.9**
1988		272.9		**272.9**
1989		83.3		**83.3**
1990	193.2			**193.2**
1991	151.3			**151.3**
1992	40.8			**40.8**
1993	3.1			3.1
1994				**
1995	146.6			**146.6**
1996	136.1			**136.1**
1997	74.9			**74.9**
1998	278.3			**278.3**
1999	37.7			37.7
2000	7.5			7.5
2001	20.6			20.6
2002	2.0			2.0
2003	15.9			15.9
2004	5.3			5.3
2005	37.4			37.4
2006	11.4			11.4
2007	122.5			**122.5**
2008	13.9			13.9
2009	3.0			3.0
2010	21.8			21.8
2011	29.2			29.2
2012	124.8			**124.8**
2013	144.9			**144.9**
2014	87.8			**87.8**
2015	183.4			**183.4**
2016	193.9			**193.9**
2017	19.3			19.3
2018	2.5			2.5
2019	1.2			1.2

Notes on Table 6:

[1] *AMS derived directly from gauge data that captures the annual peak*

[2] *AMS augmented with flows derived from Berrima Weir using a correlation*

[3] *Flows derived from hydrologic modelling without dam releases*

** It is likely that the Berrima gauge did not capture the 1977 flood peak looking at nearby*

gauges (215220 and 214003), although the peak is most likely less than the low flow censor threshold.
*** 1994 event data missing. Assumed to be less than the low flow censor threshold based on the low peak flow recorded at Berrima Weir.*

Flows less than 40 m^3/s were censored from the Bong Bong Weir record. A total of 21 years were censored from the record, including 1977 and 1994 flows (see footnotes of Table 6). The 23 years with events above this threshold are in bold in Table 6. Censoring of these flows resulted in a much better fit of the probability distribution with a much tighter confidence interval. Without censoring, the lower events resulted in an extreme skew on the distribution. These events are likely heavily affected by catchment land-use (particularly runoff capture from farm dams), and the recorded flows at the weirs are likely not representative of the true underlying runoff distribution from the catchment for these smaller events.

5.2. Berrima Weir AMS

The gauge at Berrima Weir (212272) commenced in August 1975, with water level recorded several times per day until 1980, where it is recorded every 15 minutes. The record, however, is incomplete, with a number of days with missing data. The data was analysed in conjunction with data recorded upstream at Bong Bong Weir (212031) and daily rainfall data across the catchment to determine whether the peak flow in each year had been captured. This is the gauge AMS.

Due to minimal development and changes within the catchment, the gauge AMS record is considered to be homogenous, except for the influence of Wingecarribee Dam. An analysis of dam releases was undertaken (see Section 5.1 for details) and it was found that dam releases were not significant, except for the 1978 event. To generate an AMS without any significant releases from the dam (essentially removing the runoff from the upper catchment), the 1978 peak flow was derived from the hydrologic model. Details of the calibration to the 1978 event with the dam are contained in Section 8. Since this calibration produced a good match, the model was used to simulate flows at Berrima Weir neglecting any outflows from the dam. A summary of the AMS at each step is contained in Table 7. A record of 44 years was obtained by this method.

Table 7: Derivation of AMS (m^3/s) for Berrima Weir (212272)

Year	Gauge AMS[1]	WBNM Flow without Dam[2]	Final AMS
1976	166.6		**166.6**
1977			*
1978		486.3	**Higher than 486.3 (using Bayesian censoring)**
1979	5.7		5.7
1980	6.5		6.5
1981	20.6		20.6
1982	6.3		6.3
1983	29.2		29.2
1984	146.6		**146.6**
1985	58.7		**58.7**
1986	298.3		**298.3**
1987	112.7		**112.7**
1988	458.7		**458.7**
1989	96.3		**96.3**
1990	324.0		**324.0**
1991	270.2		**270.2**
1992	42.6		**42.6**
1993	5.6		5.6
1994	38.3		38.3
1995	206.2		**206.2**
1996	171.1		**171.1**
1997	88.0		**88.0**
1998	445.0		**445.0**
1999	30.3		30.3
2000	9.7		9.7
2001	23.5		23.5
2002	3.2		3.2
2003	14.8		14.8
2004	7.1		7.1
2005	42.6		42.6
2006	11.5		11.5
2007	178.3		**178.3**
2008	14.6		14.6
2009	3.7		3.7
2010	25.4		25.4
2011	33.2		33.2
2012	139.7		**139.7**
2013	212.3		**212.3**
2014	126.2		**126.2**
2015	280.8		**280.8**
2016	316.0		**316.0**
2017	29.2		29.2
2018	7.8		7.8
2019	2.4		2.4

[1] AMS derived directly from gauge data that captures the annual peak

[2] Flows derived from hydrologic modelling without dam releases

** It is likely that the Berrima gauge did not capture the 1977 flood peak looking at nearby gauges (215220 and 214003), although the peak is most likely less than the low flow censor threshold.*

The Berrima Weir record was also censored in a similar manner to Bong Bong Weir using a threshold of 40 m^3/s. A total of 23 years were censored from the record, including the 1977 flow (see footnotes of Table 7). The 21 years with events above this threshold are in bold in Table 7. Censoring of these flows resulted in a much better fit of the probability distribution with a much tighter confidence interval. Without censoring, the lower events resulted in an extreme skew on the distribution. These events are likely heavily affected by catchment land-use (particularly runoff capture from farm dams), and the recorded flows at the weirs are likely not representative of the true underlying runoff distribution from the catchment for these smaller events.

5.3. FFA Results

Using the AMS derived above, both the Log Pearson III (LPIII) and Generalised Extreme Value (GEV) probability distributions were fitted to the data using FLIKE software (5.0.251.0). These two distributions are recommended in ARR19 (Reference 3), and fitted the data reasonably well. Graphs of the fitted distributions can be found in Figure 8 and Figure 9 for the LPIII and GEV distributions, respectively. Results are also tabulated in below.

Table 8: FFA Results at Bong Bong and Berrima Weirs for both LPIII and GEV Distributions

AEP	Bong Bong Weir Flow (m^3/s)		Berrima Weir Flow (m^3/s)	
	LPIII	GEV	LPIII	GEV
20%	140	150	215	220
10%	229	223	358	344
5%	324	305	476	461
2%	456	417	585	609
1%	557	508	639	717

The position of the 5 largest historical events for each gauge within these FFA estimates are summarised in Table 9.

Table 9: Annual exceedance probability of historic events at Bong Bong and Berrima Weirs

Bong Bong Weir				Berrima Weir			
Event (Rank)	Peak Flow (m^3/s)	LPIII AEP (1 in Y)	GEV AEP (1 in Y)	Event (Rank)	Peak Flow (m^3/s)	LP3 AEP (1 in Y)	GEV AEP (1 in Y)
1978 (1)	Not recorded	-	-	1978 (1)	631.6	91	58
1998 (2)	278.3	15	16	1988 (2)	458.7	18	20
1988 (3)	272.9	14	15	1998 (3)	445.0	17	18
2016 (4)	193.9	8	8	1990 (4)	324.0	9	9
1990 (5)	193.2	8	8	2016 (5)	316.0	8	9

6. HYDROLOGIC MODEL

6.1. Introduction

A hydrologic model is a tool for estimating the amount and timing of runoff that flows from a catchment for a given rainfall event. Hydrologic model is the best practice for determining how much flow occurs from rainfall in areas where streams are not gauged or the record length is not long enough to estimate flows. This type of hydrologic model is referred to as a runoff-routing model.

A range of runoff-routing hydrologic models is available as described in ARR19 (Reference 3). These models allow the rainfall to vary in both space and time over the catchment and will calculate the runoff generated by each sub-catchment. The generated flow hydrographs then serve as inputs at the boundaries of the hydraulic model, which provides details about flood levels and velocities.

The WBNM hydrologic runoff-routing model was used to 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. Where flow data is available at a stream gauge, 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. Further details regarding the WBNM software can be found in the WBNM User Guide (Reference 14).

A hydrological model for the entire Wingecarribee River Catchment to Wallaby Rocks was developed and used to calculate the flows for each individual sub-catchment and tributary creek for inclusion in the TUFLOW hydraulic model.

6.2. Sub-catchment delineation

In total, the catchment represented by WBNM is 229 km^2, consisting of 834 sub-catchments. The sub-catchment delineation is shown in Figure 10. The sub-catchments were derived from LiDAR topographic data with consideration of hydraulic controls such as bridge crossings and road/rail embankments. Sub-catchments within urban areas are typically smaller to capture the drainage catchment to the stormwater system, while sub-catchments within rural areas are typically larger.

6.3. Hydrologic Model Parameters

The model input parameters to represent each sub-catchment are:

- A lag factor (termed ‘C’), which can be used to accelerate or delay the runoff response to rainfall;
- A stream flow routing factor, which can accelerate or decelerate in-channel flows occurring through each sub-catchment;
- An impervious area lag factor;

- Catchment area; and
- The percentage of catchment area with a pervious/impervious surface;

The 'C' lag factor of 2.1 was found to be most appropriate for the catchment. This is higher than the recommended default value of 1.6 (for an ungauged catchment in NSW), however, is within the range of acceptable values. This value was selected considering the modelled and gauged hydrograph responses at Bong Bong and Berrima Weirs across the range of historic flood events simulated. This value produced the most reasonable match in shape, timing and peak of the hydrographs.

A stream routing factor of 1.5 was found to be most appropriate for the catchment. This is higher than the typical value of 1.0 for natural channels, however, is within the range of acceptable values. This value was selected considering the modelled and gauged hydrograph responses at Bong Bong and Berrima Weirs across the range of historic flood events simulated. This value produced the most reasonable match in shape, timing and peak of the hydrographs, in combination with the adopted 'C' value. This routing value also produced a similar response to the TUFLOW hydraulic model.

The higher C and routing values account for the storage within the catchment and across the Wingecarribee floodplain. Details of the WBNM calibration are in Section 8. A default impervious lag factor of 0.1 was adopted. Catchment areas were calculated based on sub-catchment boundaries in a GIS program. The impervious fractions within the catchment are discussed in Section 6.4 below.

6.4. Impervious Surface Area

Runoff from connected impervious surfaces such as roads, gutters, roofs or concrete surfaces occurs significantly faster than from vegetated surfaces. This results in a faster concentration of flow within the downstream area of the catchment, and increased peak flow in some situations. ARR19 (Reference 3) identifies three types of areas for the purpose of estimating urban storm losses:

- Directly Connected Impervious Areas (DCIA) which are impervious areas directly connected to the drainage system;
- Pervious Areas consisting of parks and bushland areas; and
- Indirectly Connected Areas (ICA) which consist of impervious areas which are not directly connected to the drainage system and the pervious areas which interact with indirectly connected impervious areas (ICIA).

To account for this, ARR19 recommends the use of 'Effective Impervious Area' (EIA), which is a concept identifying the amount of impervious area that acts as directly connected for total runoff purposes, including consideration of both the DCIA and ICIA. This is typically calculated as a percentage of the TIA (DCIA + ICIA). Using the literature from Australian studies in ARR19, the ratio of EIA/TIA is typically in the range from 60% to 80%. Given the reasonably large blocks of land and semi-rural nature of these towns, a lower ratio of 60% has been adopted. It is estimated that for a typical urban area within the Wingecarribee River Catchment (for example

Moss Vale, Burradoo and Berrima), the TIA is approximately 50% (i.e. 50% of the urban area is impervious). This yields an overall EIA of approximately 30% (60% x 50%). Commercial areas, such as those within Bowral were assumed to have an EIA of approximately 90%. An overall EIA was assigned to each subcatchment based on these considerations, as shown in Figure 10.

6.5. Rainfall Losses

Methods for modelling the proportion of rainfall that is “lost” to infiltration are outlined in ARR19 (Reference 3). The methods are of varying degrees of complexity, with the more complex options only suitable if sufficient data is 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 filling of localised depressions, and the continuing loss represents the ongoing infiltration of water into the saturated soils while rainfall continues. The initial/continuing loss method was adopted for this study.

6.6. Wingecarribee Reservoir

Wingecarribee Reservoir is included in the WBNM hydrologic model. The reservoir is defined by the stage-storage curve and stage-discharge curve presented in Figure 5 (see Section 3.8 for details). WBNM calculates the runoff from the catchment upstream of the dam and the volume of runoff generated can fill the reservoir. A water level is calculated based on the stage-storage curve. An outflow can then be calculated based on this water level and the stage-discharge curve. An initial water level can be set at the start of any event simulation.

For model calibration, instead of modelling the dam and estimating the dam releases that occurred, the flows recorded at the Sheepwash Bridge gauge (212275) were used directly in the WBNM model and the dam and its catchment was not included in the model. The exception was the 1978 event, where the Sheepwash Bridge gauge was not available. In this case the dam was included in the WBNM model. Further details on the model calibration is contained in Section 8.

7. HYDRAULIC MODEL

7.1. Introduction

Hydraulic modelling is the simulation of how floodwaters move through across the terrain. A 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 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. It requires high resolution information about the topography, which is available for this study from the LiDAR aerial survey. Various 2D software packages are available (SOBEK, TUFLOW, RMA-2). The TUFLOW package 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 and 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-w64 (using the finite volume HPC solver in single precision mode), and further details regarding TUFLOW software can be found in the User Manual (Reference 15).

In TUFLOW the ground topography is represented as a uniform grid with a ground elevation and Mannings ‘n’ roughness value assigned to each grid cell. The size of grid is determined as a balance between the model result definition required 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.

7.2. TUFLOW Hydraulic Model Extent and Resolution

The TUFLOW model 2D domain covers the Wingecarribee River catchment, from immediately downstream of Wingecarribee Dam to Wallaby Rocks. There are some areas excluded from the hydraulic model extent including areas upstream of the Illawarra Highway (to the south), Stony Creek upstream of Berrima Road (to the south-west), New Berrima (since it is positioned at the top of a hill) and Mittagong Creek upstream of Burradoo Train Station (to the north). The 2D domain covers an area of approximately 95 km^2. A grid size of 3 m was adopted. This is a significant improvement over the 10 m grid adopted for the 2014 Flood Study (Reference 1). This is possible due to the use of the TUFLOW Heavily Parallelised Compute (HPC) Engine, with the ability to run on a Graphics Processor Unit (GPU). The new HPC GPU models are significantly faster than the traditional Central Processing Unit (CPU). As such, the HPC Engine with GPU was used for this study, facilitating a finer grid resolution than previously possible. The TUFLOW model 2D extent is shown in Figure 11.

7.3. Terrain

The TUFLOW model 2D terrain was based on the latest available LiDAR data, which was the 1 m and 2 m datasets obtained from ELVIS (see Section 3.3). There were several modifications made to this terrain to ensure topographic features were represented correctly. These modifications are discussed in the following sections. The terrain can be seen in Figure 11.

7.3.1. Roads and Railway

In areas where road or railway infrastructure form a significant obstruction to flow or where flow paths cross under road or railway embankments, the crest of the embankment was included in the TUFLOW model as a breakline. These breaklines are sampled directly from the LiDAR to ensure that crest (the overtopping level of the embankment) is correctly represented in the model. The LiDAR data was also analysed to ensure that bridge openings were adequately represented. At the Sproules Lane crossing the bridge abutments were added in manually to the model to represent the opening in the 2D terrain.

LiDAR typically does not have sufficient resolution to adequately define the kerb and gutter system within roadways. The density of the aerial survey points is in the order of one per square metre, and the kerb/gutter feature is generally of a smaller scale than this, so the LiDAR does not pick up a continuous line of low points defining the drainage line along the edge of the kerb.

To deal with this issue, Reference 16 provides the following guidance:

> *"Stamping a preferred flow path into a model grid/mesh (at the location of the physical kerb/gutter system) may produce more realistic model results, particularly with respect to smaller flood events that are of similar magnitude to the design capacity of the kerb and gutter. Stamping of the kerb/gutter alignment begins by digitising the kerb and gutter interval in a GIS environment. This interval is then used to select the model grid/mesh elements that it overlays in such a way that a connected flow path is selected (i.e. the element linkage is orthogonal). These selected elements may then be lowered relative to the remaining grid/mesh."*

The road gutter network plays a key role for overland flow in the urbanised parts of the study area. In order to model the system effectively, the gutters were stamped into the mesh using the method described above. The method used was to digitise breaklines along the gutter lines, and reduce the ground levels along those model cells by 0.1 m, creating a continuous flow path in the model.

7.3.2. Weirs

Both Bong Bong and Berrima weirs control flows along the Wingecarribee River. The weirs were incorporated into the TUFLOW model 2D domain by applying breaklines. The breaklines were based on the structure survey undertaken for the previous flood study (Reference 1). LiDAR survey typically doesn't penetrate a water surface and as such, the terrain data for the weir pools that form behind the weirs is interpolated from the bank where the water surface ends. This results in 'ground' levels that are similar to the standing water level at the time of the survey. The actual ground level was represented by carving out the channel upstream of the weirs (where standing water is present) to a reasonable level. This produces more accurate flow behaviour upstream of the weirs.

7.3.3. Farm Dams

Rural farm dams are prevalent through the rural areas within the catchment. Breaklines for the crest of some of the larger dams that are located 'on-stream' were included to ensure that these dams were represented in the model. These breaklines were sampled from the LiDAR data.

7.3.4. Channels

Breaklines were also been included for some of the small channels, primarily in the upper catchment, to ensure that the channel invert is sufficiently represented in the TUFLOW model and conveyance of water between the TUFLOW grid cells is adequate.

7.4. Surface Roughness

Surface roughness values have been defined across the TUFLOW 2D domain, represented by the Mannings 'n' coefficient. The roughness is based upon the land use, which was visually inspected using the best available aerial imagery (see Section 3.10). The cadastre and Local Environmental Plan (LEP) zoning (see Section 3.6) was also used as a guide.

Table 10: Mannings 'n' values used in the TUFLOW model

Land Use Category	Mannings 'n'
Maintained grass / parks / ovals	0.03
Floodplain grass / pasture	0.03
Light vegetation	0.06
Dense vegetation	0.08
Creek channel (upstream of Berrima Weir) and open water	0.03
Creek channel (downstream of Berrima Weir)	0.04
Roads	0.02
Road/Rail corridor	0.035
Low density (rural) residential	0.05
Medium density (urban) residential	0.06
Industrial / commercial	0.035

Each land use category was assigned a Mannings 'n' value, as outlined in Table 10, based on typical values and adjusted during the calibration stage. The spatial distribution of these categories is shown in Figure 12.

7.5. Bend Losses

The Wingecarribee Floodplain is generally quite wide with a large volume of temporary floodplain storage. This changes quite dramatically upstream of Berrima Weir, where the floodplain is heavily constricted through the natural formation of what is termed here as the Berrima Gorge. The Wingecarribee River enters the steep sided gorge and becomes quite narrow. This change in river character is partially accounted for by the different Manning's 'n' values adopted upstream and downstream of Berrima Weir (see Table 10). The river's sinuosity also increases as it meanders through Berrima and downstream to Wallaby Rocks. At these bends, there are quite high velocities and the water is relatively deep. While 2D hydraulic models account for the energy losses associated with bends and the change in the horizontal direction of flow, there are other 3D flow features at sharp bends that are not captured with 2D models. These vertical flow patterns such as helical vortices result in additional energy losses that have been added into the model. A similar phenomenon was found when modelling the Brisbane River (Reference 17), where additional form losses were required in the hydraulic model to represent the observed head loss along the river. The Brisbane River is similar to the Wingecarribee River through the Berrima Gorge, where there is deep flow around sharp bends.

In accordance with the findings of the Brisbane River Flood Study (Reference 17), typical form losses of 1.5 for a 180 degree bend and 0.75 for a 90 degree bend were applied to the Wingecarribee River downstream of Berrima Weir.

7.6. Buildings

Buildings were represented as solid obstructions to flow by blocking them out of the TUFLOW grid. A buildings layer provided by Council (see Section 3.6). Some minor updates were made to this layer to include recent developments. These additional buildings were digitised based on the latest available aerial imagery.

7.7. Pit and Pipe Network

The pit and pipe network was included in the TUFLOW model as a 1D network dynamically linked to the 2D 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. The pit and pipe data received from Council (see Section 3.6) was used with several modifications to enable an adequate representation in the TUFLOW model:

- Pipes smaller than 450 mm in diameter were removed (including pits connected to these pipes)
- Pipes were connected to downstream pipes to ensure continuity of each branch to the outlet. In some cases, the outlet was not defined and the most likely outlet location was chosen, taking pipe sizes from the most downstream pipe available

- Pipes were checked and some were adjusted to ensure consistent pipe sizes (downstream pipes were the same size or larger than upstream pipes), including assigning reasonable pipe sizes to those where data was missing
- TUFLOW requires the polylines representing the pipes to be digitised from upstream to downstream, so these were modified where this was not the case
- Invert levels of outlets (where they were not provided) were obtained from the LiDAR data
- Invert levels of pipes (where they were not provided) were taken to be the ground level (from LiDAR) minus 0.6 m, minus the pipe diameter or height
- Upstream and downstream invert levels of pipes were checked and adjusted to ensure there is no adverse grade
- Pipes were assigned a Mannings 'n' of 0.013
- Pit details were not provided. Kerb inlet pit lintels were assumed to be 1.8 m wide.

In addition to the street stormwater network, a number of cross drainage culverts that were part of the stormwater system were also included. A total of 1,052 pipes and 1,066 inlets and outlets were included in the TUFLOW model to represent the stormwater network, and these are shown in Figure 13.

7.8. Culverts and Bridges

Culverts with a size of 450 mm width/diameter and greater were included in the TUFLOW model as 1D elements. There is an arch culvert within the study area and was represented in the TUFLOW model by calculating a width-height relationship. Depending on the source of information, invert levels were obtained from topographic survey (undertaken for the previous Flood Study, Reference 1) or estimated based on the LiDAR road levels and a depth of cover (sourced from the WMAwater survey).

Bridge structures were typically modelled in the 2D domain. Details of these structures were obtained from the survey undertaken for the previous Flood Study (Reference 1) in 2014 and from design drawings provided by Council. Additional structures which were surveyed in the field by WMAwater and large enough to influence flow behaviour were also included in the model. The bridge soffit and deck levels are included in the TUFLOW model, with an estimate of the hydraulic obstruction and losses due to the piers and deck. These loss coefficients were estimated using the relevant literature. For the waterway crossings on the railway line where it was inaccessible to collect the data, an opening was provided in the embankment and a flow constriction layer with an estimated loss coefficient of 0.5 was applied to account for the culvert or bridge obstruction.

The culvert and bridges that were included in the TUFLOW model are shown in Figure 13.

7.9. Model Boundaries

7.9.1. Inflows

Inflows into the TUFLOW model are sourced from the WBNM hydrologic model. Typically, the simulated local runoff hydrographs for each sub-catchment is applied at the sub-catchment outlet in the TUFLOW model. Where sub-catchments drain to urban pits, the flow is applied to 2D cells where pit inlets are located. In some locations where upstream portions of creeks have not been included in the TUFLOW model, total flows arriving at the TUFLOW model boundary are applied. The outflow from the dam is applied at the upstream boundary of the model.

7.9.2. Downstream Boundary

The downstream boundary for Wingecarribee River is applied downstream of Wallaby Rocks, where a constant water level of 626 mAHD is applied. This water level is low enough that water that flows through the Wallaby Rocks constriction can flow out of the model.

One other small outflow boundary is provided in the model on the railway line immediately north of Moss Vale Station. Stormwater pipes from Valetta Street discharge into a vacant lot which the flows to the north and toward the Wingecarribee River. Overland flow from the Valetta Street catchment, however, can also flow into the railway corridor and continue to the south, towards Whites Creek. A stage-flow relationship is applied at this location.

The boundaries have been set up such that they are not expected to significantly influence water levels within the study area.

8. MODEL CALIBRATION

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.

There are several recent flood events that could be used for calibration of the hydrologic and hydraulic models. The calibration events were chosen based on the availability of pluviograph rainfall data, streamflow data, availability/reliability of flood marks and observations from the community, and the magnitude of the event. The events selected are discussed below, with figures and maps of the rainfall events presented in APPENDIX D.

8.1. Flood Events

8.1.1. March 1978 Flood Event

This flood event was due to sustained rainfall occurring on the 18th to the 21st March, 1978. The storm temporal patterns can be seen in Figure D1. Only two pluviograph stations were available for this event – Robertson (St. Anthonys) gauge (068117) and Moss Vale (Torokina) gauge (068195). The Moss Vale gauge appears to have a rainfall total evenly distributed from approximately 9pm on the 20th, and misses an intense burst that occurred late in the event. Apart from this, the two gauges present a very similar temporal pattern, which shows relatively consistent rainfall over the storm event. The rainfall is between a 2% and 1% event for a 2 day duration, comparing the Moss Vale gauge to the IFD data at the centroid of the catchment, as shown in Figure D2. The Robertson gauge shows a much rarer estimated AEP, due to the high rainfall depths that fell over the upper catchment when compared to the IFD at the catchment centroid. It should be noted that the IFD at Robertson has higher rainfalls than at the catchment centroid due to orographic effects from the proximity to Macquarie Pass and the Illawarra Escarpment. An IFD sourced at Robertson would indicate an AEP more consistent with that shown for the Moss Vale gauge. The spatial distribution of rainfall is shown in Figure D3. This was generated by using daily rainfall gauge totals (to 9 am) for the 19th to 21st of March, and gridded using the natural neighbour technique. The rainfall varies from approximately 900 mm in the east of the catchment (at Robertson), to approximately 300 mm in the west (at Berrima).

The recorded flow Berrima Weir (212275) was the largest recorded at the gauge to date, peaking at approximately 630 m^3/s. This event occurred prior to the commencement of the Bong Bong Weir gauge (212031). The FFA (see Section 5.3) at Berrima Weir indicates that this event is between a 2% and 1% AEP event.

There are several flood marks available for this event, including three from the Berrima Flood Study (Reference 7) and two from the community questionnaire that WMAwater staff inspected. All of these flood marks are located in the vicinity of the Berrima township and further details of these flood marks are contained in Section 3.5.

8.1.2. April 1988 Flood Event

This flood event was due to rainfall occurring on the 28th to the 30th April, 1988, with the most intense burst occurring on the morning of the 30th. The storm temporal patterns can be seen in Figure D4. 6 pluviograph stations were available for this event, with each showing a similar temporal pattern (except for some small differences at the start of the event). The rainfall is approximately a 5% AEP event between a 6 hour and 12 hour duration at the Moss Vale (068195) gauge, as shown in Figure D5. The gauges to the east show a much rarer storm, due to the total rainfall depths received compared to the IFD, taken at the catchment centroid. The spatial distribution of rainfall is shown in Figure D6. This was generated by using daily rainfall gauge totals (to 9 am) for the 27th of April to 1st of May, and gridded using the natural neighbour technique. The rainfall varies from almost 500 mm in the east of the catchment (at Robertson), to approximately 230 mm in the west (near Moss Vale).

The recorded flow Berrima Weir was the second largest recorded at the gauge to date, peaking at approximately 460 m^3/s. This event occurred prior to the commencement of the Bong Bong Weir gauge. The FFA (see Section 5.3) at Berrima Weir indicates that this event is between a 5% and 2% AEP event.

There are several flood marks available for this event, including eight from the Berrima Flood Study (Reference 7), one from the previous Wingecarribee Flood Study (Reference 1) and two from the community questionnaire that WMAwater staff inspected. All of these flood marks are located in the vicinity of the Berrima township and further details of these flood marks are contained in Section 3.5.

8.1.3. August 1990 Flood Event

This flood event was due to rainfall occurring primarily on the 31st of July to the 2nd of August, 1990. The storm temporal patterns can be seen in Figure D7. Seven pluviograph stations were available for this event, with each showing a similar temporal pattern, with the exception of the Robertson gauge which recorded no rainfall between 12 am and 9 am on the 1st of August. The Wildes Meadow (568081) gauge also appears to have total rainfalls evenly distributed from 4pm on 1st of August.

The rainfall is between a 20% and 2% AEP event for a 2 day duration across the range of gauges available, as shown in Figure D8. The spatial distribution of rainfall is shown in Figure D9. This was generated by using daily rainfall gauge totals (to 9 am) for the 31st of July to 4th of August, and gridded using the natural neighbour technique. The rainfall varies from approximately 480 mm in the east of the catchment (at Robertson), to approximately 220 mm in the west (near Berrima).

The recorded flow at Bong Bong Weir is the third largest event recorded, being similar in magnitude to the 2016 event with a peak flow of approximately 190 m^3/s. The flow at Berrima Weir was the fourth largest recorded at the gauge to date, peaking at approximately 320 m^3/s.

The FFA (see Section 5.3) at these gauges indicates that this event is approximately a 10% AEP event.

There are a few flood marks available for this event, including two from the Berrima Flood Study (Reference 7) and one from the previous Wingecarribee River Flood Study (Reference 1). Two of these flood marks are located in the vicinity of the Berrima Township and the other is located on the Wingecarribee River floodplain, to the south east of Bowral. Further details of these flood marks are contained in Section 3.5.

8.1.4. June 1991 Flood Event

This flood event was due to rainfall occurring primarily on the 9th to 11th of June, 1991. The storm temporal patterns can be seen in Figure D10. Seven pluviograph stations were available for this event. The temporal pattern and rainfall depths for the Moss Vale gauges (568165 and 068195) and Colyers Creek (568082) gauge are consistent, while the other gauges show some variation in temporal pattern, with some large variations in total depths.

The rainfall is less than a 20% AEP event for the Moss Vale gauges, as shown in Figure D11. The other gauges indicate a rarer event due to the higher rainfall depths recorded in comparison to the IFD, which is taken at the catchment centroid. The spatial distribution of rainfall is shown in Figure D12. This was generated by using daily rainfall gauge totals (to 9 am) for the 6th to the 12th of June, and gridded using the natural neighbour technique. The rainfall varies from approximately 1,000 mm in the east of the catchment (at Robertson), to approximately 210 mm in the west (near Berrima).

The recorded flow at Bong Bong Weir is moderate, with peak flows of approximately 150 m^3/s. The flow at Berrima Weir is also moderate, peaking at approximately 270 m^3/s. The FFA (see Section 5.3) at these gauges indicates that this event is approximately a 20% AEP event.

There are no flood marks available for this event.

8.1.5. September 1995 Flood Event

This flood event was due to rainfall occurring primarily on the 25th of September, 1995. The storm temporal patterns can be seen in Figure D13. Ten pluviograph stations were available for this event, with each showing a reasonably similar temporal pattern. It appears that the Mittagong (568054) gauge stopped working during two brief intervals.

The rainfall is typically between a 20% and 5% AEP event for a 12 hour duration across the range of gauges available, as shown in Figure D14. The gauges to the east show a slightly rarer storm, due to the total rainfall depths received compared to the IFD, taken at the catchment centroid. The spatial distribution of rainfall is shown in Figure D15. This was generated by using daily rainfall gauge totals (to 9 am) for the 24th to 26th of September, and gridded using the natural neighbour technique. The rainfall varies from approximately 250 mm in the east of the catchment (at Robertson), to approximately 130 mm in the west (near Berrima).

The recorded flow at Bong Bong Weir was moderate, being similar to the 1991 event with a peak flow of approximately 150 m^3/s. The flow at Berrima Weir was also moderate, peaking at approximately 210 m^3/s. The FFA (see Section 5.3) at these gauges indicates that this event is approximately a 20% AEP event.

There is only one flood mark available for this event from the Berrima Flood Study (Reference 7). Further details of the flood mark are contained in Section 3.5.

8.1.6. August 1996 Flood Event

This flood event was due to a rainfall burst occurring on the 31st August, 1996. The storm temporal patterns can be seen in Figure D16. Ten pluviograph stations were available for this event, with each showing a reasonably similar temporal pattern.

The rainfall is typically less than a 20% AEP event across the majority of gauges, as shown in Figure D17. The gauges to the east show a slightly rarer storm, due to the total rainfall depths received compared to the IFD, taken at the catchment centroid. The spatial distribution of rainfall is shown in Figure D18. This was generated by using daily rainfall gauge totals (to 9 am) for the 30th of August to the 1st of September, and gridded using the natural neighbour technique. The rainfall varies from approximately 260 mm in the east of the catchment (near Robertson), to approximately 90 mm in the west (near Berrima).

The recorded flow at Bong Bong Weir was moderate, being similar to the 1995 event with a peak flow of approximately 140 m^3/s. The flow at Berrima Weir was also moderate, peaking at approximately 170 m^3/s. The FFA (see Section 5.3) at these gauges indicates that this event is more frequent than a 20% AEP event.

There are two flood marks available for this event from the Berrima Flood Study (Reference 7). Further details of the flood mark are contained in Section 3.5.

8.1.7. August 1998 Flood Event

This flood event was due to a rainfall burst occurring on the 7th and 8th of August 1998. The storm temporal patterns can be seen in Figure D19. Ten pluviograph stations were available for this event, with each showing a reasonably similar temporal pattern.

The rainfall is more frequent than a 5% AEP event at most gauges when compared to the IFD taken at the catchment centroid, as shown in Figure D20. The spatial distribution of rainfall is shown in Figure D21. This was generated by using daily rainfall gauge totals (to 9 am) for the 6th to the 9th of August, and gridded using the natural neighbour technique. The rainfall varies from approximately 300 mm in the south east of the catchment (near Robertson), to approximately 130 mm in the north- west (near Berrima).

The recorded flow at Bong Bong Weir was the largest on record, with a peak flow of approximately 280 m^3/s. The flow at Berrima Weir was the third highest, just behind the 1988 event, peaking at approximately 450 m^3/s. The FFA (see Section 5.3) at these gauges indicates that this event is approximately a 5% AEP event.

There are five flood marks available for this event from the previous Wingecarribee River Flood Study (Reference 1). These flood marks are located across Moss Vale, Bowral and Berrima. Further details of the flood mark are contained in Section 3.5.

8.1.8. June 2007 Flood Event

This flood event was due to two rainfall bursts. The first occurred on the 14th and 15th of June, 2007 and the second, larger burst, occurred on the 15th and 16th of June. The storm temporal patterns can be seen in Figure D22. Ten pluviograph stations were available for this event, with minor variations between them, except for the East Kangaloon (568070) gauge, which failed after 8 am on the 15th.

The rainfall is more frequent than a 20% AEP event all gauges when compared to the IFD taken at the catchment centroid, as shown in Figure D23. The spatial distribution of rainfall is shown in Figure D24. This was generated by using daily rainfall gauge totals (to 9 am) for the 14th to the 17th of June, and gridded using the natural neighbour technique. The rainfall varies from approximately 320 mm in the south east of the catchment (near Robertson), to approximately 130 mm in the west (near Moss Vale and Berrima).

The recorded flow at Bong Bong Weir was moderate, with a peak flow of approximately 120 m^3/s. The flow at Berrima Weir was also moderate, being similar to the 1996 event, peaking at approximately 180 m^3/s. The FFA (see Section 5.3) at these gauges indicates that this event is more frequent than a 20% AEP event.

Photo 9: Flooding at Bong Bong Weir from Headlam Road, 16th June 2007. *Source: WSC*

There are two flood marks available for this event from the previous Wingecarribee River Flood

Study (Reference 1). These flood marks are located in Moss Vale and Bowral. Further details of the flood mark are contained in Section 3.5. There are a number of photographs from the June 2007 flood event provided by Wingecarribee Shire Council. These are contained in APPENDIX C (Photos C51 to C78). An example is shown in Photo 9.

8.1.9. March 2012 Flood Event

This flood event was due to heavy rainfall on the 7th and 8th of March 2012. The storm temporal patterns can be seen in Figure D25. The largest burst occurred early in the morning of the 8th, recorded at both the Robertson gauge (068054) and Moss Vale gauge (068239). The Bowral gauge (068102) appears to not have accurately recorded the event. The rainfall burst is less than a 20% AEP event for all durations, compared to IFD data at the centroid of the catchment, as shown in Figure D26. The spatial distribution of rainfall is shown in Figure D27. This was generated by using daily rainfall gauge totals (to 9 am) for the 8th and 9th of March, and gridded using the natural neighbour technique. The rainfall varies from approximately 150 mm in the south, to approximately 65 mm in the north.

The recorded flow at Bong Bong Weir (212031) was moderate, reaching approximately 125 m^3/s. The flow at Berrima Weir (212272) was also moderate, peaking at approximately 140 m^3/s. The FFA (see Section 5.3) at these gauges indicates that this event is more frequent than a 20% AEP event.

There are three flood marks available for this event from the previous Wingecarribee River Flood Study (Reference 1). These flood marks are located in Moss Vale and Berrima. A flood extent was also marked in Berrima by WMAwater staff during a site visit, based on photographs that the resident held. Further details of the flood mark are contained in Section 3.5. The photograph in Photo 10 was taken during the flood event.

Photo 10: Flooding of Railway Road, Burradoo, 8th March 2012. *Source: Reference 1*

8.1.10. August 2015 Flood Event

This flood event was due to sustained rainfall occurring on the 24th to 26th of August 2015. The storm temporal patterns can be seen in Figure D28. All gauges recorded a reasonably similar temporal pattern, although a localised intense burst was recorded at the High Range gauge (068262) early in the storm that was not recorded at the other gauges. The rainfall intensity was less than a 5% AEP event across all gauges, as shown in Figure D29. There was a range of rainfall totals recorded at each of these gauges, as evidenced by the spatial distribution shown in Figure D30. This was generated by using daily rainfall gauge totals (to 9 am) for the 25th to the 27th of August, and gridded using the natural neighbour technique. The rainfall varies from approximately 320 mm in the south of the catchment to approximately 160 mm in the north of the catchment.

The recorded flow at Bong Bong Weir (212031) was reasonably large, reaching approximately 180 m^3/s. The flow at Berrima Weir (212272) was also reasonably large, peaking at approximately 280 m^3/s. The FFA (see Section 5.3) at these gauges indicates that this event is between a 20% and 10% AEP event.

Photo 11: Wingecarribee River Flooding near Burradoo on 26th August 2015

There were no surveyed flood marks for this event, however there were a few flood observations and photographs from the community, around Moss Vale, Burradoo and Berrima. An example is shown in Photo 11, with all photos contained in APPENDIX C for reference.

8.1.11. June 2016 Flood Event

This flood event was due to rainfall occurring on the 4th and 5th of June 2016. The storm temporal patterns can be seen in Figure D31. All available pluviograph gauges recorded a similar temporal pattern, with the exception of the East Kangaloon (568070) gauge, which stopped recording at 6:30 PM on the 5th. The two gauges furthest from the catchment (Robertson 068054 and High Range 068262) show the most deviation from the other gauges. The rainfall intensity was approximately between a 20% AEP and 1% AEP event across most gauges for a 6 hour to 18 hour duration, as shown in Figure D32. The rainfall was approximately a 5% AEP event for gauges within the catchment. The Robertson gauge (068054) indicates a much rarer AEP due to the high rainfall depths recorded compared to the IFD at the catchment centroid. The spatial distribution of rainfall is shown in Figure D33. This was generated by using daily rainfall gauge totals (to 9 am) for the 5th and 6th of June, and gridded using the natural neighbour technique. The rainfall varies from approximately 580 mm in the east of the catchment (near Robertson) to approximately 150 mm in the west of the catchment (near Berrima).

The recorded flow at Bong Bong Weir was the second largest on record, being similar to the 1990 event, with a peak flow of approximately 190 m^3/s. The flow at Berrima Weir was the fifth highest, also similar to the 1990 event, peaking at approximately 320 m^3/s. The FFA (see Section 5.3) at these gauges indicates that this event is approximately a 10% AEP event.

There were no surveyed flood marks for this event, however there were a couple of flood observations and photographs from the community, around Moss Vale and Berrima. An example is shown in Photo 12, with all photos contained in APPENDIX C for reference.

Photo 12: Flooding of Headlam Road near Bong Bong Weir on 5th June 2016

8.1.12. February 2020 Flood Event

This was the most recent flood event in the Wingecarribee River catchment, occurring due to rainfall bursts on the 8th and 9th of February 2020. The storm temporal patterns can be seen in Figure D34. All gauges recorded a reasonably similar temporal pattern, except for the East Kangaloon (568070) and Wildes Meadow (568081) gauges that appear to have intermittent operation during the storm event. The storm event is typically a 20% AEP event or less comparing rainfall bursts with the IFD at the catchment centroid, as shown in Figure D35.
The spatial distribution of rainfall is shown in Figure D36. This was generated by using daily rainfall gauge totals (to 9 am) for the 9th and 10th of February, and gridded using the natural neighbour technique. The rainfall varies from approximately 600 mm in the east of the catchment (near Robertson) to approximately 140 mm in the west of the catchment (near Berrima).

The recorded flow at Bong Bong Weir (212031) was reasonably small, reaching approximately 60 m^3/s. The flow at Berrima Weir (212272) was also reasonably small, peaking at approximately 70 m^3/s. The FFA (see Section 5.3) at these gauges indicates that this event is less than a 20% AEP event.

There are no surveyed flood marks, however, there are a couple of flood observations and photographs from the community for this flood event, at Bong Bong Common and in Berrima. An example is provided in Photo 13, with all photos contained in APPENDIX C for reference.

Photo 13: Flooding of Bong Bong Common on 10th February 2020

8.2. Methodology

8.2.1. Hydrologic Model Calibration

There are a number of hydrologic model parameters that can be adjusted so that modelled flood behaviour matches observed flood behaviour. The streamflow gauges at Bong Bong Weir (212031) and Berrima Weir (212272) are key for calibrating the WBNM hydrologic model parameters. The hydrologic model simulates rainfall runoff that is routed through the catchment. The hydrologic model parameters were adjusted to best match the simulated flow at Bong Bong Weir and Berrima Weir with the gauge data. This process was undertaken as follows:

1. Select flood events covering a range of flow conditions and where flood data is available to calibrate to. Events selected are presented in Section 8.1.
2. Analyse the rainfall data available for each event (as presented in Section 8.1) to determine the spatial and temporal variation in rainfall across the catchment.
3. Run each rainfall event in the WBNM model using typical catchment parameters. Rainfall for each subcatchment was sampled from the spatial grids and a range of temporal patterns were tested. For most events, the temporal patterns were quite similar (once erroneous gauges were removed, as discussed in Section 8.1). A single temporal pattern was selected that was representative of the storm across the catchment (see Table 11 for the gauge selection). This was done by visual inspection of the hydrograph shape produced by WBNM and comparing it to the recorded hydrograph. Spatially varying the temporal patterns was trialled, but this did not provide a significant improvement to the calibration.
4. These initial flows were applied in the TUFLOW model and the WBNM routing parameter was adjusted to obtain a reasonable match with the routing in the TUFLOW model (which simulates hydrodynamic processes in greater detail).
5. Considering the hydrograph shape, peak and timing of both the simulated and recorded hydrographs at Bong Bong and Berrima Weirs, the catchment lag ‘C’ value was adjusted to obtain the best fit across all flood events.
6. The continuing loss was adjusted to fit the second peak of flood events with a double peak. This was done as the second peak would not be affected by the initial loss value. The continuing loss, which is representative of the catchment soil types and infiltration rates, should be relatively consistent across rainfall events.
7. As a final adjustment, the initial loss was adjusted for each event. This varies between events as it is a function of how wet the catchment is prior to the storm event. This was adjusted to match the rising limb of each event.

8.2.2. Wingecarribee Reservoir Verification

Recorded Wingecarribee Reservoir water levels and flows at Sheepwash Bridge (212275) are also important for calibrating runoff into the dam and outflows. Since the dam will be represented in the WBNM model for the design flood events, its representation was checked using the available gauge data as follows:

1. Simulate runoff from the upstream catchment into the reservoir for each event using the calibrated hydrologic model parameters. The dam was represented in WBNM using the available stage-storage-discharge data (see Section 3.8). A starting water level was set

using the closest available reliable gauged reservoir water level.

2. Simulated water levels in the reservoir were compared to the available gauge water level data.
3. The water level in Wingecarribee Reservoir has only reached above FSL on several occasions including 1976, 1978, 1986 and 1991. In order to verify the modelled outflow, an event where discharge is triggered in the model is required (that is, when the water level is above FSL). The only event that has occurred while the Sheepwash Bridge gauge (212272) has been operational (to record dam outflows) was the 1991 event. Hence this event was used to verify the modelled dam discharge is reasonable.

It is noted that there were significant discharges from the dam during the 1978 event, given the water level in the reservoir reached its highest level ever recorded. For both the 1978 and 1991 events, the dam was included in the WBNM model to simulate the outflow. In all other events, the Sheepwash Bridge gauge indicated an insignificant contribution from the dam.

8.2.3. Hydraulic Model Calibration

The flows simulated by the calibrated WBNM model were then used as inflows into the TUFLOW hydraulic model. The TUFLOW model parameters were then adjusted in order to obtain matches to the recorded water level at Bong Bong and Berrima Weirs, as well as to any surveyed flood marks and flood observations from the community. For the comparison at the gauges, the modelled water level plus velocity head ($V^2/2g$) was compared to the recorded total head at the gauge. This is because the gauge records a still water level of total head, including velocity head. The primary calibration parameter for the hydraulic model is the surface roughness. If data is available, blockage or form losses of hydraulic structures can also be calibrated. Other features of the hydraulic model are typically the physical characteristics of the floodplain (such as the terrain) and are not modified.

8.3. Hydrologic Model Parameters

The calibrated hydrologic model parameters that remain constant across all calibration events and for all sub-catchments are as follows:

- Catchment lag ‘C’ = 2.1
- Routing factor = 1.5
- Continuing loss = 1.8 mm/hr

The model parameters that vary for each calibration event are the initial loss and temporal pattern gauge. These are a function of the rainfall event and the antecedent moisture conditions in the catchment at the start of the modelled storm burst. The adopted parameters are summarised in Table 11.

Table 11: WBNM Hydrologic Model Adopted Initial Loss and Temporal Pattern

Storm Event	Initial Loss (mm)	Temporal Pattern Gauge
March 1978	100	068117
April 1988	30	068117
August 1990	20	568165
June 1991	150	568165
September 1995	95	068117
August 1996	30	568113
August 1998	20	068102
June 2007	25	568183
March 2012	20	568183
August 2015	40	568165
June 2016	180	568165
February 2020	160	568183

8.4. Hydraulic Model Parameters

The hydraulic model parameters adopted include:

- Manning's 'n' surface roughness values as outlined in Table 10
- No blockage of hydraulic structures assumed
- Initial water levels for Bong Bong Weir and Berrima Weir assumed to be at the weir crest

8.5. Calibration Results

Calibration results are discussed for each event in the following sections, with figures presented in APPENDIX E.

8.5.1. March 1978 Event Calibration Results

The WBNM calibration to the Berrima Weir gauge flow hydrograph for the March 1978 event is shown in Figure E1. This event occurred prior to the commencement of the Bong Bong Weir gauge, and hence a comparison cannot be undertaken for this gauge. The match to the Berrima Weir gauge is very good. The rate of rise on the rising limb is similar to the gauge, although the modelled flows fall short of the first peak flows. The modelled second (largest) peak is within 2% of the gauge peak flow, with a similar time of peak as well.

The March 1978 event caused the highest recorded water level in the Wingecarribee Reservoir. This is expected to be coupled with the highest dam releases, although this event occurred prior to the commencement of the Sheepwash Bridge gauge, so the dam releases are unknown. The dam was included in the WBNM model to simulate the dam outflow. The dam behaviour was verified by comparing the recorded and modelled dam water levels, as shown in Figure E2. Only daily water level data was available, but the modelled water level follows the recorded water level closely. This provides confidence that the modelled peak outflow of approximately 185 m^3/s

is a reasonable approximation.

The TUFLOW calibration to the Berrima Weir gauge is shown in Figure E3. Both flow and water level are presented. The simulated flow in the TUFLOW model at Berrima Weir is slightly lower than the WBNM flow, being approximately 10% lower than the gauge peak. The simulated peak water level at the weir is much higher (approximately 0.65 m) than the gauge, although the shape of the rising limb is similar.

The TUFLOW calibration to available flood marks is shown in Figure E4, along with the modelled flood depths and levels. There are five flood marks available for this event, and these are summarised in Table 12 with the difference between the modelled and observed flood level.

Table 12: Calibration to Flood Marks for the March 1978 Event

Flood Mark	Location	Source	Difference[1] (m)
FM18	Cnr Wingecarribee St / Old Hume Hwy, Berrima	Bewsher 2000	0.3
FM20	Jellore St, Berrima	Bewsher 2000	0.0
FM49	Lot 10 Wingecarribee St, Berrima	Bewsher 2000	-1.7
FM53	Wingecarribee St, Berrima	WMAwater 2020	-1.3
FM54	Wingecarribee St, Berrima	WMAwater 2020	-0.1

[1] Difference between modelled and observed flood level

FM18 and FM20 are located upstream and downstream of the Berrima Bridge (Old Hume Highway), respectively. The match to flood mark 18 is approximately 0.3 m higher than the observed flood level while flood mark 20 indicates a very close match. The accuracy of FM18 is unknown, though the accuracy of FM20 is noted as ‘good’.

The remaining flood marks are from Wingecarribee Street, a small distance downstream from FM20 on a sharp bend in the river. At flood marks 49 and 53, the modelled flood level is over a metre lower than the observed levels. The reliability of FM49 marks is noted as ‘low’. FM53 was visited by WMAwater staff and the mark was noted to be from the 1970’s. It was assumed to be the 1978 event, although it is noted that 1975 may have been a larger event (noting the comments on FM18 in Table 1), although no stream gauge data exists in the catchment to confirm this. This means that if this mark was for the 1975 event, the 1978 event could have potentially been lower. This is also the case for flood mark 54, although the modelled level is very close to the observed level. Given the close proximity of the flood marks to each other in this location, it is unlikely that they are all correct, as the observed flood level varies by 1.7 m. Matching two of the levels in this area (FM20 and FM54) is considered reasonable particularly since the most reliable mark (FM20) was matched.

8.5.2. April 1988 Event Calibration Results

The WBNM calibration to the Berrima Weir gauge flow hydrograph for the April 1988 event is shown in Figure E5. This event occurred prior to the commencement of the Bong Bong Weir gauge, and hence a comparison cannot be undertaken for this gauge. The match to the Berrima Weir gauge is very good. The smaller first peak of the event is not matched by the model, however, the second (largest) peak is within 5% of the gauge peak flow. The modelled rate of rise and fall is slightly higher than the gauge.

The TUFLOW calibration to the Berrima Weir gauge is shown in Figure E6. Both flow and water level are presented. The simulated flow in the TUFLOW model at Berrima Weir is slightly lower than the WBNM flow, although still within 5% of the gauge peak. The simulated peak water level at the weir is higher than the gauge (approximately 0.4 m).

The TUFLOW calibration to available flood marks is shown in Figure E7, along with the modelled flood depths and levels. There are 11 flood marks available for this event, and these are summarised in Table 13 with the difference between the modelled and observed flood level.

Table 13: Calibration to Flood Marks for the April 1988 Event

Flood Mark	Location	Source	Difference[1] (m)
FM19	Jellore St, Berrima	Bewsher 2000	-0.2
FM22	Lot 13 Wingecarribee St, Berrima	Bewsher 2000	0.0
FM23	Lot 3 Jellore St, Berrima	Bewsher 2000	-0.8
FM24	Lot 6-8 Wingecarribee St, Berrima	Bewsher 2000	-0.3
FM25	Jellore St, Berrima	Bewsher 2000	-0.9
FM26	15-17 Market Pl, Berrima	Bewsher 2000	-0.4
FM27	Lot 1 and 2 Cnr Argyle St / Villiers St, Berrima	Bewsher 2000	-0.3
FM28	Cnr Wingecarribee St / Old Hume Hwy	Bewsher 2000	-0.2
FM38	Town Bridge, Berrima	SMEC 2014	-1.0
FM50	Wingecarribee St, Berrima	WMAwater 2020	0.0
FM55	Wingecarribee St, Berrima	WMAwater 2020	-0.2

[1] Difference between modelled and observed flood level

All flood marks for this event are located in Berrima. The modelled flood level is up to 1 m lower than the observed level. There is reasonable consistency between the 11 flood marks through Berrima. It is unclear why the modelled flood level is overestimated at Berrima Weir, but generally too low at these flood marks. Reference 7 indicates that increased roughness was required to match these levels in the Berrima Flood Study model, which was attributed to willow tree proliferation in this area between 1988 and 1998. The largest difference is at the location of the bridge, with the match improving both upstream and downstream of the bridge. This may suggest that there were additional losses associated with the bridge structure and perhaps blockage due to debris may have been a contributing factor. The most upstream flood mark is only 0.2 m lower. The downstream flood marks are up to 0.3 m lower, except for flood mark 23. It is noted that the confidence in FM23 is noted as 'doubtful', and the levels are not consistent with nearby levels. At two locations, there are two marks close to each other (FM24 and FM50, FM22 and FM55). At these locations one of the flood marks was matched very well (FM50 and

FM22), while the other was lower. It is reasonable that only one of the marks at these locations would be matched.

8.5.3. August 1990 Event Calibration Results

The WBNM calibration to the Bong Bong Weir and Berrima Weir gauge flow hydrographs for the August 1990 event is shown in Figure E5. The match to the Bong Bong Weir gauge is quite good, with the shape of the hydrograph, including the rising and falling limbs and three flood peaks being replicated. The modelled peak is within 15% of the gauge peak. The modelled flow at Berrima Weir is generally under the gauge flow. The rising and falling limbs of the hydrograph, as well as the timing is matched, however, the modelled peak is approximately 25% less than the gauge peak.

The August 1990 event is the highest the Wingecarribee Reservoir water level has been while the Sheepwash Bridge gauge has been operational. This corresponds to the largest recorded flows at the Sheepwash Bridge gauge. The Wingecarribee Dam was included in the WBNM model to simulate the dam outflow. The dam behaviour was verified by comparing the recorded and modelled dam water levels, and recorded and modelled flows at the Sheepwash Bridge, as shown in Figure E9. Generally, the modelled water level closely follows the recorded water level, although the modelled shows a faster rate of rise with a slightly higher peak water level. This translates to an earlier and higher peak outflow compared to the Sheepwash gauge, although the general shape of the flow hydrograph is reasonable.

The TUFLOW calibration to the Bong Bong Weir and Berrima Weir gauges is shown in Figure E10. Both flow and water level are presented. The simulated flow in the TUFLOW model at Bong Bong Weir is slightly higher than the WBNM model and is within 10% of the gauge flow. The water level at Bong Bong Weir is under the gauge level by up to 0.2 m, although the shape is quite similar. The modelled flow at Berrima Weir is very similar to the WBNM flow, with the peak being lower than the gauge peak. The simulated peak water level at the weir is also slightly lower, by approximately 0.1 m.

The TUFLOW calibration to available flood marks is shown in Figure E11, along with the modelled flood depths and levels. There are three flood marks available for this event, and these are summarised in Table 14 with the difference between the modelled and observed flood level.

Table 14: Calibration to Flood Marks for the April 1990 Event

Flood Mark	Location	Source	Difference[1] (m)
FM29	Lot 2 Jellore St, Berrima	Bewsher 2000	-1.3
FM30	15-17 Market Pl, Berrima	Bewsher 2000	-0.7
FM35	180 Sproules Ln, Bowral	SMEC 2014	-0.6

[1] Difference between modelled and observed flood level

Flood mark 35 is located to the south west of Bowral, near the confluence of Kellys Creek and Wingecarribee River. The model indicates a flood level 0.6 m below the observed flood level. The flood level in this location is relatively flat, and only the modelled flood level in the largest event (1978) reaches the observed level. The confidence of this flood mark was recorded to be ‘low’ at the time of the survey. This was also the case for the 1990 and 2007 events at this location. Flood marks 29 and 30 are located in Berrima, on the downstream and upstream sides of the Berrima Bridge (respectively). The modelled flood levels are substantially lower than the observed levels, although the match at Berrima Weir was reasonable. The accuracy of these flood marks was considered to be ‘doubtful’ (FM29) and ‘satisfactory’ (FM30).

8.5.4. June 1991 Event Calibration Results

The WBNM calibration to the Bong Bong Weir and Berrima Weir gauge flow hydrographs for the June 1991 event is shown in Figure E12. The match to the Bong Bong Weir gauge peak is reasonable, being within 10%, although the general shape and timing of the hydrograph is not well matched. This is also the case for the Berrima Weir calibration, with the peak being approximately 20% lower. A reasonably high initial loss was required to get a similar response for the rising limb of the hydrograph, although beyond the first peak the modelled hydrographs lag behind the gauge hydrographs. It is thought that there was significant rainfall variability across the catchment that is not represented by the rainfall gauges available. The 1991 event showed the most variability between pluviograph gauges and a better match could not be obtained using other gauges.

The TUFLOW calibration to the Bong Bong Weir and Berrima Weir gauges is shown in Figure E13. Both flow and water level are presented. The simulated flow in the TUFLOW model at Bong Bong Weir is slightly higher than the WBNM model and is within 2% of the peak gauge flow. The hydrograph, however, still has the timing issues that were evident with the WBNM flows. The modelled water level at Bong Bong Weir is under the gauge level by approximately 0.1 m. The modelled flow at Berrima Weir is similar to the WBNM flow, with the peak being lower than the gauge peak. The simulated peak water level at the weir is also slightly lower, by approximately 0.1 m.

The TUFLOW calibration map is shown in Figure E14, with the modelled flood depths and levels. There are no flood marks available for this event, and no flood observations.

8.5.5. September 1995 Event Calibration Results

The WBNM calibration to the Bong Bong Weir and Berrima Weir gauge flow hydrographs for the September 1995 event is shown in Figure E15. The match to the peak of both gauges is good, being within 10%, although both modelled peaks lag behind the gauge peaks. This is due to the reasonably high initial loss used. A lower initial loss could have been adopted to match the timing of the peaks, although the modelled peak would be much higher than the gauge peak.

The TUFLOW calibration to the Bong Bong Weir and Berrima Weir gauges is shown in Figure E16. Both flow and water level are presented. The simulated flow in the TUFLOW model at Bong Bong Weir is slightly higher than the WBNM model and is within 20% of the peak gauge flow and lags behind the gauge flow. The difference between the modelled and gauge water level at Bong Bong Weir is less than 0.1 m. The modelled flow at Berrima Weir is slightly lower than the WBNM flow, and is also slightly lower than the gauge peak and lagged. The simulated peak water level at the weir is within 0.1 m of the gauge level.

The TUFLOW calibration to available flood marks is shown in Figure E17, along with the modelled flood depths and levels. There is one flood mark available for this event, and it is presented in Table 15 with the difference between the modelled and observed flood level.

Table 15: Calibration to Flood Marks for the September 1995 Event

Flood Mark	Location	Source	Difference[1] (m)
FM31	Lot 3 Wingecarribee St, Berrima	Bewsher 2000	-0.3

[1] Difference between modelled and observed flood level

At the upstream end of Berrima (flood mark 31), the flood level is within 0.3 m of the observed level. The accuracy of the flood mark is uncertain due to the age and lack of metadata to assess its reliability.

8.5.6. August 1996 Event Calibration Results

The WBNM calibration to the Bong Bong Weir and Berrima Weir gauge flow hydrographs for the August 1996 flood event is shown in Figure E18. This presents one of the best matches between the modelled and gauge flows. Both modelled peaks are within 1% of the gauge peaks, with the rising and falling limbs of the hydrograph also very well matched. There is some volume missing from the receding limb, which is thought to be driven by rainfall over the catchment that has not been captured by the rainfall gauges.

The TUFLOW calibration to the Bong Bong Weir and Berrima Weir gauges is shown in Figure E19. Both flow and water level are presented. The simulated flow in the TUFLOW model at Bong Bong Weir is slightly higher than the WBNM model and is within 10% of the peak gauge flow and lags behind the gauge flow. The difference between the modelled and gauge water level at Bong Bong Weir is approximately 0.1 m. The modelled flow at Berrima Weir is slightly lower than the WBNM flow and peaks slightly earlier. The modelled peak flow is within 10% of the gauge peak and hydrograph shape is similar. The simulated peak water level at the weir is almost identical to the gauge level.

The TUFLOW calibration to available flood marks is shown in Figure E20, along with the modelled flood depths and levels. There are two flood marks available for this event, and these are summarised in Table 16 with the difference between the modelled and observed flood level.

Table 16: Calibration to Flood Marks for the August 1996 Event

Flood Mark	Location	Source	Difference[1] (m)
FM32	End of Wingecarribee St, Berrima	Bewsher 2000	0.4
FM33	Lot 10 DP758098 Sutton St, Berrima	Bewsher 2000	-0.3

[1] Difference between modelled and observed flood level

At the upstream end of Berrima (at the end of Wingecarribee Street, flood mark 32) the modelled flood level is approximately 0.4 m higher than that observed, although the accuracy of the surveyed flood level is uncertain. Just downstream of the Berrima Bridge (flood mark 33) the modelled flood level is approximately 0.3 m lower than the observed level. Again, the accuracy of this flood mark is uncertain.

8.5.7. August 1998 Event Calibration Results

The WBNM calibration to the Bong Bong Weir and Berrima Weir gauge flow hydrographs for the August 1998 event is shown in Figure E21. The modelled peak flow is less than the gauge peak, being up to 25% under. The shape and timing of the hydrograph is generally well matched. The calibration of this event would benefit from a slightly reduced continuing loss, if there were sufficient justification.

The TUFLOW calibration to the Bong Bong Weir and Berrima Weir gauges is shown in Figure E22. Both flow and water level are presented. The simulated flow in the TUFLOW model at Bong Bong Weir is slightly higher than the WBNM model and is within 3% of the peak gauge flow. The difference between the modelled and gauge water level at Bong Bong Weir is approximately 0.1 m. The modelled flow at Berrima Weir is similar to the WBNM flow and is less than the gauge peak. The simulated peak water level at the weir is approximately 0.1 m lower than the peak gauge level.

Table 17: Calibration to Flood Marks for the August 1998 Event

Flood Mark	Location	Source	Difference[1] (m)
FM34	3 Victor Cr, Moss Vale	SMEC 2014	0.2
FM39	180 Sproules Ln, Bowral	SMEC 2014	-0.6
FM40	6 Oldbury Rd, Berrima	SMEC 2014	-1.1
FM45	154 Headlam Rd, Moss Vale	SMEC 2014	0.6
FM48	Town Bridge, Berrima	SMEC 2014	-1.4
FM56	Oxley St, Berrima	Bewsher 2000	-0.7
FM57	Jellore St, Berrima	Bewsher 2000	-1.1
FM58	Downstream of Berrima Bridge	Bewsher 2000	-1.4
FM59	Upstream of Berrima Bridge	Bewsher 2000	-1.4
FM60	Bend at Wingecarribee St, Berrima	Bewsher 2000	-1.1
FM61	Bend at Schotts Ln, Berrima	Bewsher 2000	-1.0

[1] Difference between modelled and observed flood level

The TUFLOW calibration to available flood marks is shown in Figure E23, along with the modelled flood depths and levels. There are five flood marks available for this event, and these are summarised in Table 17 with the difference between the modelled and observed flood level.

Flood mark 39 is located to the south west of Bowral, near the confluence of Kellys Creek and Wingecarribee River. The model indicates a flood level 0.6 m below the observed flood level. The flood level in this location is relatively flat, and only the modelled flood level in the largest event (1978) reaches the observed level. The confidence of this flood mark was recorded to be 'low' at the time of the survey. This was also the case for the 1990 and 2007 events at this location. Flood mark 34 is located on a relatively steep and shallow overland flow path to the east of Moss Vale. The difference of 0.2 m could be due to terrain data and exact location of the mark. Flood mark 45 is located near Headlam Road, immediately downstream of Bong Bong Weir. The modelled level is approximately 0.6 m higher than the observed level. Given the good match in water level at the gauge, it is likely that this flood mark is reliable. It is possible that the observation did not take place at the peak of the flood.

Flood marks 40, 48 and 56 to 61 are located in Berrima. The modelled flood level is up to 1.4 m lower than the observed level. Although one resident noted in the survey that the 1998 flood mark on Berrima Bridge (FM40) is "reasonably accurate, though perhaps 0.5 m too low", there is consistency between the 8 flood marks through Berrima. It is unclear why the modelled flood level is a good match at Berrima Weir, but too low at these flood marks. Reference 7 indicates that increased roughness was required to match these levels in the Berrima Flood Study model, which was attributed to willow tree proliferation in this area between 1988 and 1998. The largest difference is at the location of the bridge, with the match improving slightly both upstream and downstream of the bridge. This may suggest that there were additional losses associated with the bridge structure and perhaps blockage due to debris may have been a contributing factor.

8.5.8. June 2007 Event Calibration Results

The WBNM calibration to the Bong Bong Weir and Berrima Weir gauge flow hydrographs for the June 2007 event is shown in Figure E24. The match to the Bong Bong Weir gauge peak is reasonable, being approximately 10% higher. The Berrima Weir modelled peak is almost identical to the gauge peak. The shape of the hydrograph is well matched, including the double peak shape and rising/falling limbs.

The TUFLOW calibration to the Bong Bong Weir and Berrima Weir gauges is shown in Figure E25. Both flow and water level are presented. The simulated flow in the TUFLOW model at Bong Bong Weir is slightly higher than the WBNM model and is approximately 20% higher than the peak gauge flow. The difference between the modelled and gauge water level at Bong Bong Weir is less than 0.1 m. The modelled flow at Berrima Weir is similar to the WBNM flow, matching well to the gauge peak. The simulated peak water level at the weir is within 0.1 m of the peak gauge level.

The TUFLOW calibration to available flood marks is shown in Figure E26, along with the modelled flood depths and levels. There are two flood marks available for this event, and these are summarised in Table 18 with the difference between the modelled and observed flood level.

Table 18: Calibration to Flood Marks for the June 2007 Event

Flood Mark	Location	Source	Difference[1] (m)
FM37	388 Headlam Rd, Moss Vale	SMEC 2014	0.2
FM44	180 Sproules Ln, Bowral	SMEC 2014	-0.7

[1] Difference between modelled and observed flood level

Flood mark 44 is located to the south west of Bowral, near the confluence of Kellys Creek and Wingecarribee River. The model indicates a flood level 0.7 m below the observed flood level. The flood level in this location is relatively flat, and only the modelled flood level in the largest event (1978) reaches the observed level. The confidence of this flood mark was recorded to be 'low' and 'not precise' at the time of the survey. This was also the case for the 1990 and 2007 events at this location. Flood mark 37 is located to the east of Moss Vale, on a tributary of Kellys Creek. The modelled flood level is approximately 0.2 m higher than the observed level, which was noted as 'low' confidence.

There are also a number of photos provided for this event from Council. These are included in Photos C51 to C78. There are a number of locations shown in these photos, and only a few of them have identifiable landmarks that can be used to compare flood depths or extents with the model. These are generally from two areas described below:

- Bong Bong Common: There are several photos taken around Bong Bong Common, the Bong Bong track and Bong Bong Bridge (Argyle Street). Photo C58 appears to have been taken from the Bong Bong Bridge looking east toward Bong Bong Weir. The Flood extent compared to the telegraph pole is replicated well by the TUFLOW model. The flooding of the Bong Bong Track (Photos C52, C53, C55 and C74) is also very similar to that modelled.
- Burradoo Railway: There are several photos taken around Railway Street and the Burradoo Railway Bridge. The flood extent on Railway Street (Photos C77 and C78) is similar to that modelled.

8.5.9. March 2012 Event Calibration Results

The WBNM calibration to the Bong Bong Weir and Berrima Weir gauge flow hydrographs for the March 2012 event is shown in Figure E27. The match to the peak of both gauges is within 5% and the rising and falling limbs are reproduced reasonably well.

The TUFLOW calibration to the Bong Bong Weir and Berrima Weir gauges is shown in Figure E28. Both flow and water level are presented. The simulated flows in the TUFLOW model at Bong Bong Weir and Berrima Weir is higher than the WBNM model and peaks a little earlier. Both flows are within 5% of the peak gauge flows, while water levels are approximately 0.1 m lower than the peak gauge levels.

Table 19: Calibration to Flood Marks for the March 2012 Event

Flood Mark	Location	Source	Difference[1] (m)
FM41	6 Oldbury St, Berrima	SMEC 2014	-0.2
FM42	388 Headlam Rd, Moss Vale	SMEC 2014	-0.4
FM43	40C Church Rd, Moss Vale	SMEC 2014	-0.1
FM52	Wingecarribee St, Berrima	WMAwater 2020	-0.4

[1] Difference between modelled and observed flood level

The TUFLOW calibration to available flood marks is shown in Figure E29, along with the modelled flood depths and levels. There are four flood marks available for this event, and these are summarised in Table 19 with the difference between the modelled and observed flood level.

Flood mark 42 is located on a major tributary of Kellys Creek, to the east of Moss Vale. The modelled flood level is approximately 0.4 m lower than what was observed. The flood mark confidence is noted as ‘good’. Flood mark 43 is located on a small tributary that flows to the east of Moss Vale. The flood level is approximately 0.1 m lower than the observed level at a shed. The modelled flood depth is quite shallow (<0.3 m), so it may be that local features, such as the shed may have caused a slightly higher flood level.

Flood marks 41 and 52 are located in Berrima. Flood mark 41 is located upstream of Berrima Bridge and the modelled flood level is approximately 0.2 m lower than the observed level. Flood mark 52 is located downstream of Berrima Bridge and the modelled flood level is approximately 0.4 m lower.

There was also a photograph taken at Railway Road, Burradoo (see Photo 10), and the modelled flood behaviour at this location shows a very similar extent.

8.5.10. August 2015 Event Calibration Results

The WBNM calibration to the Bong Bong Weir and Berrima Weir gauge flow hydrographs for the August 2015 event is shown in Figure E30. The modelled peak at Bong Bong Weir and Berrima Weir is approximately 10% and 15% lower than gauge peaks, respectively. The shape and timing of the hydrograph is reasonably matched, with some differences evident that are a product of the adopted rainfall.

The TUFLOW calibration to the Bong Bong Weir and Berrima Weir gauges is shown in Figure E31. Both flow and water level are presented. The simulated flow in the TUFLOW model at Bong Bong Weir is slightly higher than the WBNM model and peaks a little earlier, providing a match within 5% of the gauge peak flow. The modelled water level at the weir is within 0.2 m. At Berrima Weir, the modelled peak flow is approximately 15% lower than the gauge peak while the water level is within 0.1 m.

The TUFLOW calibration to available flood observations is shown in Figure E32, along with the modelled flood depths and levels. There are no surveyed flood marks available for this event. On Headlam Road, to the north east of Moss Vale, it was noted that the road floods to unsafe depths during large flood events. The modelled depth over Headlam Road is up to 0.5 m. The photos in C15 and C16 show the flooding and indicate a depth of between 0.4 m and 0.6 m over the road.

In Burradoo, it was noted that paddocks and fences were inundated to a depth of 1-2 m. The photo in C49. While it is difficult to discern any specific features within the photo, the modelled flood depths across the Wingecarribee floodplain at the rear of the property is typically in the order of 1-1.5 m across the floodplain, and up to 3 m deep in the river channel. This matches with the description provided.

In Berrima, photos of the 2015 flood event were provided, and are shown in Photos C6 to C8. These photos indicate ponding in the yard and a flowpath along the back fence. The model replicates this, with water ponding in the yards and a substantial flow along the back fence.

8.5.11. June 2016 Event Calibration Results

The WBNM calibration to the Bong Bong Weir and Berrima Weir gauge flow hydrographs for the June 2016 event is shown in Figure E33. The modelled peak at Bong Bong Weir is approximately 20% higher than the gauge peak, while the modelled Berrima peak is approximately 10% lower than the gauge peak. A very high initial loss was required to reduce the peaks, and this results in a delayed response, although the modelled rate of rise is much higher. This also causes the modelled peak at Berrima Weir to lag behind the gauge peak. The receding limbs of the hydrographs, however, are good.

The TUFLOW calibration to the Bong Bong Weir and Berrima Weir gauges is shown in Figure E34. Both flow and water level are presented. The simulated flow in the TUFLOW model at Bong Bong Weir is slightly higher than the WBNM model and is approximately 30% higher than the gauge peak flow. The modelled peak water level at Bong Bong Weir, however, is almost identical to the peak gauge water level. The modelled water level and flow rise and fall at a faster rate than what was recorded. At Berrima Weir, the flow is slightly lower than the WBNM model, being approximately 20% lower than the gauge peak. The simulated peak water level is within 0.1 m of the gauge peak, and rises and falls at a faster rate than the gauge.

The TUFLOW calibration to the available flood observations is shown in Figure E35, along with the modelled flood depths and levels. At a property in East Bowral it was note that the front one third of the property was inaccessible. The modelling results show that there is a flow path that surrounds the residence and inundates the front yard of the property. On Headlam Road, to the north east of Moss Vale, it was noted that the road floods to unsafe depths during large flood events. The modelled depth over Headlam Road is up to 0.6 m. Photo C17 shows floodwater over the road and indicates a depth of between 0.4 m and 0.6 m over the road.

One property in Burradoo observed that the flood covered the walking track and almost reached the back fence. The modelled flood inundates the walking track to a depth of just over 1 m at this location and the mainstream flood extent is approximately 70 m from the property fence line. One property in Berrima had a fence that was damaged in the event, with images shown in Photo C9 to C11. This indicates a high velocity flow path along the back fence. The model replicates this, with a substantial flow simulated along the back fence.

8.5.12. February 2020 Event Calibration Results

The WBNM calibration to the Bong Bong Weir and Berrima Weir gauge flow hydrographs for the February 2020 event is shown in Figure E36. The modelled peaks at Bong Bong Weir and Berrima Weir are within 3% of the gauge peaks. There is a lag between the gauge and modelled peak flows, potentially due to the high initial loss adopted or due to the adopted temporal pattern not being representative of rainfall across the entire catchment. This high initial loss, however, is reasonable considering the extremely dry conditions that preceded the event. The shape of the rising limbs at both gauges is matched quite well, providing further justification of the adopted initial loss.

The TUFLOW calibration to the Bong Bong Weir and Berrima Weir gauges is shown in Figure E37. Both flow and water level are presented. The simulated flows in the TUFLOW model at Bong Bong Weir and Berrima Weir are similar to the WBNM model, being within 8% of the gauge peak flow. The modelled peak water level at Bong Bong Weir is approximately 0.1 m lower than the gauge peak water level, while it is within 0.2 m at Berrima Weir. The same timing issues as the WBNM model are present in the TUFLOW model.

The TUFLOW calibration to available flood observations is shown in Figure E38, along with the modelled flood depths and levels. Flooding of Bong Bong Common was observed, and Photos C25 to C29 show this and videos were also provided. While it is unclear exactly where these images were taken, they appear to be on the western bank of the Wingecarribee River, opposite Bong Bong Common. The model indicates some inundation of the Bong Bong track and the extent of flooding on the western side is up to a line of trees – which is what the photos and videos indicate. Flooding was also noted at a property in Berrima, with Photos C31 to C33 provided from the event. The photos indicate elevated water levels in the river, with the flood extent reaching to the first tall trees on the northern bank (from where the photos were taken). This extent is very similar to that modelled.

8.5.13. Additional Flood Observations

There were a number of responses from the community that were not associated with a particular flood event, but rather general observations of flood issues in the catchment. These are discussed below.

- Flooding of Headlam Road, Moss Vale in large storm events. This is discussed in recent flood events from 2015, 2016 and 2020, as photos were provided. It is noted that Headlam Road is inundated in other events as well.
- One resident noted that water ponds on the nature strip on the northern side of Kangaloon Road near the intersection with Boardman Road South and this is replicated in the model.
- One resident provided a number of photos of flooding around Kangaloon Road and Boardman Road South. Although this event was not modelled, general flood behaviour, including overtopping of Boardman Road South is replicated in the model.
- There were several other property-specific descriptions of flooding that were checked and verified. The general behaviour of flooding described is replicated by the model.

8.6. Calibration Discussion

The WBNM and TUFLOW models were calibrated to the available gauge data at Bong Bong Weir and Berrima Weir. The available flood marks provided further information for calibrating the TUFLOW model and flood observations provided additional verification. The calibration was aimed at obtaining a single parameter set that could provide a reasonable match across all 12 calibration events. The only event-specific parameter was the initial loss. Further tweaking of parameters for individual events was considered to be a 'curve-fitting' exercise rather than a meaningful calibration. A summary of the calibration results for each event is provided in Table 20.

Table 20: Summary of calibration results for each event

Flood Event	WBNM Calibration to Gauges	TUFLOW Calibration to Gauges	TUFLOW Calibration to Flood Marks	TUFLOW Calibration to Flood Extents
March 1978	Good	Good	Fair	N/A
April 1988	Excellent	Excellent	Fair	N/A
August 1990	Fair	Fair	Poor	N/A
June 1991	Poor	Poor	N/A	N/A
September 1995	Fair	Fair	Good	N/A
August 1996	Excellent	Excellent	Fair	N/A
August 1998	Fair	Fair	Poor/Fair	N/A
June 2007	Excellent	Excellent	Fair	N/A
March 2012	Excellent	Excellent	Good	Good
August 2015	Good	Good	N/A	Good
June 2016	Poor	Poor	N/A	Good
February 2020	Fair	Fair	N/A	Good

While there are some events where a poor calibration was achieved and others where an excellent calibration was achieved, overall the calibration is considered to be a good match to actual flood behaviour. This is considering the uncertainty of the rainfall data that is the primary driver of the flood event. While there is reasonable coverage of both daily rainfall data (for spatial distribution of total rainfall depths) and pluviograph rainfall data (for temporal distribution of rainfall), the catchment covers a large area and there will be rainfall variations across the catchment that are not represented at the gauges.

8.7. Sensitivity Analysis

During the calibration process, sensitivity to a wide range of hydrologic and hydraulic model parameters was tested to determine the relative influence on results, and identify the parameters that were most appropriate for adjustment to improve the calibration fit. As an example of this process, the sensitivity of WBNM model results to the input rainfall data for the March 2012 event was used with a range of losses and temporal patterns.

The temporal pattern sensitivity can be seen in Diagram 3 and Diagram 4 for WBNM flows at Bong Bong Weir and Berrima Weir, respectively. Each run uses the same spatial variation of rainfall and losses, but with a different rainfall gauge for the temporal pattern. The temporal pattern can result in changes in peak flow of approximately ±15%. A run was also undertaken with spatially varying the temporal patterns by assigning each sub-catchment to a particular pluviograph station using Thiessen polygons. This did not result in any significant improvement to the hydrograph shape.

Diagram 3: Temporal Pattern Sensitivity at Bong Bong Weir – March 2012

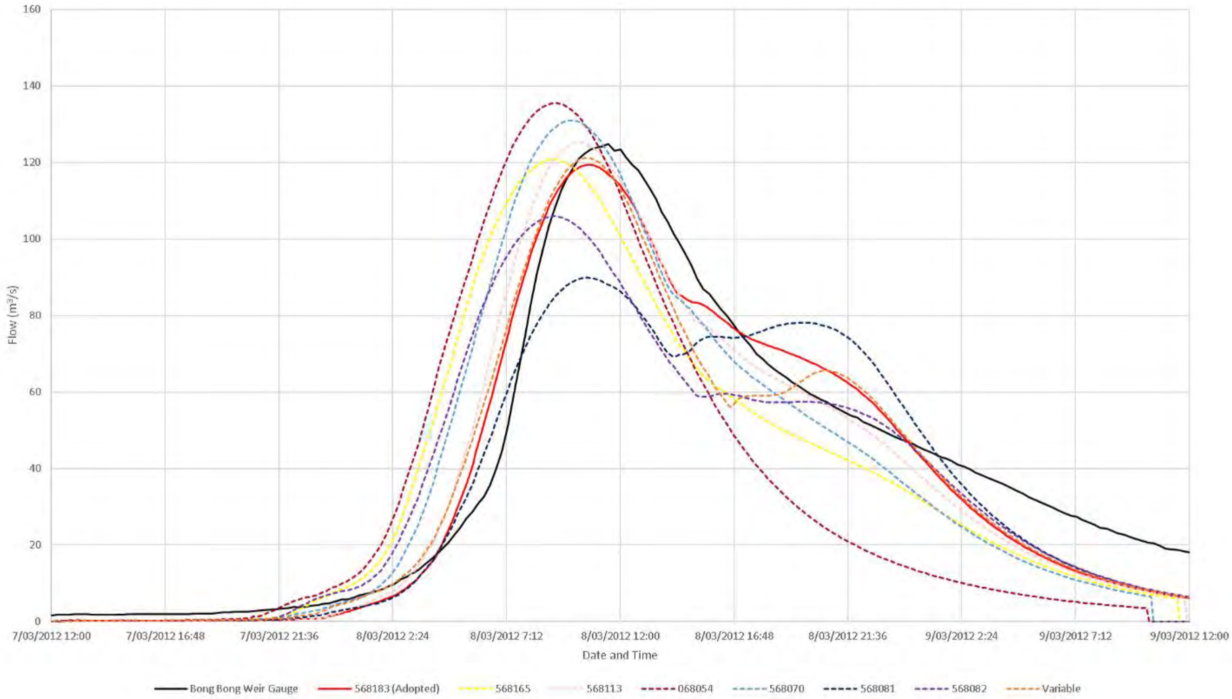
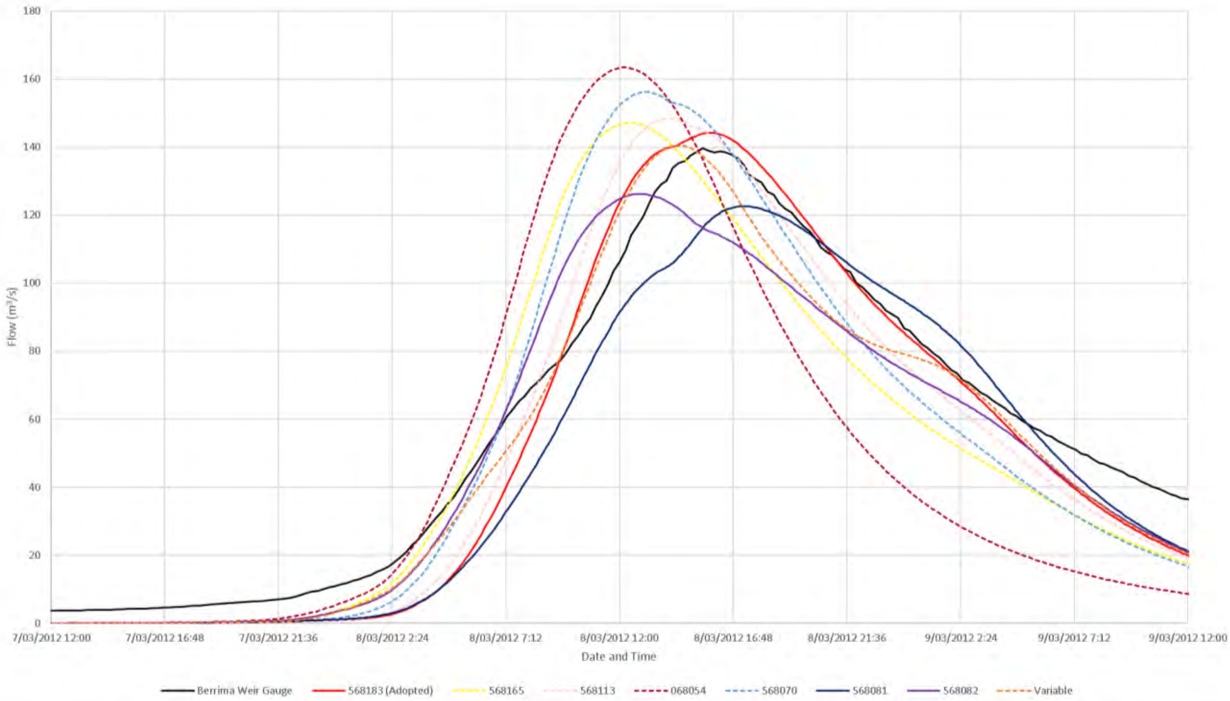


Diagram 4: Temporal Pattern Sensitivity at Berrima Weir – March 2012



The initial loss sensitivity can be seen in Diagram 5 and Diagram 6 for WBNM flows at Bong Bong Weir and Berrima Weir, respectively. Each run uses the same spatial and temporal rainfall patterns, but with different initial loss values. An initial loss of 0 mm and 40 mm is shown, as well as the adopted 20 mm. Increasing the initial loss results in a reduction in peak flow of up to 20%. Decreasing the initial loss results in an increase in peak flows of approximately 3%.

Diagram 5: Initial Loss Sensitivity at Bong Bong Weir – March 2012

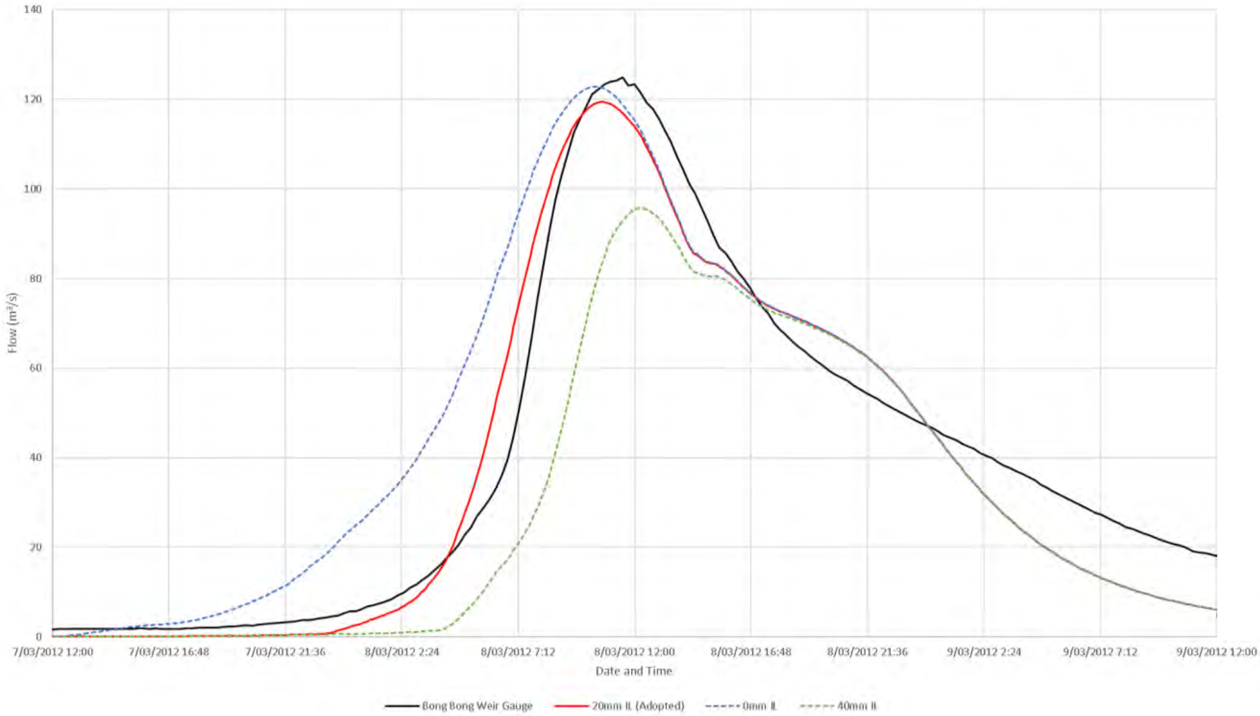
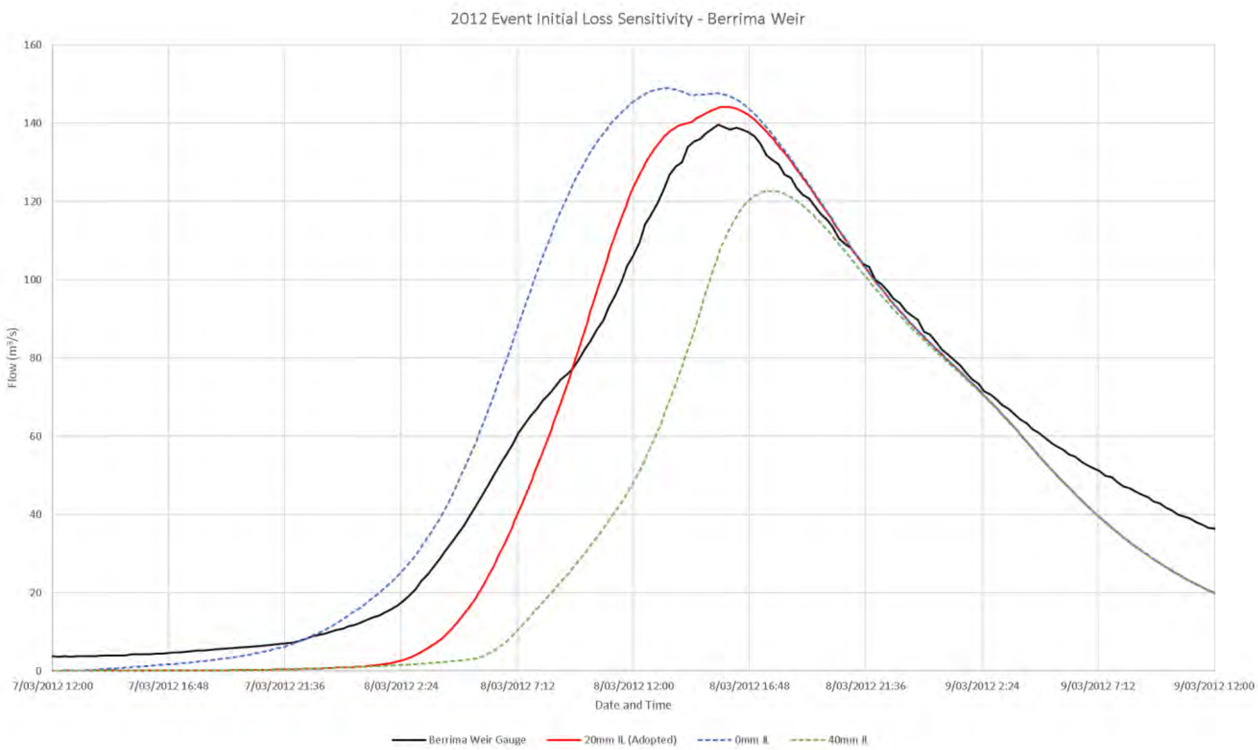


Diagram 6: Initial Loss Sensitivity at Berrima Weir – March 2012



The continuing loss sensitivity can be seen in Diagram 7 and Diagram 8 for WBNM flows at

Bong Bong Weir and Berrima Weir, respectively. Each run uses the same spatial and temporal rainfall patterns, but with different continuing loss values. A continuing loss of 1.3 mm/h and 2.3 mm/h is shown, as well as the adopted 1.8 mm/h. Increasing or decreasing the continuing loss by 0.5 mm results in a change in peak flow of approximately 10%.

Diagram 7: Continuing Loss Sensitivity at Bong Bong Weir – March 2012

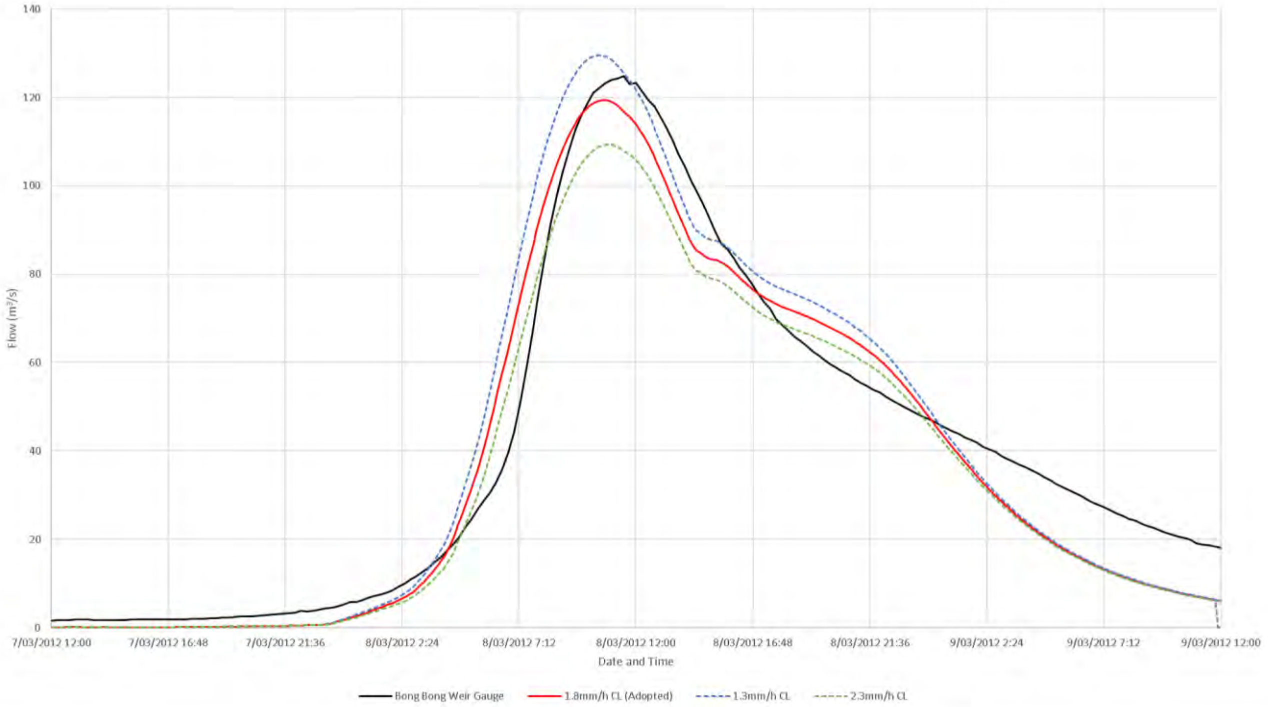
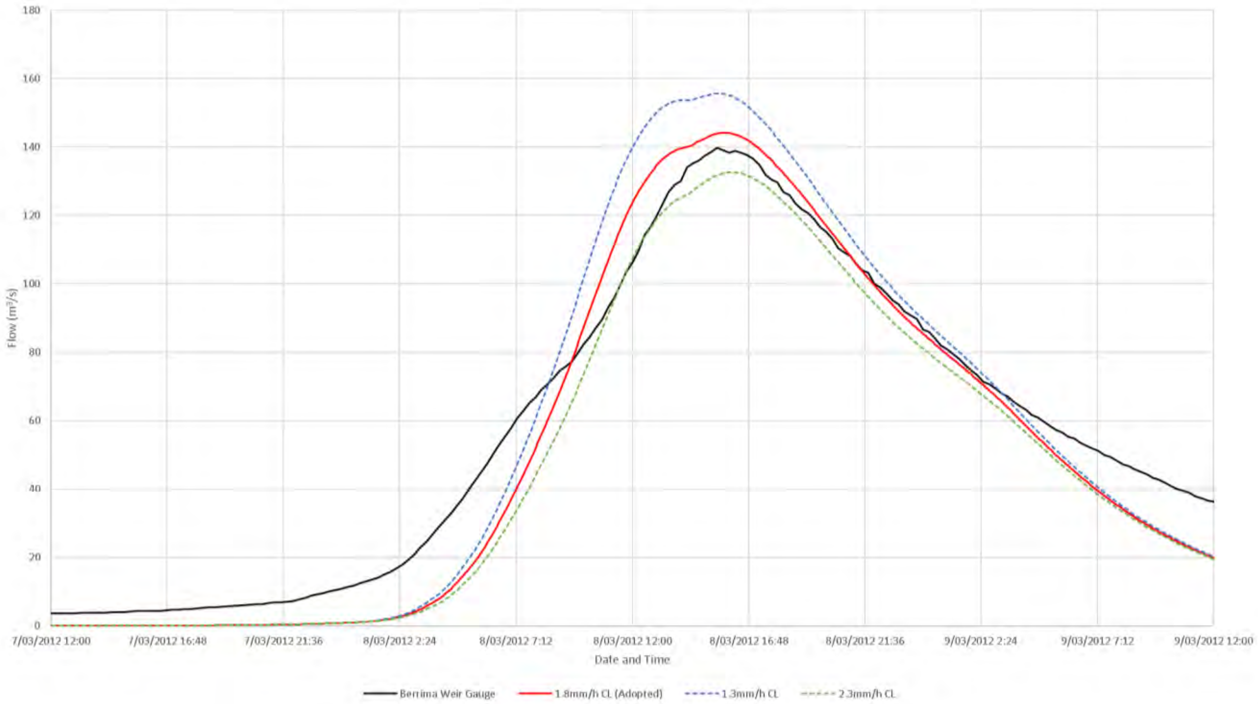


Diagram 8: Continuing Loss Sensitivity at Berrima Weir – March 2012



As demonstrated, the flood hydrograph is reasonably sensitive to a number of rainfall parameters. Given the variable nature of storm events over a catchment this size, there is considerable uncertainty in the representative rainfall applied over the catchment. Considering this uncertainty, the adopted calibration results are considered good overall. Some events present a better match than others, but consideration was given to finding WBNM parameters that are consistent across all events, rather than tweaking parameters in a curve-fitting exercise. There is confidence that the WBNM hydrologic model can represent runoff into the Wingecarribee Reservoir, storage within the reservoir, outflow from the Wingecarribee Dam and runoff across the Wingecarribee River catchment. The TUFLOW hydraulic model was able to reasonably simulate recorded flood levels at reliable flood mark locations and the gauges. There were some large deviations around the Berrima Bridge, but generally flood levels were a reasonable match. There is confidence that the TUFLOW hydraulic model can represent conveyance and routing along the Wingecarribee River and its tributaries, including flood levels and velocities across the floodplain and at hydraulic structures.

9. DESIGN EVENT METHODOLOGY

9.1. Overview

Design flood modelling for this study was undertaken using the rainfall-runoff method, assuming that design rainfalls for a given AEP will produce at-site flooding of an equivalent AEP. This assumption was verified by comparing the rainfall-runoff modelling results with the at-site FFA to confirm consistency.

Inflows for the calibrated TUFLOW hydraulic model were determined by modelling design rainfall events in the WBNM model. A range of storm burst durations were tested to determine the critical duration at different locations across the catchment.

ARR19 guidelines for design rainfall-runoff modelling were adopted for this study, to determine the 20%, 10%, 5%, 2%, 1%, 0.5%, and 0.2% AEP design behaviour across the catchment. The PMF behaviour was modelled by using relevant Bureau of Meteorology guidance. The ARR19 temporal patterns, the procedure for the selection of the critical pattern duration and adopted hydrologic model parameters are discussed in the following sections. The method for deriving design outflows from the Wingecarribee Reservoir is also discussed. The resulting flood behaviour simulated in the TUFLOW model is subsequently presented in Section 10, including an analysis of the results.

9.2. IFD Data

The IFD information was obtained from the Bureau of Meteorology (BoM). IFD information was sourced for each subcatchment individually from the BoM's gridded IFD data and applied in the WBNM hydrologic model. A summary of design rainfall depths at the centroid of the Wingecarribee River catchment is provided in Table 21.

Table 21: Design rainfall depths (mm) at the centroid of the Wingecarribee River catchment

Duration	**AEP**					
(min)	20%	10%	5%	2%	1%	0.5%
30	26.2	31.3	36.6	44	50.2	53.3
60	33.4	39.7	46.3	55.7	63.4	67.7
90	38.8	46.1	53.6	64.2	73	77.9
120	43.7	51.8	60.1	71.8	81.3	86.7
180	52.6	62.2	72	85.6	96.5	102
360	75.8	89.8	104	122	136	143
720	113	135	156	183	204	213
1080	142	170	199	234	259	273
1440	164	199	234	275	306	324
2160	196	240	286	338	378	418
2880	217	268	321	383	430	481
4320	241	301	364	438	496	558

There is a strong gradient in rainfall from the east of the catchment (at Robertson) to the west of the catchment (at Berrima). This gradient can be seen in the major historic events (Figure D3 and Figure D6 for example) and is also evident in the IFD data. IFD tables at Robertson and Berrima are presented in Table 22 and Table 23, as well as the difference between these locations and the catchment centroid.

Table 22: Design rainfall depths (mm) at Robertson (difference to the catchment centroid, %)

Duration	**AEP**					
(min)	**20%**	**10%**	**5%**	**2%**	**1%**	**0.5%**
30	28.1 (7%)	33.5 (7%)	39.1 (7%)	47.2 (7%)	53.7 (7%)	57.1 (7%)
60	36.5 (9%)	43.5 (10%)	50.8 (10%)	61.3 (10%)	69.9 (10%)	74.6 (10%)
90	43.4 (12%)	51.7 (12%)	60.2 (12%)	72.4 (13%)	82.4 (13%)	87.9 (13%)
120	49.8 (14%)	59.2 (14%)	68.9 (15%)	82.6 (15%)	93.8 (15%)	99.9 (15%)
180	61.9 (18%)	73.5 (18%)	85.3 (18%)	102 (19%)	115 (19%)	122 (20%)
360	95.3 (26%)	113 (26%)	131 (26%)	154 (26%)	172 (26%)	181 (27%)
720	152 (35%)	182 (35%)	210 (35%)	246 (34%)	272 (33%)	285 (34%)
1080	197 (39%)	237 (39%)	276 (39%)	322 (38%)	356 (37%)	375 (37%)
1440	234 (43%)	282 (42%)	330 (41%)	386 (40%)	428 (40%)	454 (40%)
2160	286 (46%)	348 (45%)	411 (44%)	485 (43%)	539 (43%)	596 (43%)
2880	320 (47%)	393 (47%)	467 (45%)	555 (45%)	621 (44%)	693 (44%)
4320	359 (49%)	445 (48%)	534 (47%)	642 (47%)	725 (46%)	813 (46%)

Table 23: Design rainfall depths (mm) at Berrima (difference to the catchment centroid, %

Duration	**AEP**					
(min)	20%	10%	5%	2%	1%	0.5%
30	24.2 (-8%)	29 (-7%)	33.9 (-7%)	40.9 (-7%)	46.6 (-7%)	49.5 (-7%)
60	29.8 (-11%)	35.4 (-11%)	41.2 (-11%)	49.5 (-11%)	56.3 (-11%)	60.1 (-11%)
90	33.6 (-13%)	39.8 (-14%)	46.1 (-14%)	55.1 (-14%)	62.5 (-14%)	66.7 (-14%)
120	36.9 (-16%)	43.5 (-16%)	50.4 (-16%)	60 (-16%)	67.9 (-16%)	72.3 (-17%)
180	42.8 (-19%)	50.4 (-19%)	58.1 (-19%)	68.9 (-20%)	77.7 (-19%)	82.3 (-19%)
360	58.1 (-23%)	68.5 (-24%)	79 (-24%)	93.2 (-24%)	104 (-24%)	109 (-24%)
720	83.2 (-26%)	99.1 (-27%)	115 (-26%)	135 (-26%)	151 (-26%)	158 (-26%)
1080	103 (-27%)	124 (-27%)	145 (-27%)	171 (-27%)	191 (-26%)	201 (-26%)
1440	120 (-27%)	145 (-27%)	170 (-27%)	201 (-27%)	225 (-26%)	238 (-27%)
2160	144 (-27%)	176 (-27%)	210 (-27%)	249 (-26%)	279 (-26%)	311 (-26%)
2880	161 (-26%)	199 (-26%)	238 (-26%)	284 (-26%)	319 (-26%)	360 (-25%)
4320	181 (-25%)	226 (-25%)	273 (-25%)	328 (-25%)	371 (-25%)	418 (-25%)

The Robertson IFD is up to 50% higher than the catchment centroid for long duration storms, while Berrima is up to 25% lower than the catchment centroid. This variation was taken into account in the design modelling by sampling the relevant data for each sub-catchment separately.

9.3. ARR19 Temporal Patterns

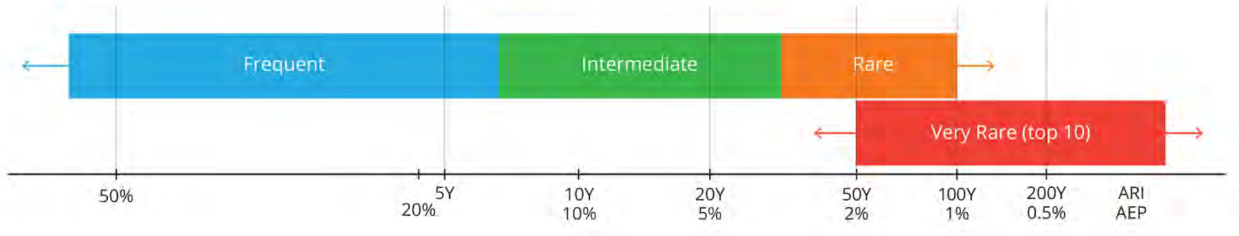
Temporal patterns are a hydrologic tool that describe how rain falls over time and are used in hydrograph estimation. Previously, with ARR87 guidelines (Reference 2), a single temporal pattern was adopted for each rainfall event duration. However, ARR19 (Reference 3) discusses the potential inaccuracies with adopting a single temporal pattern and recommends an approach where an ensemble of different temporal patterns is investigated.

Temporal patterns for this study were obtained from the ARR19 Datahub (Reference 3, http://data.arr-software.org/). A summary of the Datahub information at the catchment centroid is presented in Attachment A. The revised ARR19 temporal patterns attempt to address the key concerns practitioners found with the ARR87 temporal patterns. It is widely accepted that there are a large variety of temporal patterns possible for rainfall events of similar magnitude. This variation in temporal pattern can result in significant effects on the estimated peak flow. As such, the revised temporal patterns have adopted an ensemble of ten different temporal patterns for a particular design rainfall event. Given the rainfall-runoff response can be quite catchment specific, using an ensemble of temporal patterns attempts to produce the median catchment response.

As hydrologic modelling has advanced, it is becoming increasingly important to use realistic temporal patterns. The ARR87 temporal patterns only provided a pattern of the most intense burst within a storm, whereas the ARR19 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 ARR19 method divides Australia into 12 temporal pattern regions, with the Wingecarribee River catchment falling within the East Coast South region.

ARR19 provides 30 patterns for each duration and are sub-divided into three temporal pattern bins based on the frequency of the events. Diagram 9 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 ARR19 that have been utilised in this study for the 20% AEP to 0.5% AEP events.

Diagram 9: Temporal Pattern Bins



9.4. Critical Duration Assessment

The critical duration is the temporal pattern and duration that best represents the flood behaviour across the catchment for a specific design AEP. It is usually related to catchment size, in that larger catchments have a longer critical duration.

With ARR19 methodology, the critical storm duration for a location is the design storm duration which produces the highest average flow across the full range of durations at that location of interest. The adopted temporal pattern (out of the ensemble of 10 for a given duration), is the pattern which produces the peak flows just greater than the average of the 10 peak flows for the critical duration. The hydrologic model (WBNM) was used to assess the peak flows at key locations, to select the critical duration and representative temporal pattern to run in the TUFLOW model.

For this study, two separate critical durations were adopted – a longer duration for mainstream flooding of the Wingecarribee River, and a shorter duration for minor tributaries and urban overland flow areas. The results mapped for this study are the combination of the two selected representative patterns. The methodology for selecting the representative patterns is outlined below.

9.4.1. Mainstream Critical Duration

The two weirs (Bong Bong and Berrima) were selected as the locations for the mainstream Wingecarribee River critical duration assessment, as well as the outlet of the Wingecarribee Reservoir.

A range of storm durations and the ensemble of temporal patterns were run in WBNM and the results were analysed at each of these locations. A box plot of 1% AEP flows for each of the weirs can be seen in Diagram 10 to Diagram 11.

This analysis was undertaken without incorporating outflows from the dam into the results at Bong Bong and Berrima weirs. Determination of the critical duration and AEP neutral outflows for the dam is provided in Section 9.8.

Diagram 10: Box Plot of Peak Flows at WR_322 (Bong Bong Weir) – 1% AEP Event

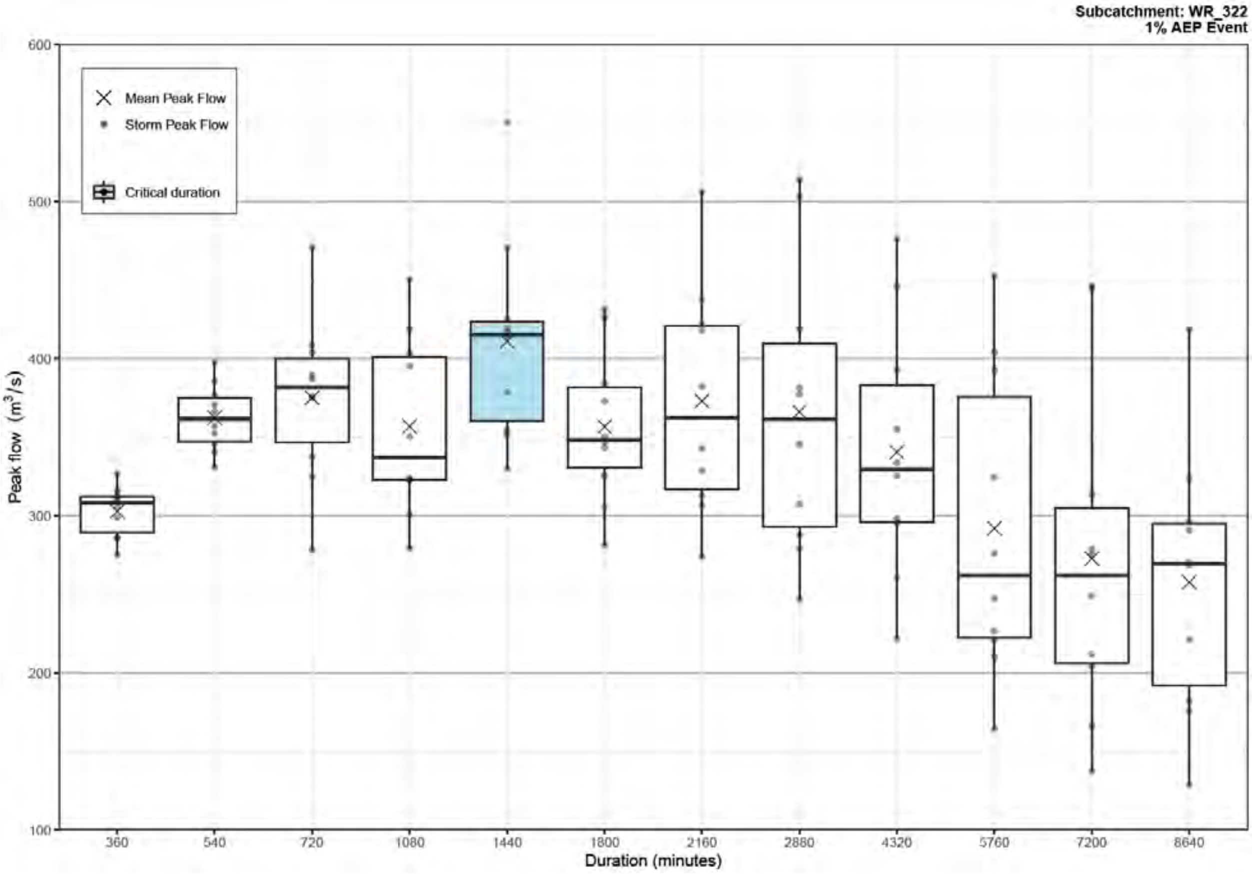
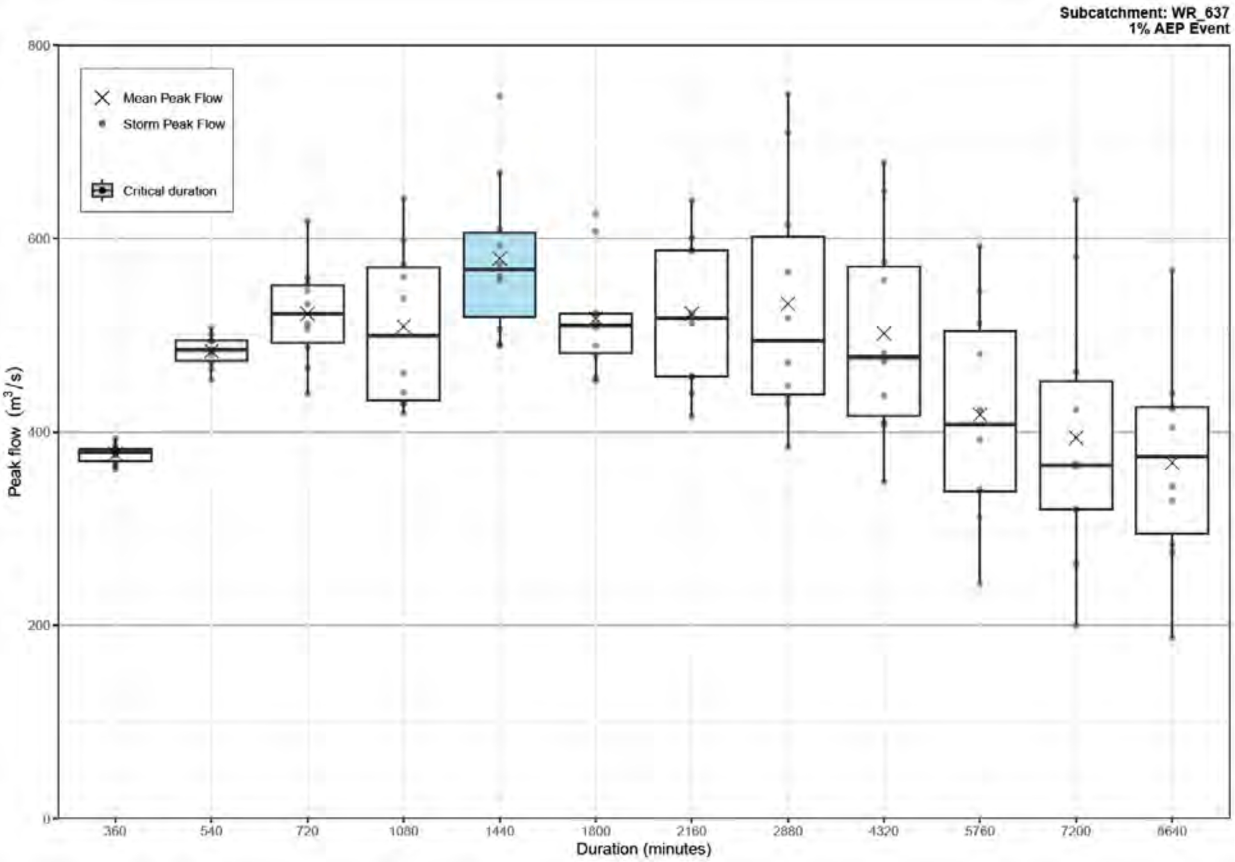


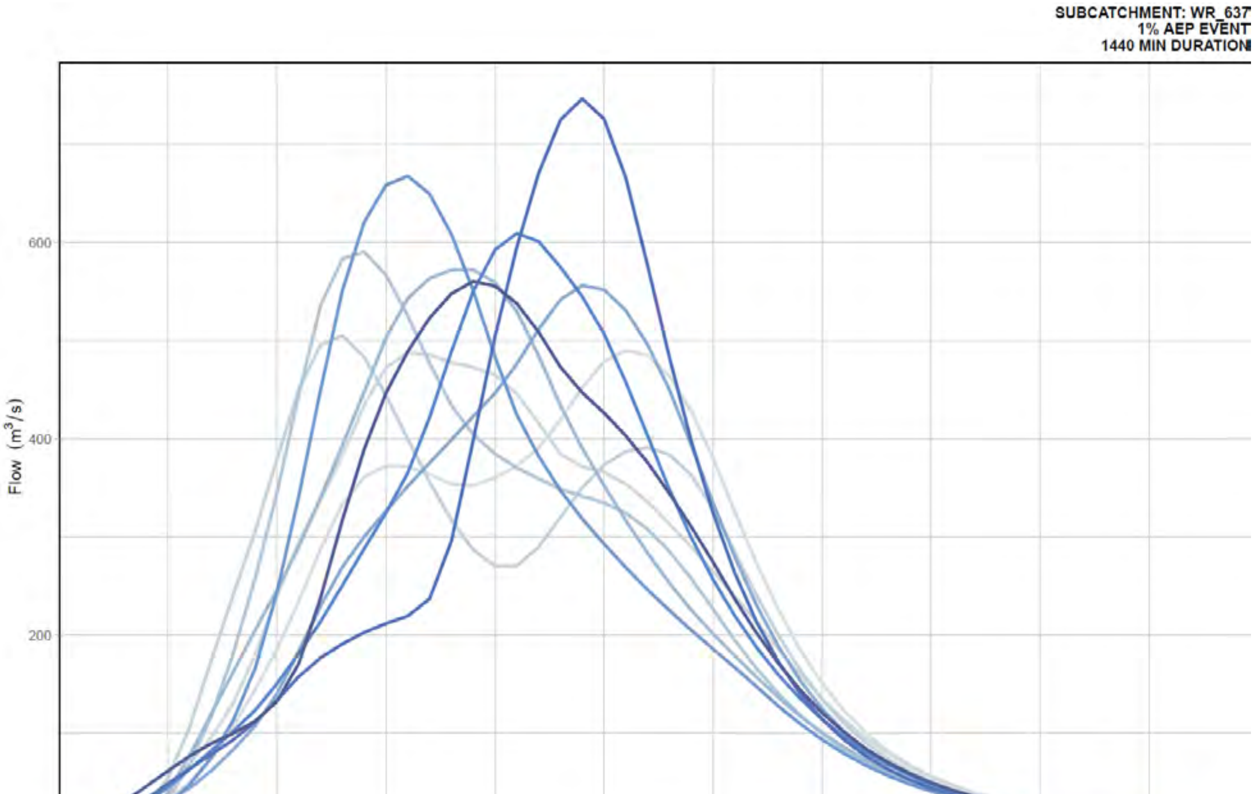
Diagram 11: Box Plot of Peak Flows at WR_637 (Berrima Weir) – 1% AEP Event



The black dots show the result from each temporal pattern in the ensemble. The box and whiskers for each duration indicate the spread of results obtained from the ensemble of temporal patterns. The box defines the first quartile to the third quartile of the results and the bottom and top line (also called 'whiskers') represent the maximum and minimum values. The black dots beyond these lines are statistical outliers. The horizontal line within the box represents the median value. The red circle is the mean value.

It can be observed that for the 1% AEP event, similar mean peak flows occur for a range of durations from 540 minutes (9 hours) up to 2880 minutes (two days). The 1440 minute (24 hour) storm burst is critical at each of the weirs (highest mean flows from the ensemble of temporal patterns). The range of flows and the timing of peak flows produced by the 1440 minute storm is reasonably large. This is demonstrated by the flow hydrographs shown in Diagram 12.

Diagram 12: 1440 minute 1% AEP flow hydrographs at Berrima Weir



The different temporal patterns were analysed to find an appropriate pattern that produced a close match to the mean behaviour across the catchment, including at the Wingecarribee Reservoir spillway outlet (see Section 9.8 for more discussion about the reservoir). This analysis was undertaken for all the design AEPs. A single duration and temporal pattern was adopted for each bin (see Diagram 9), being representative across the range of events and locations. The adopted representative temporal pattern and a summary of the flows (without any releases from the dam) are provided in Table 24.

Table 24: Summary of ensemble flows and the adopted temporal patterns for mainstream flow (without dam releases)

Location	Ensemble Results		Adopted Representative Results			
	Critical Duration (mins)	Mean (Critical) Flow (m^3/s)	Duration (mins)	Temporal Pattern ID	Peak Flow (m^3/s)	% Difference (Peak Flow minus Critical Flow)
50% AEP Event						
Bong Bong	1080	95.9	1440	4885	96.5	0.6%
Berrima	1080	128.3			127.6	-0.6%
20% AEP Event						
Bong Bong	720	168.0	1440	4871	181.6	8.1%
Berrima	1440	229.6			247.7	7.9%
10% AEP Event						
Bong Bong	1440	219.2	1440	4871	236.2	7.7%
Berrima	1440	304.7			322.9	6.0%
5% AEP Event						
Bong Bong	1440	273.9	1440	4871	292.3	6.7%
Berrima	1440	382.2			399.4	4.5%
2% AEP Event						
Bong Bong	1440	357.5	1440	4728	373.6	4.5%
Berrima	1440	499.2			532.3	6.6%
1% AEP Event						
Bong Bong	1440	411.1	1440	4728	425.1	3.4%
Berrima	1440	579.7			610.2	5.3%
0.5% AEP Event						
Bong Bong	1440	441.5	1440	4728	455.7	3.2%
Berrima	1440	623.8			656.2	5.2%
0.2% AEP Event						
Bong Bong	1440	495.3	1440	4728	509.8	2.9%
Berrima	2880	719.7			738.0	2.5%

9.4.2. Tributary Critical Duration

Several locations in minor tributary areas were selected for the tributary critical duration assessment. The chosen subcatchments are listed below and can be seen on Figure 14:

- WR_70 – Throsby Park at Watkins Drive
- WR_182 – Moss Vale at Beaconsfield Road
- WR_308 – Throsby Park at Headlam Road
- WR_372 – East Bowral (Isabella Way) at Kangaloon Road
- WR_430 – Bowral (Cypress Parade) at Old South Road
- WR_472 – East Bowral (Robina Drive Park) at Kangaloon Road

A range of storm durations and the ensemble of temporal patterns were run in WBNM and the results were analysed at each of these locations. A box plot of 1% AEP flows for each of these locations can be seen in Diagram 13 to Diagram 18.

For the 1% AEP event, similar mean peak flows occur for a range of durations from 360 minutes up to 720 minutes. The 720 minute (12 hour) storm is critical at the locations analysed. However the range of flows produced by the 720 minute storm is quite large, and selecting the temporal pattern which produces the peak flow just above the mean flow in some instances results in peak flows significantly than the mean critical flow.

It can be seen from the box plots that the mean flow from the 720 minute storm (the critical flow) is within range of flows produced in other storm durations. This means that are temporal patterns in other durations that closely match the critical flow. Using the information contained in the box plots and the flow hydrographs, a representative duration and temporal pattern was selected that closely matches the critical flow across the key subcatchments.

This analysis was undertaken for all the design AEPs. A single duration and temporal pattern was adopted for each bin (see Diagram 9), being representative across the range of events and locations. The adopted representative temporal pattern and a summary of the flows is provided in Table 25.

Diagram 13: 1% AEP Peak Flows at WR_70 – Throsby Park at Watkins Drive

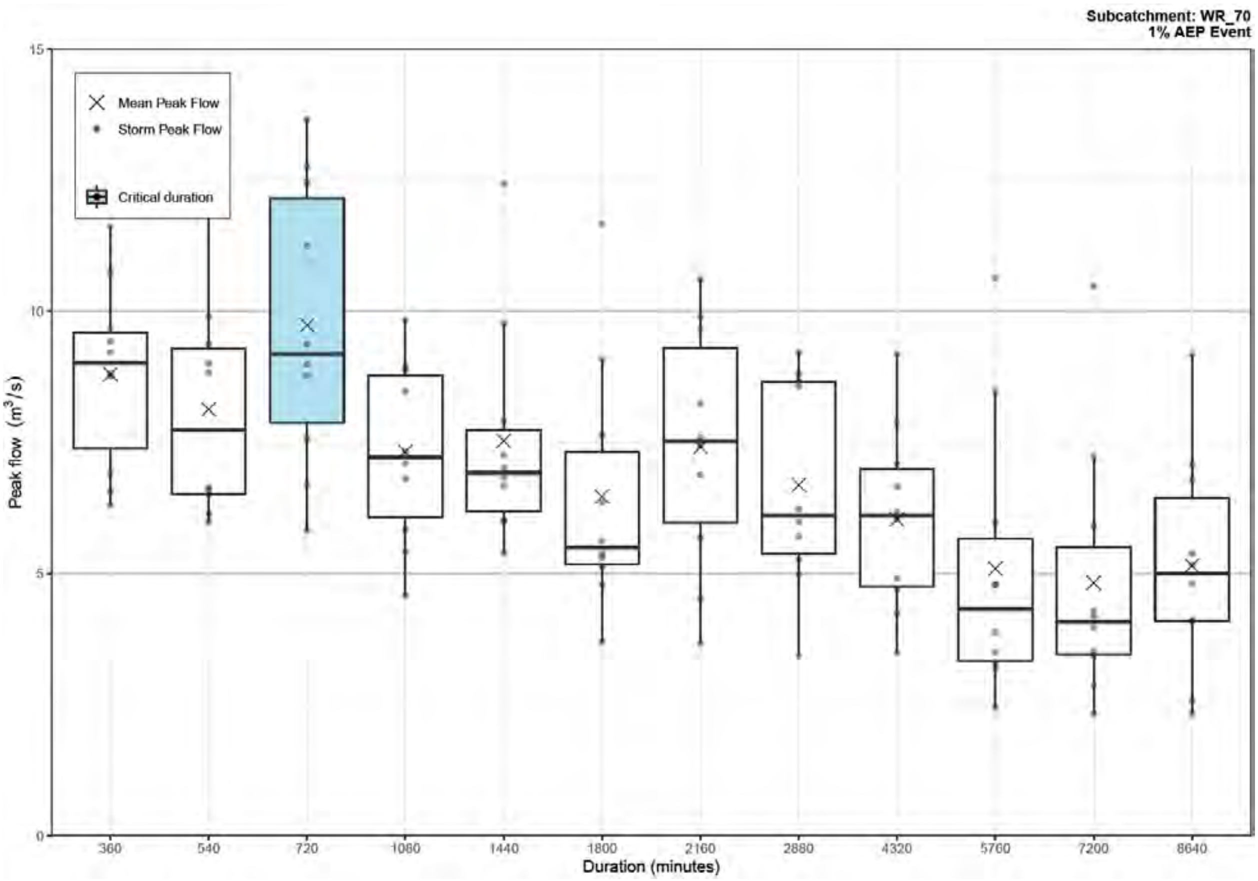


Diagram 14: 1% AEP Peak Flows at WR_182 – Moss Vale at Beaconsfield Road

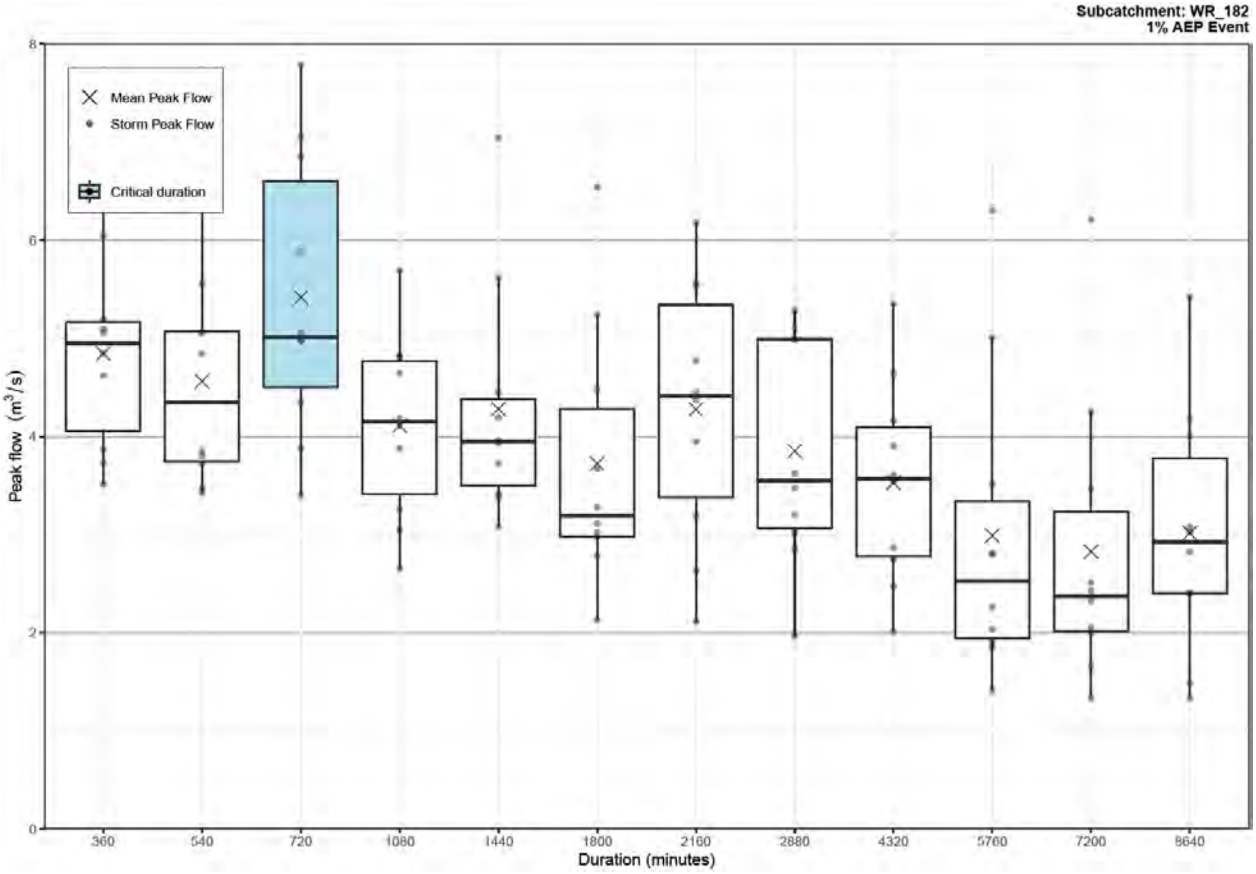


Diagram 15: 1% AEP Peak Flows at WR_308 – Throsby Park at Headlam Road

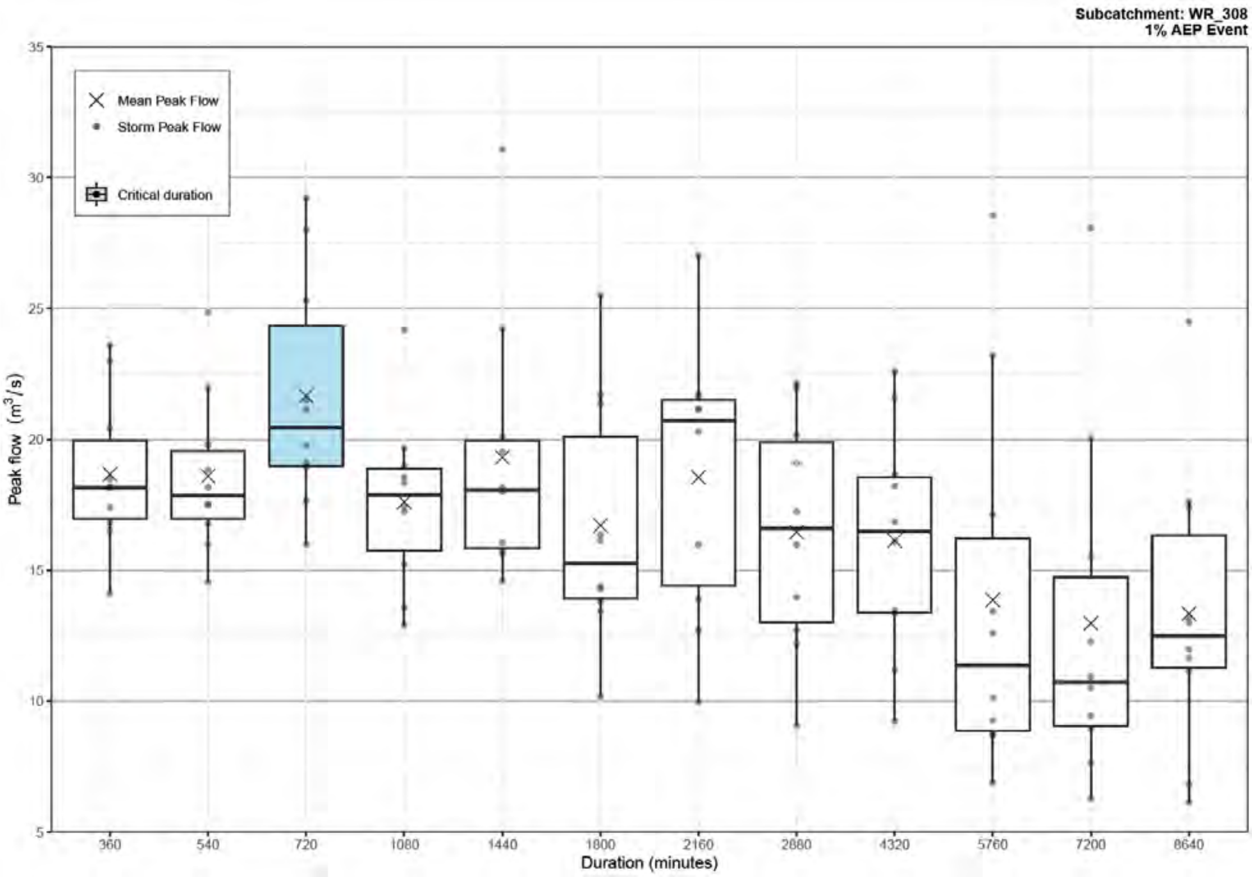


Diagram 16: 1% AEP Peak Flows at WR_372 – East Bowral (Isabella Way) at Kangaloon Road

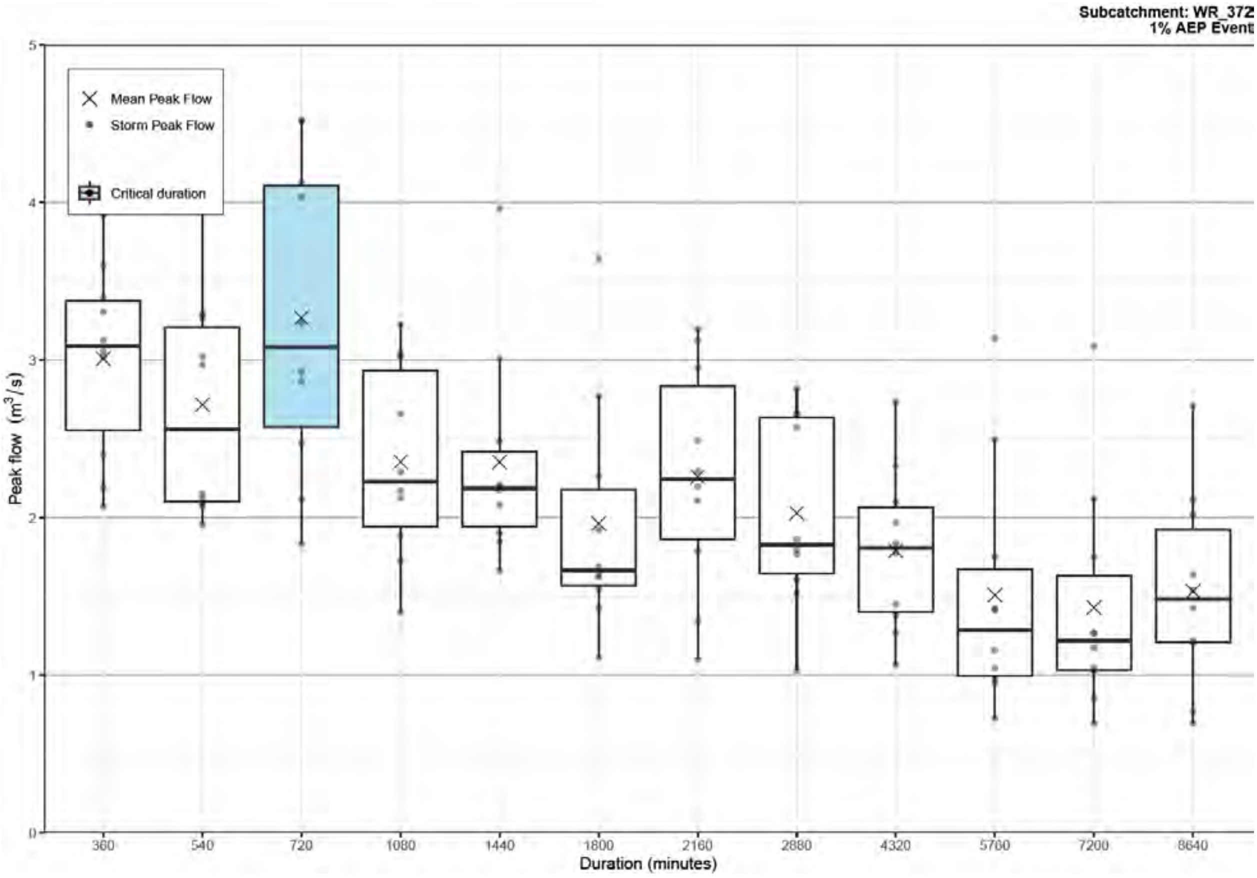


Diagram 17: 1% AEP Peak Flows at WR_430 – Bowral (Cypress Parade) at Old South Road

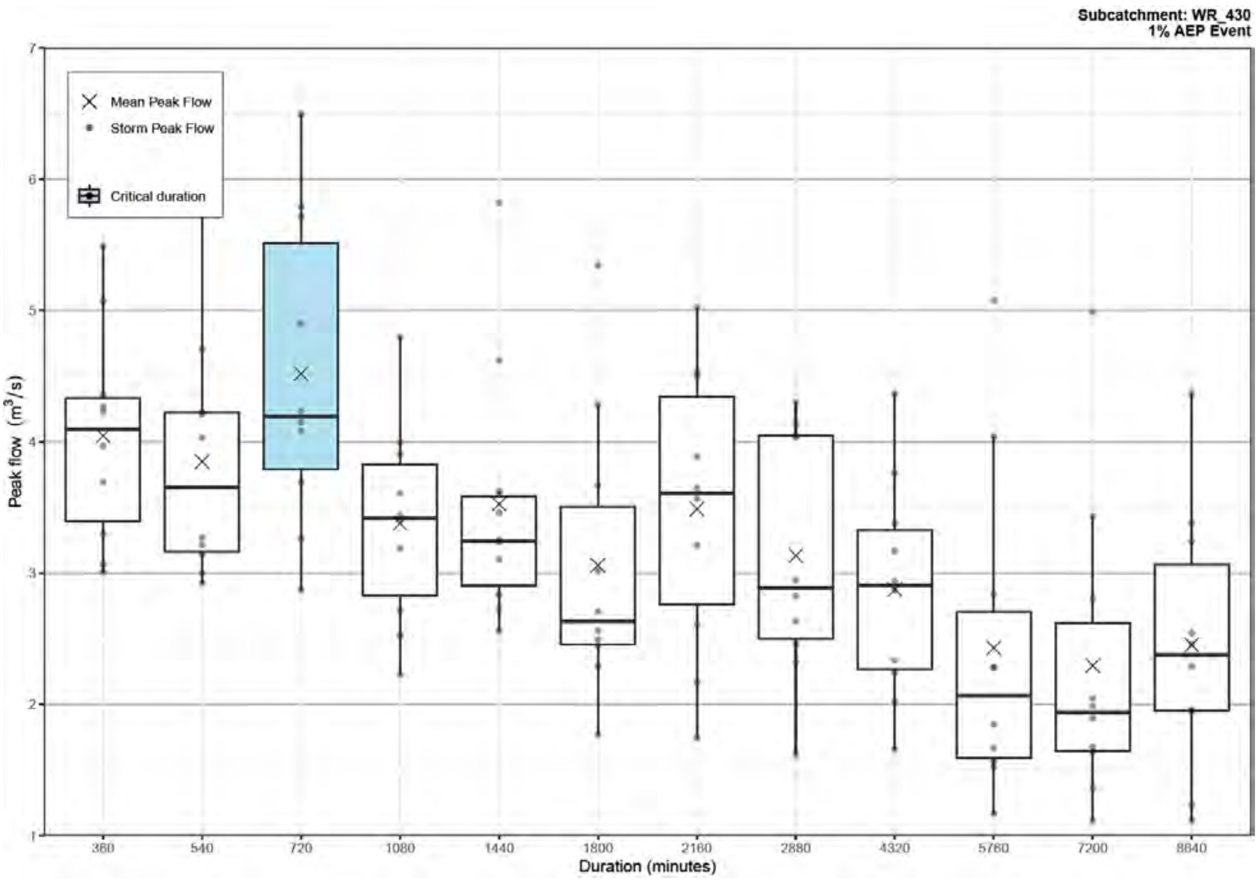


Diagram 18: 1% AEP Peak Flows at WR_472 – East Bowral (Robina Dr Park) at Kangaloon Rd

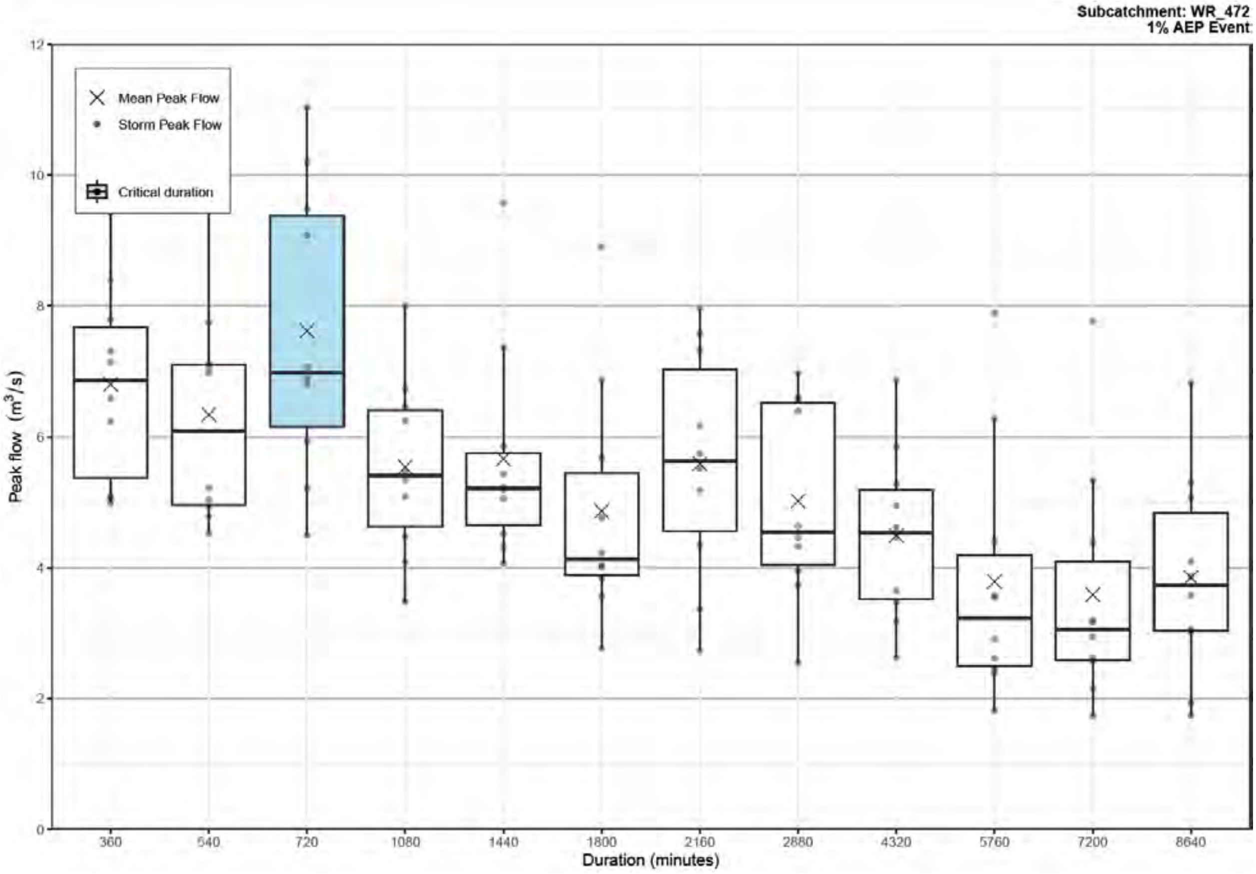


Table 25: Summary of ensemble flows and the adopted temporal patterns for overland flow

Location	Ensemble Results		Adopted Representative Results			
	Critical Duration (mins)	Mean (Critical) Flow (m^3/s)	Duration (mins)	Temporal Pattern ID	Peak Flow (m^3/s)	% Difference (Peak Flow minus Critical Flow)
50% AEP Event						
WR_70	360	2.7	540	4775	2.9	7.1%
WR_182	720	1.4			1.6	9.4%
WR_308	720	5.8			5.9	1.1%
WR_372	360	1.0			1.0	0.8%
WR_430	720	1.3			1.3	3.5%
WR_472	360	2.2			2.2	1.8%
20% AEP Event						
WR_70	360	4.4	720	4800	4.7	5.6%
WR_182	360	2.4			2.6	5.8%
WR_308	360	9.4			10.1	6.9%
WR_372	360	1.6			1.6	-1.2%
WR_430	360	2.1			2.2	2.2%
WR_472	360	3.6			3.7	2.4%

Location	Ensemble Results		Adopted Representative Results			
	Critical Duration (mins)	Mean (Critical) Flow (m^3/s)	Duration (mins)	Temporal Pattern ID	Peak Flow (m^3/s)	% Difference (Peak Flow minus Critical Flow)
10% AEP Event						
WR_70	360	5.4	720	4800	5.8	6.3%
WR_182	360	3.0			3.2	6.0%
WR_308	360	11.7			12.6	7.4%
WR_372	360	1.9			1.9	-1.1%
WR_430	360	2.6			2.7	3.1%
WR_472	360	4.4			4.5	3.7%
5% AEP Event						
WR_70	360	6.5	720	4800	6.8	5.4%
WR_182	360	3.6			3.8	5.3%
WR_308	360	14.1			15.1	6.6%
WR_372	360	2.3			2.2	-2.1%
WR_430	360	3.1			3.2	2.5%
WR_472	360	5.2			5.3	3.4%
2% AEP Event						
WR_70	720	8.5	540	4675	8.8	3.5%
WR_182	720	4.7			4.9	5.0%
WR_308	720	18.8			19.4	3.0%
WR_372	720	2.9			2.9	2.5%
WR_430	720	3.9			4.2	6.0%
WR_472	720	6.7			6.9	3.4%
1% AEP Event						
WR_70	720	9.7	540	4675	9.9	1.6%
WR_182	720	5.4			5.6	2.7%
WR_308	720	21.7			22.0	1.6%
WR_372	720	3.3			3.3	0.9%
WR_430	720	4.5			4.7	4.1%
WR_472	720	7.6			7.8	1.7%
0.5% AEP Event						
WR_70	720	10.2	540	4675	10.4	1.8%
WR_182	720	5.6			5.8	2.7%
WR_308	720	22.7			23.1	1.9%
WR_372	720	3.4			3.4	0.4%
WR_430	720	4.7			4.9	3.5%
WR_472	720	8.0			8.1	1.1%

Location	Ensemble Results		Adopted Representative Results			
	Critical Duration (mins)	Mean (Critical) Flow (m^3/s)	Duration (mins)	Temporal Pattern ID	Peak Flow (m^3/s)	% Difference (Peak Flow minus Critical Flow)
0.2% AEP Event						
WR_70	720	11.2	540	4675	11.3	1.5%
WR_182	720	6.2			6.4	2.3%
WR_308	720	25.0			25.5	1.9%
WR_372	720	3.7			3.8	0.6%
WR_430	720	5.2			5.4	3.6%
WR_472	720	8.7			8.8	1.2%

9.4.3. Critical Duration Summary

A summary of the adopted durations and temporal patterns is provided in Table 26.

Table 26: Adopted durations and temporal patterns for design flood events

Event	AEP Bin	Adopted Durations (mins)	Adopted Temporal Pattern ID
50% AEP	Frequent	540 / 1440	4775 / 4885
20% AEP	Intermediate	720 / 1440	4800 / 4871
10% AEP			
5% AEP			
2% AEP	Rare	540 / 1440	4657 / 4728
1% AEP			
0.5% AEP			
0.2% AEP			
PMF	Not applicable	90 / 360 / 2160 (dam)	Not applicable

The probable maximum precipitation (PMP) uses a single temporal pattern. In this case, the peak flows at each of the key subcatchments were analysed to determine the critical duration (duration which produces the peak flows). At all the locations of interest, the 90 minute and 360 minute storms were the critical duration adopted for the PMF design flood event for tributary and mainstream flows respectively. The PMF critical duration adopted for the Wingecarribee Reservoir was 2160 minutes (36 hours). The PMP hydrology is discussed further in Section 9.9.

9.5. Rainfall Losses

Design rainfall losses were obtained from the ARR19 Datahub[1]. In accordance with guidelines from the NSW Office of Environment and Heritage (OEH, now DPIE, Reference 18), probability neutral burst initial losses and factored continuing losses were adopted. A summary of the Datahub output at the catchment centroid is presented in Attachment A (located after Figures,

1 http://data.arr-software.org/

before Appendices).

Probability neutral burst initial losses were applied to the design storm bursts in accordance with OEH guidance (Reference 18). The initial losses vary with duration and AEP and are presented in Table 27 (for the catchment centroid, as presented in Attachment A).

Table 27: Probability Neutral Burst Initial Losses (mm)

Duration	**AEP**					
(min)	20%	10%	5%	2%	1%	0.5%
30	9.1	9.3	10.0	9.3	8.4	8.4
60	9.1	9.3	10.0	9.3	8.4	8.4
90	11.6	10.4	11.1	9.1	6.6	6.6
120	10.2	9.4	9.8	8.7	6.2	6.2
180	8.9	8.8	8.0	7.5	4.5	4.5
360	8.4	8.1	6.5	6.4	2.1	2.1
720	10.4	10.4	9.2	9.3	2.2	2.2
1080	12.4	12.4	10.0	11.3	3.7	3.7
1440	14.6	14.2	13.2	13.3	7.1	7.1
2160	16.9	16.1	15.4	16.4	7.0	7.0
2880	18.9	18.5	20.7	17.8	8.3	8.3
4320	24.6	25.6	26.0	19.9	7.0	7.0

The continuing losses across the Wingecarribee catchment from the Datahub are in the range of 4.7 to 4.8 mm/hr. When these losses are factored by 0.4, in accordance with OEH guidance (Reference 18), the resulting value is a continuing loss of approximately 1.9 mm/hr. This value is consistent with the continuing loss of 1.8 mm/hr found to produce the best fit to historical behaviour as part of the model calibration. The calibrated loss of 1.8 mm/hr was used for design event modelling in this study.

9.6. Areal Reduction Factors

Table 28: Areal Reduction Factors for the Design Storm Events

Duration	**AEP**					
(min)	20%	10%	5%	2%	1%	0.5%
360	0.90	0.89	0.88	0.87	0.87	0.86
540	0.92	0.92	0.91	0.90	0.90	0.90
720	0.93	0.92	0.92	0.91	0.91	0.90
1080	0.95	0.94	0.94	0.94	0.94	0.93
1440	0.96	0.96	0.96	0.96	0.96	0.96
1800	0.97	0.97	0.97	0.96	0.96	0.96
2160	0.97	0.97	0.97	0.97	0.97	0.97

Areal Reduction Factors (ARF) were applied in the WBNM model for the design storm events based on ARR19 (Reference 3). The design rainfall estimates are based on point rainfalls and in reality, the catchment-average rainfall depth will be less. It allows for the fact that larger catchments are less likely than smaller catchments to experience high intensity storms simultaneously over the whole catchment area. The ARF is dependent on area and for the purpose of the Wingecarribee study area, the catchment area to Bong Bong Weir was taken as this is the location of the most upstream towns of interest. The ARF varies with AEP and duration and the resulting matrix of ARFs for the design storms are shown in Table 28. The equation used to derive these reduction factors can be found in Attachment A.

9.7. Blockage

Design blockage for hydraulic structures was adopted in accordance with Reference 3. The debris availability, debris mobility and debris transportability was deemed to be in the Low to Medium categories for the catchment, due to the large amount of cleared land. The overall debris potential was classified as Low in mainstream areas, and medium in urbanised areas. With this classification, and debris blockage was applied to all road crossing culvert and bridge structures in the model as follows:

- Pipe diameter or box culvert width less than or equal to 1.2 m – 50% debris blockage.
- Pipe diameter or box culvert width greater than 1.2 m – 25% debris blockage.
- Bridges (with span opening at least 3 m) = 10% debris blockage.

9.8. Wingecarribee Reservoir Outflows

Wingecarribee Dam has two outlets:

1. A main spillway which flows into the Wingecarribee River, just upstream of Sheepwash Drive, and
2. An additional sluice gate from the northern end of the dam, which releases water into an engineered channel named the Glenquarry Cut, flowing into Glenquarry Creek and ultimately to the Nepean River.

WaterNSW, the organisation which owns and operates the dam, did not provide details of how the dam outlet sluices and gates are operated during flood events, apart from providing a rating curve for the main spillway. The rating curve indicates that outflows only occur above the Full Supply Level (FSL) of the reservoir, but the spillway crest allows for releases into the Wingecarribee River from approximately 5.5 m below FSL, if the radial gates are opened. It is unclear from the information provided whether the rating curve describes the operational release strategy to be targeted by the gate operations at various reservoir levels above FSL – this is what WMAwater has assumed for the purpose of this study as no other information is available to the contrary.

As far as WMAwater is aware, there have been very few major releases from the main Wingecarribee Reservoir spillway. The most notable release occurred during the March 1978 flood event, although gauge records from the Sheepwash Road gauge are unavailable for this event. It is surmised from the water level records in the reservoir (peak level around 0.2 m above FSL), and from calibration modelling of the event, that a peak flow in the order of 100 to 150 m^3/s was released in the 1978 flood. Apart from that event, there do not appear to have been any releases exceeding 50 m^3/s since the dam was constructed.

9.8.1. Reservoir Initial Water Level (IWL) Analysis

The initial water level in the dam at the start of a design storm burst is a key assumption for whether a given storm event will raise the level enough to produce outflows. It would be possible to have a 1% AEP rainfall event over the reservoir when it is relatively empty and have no outflows. Alternatively, it is possible to have a 20% AEP storm over the reservoir when it is nearly full, resulting in significant outflows. The initial water level for which a critical duration design storm burst of a given AEP would produce an outflow of a similar AEP is referred to as the “probability neutral initial condition.” WMAwater undertook stochastic analysis of the dam to determine this probability neutral initial condition, as well as to estimate the approximate AEP for releases from the dam to occur.

Diagram 19 shows the historical daily distribution of water level in the Wingecarribee Reservoir. It indicates the probability of the water level exceeding a given level on any day during the history of the dam records.

Diagram 19: Historical daily water level distriubtion in Wingecarribee Reservoir

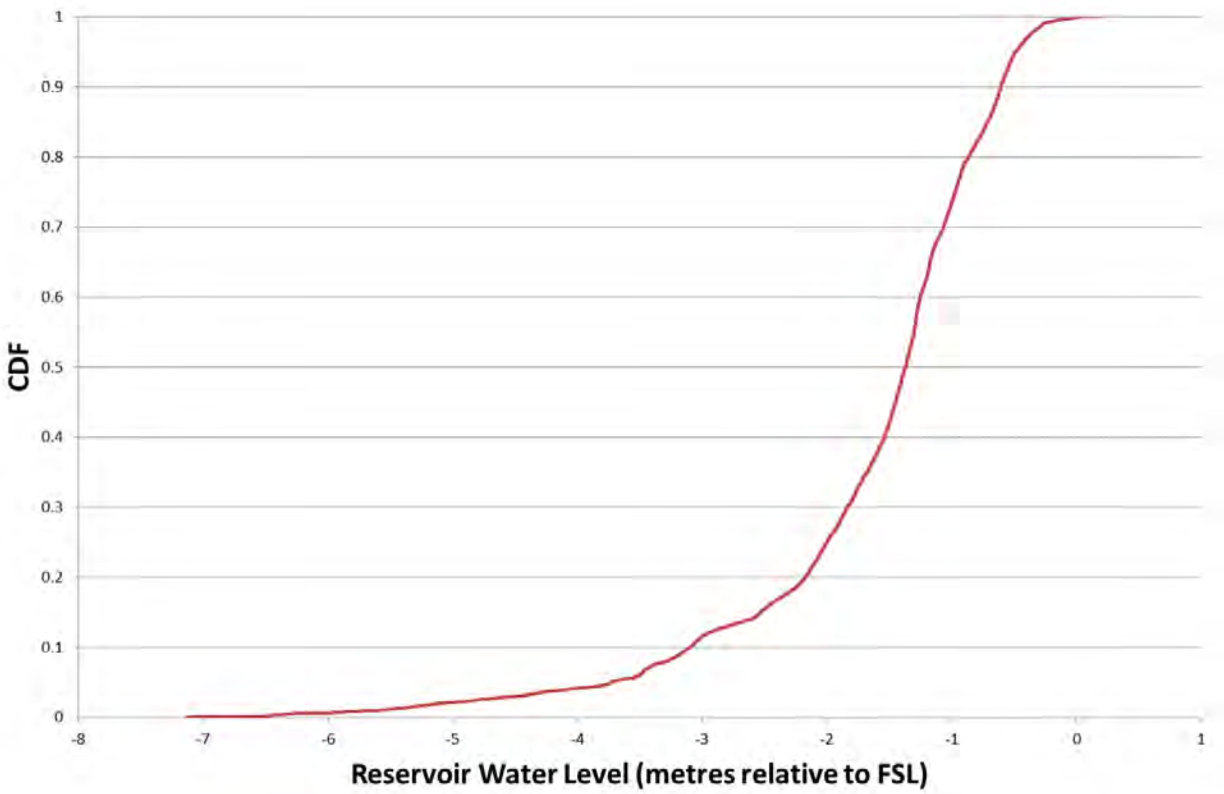


Diagram 20 shows a box plot of the daily dam level for the entire record, with the blue box indicating the first and third quartiles (i.e. the 25th to 75th percentile values), and the whiskers showing the remaining values outside this range. The black line indicates the median and red dot indicates the mean value. Diagram 21 shows the same information broken down by month, to demonstrate the seasonal variation.

Diagram 20: Box plot of historical daily water level in Wingecarribee Reservoir

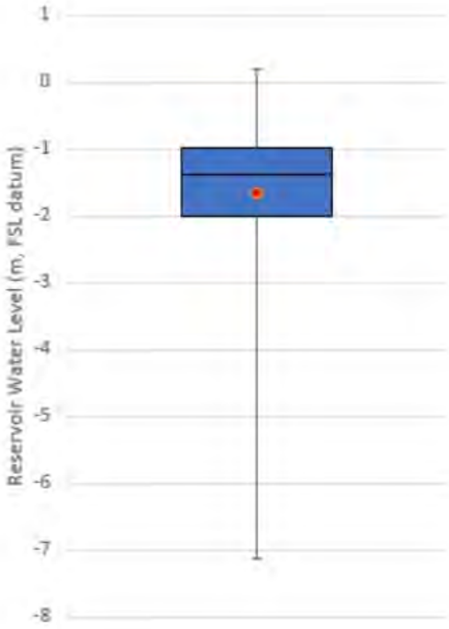
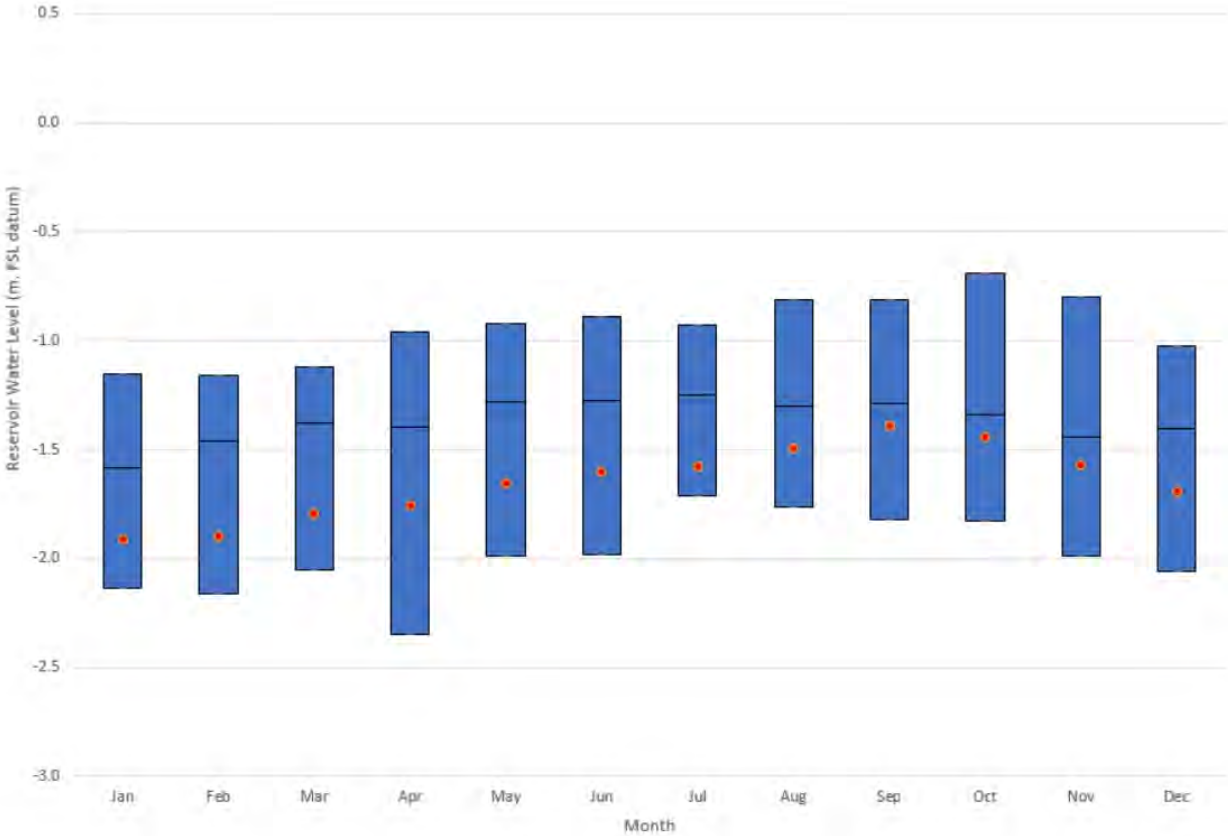


Diagram 21: Seasonal variation in daily water level in Wingecarribee Reservoir



These charts indicate that median water level in the dam is approximately 1.4 m below FSL, and the mean is approximately 1.6 m below FSL. Both of these values vary seasonally, with the reservoir level typically being lowest in summer and highest in late winter and early spring. This seasonality is presumably due to combination of factors including higher evaporation and increased water supply demand in summer relative to the cooler months, as well as higher inflows in winter due to higher catchment soil moisture and seasonal rainfall patterns.

The level in the dam has been between 1.0 m and 2.0 m below FSL for approximately 50% of the historical record, suggesting this is a typical targeted operating level.

The most likely flood-producing weather mechanism for the catchment is an “East Coast Low,” which can occur at any time during the year but are most common in autumn and winter, with a maximum frequency in June. The June water levels for the reservoir show a similar distribution to the full-year distribution. For the purposes of this study, it was assumed that the initial water level prior to a flood-producing weather event could be randomly sampled from the statistical distribution obtained from the full daily record of levels in the reservoir.

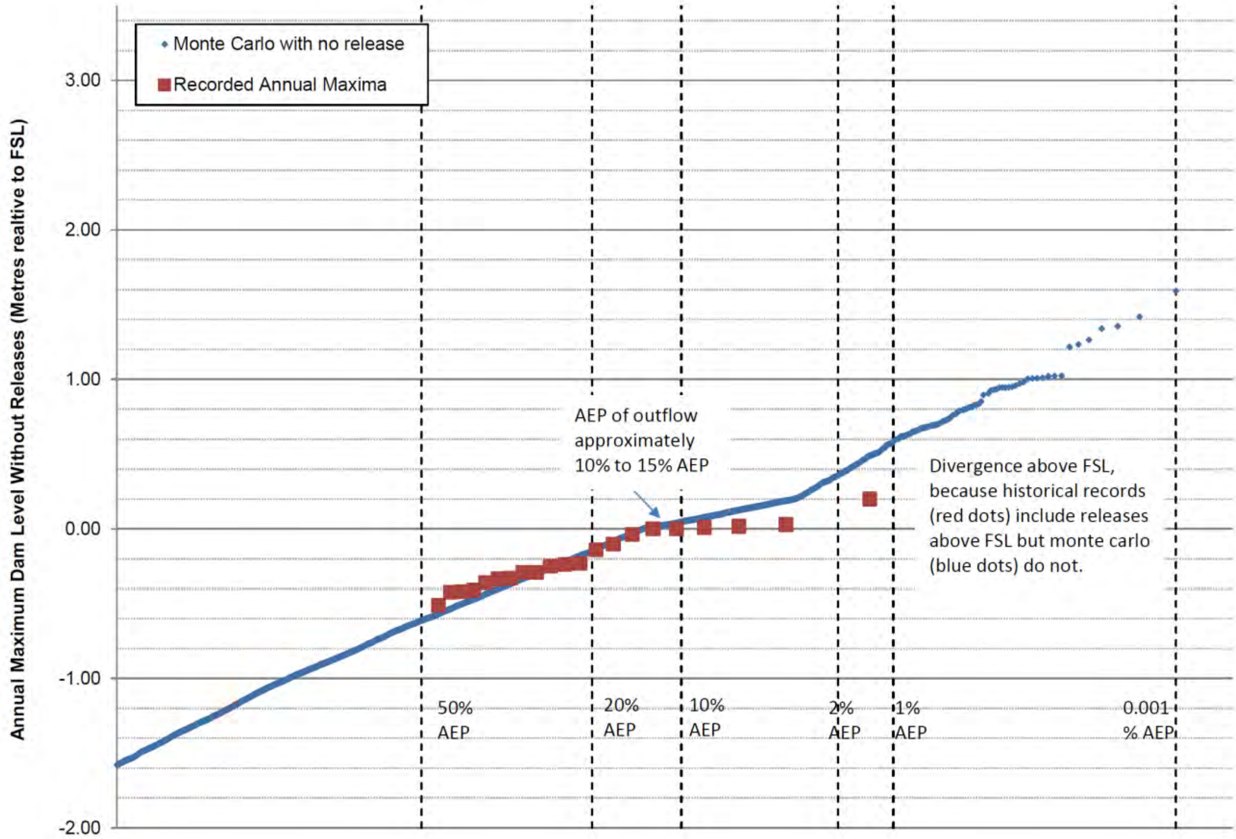
WMAwater undertook a Monte-Carlo stochastic analysis of annual maximum runoff into the reservoir and corresponding water levels, to estimate the AEP for outflow events (when the water level exceeds FSL). This involves a 10,000 year simulation using the following methodology:

- Randomly samples an initial water level from the historical daily record (excluding the top and bottom 10%),
- Randomly sample the maximum rainfall AEP for the year,
- Determine the runoff volume into the dam and resulting annual maximum water level
- Adjust the runoff coefficient to produce a good match to the historical annual maximum recorded water level and verify consistency of this coefficient with the calibrated WBNM hydrologic modelling.

This analysis was undertaken separately for a range of storm burst durations to understand the sensitivity to duration. The main purpose of this analysis was to identify the probability neutral AEP for the dam to overflow to inform design event modelling of the dam. The historical records indicate overtopping occurs at around a 10% to 15% AEP likelihood (see Diagram 22). The Monte-Carlo analysis reproduced this behaviour well with runoff coefficients that match those obtained from the calibrated hydrologic model for the non-dam catchment (0.7 for the Monte-Carlo 24-hour compared to 0.77 for the 5% AEP design inputs). Note that this analysis does not model any releases from the dam, which is why there is a divergence in the levels above FSL. The historical levels above FSL include releases but the Monte-Carlo analysis does not. The purpose of this analysis was to get an estimate of how often the dam will overtop using this analysis, and then use WBNM to determine design releases for each AEP.

Based on this analysis, outflows from the dam spillway are assumed to have an AEP of approximately 15%, and it is necessary to estimate the release hydrograph to input into the TUFLOW model for design events of 10% AEP and rarer. The probability neutral initial water level for the dam was determined to be approximately 1.5m below FSL.

Diagram 22: Monte Carlo simulation results (blue dots) versus historical annual maximum water levels in Wingecarribee Reservoir (red dots).



9.8.2. Reservoir Design Outflow Estimation

To estimate the design outflows from the dam, WMAwater configured the WBNM model to represent the dam catchment, storage volume, and spillway outflow rating curve. The dam was modelled for a full range of design storm AEPs and durations (with a 10-storm ensemble approach). Sensitivity was undertaken to determine the influence of assumed starting initial water levels (4 different scenarios).

The probability neutral IWL which produced outflows at around 15% AEP was found to be approximately 1.5m below FSL, which is consistent with the median/mean values from the historical dam levels, and the outcomes from the Monte Carlo assessment. The critical duration for dam outflow was found to be the 48 hour duration. The WBNM results produce an outcome consistent with the other analysis and historical information, in that there is no little to no outflow for the critical duration in the 20% AEP event, and outflow begins at the 10% AEP event. For the 1% AEP, the design outflow is in the order of 100 to 150 m^3/s for the 1% AEP event, which is consistent with (slightly larger than) the recorded outflow for the largest event on record (1978).

The results from WBNM for water levels and critical duration from modelling the full ensemble of design storms for various AEPs are provided in Table 29. Since a rating curve is used to determine the outflows (starting at FSL), the water level above FSL is a proxy for flow released from the reservoir.

Table 29: Peak level (m) in Wingecarribee Reservoir (relative to FSL) and critical duration

AEP (%)	IWL= -0.5 m	Critical Duration (minutes)	IWL= -1.0 m	Critical Duration (minutes)	IWL= -1.5 m	Critical Duration (minutes)	IWL= -2.0 m	Critical Duration (minutes)
50	0.03	8640	-0.48	n/a	-0.93	n/a	-1.42	n/a
20	0.07	2160	0.02	5760	-0.24	n/a	-0.69	n/a
10	0.10	2160	0.06	4320	0.03	5760	-0.24	n/a
5	0.14	2160	0.10	2160	0.07	5760	0.03	5760
2	0.17	2880	0.15	2160	0.11	2880	0.08	4320
1	0.22	2880	0.18	4320	0.14	4320	0.11	2880
0.5	0.26	2880	0.27	2880	0.19	4320	0.16	4320
0.2	0.32	2880	0.35	2880	0.25	4320	0.22	4320

It can be seen that for a higher antecedent IWL assumption, the critical duration is reduced. This is to be expected as a lower IWL will require a longer duration storm with higher volume of runoff to fill up the dam. The IWL assumption also affects the AEP at which any overtopping occurs. The results for an IWL assumption of FSL minus 1.5 m (highlighted in green) give the closest match to the historical overtopping behaviour (i.e. overtopping occurs between 20% AEP and 10% AEP, with relatively minor overtopping of 0.03 m above FSL in the 10% AEP). The overtopping depth above FSL is 0.14 m for the 1% AEP event, which corresponds to a peak outflow of approximately 100 m^3/s. The largest peak release from the historical calibration data was inferred to be approximately 100 m^3/s in the 1978 event.

These results demonstrate a reasonable match to the historical overtopping frequency around 10% AEP as well as a reasonable match to the overtopping depth above FSL (and therefore spillway outflow via rating curve) compared with historical data.

The critical duration for the reservoir using the above results under a probability neutral IWL assumption ranges from 2880 minutes (48 hours) to 5760 minutes (96 hours). This is significantly longer than the 24 critical duration for the rest of the study area catchment to the main weirs. In order to simplify the design modelling process, WMAwater adopted the following adjustments:

1. Assume a slightly increased IWL for the reservoir, whereby part of the rainfall from a longer duration storm has already occurred prior to the burst, then apply a 24 hour design storm burst (identical to the rest of the catchment) which produces similar outflow behaviour to the results from Table 29.
2. Adjust the timing of the outflow from the spillway (brought forward by 6 hours) to align with the peak flows from the rest of the catchment. This corresponds to an assumption that pre-burst rainfalls across the catchment generally fall earlier closer to the coast and Illawarra escarpment, which is reasonable based on historical rainfall patterns.

The dam design outflows obtained using this method are summarised in Table 30 below.

Table 30: Results and IWL assumptions for reservoir (relative to FSL) using 24 hr design burst

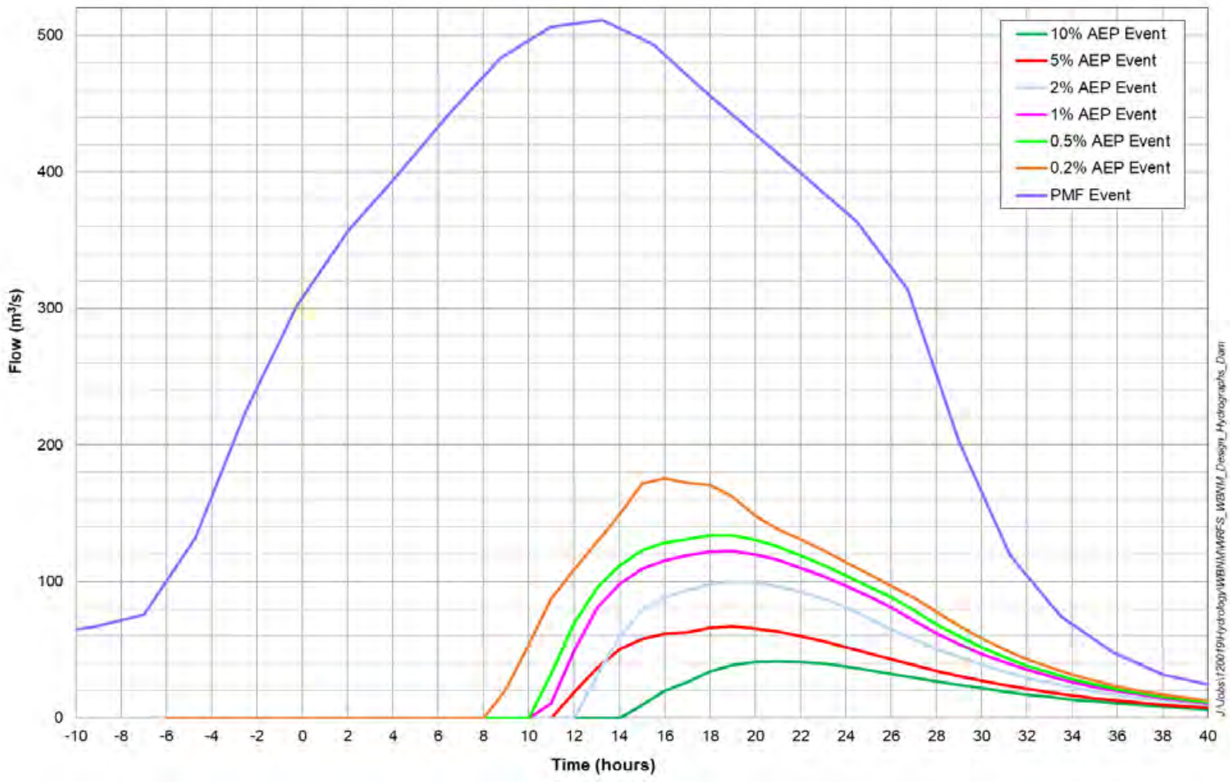
AEP (%)	Peak dam water level relative to FSL (m)	Peak dam outflow (m^3/s)	Adopted IWL relative to FSL (m)	Design Storm Adopted
50	-0.48	0.0	-1	dur1440_50pAEP_TP4885
20	-0.08	0.0	-1	dur1440_20pAEP_TP4871
10	0.05	41.6	-0.8	dur1440_10pAEP_TP4871
5	0.08	67.0	-0.8	dur1440_5pAEP_TP4871
2	0.13	99.7	-0.8	dur1440_2pAEP_TP4728
1	0.17	122.7	-0.8	dur1440_1pAEP_TP4728
0.5	0.19	134.4	-0.8	dur1440_1in200AEP_TP4728
0.2	0.25	175.9	-0.7	dur1440_1in500AEP_TP4728

The results in the second column of Table 30 can be compared to the results highlighted with green text in Table 29. The cells highlighted blue in Table 30 indicate the combination of IWL assumption and 24 hour storm burst required to produce these results. It can be seen that assuming an IWL value of FSL -0.8 m, with a 24 hour storm burst, gives a good match to the results in Table 29, being generally equivalent or slightly higher. This approach leads to some slight conservatism (increased reservoir outflows compared to the probability neutral analysis with IWL of 1.5m below FSL). This is appropriate given the uncertainty about the true operation of the dam in larger events (given major outflows have not occurred in over 40 years), and the relatively short record length of gauge records for FFA. The storm patterns in the final column of Table 2 were selected based on their suitability to meet or slightly exceed the critical peak mean flow value at Bong Bong Weir and Berrima Weir from the ensemble storm modelling, as per Section 9.4.

9.8.3. Summary of Adopted Design Outflows for Wingecarribee Reservoir

Table 30 summarises the estimated peak dam releases for design events modelled in this study. Diagram 23 shows the flow hydrographs, incorporating timing adjustments to align the releases with the flows from the rest of the catchment. The zero time on these charts aligns with the start of the design burst rainfall for the rest of the catchment.

Diagram 23: Wingecarribee Dam Design Outflow Hydrographs



9.9. PMP and PMF Methodology

The PMP rainfalls were obtained by using relevant Bureau of Meteorology guidance as follows.

- Using the Generalised Short Duration Method (GSDM, Reference 19) to estimate the probable maximum precipitation (PMP) for durations up to 6 hours,
- Using the Generalised Southeast Australia Method (GSAM, Reference 20) for durations 12 hours and longer, and
- Interpolating the PMP rainfall for durations from 6 hours to 12 hours from the above results.

The PMP rainfalls were implemented in the calibrated WBNM model (including the representation of the Wingecarribee Reservoir storage and spillway outflows). The reservoir was assumed to have a starting water level at FSL for the PMF event. This is consistent with the approach for adopting conservative assumptions to determine the PMF from the PMP, as opposed to the PMP Dam Flood event (or PMPDF) which would require probability neutral IWL assumptions. The results at the dam were compared to the PMF dam outflows provided to WMAwater by WaterNSW (Diagram 24).

The results are very similar, indicating a consistency of methodology between the WaterNSW results (which were supplied without supporting documentation), and the WMAwater results using the calibrated WBNM model.

Diagram 24: Comparison of WMAwater dam flows (WBNM) with WaterNSW results for PMF

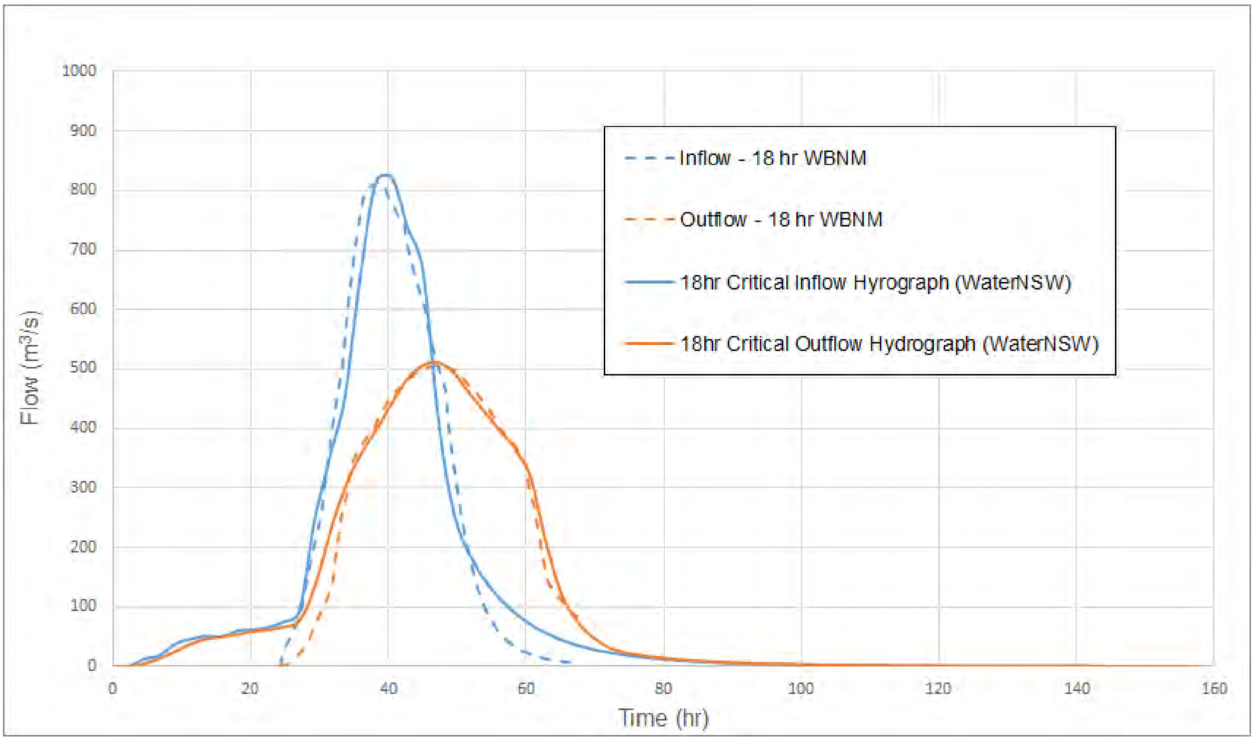


Diagram 25: Wingecarribee Dam peak flows for various PMF durations (WBNM)

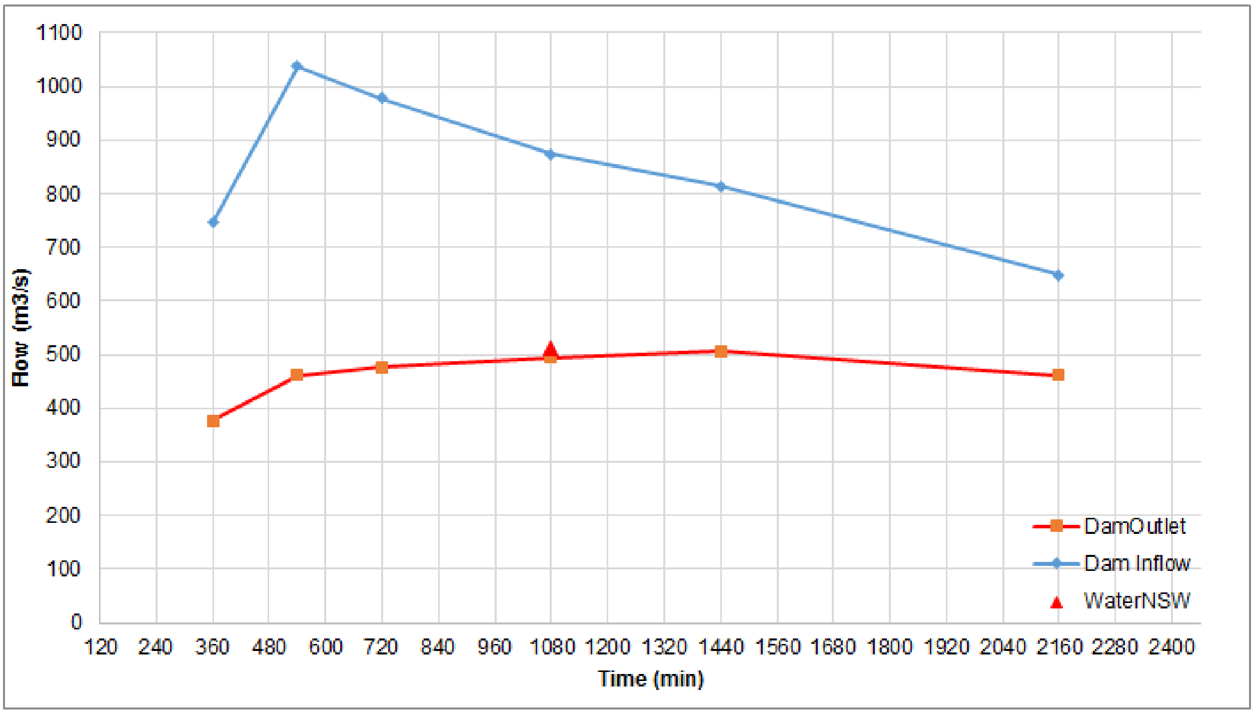


Diagram 25 shows the PMF peak inflow and outflow to the dam from the WMAwater WBNM results, for the range of durations investigated, as well as the WaterNSW result for the 18 hour PMF. The WBNM results indicate a slightly longer PMF critical duration of 24 hours, but an identical peak outflow of ~500 m^3/s with the WaterNSW results.

Diagram 26 and Diagram 27 show the PMF peak flow at Bong Bong Weir and Berrima Weir respectively, for the range of durations investigated (including modelling of the dam using the same duration).

These results indicate the 6 hour storm is critical for the majority of the study area, apart from the reservoir which has an 18 hour to 24 hour critical duration.

Diagram 26: Peak flow at Bong Bong Weir for various PMF durations (WBNM)

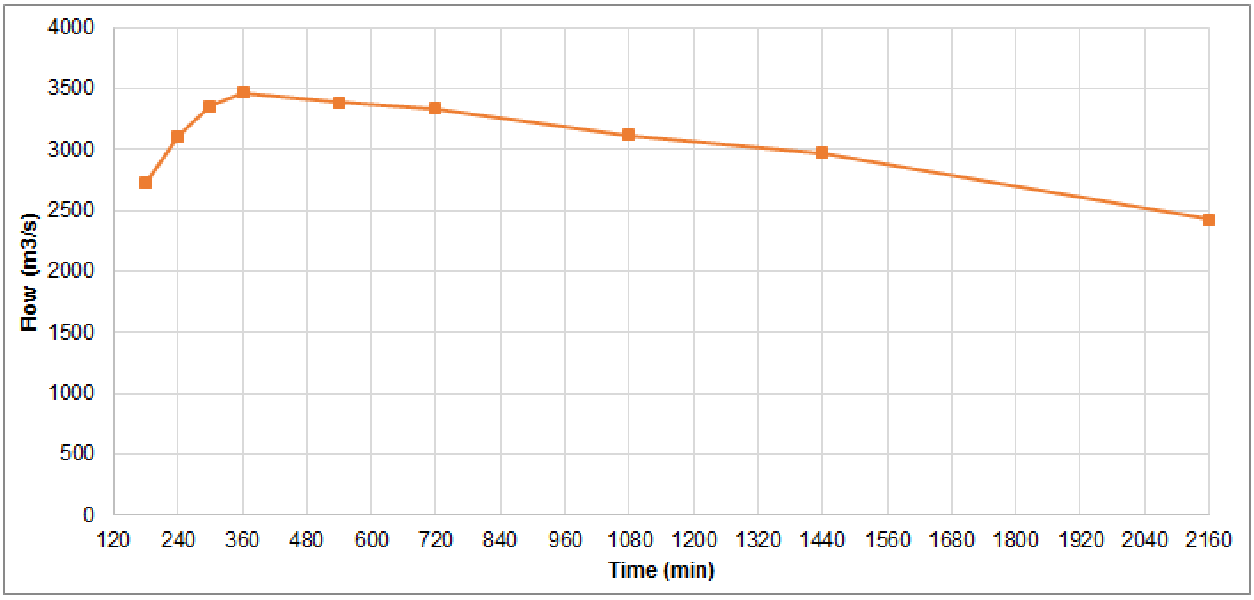
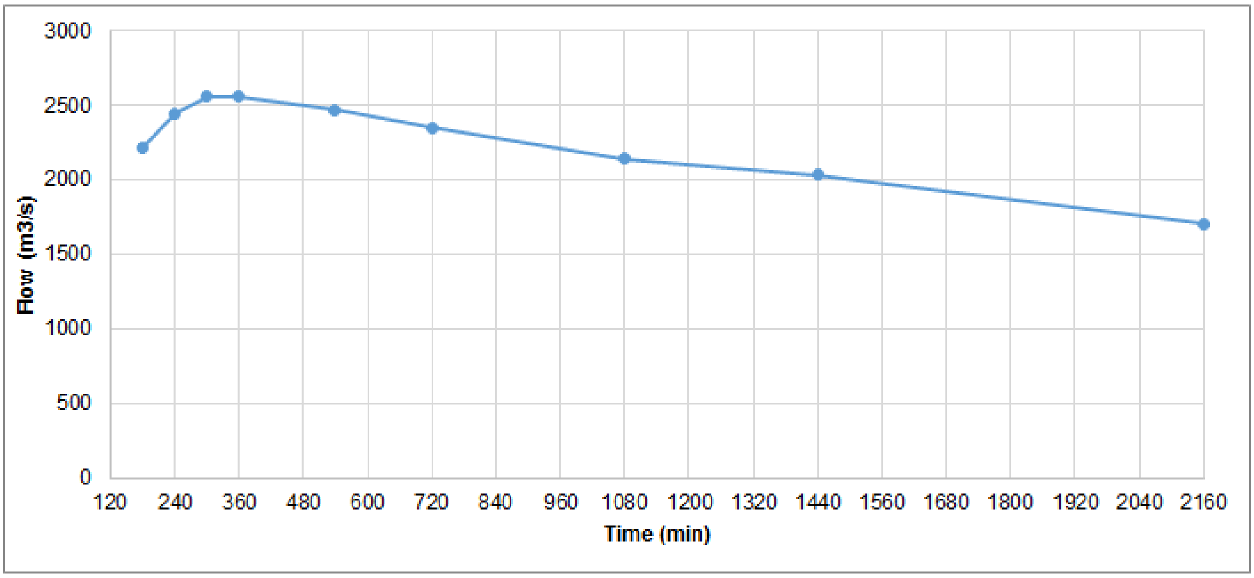


Diagram 27: Peak flow at Berrima Weir for various PMF durations (WBNM)



For design modelling in TUFLOW, WMAwater adopted the 6 hour storm for the PMF modelling of the catchment, but incorporating the WaterNSW 18 hour outflow hydrograph from the dam. This requires a time shift so that the dam outflow is assumed to occur at a similar time as the peak runoff for the rest of the catchment. WMAwater adjusted the timing of the hydrographs based on the dam outflow being coincident with the peak PMF outflow timing from the reservoir for the 6 hour storm.

10. DESIGN FLOOD MODELLING RESULTS

The results for the design flood events are presented in the following maps:

- Peak flood depth and level contours in Figure F1 to Figure F9;
- Peak flood velocities in Figure F10 to Figure F18;
- Hydraulic hazard based on the NSW Floodplain Development Manual in Figure F19 to Figure F21;
- Hydraulic hazard based on the Australian Disaster Resilience Handbook in Figure F22 to Figure F24;
- Hydraulic classification (flood function) in Figure F25 to Figure F27;
- Flood Emergency Response information in Figure F28 to Figure F30;
- Provisional Flood Planning Area (FPA) in Figure F31; and
- Provisional Flood Risk Precincts (FRP) in Figure F32.

The FPA and FRP mapping is marked as provisional, since these layers may be further reviewed and subject to change under a subsequent Floodplain Risk Management Study and Plan (FRMSP) for the catchment.

Peak flood level profiles are shown on Figure G1 to Figure G2 (Appendix G);

Discussion of the results is provided in the following sections.

10.1. Overview of Flood Behaviour

Table 31 summarises peak flows for a range of AEPs at various points along the Wingecarribee River main branch.

Table 31: Mainstream peak flow summary

ID	Location	Design Event								
		50% AEP	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP	PMF
R01	Sheepwash Road, Glenquarry (dam outlet)	1	2	41	66	99	121	133	174	508
R02	Sproules Lane, Glenquarry	27	50	64	124	175	210	229	282	972
R03	Wingecarribee River at Boardman Road South	43	80	104	170	228	271	295	356	1332
R16	Bong Bong Weir	106	210	271	365	479	556	597	689	2886
R17	Argyle Street, Moss Vale	111	218	281	374	498	578	622	716	3044
R19	Railway, Burradoo	113	222	279	359	465	525	554	618	1971
R21	Berrima Weir	140	265	337	422	547	625	666	749	2180
R22	Old Hume Highway, Berrima	140	265	338	423	548	626	667	750	2074
R24	Hume Motorway Bridge, Berrima	140	266	340	426	552	631	673	757	1828

For a given AEP, flows typically increase with increasing distance downstream, due to the increasing total contributing catchment area. This pattern is observed as far as Berrima Weir, beyond which the river is contained within a relatively steep gorge with relatively little additional inflows.

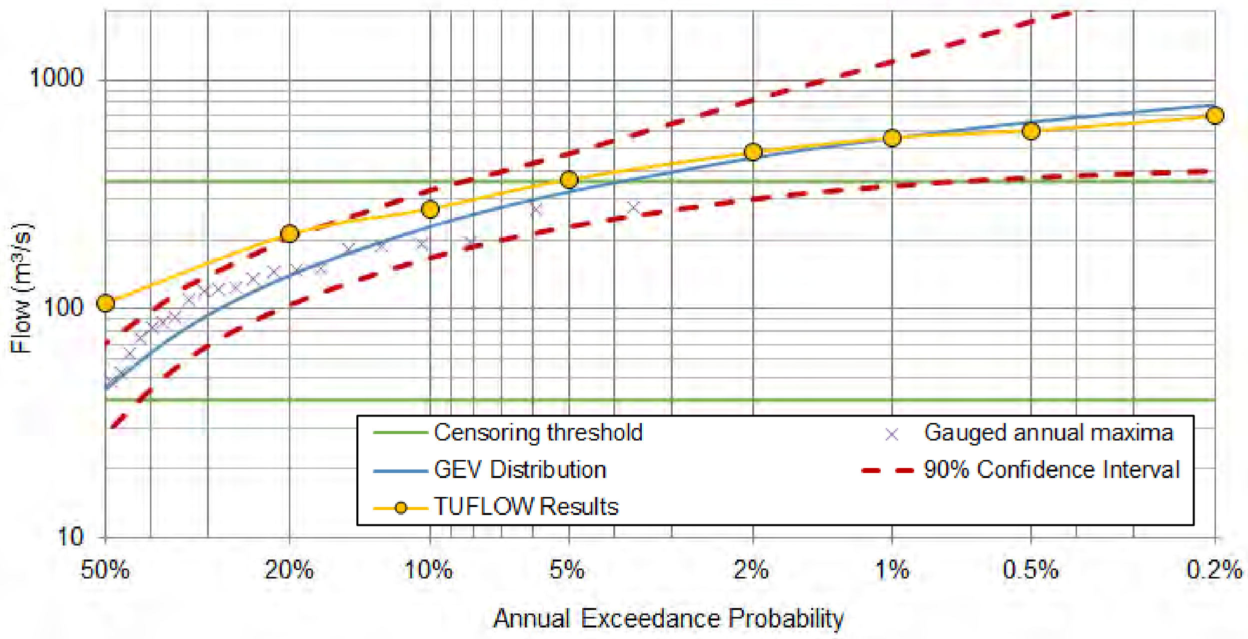
Flows at the railway crossing at Burradoo are generally slightly lower than upstream at Bong Bong Weir, and downstream at Berrima Weir. The railway acts as a constriction on the floodplain, resulting in some attenuation of peak flow at the railway bridge. This attenuation is offset by additional tributary flows joining the river downstream of the railway line, most notably from Mittagong Creek.

In the PMF event, peak flow at the railway at Burradoo and at Berrima Weir are significantly lower than the peak flow at Bong Bong Weir, despite the additional contributing catchment area. This is because during such an extreme event, the Berrima gorge acts as a significant constriction, creating a large storage area and detention effect that stretches all the way upstream to Bong Bong Weir. This is demonstrated by the flood level profile (Figure G2), which shows a level backwater pool extending a significant increase upstream of the gorge.

Generally, there are no major break-outs or diversions away from the main river channel except for the PMF event. In the PMF, flow will occur across saddle points in the high ground at both Burradoo (across Argyle Road near Eridge Park Road), and at Berrima (across the Old Hume Highway near Wingecarribee Street and the correctional centre).

10.2. Comparison of Design Results with FFA

Diagram 28: FFA and design modelling results at Bong Bong Weir (LP3 distribution)



Comparisons of the peak design flows with the FFA and historical gauge records at the two weir gauges are provided below in Diagram 28 and Diagram 29 (LP3 Distribution), and Diagram 30 and Diagram 31 (GEV Distribution).

Diagram 29: FFA and design modelling results at Berrima Weir (LP3 distribution)

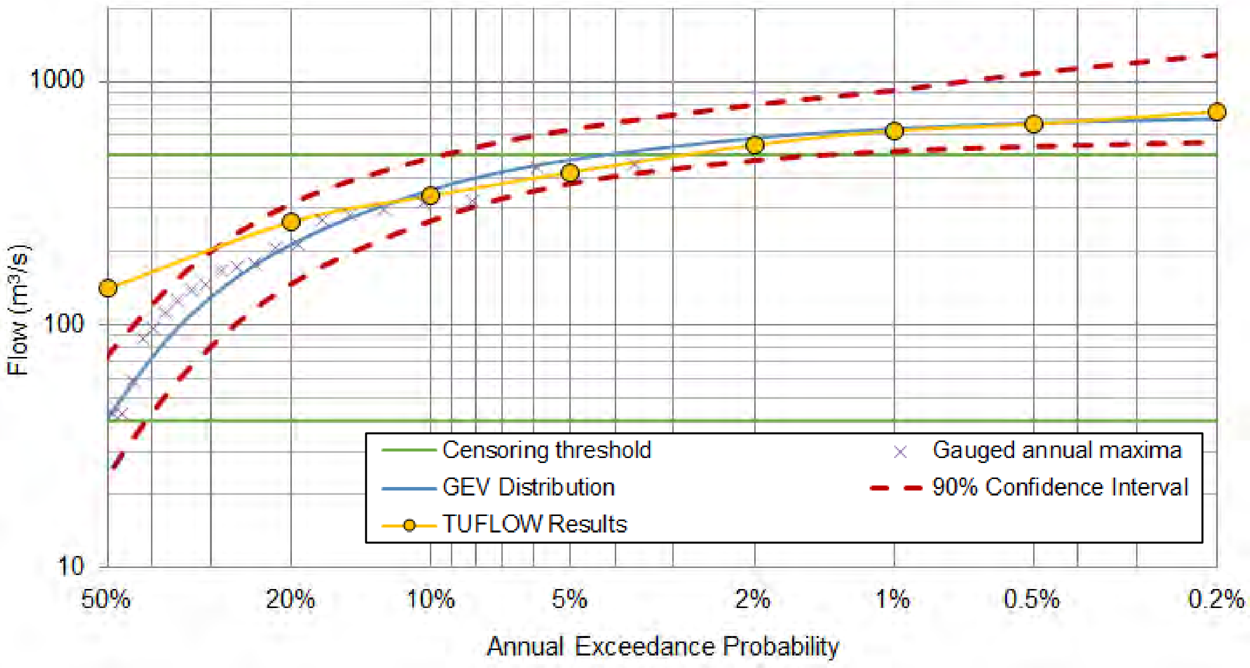


Diagram 30: FFA and design modelling results at Bong Bong Weir (GEV distribution)

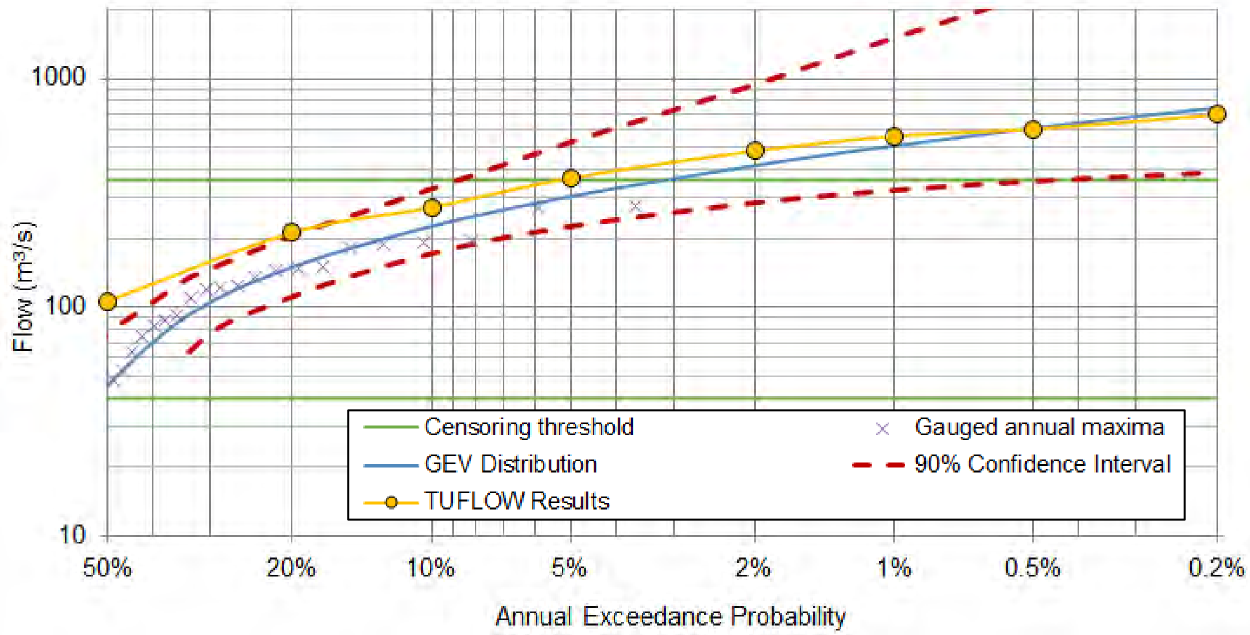
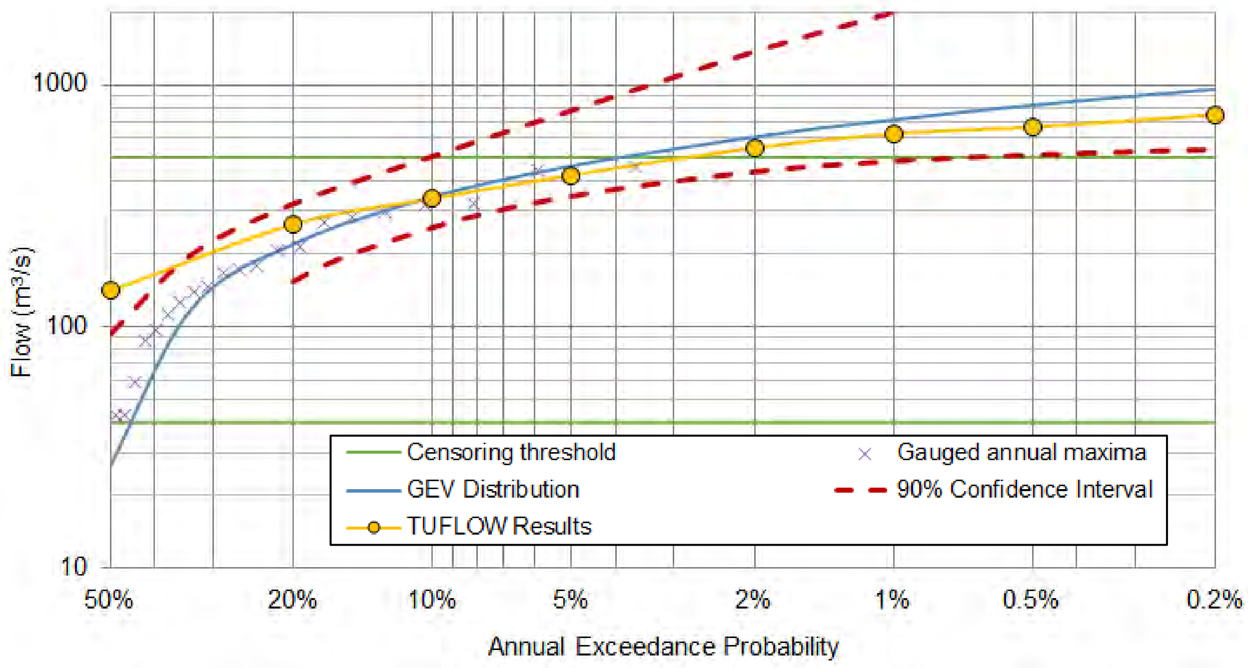


Diagram 31: FFA and design modelling results at Berrima Weir (GEV distribution)

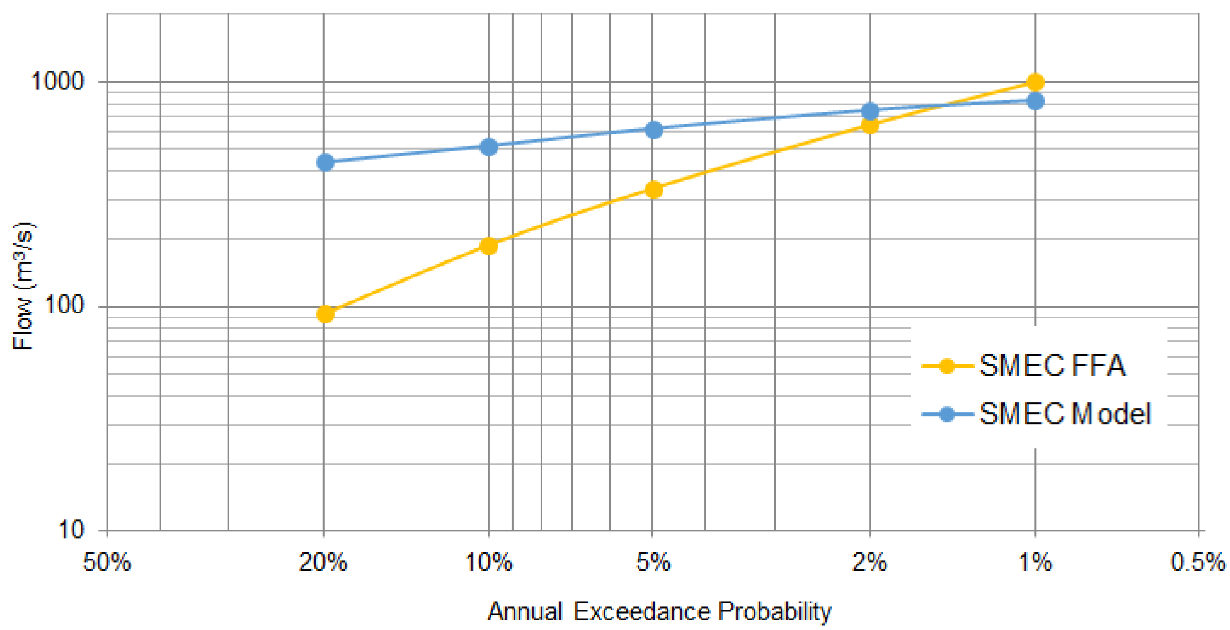


10.3. Comparison of Design Results with Previous Flood Study

Diagram 32 shows the equivalent results from the previous SMEC Flood Study (Reference 1) for comparison.

Diagram 32: Design modelling results and FFA from SMEC Flood Study

Bong Bong Weir:



Berrima Weir:

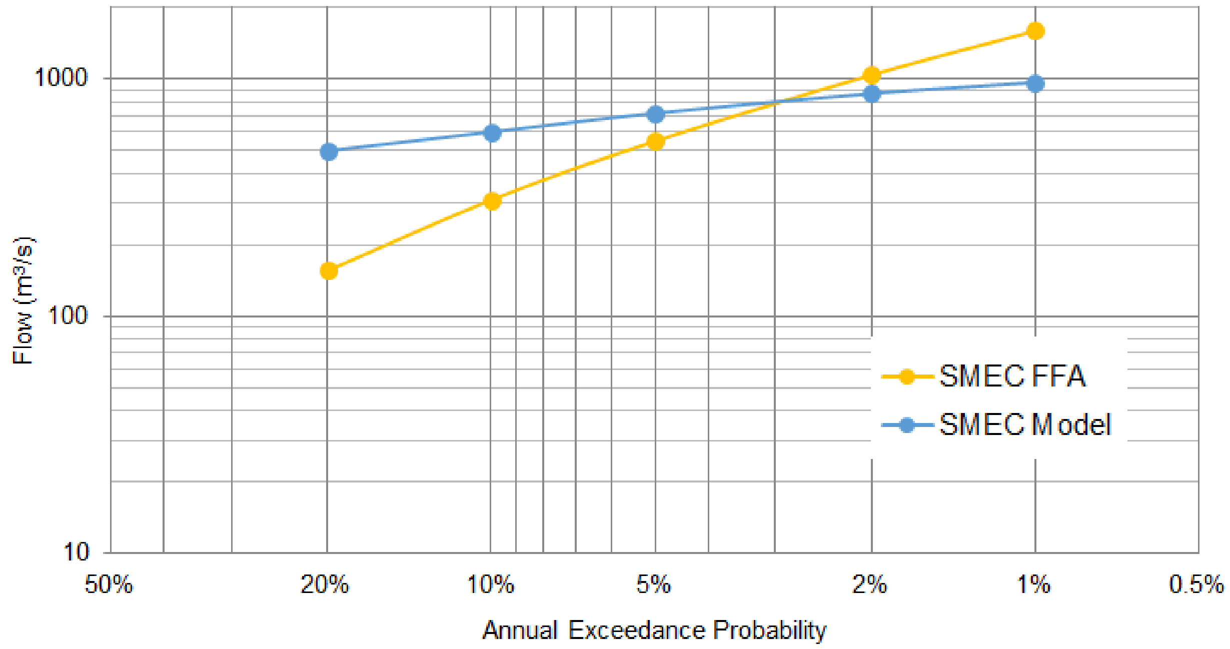


Table 32 provides the peak flows at the weirs as presented on the charts above, as well as the difference compared to the SMEC Flood Study estimates.

Table 32: Peak design flows at Bong Bong Weir and Berrima Weir, compared to SMEC Results

AEP (%)	Peak Flow (m^3/s) TUFLOW (WMA water)		Peak Flow (m^3/s) TUFLOW (SMEC)		Difference (%)	
	Bong Bong	Berrima	Bong Bong	Berrima	Bong Bong	Berrima
50	106	140	-	-	-	-
20	210	265	440	500	-52%	-47%
10	271	337	520	600	-48%	-44%
5	365	422	620	720	-41%	-41%
2	479	547	750	870	-36%	-37%
1	556	625	830	970	-33%	-36%
0.5	597	666	920	1080	-35%	-38%
0.2	689	750				
PMF	2886	2180	4050	5120	-29%	-57%

There is a significant change in the peak flow estimates between the previous SMEC study and the new study. These differences can be partially explained by the shift in methodology from ARR87 to ARR19, and partially by differences in the model schematisation and design modelling approach. The SMEC report did not clearly explain several aspects of the adopted methodology, most notably the assumptions about outflows from Wingecarribee Reservoir. The present study contains significantly more detail in the modelling (both for mainstream and overland flow areas) than the SMEC study. There was a relatively poor match between the FFA and design flow estimates from the SMEC study, compared to a good match obtained in this study. The results from this study appear to be more accurate and robust than the SMEC study based on these considerations.

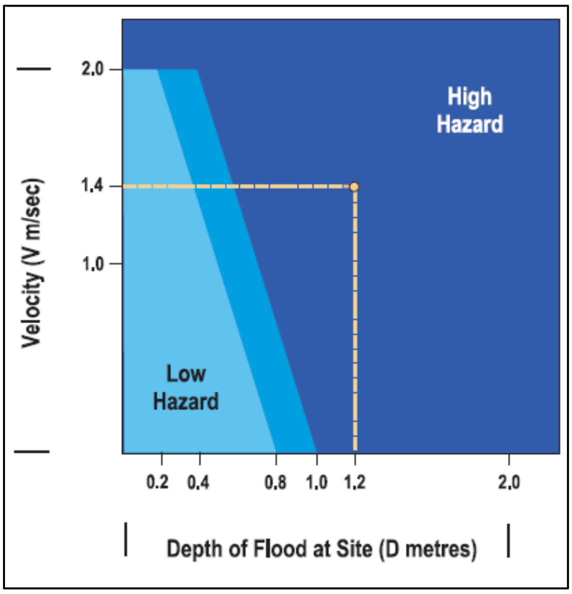
10.4. Hydraulic Hazard Categorisation

Hydraulic hazard is a measure of potential risk to life and property damage from flood. 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 were determined for the Lochinvar Creek catchment by two methods – one in accordance with the NSW Floodplain Development Manual (Reference 4), and the other in accordance with the Australian Disaster Resilience Handbook Collection (Reference 21). Each is discussed below.

10.4.1. Floodplain Development Manual Categorisation

Diagram 33: Provisional “L2” Hydraulic Hazard Categories (Source: Reference 4)



Appendix L of the NSW Floodplain Development Manual (FDM, Reference 4) gives one method for hydraulic hazard, which is shown in Diagram 33. In this study, the transition zone was considered to be high hazard.

The hydraulic hazard utilising the FDM categorisation is mapped on Figure F19 to Figure F21 for the 10% AEP, 1% AEP and PMF events. The FDM hazard categorisation has been included for applicability to existing council policy documents that may refer to this hazard classification.

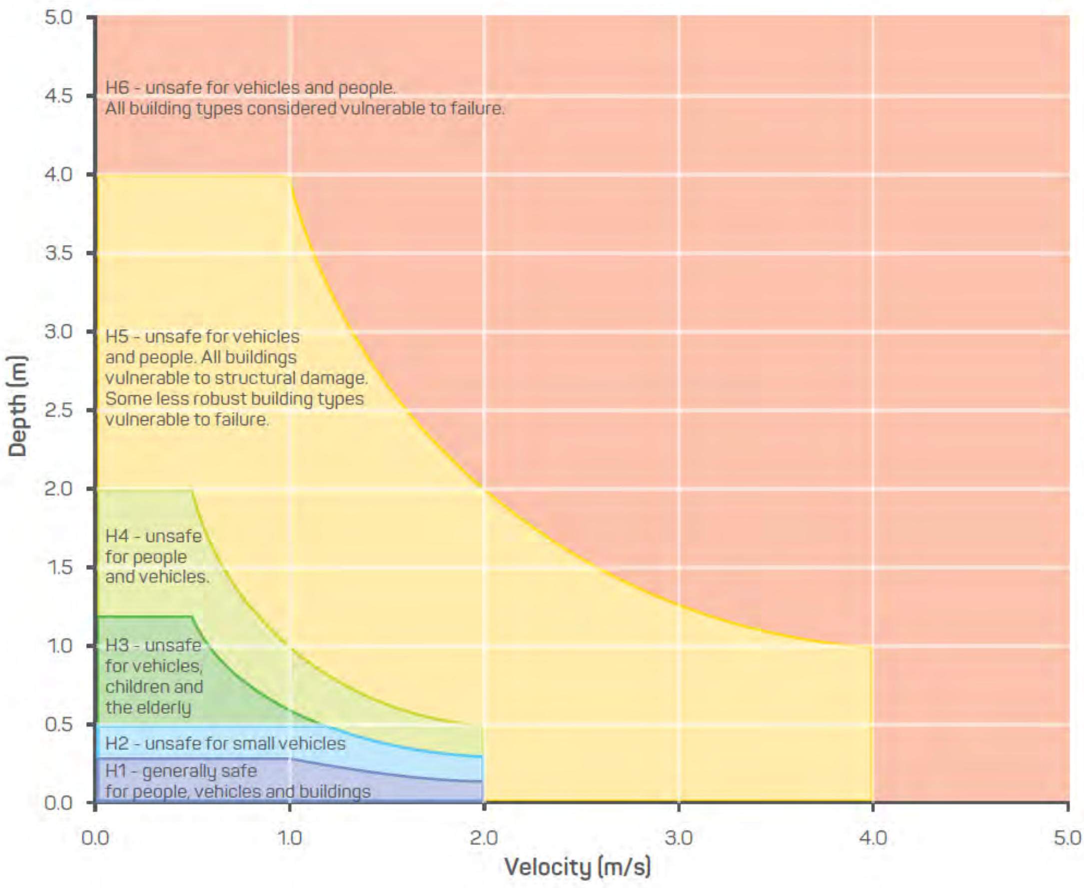
10.4.2. Australian Disaster Resilience Categorisation

The Australian Disaster Resilience (ADR) Handbook Collection deals with floods in Handbook 7 (Managing the Floodplain: A Guide to Best Practice in Flood Risk Management in Australia). The supporting guideline 7-3 (Reference 21) contains information relating to the categorisation of flood hazard. A summary of this categorisation is provided in Diagram 34.

This classification provides a more detailed distinction and practical application of hazard categories than the FDM method, identifying the following 6 classes of hazard:

- H1 – No constraints, generally safe for vehicles, people and buildings;
- H2 – Unsafe for small vehicles;
- H3 – Unsafe for all vehicles, children and the elderly;
- H4 – Unsafe for all people and all vehicles;
- H5 – Unsafe for all people and all vehicles. All building types vulnerable to structural damage. Some less robust building types vulnerable to failure. Buildings require special engineering design and construction; and
- H6 – Unsafe for all people and all vehicles. All building types considered vulnerable to failure.

Diagram 34: General flood hazard vulnerability curves (Source: Reference 21)



The hazard categories using the ADR classification are mapped on Figure F22 to Figure F24 for the 10% AEP, 1% AEP and PMF events.

10.5. Hydraulic Categorisation (Flood Function)

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 NSW Governments Floodplain Development Manual (Reference 4) 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 areas of the floodplain where a significant discharge of water occurs during flood events and by definition, if blocked would have a significant effect on flood levels and/or distribution of flood flow. Flood storages are important areas for the temporary storage of floodwaters and if filled would result in an increase in nearby flood levels and the peak discharge downstream may increase due to the loss of flood attenuation. The remainder of the floodplain is defined as flood fringe.

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* (Reference 22), rely on combinations of velocity and depth criteria to define the floodway.

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

- Floodway is defined as areas where:
    - o the peak value of velocity multiplied by depth (V x D) > 0.2 m^2/s, **AND** peak velocity > 0.2 m/s, **OR**
    - o peak velocity > 0.4 m/s **AND** peak depth > 0.1 m, **OR**
    - o defined waterway channel areas as per NSW Government SIX Maps[2]

  The remainder of the floodplain is either Flood Storage or Flood Fringe;
- Flood Storage comprises areas outside the floodway where peak depth > 0.3 m; and
- Flood Fringe comprises areas outside the Floodway where peak depth < 0.3 m.

The provisional hydraulic categories have been mapped on Figure F25 to Figure F27 for the 10% AEP, 5% AEP and 1% AEP events.

2 https://six.nsw.gov.au/

10.6. Flood Emergency Response Planning

10.6.1. Road Inundation

Table 33 and summarises the overtopping depths for key access roads in the study area. The locations of these results are indicated on Figure 15.

Table 33: Overtopping depths at road crossings

ID (Figure 15)	Road	Design AEP								
		50%	20%	10%	5%	2%	1%	0.5%	0.2%	PMP
1	Sheepwash Road, Glenquarry	NF	NF	NF	NF	NF	NF	NF	NF	0.8
2	Sproules Lane, Glenquarry	NF	NF	NF	0.3	0.39	0.44	0.46	0.52	1.18
4	Kangaloon Road, Glenquarry	NF	NF	0.1	0.45	0.6	0.66	0.69	0.73	1.55
5	Kangaloon Road, Bowral	NF	NF	NF	NF	0.15	0.19	0.21	0.24	1.02
6	Illawarra Highway	NF	NF	NF	NF	NF	NF	NF	NF	0.67
7	Illawarra Highway	NF	NF	NF	NF	NF	NF	NF	NF	0.71
8	Illawarra Highway	NF	NF	NF	NF	NF	NF	NF	NF	0.58
9	Illawarra Highway	NF	NF	NF	NF	NF	NF	NF	NF	0.07
10	Illawarra Highway	NF	NF	NF	NF	NF	NF	NF	NF	0.18
11	Illawarra Highway	NF	NF	NF	NF	NF	NF	NF	NF	0.47
12	Illawarra Highway	NF	0.14	0.19	0.21	0.24	0.25	0.26	0.27	0.53
13	Illawarra Highway	NF	NF	NF	NF	NF	NF	NF	NF	1.11
14	Illawarra Highway	NF	NF	0.15	0.18	0.22	0.24	0.24	0.25	0.57
15	Headlam Road	0.62	0.68	0.71	0.75	1.07	1.28	1.41	1.7	5.37
17	Argyle Street, Moss Vale	NF	NF	NF	NF	NF	NF	0.05	0.35	4.07
18	Moss Vale Road, Burradoo	NF	NF	NF	NF	NF	NF	NF	0.07	1.05
19	Railway Road, Burradoo	1.03	1.6	1.98	2.48	3.24	3.7	3.94	4.41	9.5
20	Berrima Road, New Berrima	NF	NF	NF	NF	NF	NF	NF	NF	0.75
22	Old Hume Highway Bridge, Berrima	NF	NF	NF	NF	NF	NF	NF	NF	1.9
23	Old Hume Highway, Berrima	NF	NF	NF	NF	NF	NF	NF	NF	1.12
24	Hume Motorway	NF	NF	NF	NF	NF	NF	NF	NF	NF

NF = Not Flooded

Table 34 indicates the AEP at which shallow overtopping first occurs, the AEP when the overtopping depth reaches hazardous levels of 0.3 m or greater (i.e. H2 hazard or greater) when the road can be considered completely cut to emergency vehicles, as well as relating the AEP when the road is cut to the corresponding gauge level at Bong Bong and Berrima weirs. These gauge levels are available in real time from the Bureau of Meteorology and WaterNSW websites, although as far as WMAwater is aware, the Bureau does not issue quantitative flood warnings with predicted gauge heights for the Bong Bong or Berrima weirs during flood events. Table 35 indicates the modelled peak gauge heights for the full range of design events considered in this study.

Table 34: Summary of AEP and gauge levels when access roads are cut

ID (Figure 15)	Road	Road Flood immunity		Indicative gauge levels when cut > 0.3 m	
		AEP First Overtopped	AEP Depth Exceeds 0.3 m	Bong Bong gauge height (m)	Berrima gauge height (m)
1	Sheepwash Road, Glenquarry	PMF	PMF	5.9	10.2
2	Sproules Lane, Glenquarry	5% AEP	2% AEP	1.8	4.1
4	Kangaloon Road, Glenquarry	10% AEP	5% AEP	1.5	3.3
5	Kangaloon Road, Bowral	2% AEP	PMF	5.9	10.2
6	Illawarra Highway	PMF	PMF	5.9	10.2
7	Illawarra Highway	PMF	PMF	5.9	10.2
8	Illawarra Highway	PMF	PMF	5.9	10.2
9	Illawarra Highway	PMF	> PMF	-	-
10	Illawarra Highway	PMF	> PMF	-	-
11	Illawarra Highway	PMF	PMF	5.9	10.2
12	Illawarra Highway	20% AEP	PMF	5.9	10.2
13	Illawarra Highway	PMF	PMF	5.9	10.2
14	Illawarra Highway	10% AEP	PMF	5.9	10.2
15	Headlam Road	50% AEP	50% AEP	0.8	2.0
17	Argyle Street, Moss Vale	0.2% AEP	0.2% AEP	2.4	5.2
18	Moss Vale Road, Burradoo	0.2% AEP	PMF	5.9	10.2
19	Railway Road, Burradoo	50% AEP	50% AEP	0.8	2.0
20	Berrima Road, New Berrima	PMF	PMF	5.9	10.2
22	Old Hume Highway Bridge, Berrima	PMF	PMF	5.9	10.2
23	Old Hume Highway, Berrima	PMF	PMF	5.9	10.2
24	Hume Motorway	> PMF	> PMF	-	-

> PMF indicates the road is not overtopped even in a PMF event

Table 35: Bong Bong and Berrima gauge levels for design events

Design AEP	Bong Bong Gauge Height (m)	Berrima Gauge Height (m)
50%	0.8	2.0
20%	1.1	2.6
10%	1.3	2.9
5%	1.5	3.3
2%	1.8	4.1
1%	2.0	4.5
0.5%	2.2	4.7
0.2%	2.4	5.2
PMF	5.9	10.2

10.6.2. Classification of Communities

To assist in the planning and implementation of response strategies, the NSW State Emergency Service (SES) in conjunction with the NSW Office of Environment and Heritage (OEH) has developed guidelines to classify communities according to the impact that flooding has upon them. These Emergency Response Planning (ERP) classifications (based on guidance in Reference 23 and Reference 24) consider flood affected communities as those in which the normal functioning of services is altered, either directly or indirectly, because a flood 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. Reference 24 recommends classification according to the criteria in Table 36.

Table 36: Emergency Response Planning Classification of Communities

Primary classification	Description	Secondary classification	Description	Tertiary classification	Description	Example figures
Flooded (F)	The area is flooded in the PMF	Isolated (I)	Areas that are isolated from community evacuation facilities (located on flood-free land) by floodwater and/or impassable terrain as waters rise during a flood event up to and including the PMF. These areas are likely to lose electricity, gas, water, sewerage and telecommunications during a flood.	Submerged (FIS)	Where all the land in the isolated area will be fully submerged in a PMF after becoming isolated.	Figure 1 Figure 7 with ring levee Figure 8 with impassable terrain
				Elevated (FIE)	Where there is a substantial amount of land in isolated areas elevated above the PMF.	Figure 2
		Exit Route (E)	Areas that are not isolated in the PMF and have an exit route to community evacuation facilities (located on flood-free land).	Overland Escape (FEO)	Evacuation from the area relies upon overland escape routes that rise out of the floodplain.	Figure 3
				Rising Road (FER)	Evacuation routes from the area follow roads that rise out of the floodplain.	Figure 4, Figure 6 with levee
Not Flooded (N)	The area is not flooded in the PMF			Indirect Consequence (NIC)	Areas that are not flooded but may lose electricity, gas, water, sewerage, telecommunications and transport links due to flooding.	Figure 5
				Flood Free	Areas that are not flood affected and are not affected by indirect consequences of flooding.	

Notes:

1. Classifications are based upon the probable maximum flood (PMF) or a similar extreme flood, if the PMF is not available. Where classifications are being retrofitted to areas covered by existing studies and the PMF or a similar extreme flood is not available, and a decision is made to not estimate or approximate an extreme event, classifications should be clearly indicated as 'Preliminary based upon the largest flood available'.
2. Isolated areas may also be known as:
   - flood islands, where areas are isolated solely by flood waters. Where flood islands are completely submerged in the PMF, these may be called low-flood islands. Where flood islands have elevated areas above the PMF, they may be called high-flood islands.
   - trapped perimeter areas, where areas are isolated by a combination of floodwaters and impassable terrain. Where trapped perimeter areas are completely submerged in the PMF, these may be called low-trapped perimeter areas. Where trapped perimeter areas have elevated areas above the PMF, they may be called high-trapped perimeter areas.

Key considerations for flood emergency response planning include:

- Cutting of external access isolating an area;
- Key internal roads being cut;
- Transport infrastructure being shut down or unable to operate at maximum efficiency;
- Flooding of any key response infrastructure such as hospitals, evacuation centres, emergency service sites;
- Risk of flooding to key public utilities such as gas, electricity and sewerage; and

- The extent of the area flooded and the duration of inundation.

Flood liable land within the study area where there are habitable areas (identified as buildings on the aerial imagery) have been classified according to the ERP classification above. When classifying communities, consideration was given to flood depths for the purpose of being able to move through floodwaters on foot or in a vehicle, drawing on hazards presented in the Australian Disaster Resilience Handbook Collection (Reference 21).

The ERP classification of communities for the study area are shown in Figure F28 to Figure F30 for the 5% AEP, 1% AEP and PMF events. These figures also show major access roads to each of the relevant areas, as well as the AEP when the road is cut by more than 0.3 m of depth.

A summary of the communities identified on the FERC mapping is as follows:

- <u>Railway Road, Burradoo</u> – there is an area between the Wingecarribee River and the Main Southern Railway Line that is primarily accessed via a causeway across the Wingecarribee River (near the railway bridge), which is frequently cut by floodwaters (50% AEP). This community is therefore frequently isolated, and while most of the buildings in this area are located above the 1% AEP level, the area would be completely inundated by high hazard floodwater in a PMF event (i.e. “low flood island”). This is the most notable area of the floodplain where people could become trapped during an extreme event.
- <u>Mittagong Creek, Burradoo</u> – there is a small community on the western side of the railway line that becomes fully inundated in a PMF event, but there is a level crossing over the railway line that provides rising egress from the area, and there is a far lower risk of people becoming trapped in properties at this location.
- <u>Headlam Road, Moss Vale</u> – A large number of rural properties east of Moss Vale are accessed via Headlam Road, which is cut relatively frequently (50% AEP event) and isolates this community. However, most of the land and buildings accessed by this area is above the PMF event (“high flood island”), and the duration of inundation is unlikely to be sufficient to require resupply/evacuation except in the case of individual health emergencies.
- <u>Sproules Lane, Glenquarry</u> – A large number of rural properties in Glenquarry are accessed via Sproules Lane, which has a reasonable flood standard (cut in a 5% to 2% AEP event). This community can therefore be isolated by floodwaters (although reasonably infrequently), however most of the land and buildings in this area is above the PMF event (“high flood island”), and the duration of inundation is unlikely to be sufficient to require resupply/evacuation except in the case of individual health emergencies.
- <u>Iona Park Road</u> – Several rural properties between Glenquarry and Moss Vale have their main access via Iona Park Road from the Illawarra Highway. This road provides rising egress, and the Illawarra Highway itself has flood immunity exceeding the 1% AEP standard, providing rising access from this area to either Moss Vale or Robertson.
- <u>Moss Vale Enterprise Corridor and Beaconsfield Road</u> – Some residential and rural properties around Beaconsfield Road, Lackey Road and the Moss Vale Enterprise Corridor can become isolated due to local road access being cut, although this is only

likely in very extreme events (i.e. much larger than 1% AEP), and the duration of isolation would be short (a few hours maximum). Therefore, while this area is technically classified as "FIE" (Flooded/Isolated/Elevated), this situation only arises in the most extreme flood events, and even then flood risks remain relatively low. This area is therefore unlikely to require significant resources for evacuation/resupply/during responses during or after flood events in the area.

- Eridge Park Road Burradoo – There is a small group of properties on the eastern side of Eridge Park Road which back onto the floodplain, which have been classified as FIS (Flooded/Isolated/Submerged). The buildings and access driveways on these properties are well above the 1% AEP level. However, in a PMF event, it is possible that the access driveways could be cut, isolating people in the dwellings, before the dwellings themselves are submerged.

10.7. Preliminary Flood Planning Area

10.7.1. Background

A key outcome of this study is the identification of land subject to flood-related development controls. The *Wingecarribee Local Environment Plan 2010* (the LEP, Reference 25) is applicable under clause 7.9(2) to "land that is shown as "Flood Planning Area" on the Flood Planning Map, and other land at or below the Flood Planning Level [defined as the 1% AEP level plus 0.5m freeboard]. Land subject to this clause must usually be identified as such on Section 10.7 planning certificates.

The Flood Planning Area (FPA) is relatively straightforward to define for mainstream flooding in ponded areas or along large river channels. It is the extent formed by using the 1% AEP flood level plus 0.5 m freeboard, stretched outwards where required at the fringe of the floodplain. In mainstream flow areas, the creek banks often rise by 0.5 m within a reasonably short distance of the 1% AEP flood extent, so the stretching process does not usually introduce major additional areas within the FPA. This method was found to be suitable for the majority of the study area floodplains along the main channels.

Where overland flow is being modelled however, the "standard" FPA definition (1% plus 0.5 m) will tend to include lots that are not in fact flooded, sometimes even in the PMF, or those subject to only nuisance inundation. This will tend to apply even if a reduced freeboard (for example 0.3 m) is used. When defining the FPA for an overland flow area, a variety of criteria for defining the FPA are best examined initially. The purpose of this work is to seek a method, based on a quantitative and repeatable criteria, that consistently produces a FPA that best reflects those properties requiring management by way of 10.7 certificates in regard to flood related development controls. This is separate to standard stormwater design considerations that will apply to all developments, and which are assumed to manage drainage at an intra-lot scale for small catchment areas.

The state government does not provide a prescriptive methodology for defining the FPA. WMAwater developed an FPA for this study using techniques specific to the catchment area, based on consideration of the flow behaviour and testing of several methods. The methodology is documented below.

10.7.2. Methodology

There are a range of alternative approaches for deriving the FPA. One approach, which aims to retain consistency with the LEP definition, is to add 0.5 m freeboard to the peak water level and attempt to "stretch" this surface across the terrain, as described above. Another technique is to identify cadastral lots affected by flooding, including consideration of the 1% AEP and possibly a larger event as a surrogate for the freeboard allowance, then identify the entire lot as within the FPA. This is often an appropriate technique for overland flow areas, but has the disadvantage that there is not a clearly defined spatial extent within the lot for inclusion on planning maps.

For this study, the "add and stretch" technique was adopted with some modifications to filter out spurious results in overland flow areas. A summary of these steps is as follows:

1. The 1% AEP flood surface was filtered to identify "mainstream" flow based on a hazard classification of H3 or higher (see Section 10.4.2). This filtering identifies the main creek and overland flow paths and reduces the issues associated with attempting to add freeboard and stretch in minor overland flow areas.
2. 0.5 m freeboard was added to the surface obtained from step 1, and the surface was extrapolated outwards, and cut off where it intersected with the terrain.
3. The result was trimmed in some locations based on judgement that it would not be appropriate to stretch the extent beyond certain hydraulic controls, particularly some road crests and the embankments of farm dams or other depressions.
4. Areas of continuous overland flow with significant depth and/or velocity (depth greater than 0.1 m, velocity greater than 1.5 m/s, or depth-velocity product greater than 0.15 m^2/s) were then added back into the FPA extent derived above as "overland flow FPA area."

10.7.3. Flood Planning Area Mapping

The Flood Planning Area result obtained using the above methodology is mapped on Figure 42 of the relevant appendix for each catchment. The areas designated as "mainstream" and incorporating the 0.5 m freeboard are identified by different shading on the maps to those areas identified as overland flow (which do not incorporate freeboard).

10.8. Advice on Land-Use Planning

It is considered good practice to only 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 shift flood risks to other areas.

10.8.1. Existing Flood Planning Controls

Wingecarribee Shire Council implements flood-related planning controls via LEP and a range of Development Control Plans (DCPs) which vary for different localities. The LEP specifies that land is subject to flood-related restrictions on development if it is

- shown as “Flood planning area” on the Flood Planning Map [in the LEP], or
- other land at or below the flood planning level [defined in the LEP to be the 1% AEP flood level plus 0.5 m freeboard].

The LEP outlines the nature of these restrictions, and more detailed requirements are specified in the DCP for different land uses. The LEP and DCP refer to mapping outputs that have been produced as part of this and other flood studies undertaken for Council. Land use planning in Wingecarribee Shire Council considers the flood hazard, flood function and evacuation potential of the land.

10.8.2. Recommended Updates

This is a typical approach for consideration of flooding in land use planning, although WMAwater recommends that Council consider the following refinements:

- The time required to modify mapping in the LEP is significant, due to the consultation and exhibition requirements, and the approval requirements from state government departments. This means that the flood maps in the LEP will usually not reflect studies that have been recently undertaken. Council should therefore consider revising the LEP so that mapping of the Flood Planning Area (FPA) is either provided in the relevant DCP, or via some other method (for example by referring to a mapped Flood Planning Area from any flood study adopted by Council). The preliminary FPA for the Wingecarribee River study area is provided in Figure F31 (see Section 10.7 above for details).
- Council’s DCPs provide differentiated prescriptive controls for overland flow which are different to those for mainstream flow. If Council does not already differentiate the nature of flood affectation on Section 10.7 certificates, it may provide more clarity to do so. The FPA extents developed from this study identify overland flow and mainstream affected areas separately.

10.8.3. Flood Risk Precincts

Wingecarribee Shire Council categories different parts of the floodplain into “Flood Risk Precincts” (FRPs) which are designed to combine various planning constraints into a single categorisation. The Flood Risk Precinct definition adopted by Council specifies four categories, which take into account likelihood of inundation, hydraulic hazard, and isolation as per Table 37.

Table 37: Wingecarribee Shire Flood Risk Precinct definitions

FRP	Definition	Explanatory notes
High	This Precinct contains that land below the 100 year flood that is either subject to a high hydraulic hazard or where there are significant evacuation difficulties.	The high flood risk precinct is where high flood damages, potential risk to life, and evacuation problems would be anticipated or development would significantly and adversely affect flood behaviour. Most development should be restricted in this precinct. In this precinct, there would be a significant risk of flood damages without compliance with flood related building and planning controls.
Medium	This Precinct contains that land below the 100 year flood that is not subject to a high hydraulic hazard and where there are no significant evacuation difficulties.	In this precinct there would still be a significant risk of flood damage, but these damages can be minimised by the application of appropriate development controls.
Low (Fringe)	This Precinct contains that land between the extents of the 100 year flood and the 100 year flood plus 0.5m freeboard).	In this precinct there would still be a significant risk of flood damage, but these damages can be minimised by the application of appropriate development controls.
Low (PMF)	This Precinct contains that land within the floodplain (i.e. within the extent of the PMF) but not identified within any of the above FRPs.	The Low Flood Risk Precinct is where risk of damages is low for most land uses and most land uses (apart from some vulnerable or critically important societal uses) would be unrestricted within this precinct.

Guideline 7-5 of the Australian Disaster Resilience Handbook Collection (Reference 24) recommends using Flood Planning Constraint Categories (FPCCs) to better inform land use planning activities. These categories condense the abundant 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 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 use of four constraint categories is recommended. It is recommended that isolation potential also be considered for the high constraint category. This could include areas classified as 'low flood island', 'low trapped perimeter', 'high flood island' and 'high trapped perimeter' (see Section 10.6.2 for details).

The FRPs definitions adopted by Wingecarribee Council are essentially consistent with the intent and recommendations contained within Reference 24. Mapping of the FRPs using the above definitions is provided on Figure F32.

There are widespread areas in the study area affected by potential isolation from flooding (refer to Section 10.6.2 and Figure F28 to Figure F30). However, the majority of isolated areas are not inundated in the PMF, with buildings located on high ground, and the duration of isolation will not usually be significant enough to create substantially elevated risk to life. There are some localised areas, particularly along the railway corridor, that can become isolated and then completely inundated in a PMF. These areas are identified on Figure F30 and highlighted on the FRP map (Figure F32). Wingecarribee Shire Council should consider what Flood Risk Precinct classification in these areas. WMAwater recommends that these areas be classified as at least Medium FRP. This would avoid development being completely prohibited in these areas, while ensure that prescriptive controls relating to evacuation are considered as part of any proposed development.

Areas of minor overland flow were filtered from the results for the purposes of defining the Flood Planning Area and Flood Risk Precincts (this only affects the two Low Flood Risk Precinct extents. The filtering was consistent with that applied to the overland flood FPA, removing areas where all the following are true:

- depth less than 0.1 m,
- velocity less than 1.5 m/s,
- discontinuous areas less than 200 m^2, and
- depth-velocity product less than 0.15 m^2/s).

11. CLIMATE CHANGE AND DESIGN FLOOD SENSITIVITY ANALYSIS

11.1. Climate Change

The sensitivity of the simulated 1% AEP peak flood levels and flows to potential rainfall changes from climate change was investigated. Climate change is expected to increase sea levels (not relevant for this catchment), and also short duration extreme rainfall intensities (including the durations relevant for this catchment).

Sensitivity analysis of an increase in rainfall intensity was undertaken by comparing the 0.5% and 0.2% AEP events with the 1% AEP event. These events are commonly used as proxies to assess an increase in rainfall intensity. Within the Wingecarribee River catchment, these events correspond to an increase in 24-hour burst rainfall intensity of approximately 6% for the 0.5% AEP event and 16% for the 0.2% AEP event.

Reference 3 indicates that rainfall intensity increases may scale with mean surface level temperature increases at a rate of about 5% per degree Celsius of warming. Therefore the two scenario considered here provide an approximate indication of the change in 1% AEP flood behaviour that may occur under warming scenarios of 1 degree and 3 degrees Celsius respectively.

The peak flood depth and level results of the 1%, 0.5% and 0.2% AEP events are shown in Figure F6, Figure F7 and Figure F8, respectively. A comparison of flood levels is provided in Figure H1 and Figure H2, with a comparison of peak flows at key locations in Table 38 (see Figure 15 for locations).

Table 38: Design sensitivity analysis – change in 1% AEP flow for rainfall increases

ID	Location	1% AEP Design Peak Flow (m^3/s)	Sensitivity Scenario Change in Peak Flow (%)	
			0.5% AEP Rainfall	0.2% AEP Rainfall
R01	Sheepwash Road, Glenquarry	121.2	10%	43%
R02	Sproules Lane, Glenquarry	210.3	9%	34%
R03	Wingecarribee River at Boardman Rd South	271.3	9%	31%
R16	Bong Bong Weir	555.9	7%	24%
R17	Argyle Street, Moss Vale	578.5	7%	24%
R19	Railway, Burradoo	524.6	6%	18%
R21	Berrima Weir	625.1	7%	20%
R22	Old Hume Highway, Berrima	625.9	7%	20%
R24	Hume Motorway Bridge, Berrima	631.2	7%	20%

The 0.5% AEP event flood level is less than 0.1 m higher than the 1% AEP level for most of the catchment upstream of Bong Bong, and the tributary flowpaths. Downstream of Burradoo and through Berrima, increases are in the order of 0.2 m to 0.3 m.

The 0.2% AEP event flood level is typically 0.1 m to 0.3 m higher than the 1% AEP level for the Wingecarribee River upstream of Bong Bong, 0.3 m to 0.5 m near Burradoo and Moss Vale, and more than 0.5 m higher downstream of Burradoo. The increase in flood level on the tributary flow paths is typically less than 0.1 m.

11.2. Hydraulic Model Parameters

11.2.1. Manning's 'n'

The Manning's 'n' parameter in the TUFLOW model represents the surface roughness, and the adopted design values are outlined in Section 7.4. A sensitivity analysis was conducted with an increase and decrease in these values by 30%. The change in 1% AEP peak flood level is illustrated on Figure H3 and Figure H4 respectively.

There is an increase in peak flood levels with an increase in the Manning's 'n' values. The 1% AEP flood levels increase by approximately 0.1 to 0.2 m for the Wingecarribee River in the upper catchment, and by 0.3 m to 0.5 m in the lower catchment downstream of Burradoo. The increase in flood level on the tributary flow paths is typically less than 0.1 m.

With a decrease in Manning's 'n', there is a more muted effect on flood levels, with no significant change in the upstream catchment or tributary flow paths, and a reduction in the order of 0.1 m to 0.2 m in the lower catchment downstream of Burradoo.

The effect on flows is relatively minor. Table 39 indicates that the most significant effect on flow from changes to Mannings n is slightly increased floodplain attenuation between Burradoo and Berrima, resulting in an 8% reduction in peak flows through this area.

Table 39: Design sensitivity analysis – change in 1% AEP flow for Mannings n roughess

ID	**Location**	**1% AEP Design Peak Flow (m^3/s)**	**Sensitivity Scenario Change in Peak Flow (%)**	
			Higher Mannings n	Lower Mannings n
R01	Sheepwash Road, Glenquarry	121.2	0%	0%
R02	Sproules Lane, Glenquarry	210.3	-1%	0%
R03	Wingecarribee River at Boardman Rd South	271.3	-1%	0%
R16	Bong Bong Weir	555.9	-3%	1%
R17	Argyle Street, Moss Vale	578.5	-3%	1%
R19	Railway, Burradoo	524.6	-8%	2%
R21	Berrima Weir	625.1	-8%	3%
R22	Old Hume Highway, Berrima	625.9	-8%	3%
R24	Hume Motorway Bridge, Berrima	631.2	-8%	2%

11.2.2. Hydraulic Structure Blockage and Energy Loss

The design blockage and energy loss assumptions are documented in Section 7.8 and 9.7 respectively. There is typically insufficient historical flood information at these structures to undertake detailed calibration of the parameters. However these parameters typically only result in localised changes to flood behaviour in the immediate surrounds of the structure.

Changes to these assumptions were investigated as per the following scenarios:

- A “low” blockage/loss scenario, with no debris blockage and energy loss parameters 50% lower than the adopted design parameters;
- A “high” blockage/loss scenario, with double the assumed amount of debris blockage, and energy loss parameters increased by 50%.

The change in 1% AEP peak flood level is illustrated on Figure H5 and Figure H6 for the high/low blockage and loss scenarios respectively. The effect on peak 1% AEP flow is summarised in Table 40.

Table 40: Design sensitivity analysis – change in 1% AEP flow for blockage and energy loss

ID	Location	1% AEP Design Peak Flow (m^3/s)	Sensitivity Scenario Change in Peak Flow (%)	
			Higher Blockage / Loss	Lower Blockage / Loss
R01	Sheepwash Road, Glenquarry	121.2	0%	0%
R02	Sproules Lane, Glenquarry	210.3	0%	0%
R03	Wingecarribee River at Boardman Rd South	271.3	0%	0%
R16	Bong Bong Weir	555.9	1%	-2%
R17	Argyle Street, Moss Vale	578.5	1%	-2%
R19	Railway, Burradoo	524.6	1%	-1%
R21	Berrima Weir	625.1	0%	-1%
R22	Old Hume Highway, Berrima	625.9	0%	-1%
R24	Hume Motorway Bridge, Berrima	631.2	0%	-1%

These parameters have no significant influence on the flow attenuation through the catchment. There are localised significant changes to the afflux upstream of the structures as indicated on Figure H5 and Figure H6.

11.2.3. Downstream Boundary

The downstream boundary of the model is located in the steep gorge at Wallaby Rocks, Medway. The model boundary is located well downstream of the area of interest, and flow in this area is upstream controlled due to the steep hydraulic gradient of the gorge. The downstream boundary therefore has no influence on the results and sensitivity analysis was not required.

11.3. Hydrologic Model Parameters

11.3.1. Rainfall Losses and Catchment Lag / Routing

The adopted rainfall losses derived from the model calibration process closely matched those from ARR19 data hub. However as identified in Section 8.7, losses were identified during the calibration as a relatively influential parameter, and it is appropriate to quantify the effects of uncertainty associated with the parameter on the design modelling results. As a sensitivity test, the continuing loss was reduced by 0.5 mm/hr (a change of approximately 27% compared to the adopted value).

The catchment lag factor (termed ‘C’ in the WBNM model) can be used to accelerate or delay the runoff response to rainfall. As identified in Section 8.7, catchment lag and routing parameters were identified during the calibration as relatively influential parameters, and it is appropriate to quantify the effects of uncertainty associated with the parameter on the design modelling results. As a sensitivity test, the catchment lag was reduced to 1.6 (a 24% reduction compared to the adopted design value of 2.1), and the routing parameter was reduced to 1.0 (a 33% reduction compared to the adopted design value of 1.5).

Table 41: Design sensitivity analysis – change in 1% AEP flow for hydrologic parameters

ID	Location	1% AEP Design Peak Flow (m^3/s)	Sensitivity Scenario Change in Peak Flow (%)	
			Lower Continuing Loss	Lower Catchment Lag / Routing
R01	Sheepwash Road, Glenquarry	121.2	4%	10%
R02	Sproules Lane, Glenquarry	210.3	3%	7%
R03	Wingecarribee River at Boardman Rd South	271.3	3%	7%
R16	Bong Bong Weir	555.9	3%	5%
R17	Argyle Street, Moss Vale	578.5	3%	5%
R19	Railway, Burradoo	524.6	2%	4%
R21	Berrima Weir	625.1	3%	5%
R22	Old Hume Highway, Berrima	625.9	3%	5%
R24	Hume Motorway Bridge, Berrima	631.2	3%	4%

A reduction in losses, catchment lag and routing parameters results in an increase in peak flows and levels. A map of the effect on peak flood levels is provided in Figure H7 and Figure H8.

These parameters have a relatively muted effect on peak flows, flow attenuation/routing and peak flood levels relative to other design model assumptions, such as rainfall intensity. As indicated in Table 41, the effect on flow is typically within 5%, which is less than the change that would be caused by a 6% increase in rainfall intensity (0.5% AEP vs 1% AEP). Peak flood levels are reasonably insensitive, with a variation of between 0.1 m and 0.2 m for the Wingecarribee River downstream of Burradoo, and no significant change elsewhere in the study area.

12. REFERENCES

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FIGURES

Figures

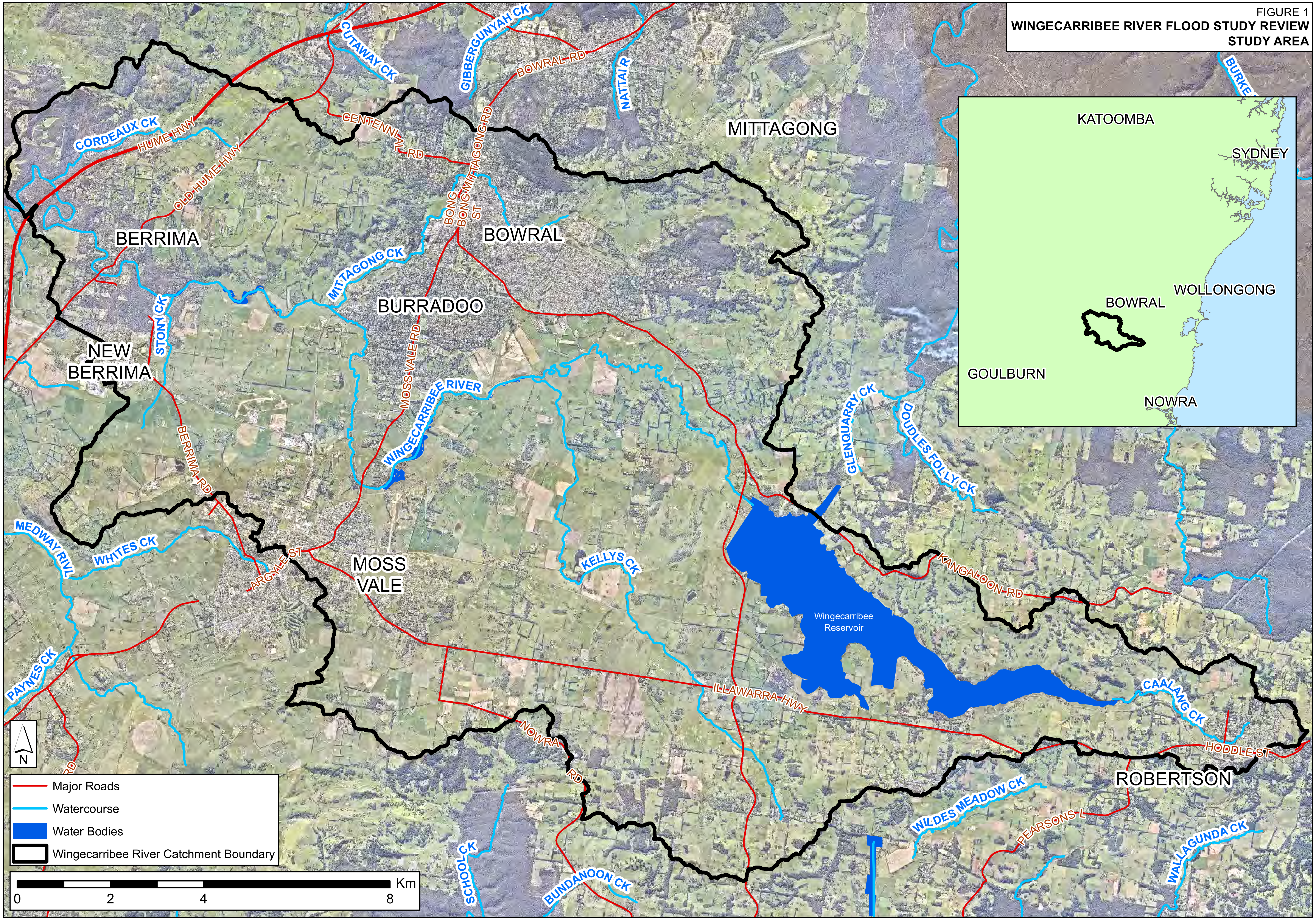


FIGURE 1
WINGECARRIBEE RIVER FLOOD STUDY REVIEW
STUDY AREA
MITTAGONG
BOWRAL
BERRIMA
BURRADOO
NEW BERRIMA
MOSS VALE
ROBERTSON
Wingecarribee Reservoir
CORDEAUX CK
HUME HWY
OLD HUME HWY
CENTENNIAL RD
CUTAWAY CK
GIBBERGUNYAH CK
BOWRAL RD
NATTAI R
BONG BONG ST
MITTAGONG RD
MITTAGONG CK
STONY CK
MOSS VALE RD
WINGECARRIBEE RIVER
BERRIMA RD
ARGYLE ST
MEDWAY RIVL
WHITES CK
PAYNES CK
KELLYS CK
GLENQUARRY CK
DOUDLES FOLLY CK
KANGALOON RD
ILLAWARRA HWY
NOWRA RD
CAALANG CK
HODDLE ST
WILDES MEADOW CK
PEARSONS L
WALLAGUNDA CK
SCHOOL CK
BUNDANOON CK
BURKE
KATOOMBA
SYDNEY
WOLLONGONG
GOULBURN
NOWRA
N
Major Roads
Watercourse
Water Bodies
Wingecarribee River Catchment Boundary
0
2
4
8
Km

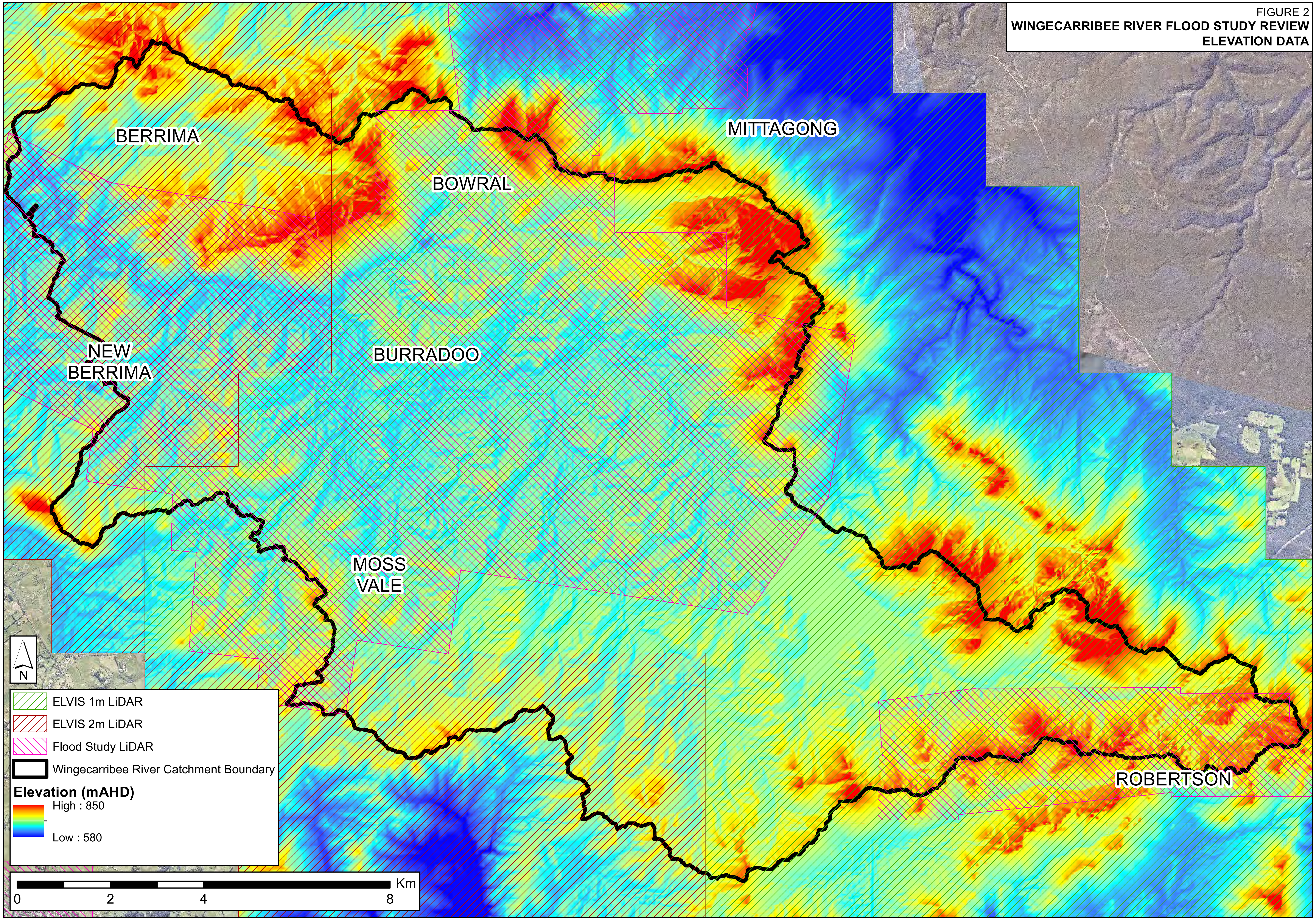


FIGURE 2
WINGECARRIBEE RIVER FLOOD STUDY REVIEW
ELEVATION DATA

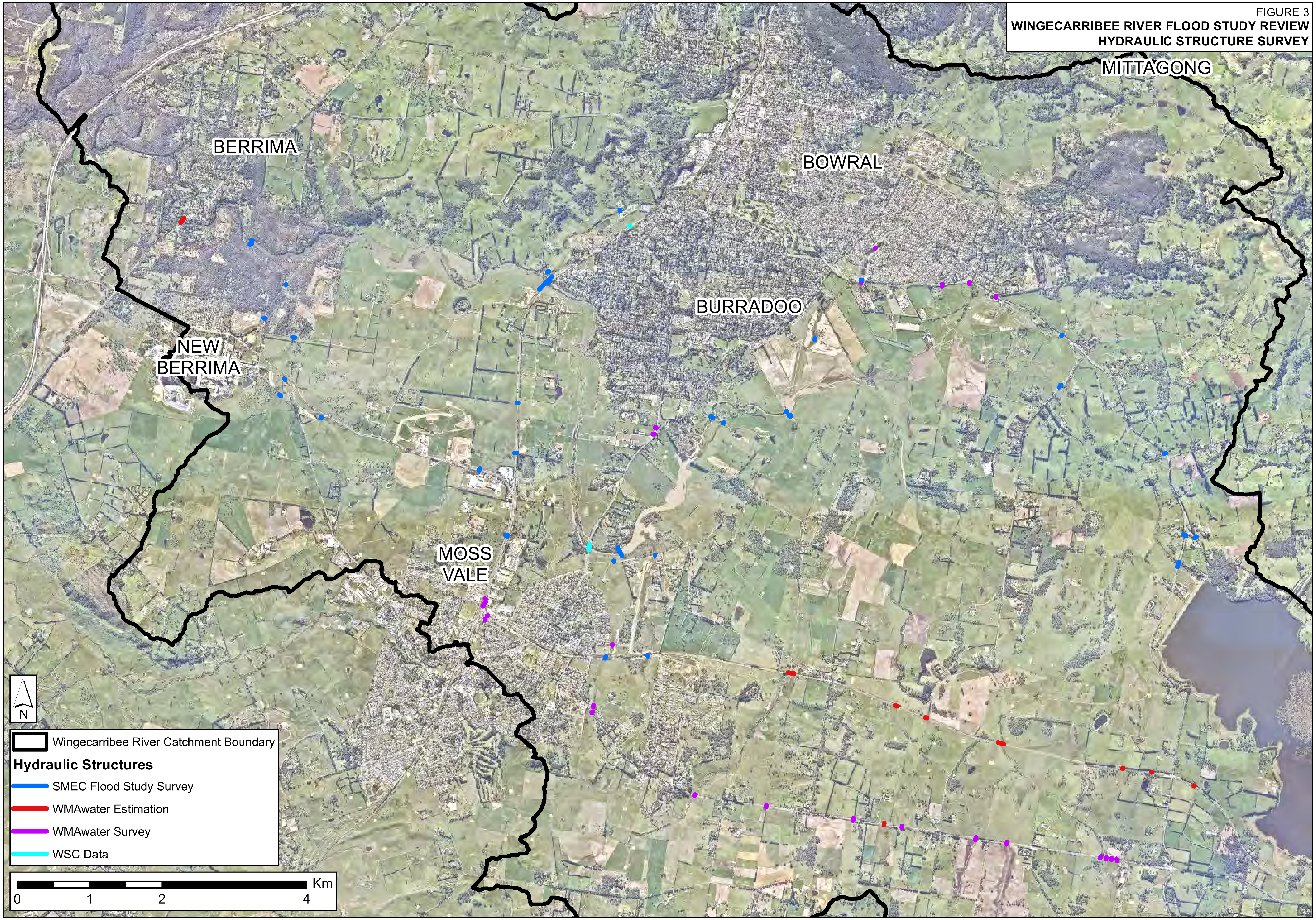


FIGURE 3
WINGECARRIBEE RIVER FLOOD STUDY REVIEW
HYDRAULIC STRUCTURE SURVEY

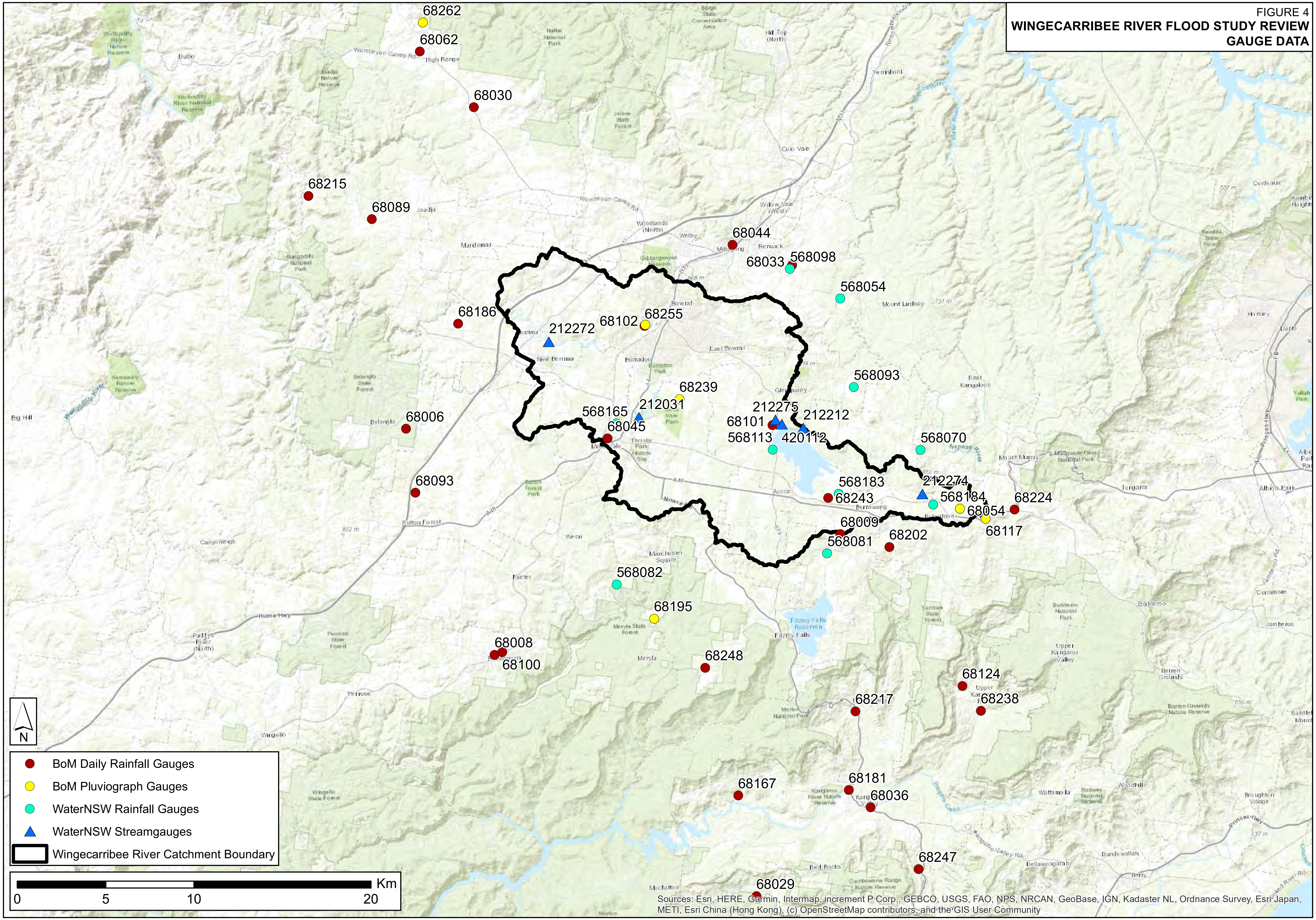
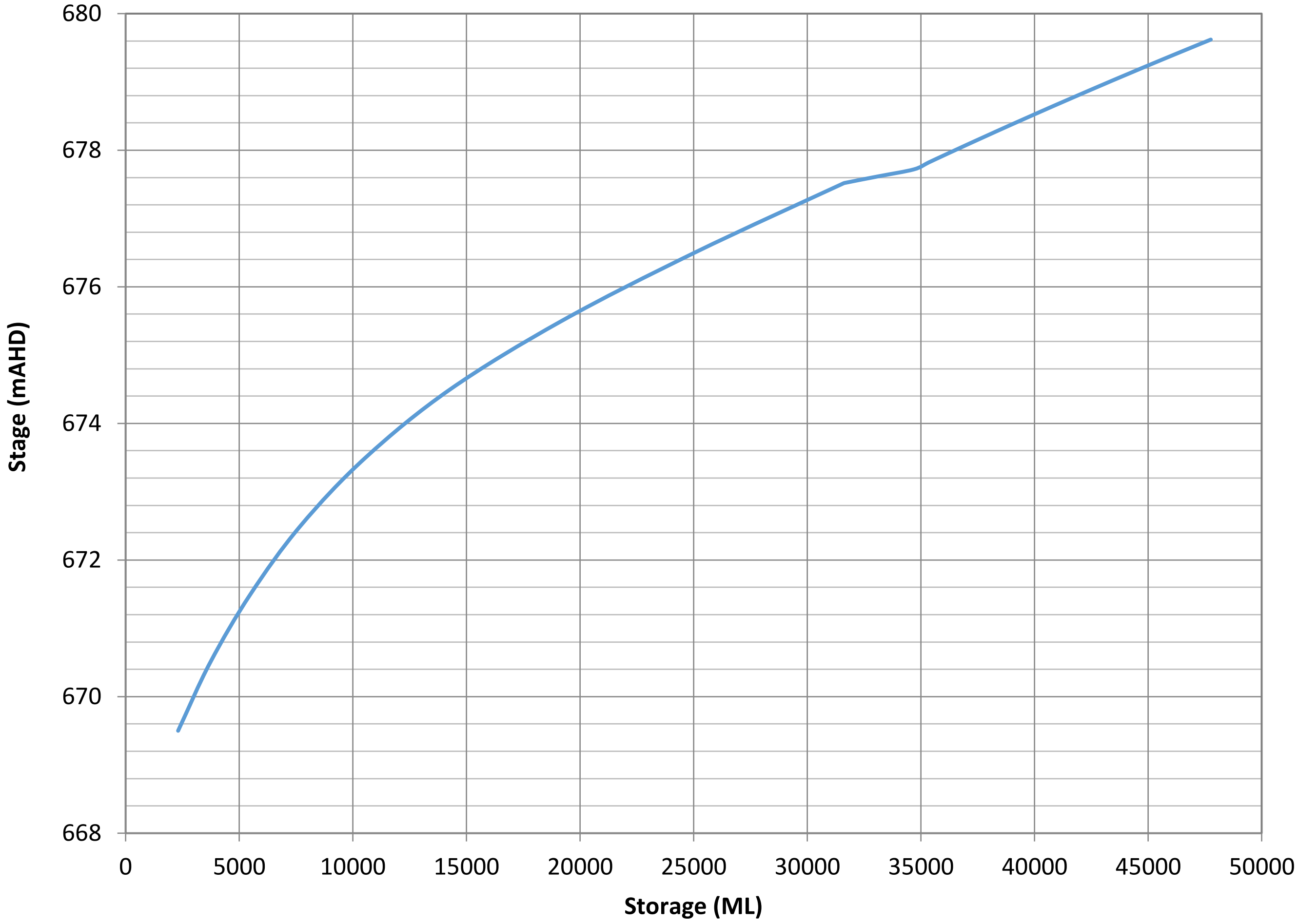
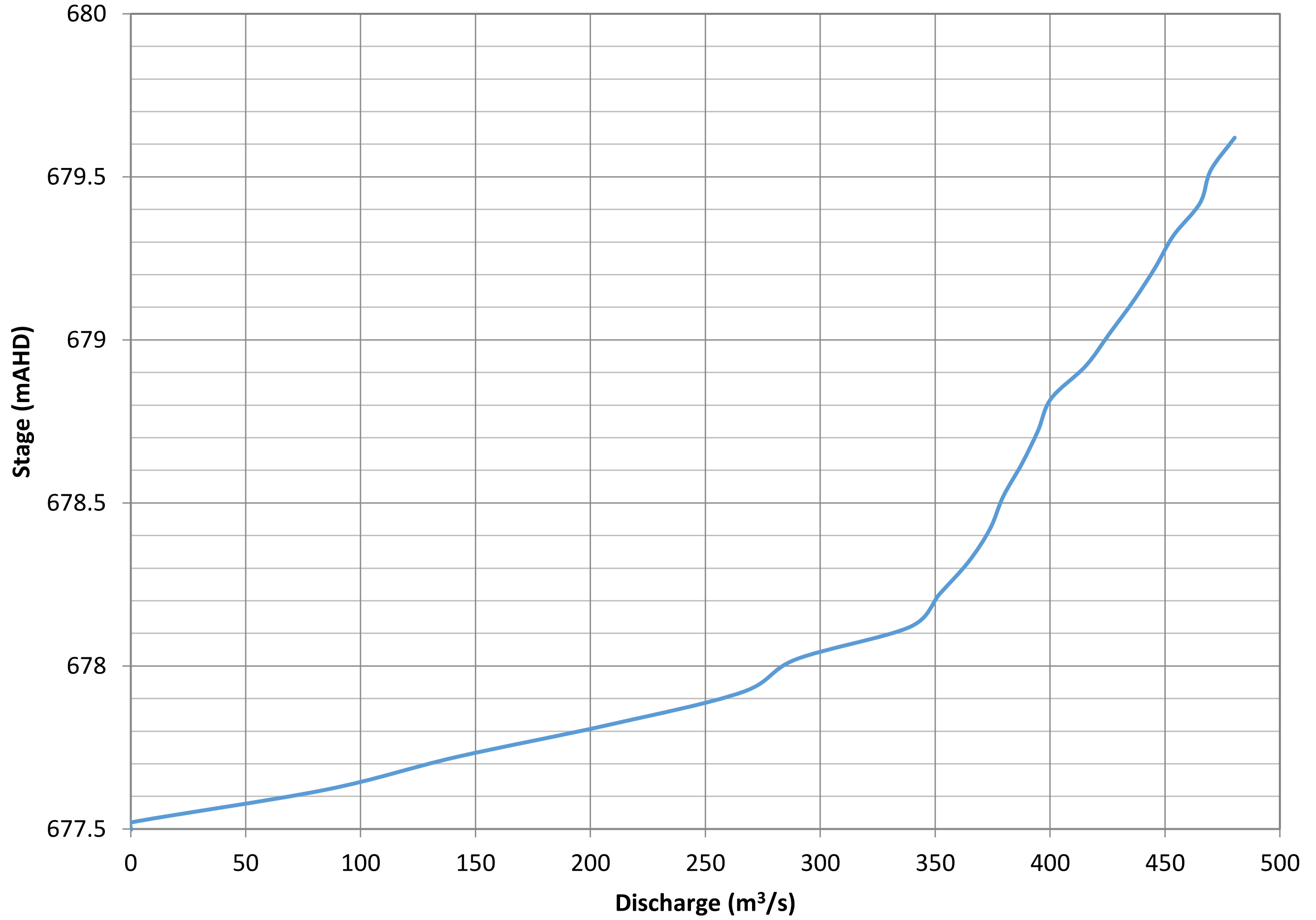


FIGURE 4
WINGECARRIBEE RIVER FLOOD STUDY REVIEW
GAUGE DATA
68262
68062
68030
68215
68089
68044
68033
568098
568054
68186
68102
68255
212272
568093
68239
212031
568165
68045
212275
68101
212212
568113
420112
568070
68006
68093
568183
68243
212274
568184
68054
68224
68117
68009
568081
68202
568082
68195
68008
68100
68248
68124
68217
68238
68167
68181
68036
68247
68029
N
BoM Daily Rainfall Gauges
BoM Pluviograph Gauges
WaterNSW Rainfall Gauges
WaterNSW Streamgauges
Wingecarribee River Catchment Boundary
Km
0
5
10
20
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

FIGURE 5
WINGECARRIBEE DAM
STAGE-STORAGE CURVE



STAGE-DISCHARGE CURVE



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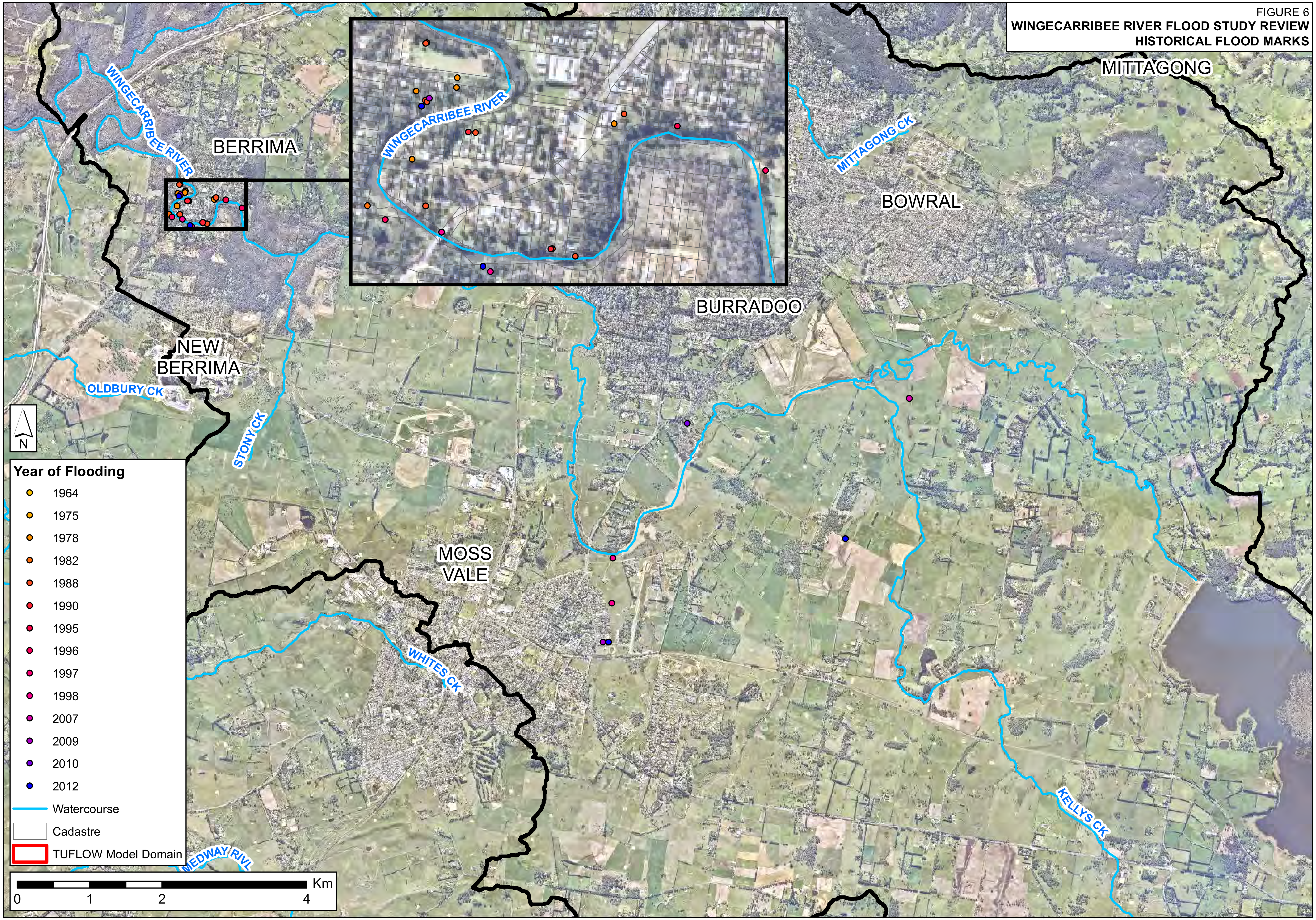


FIGURE 6
WINGECARRIBEE RIVER FLOOD STUDY REVIEW
HISTORICAL FLOOD MARKS

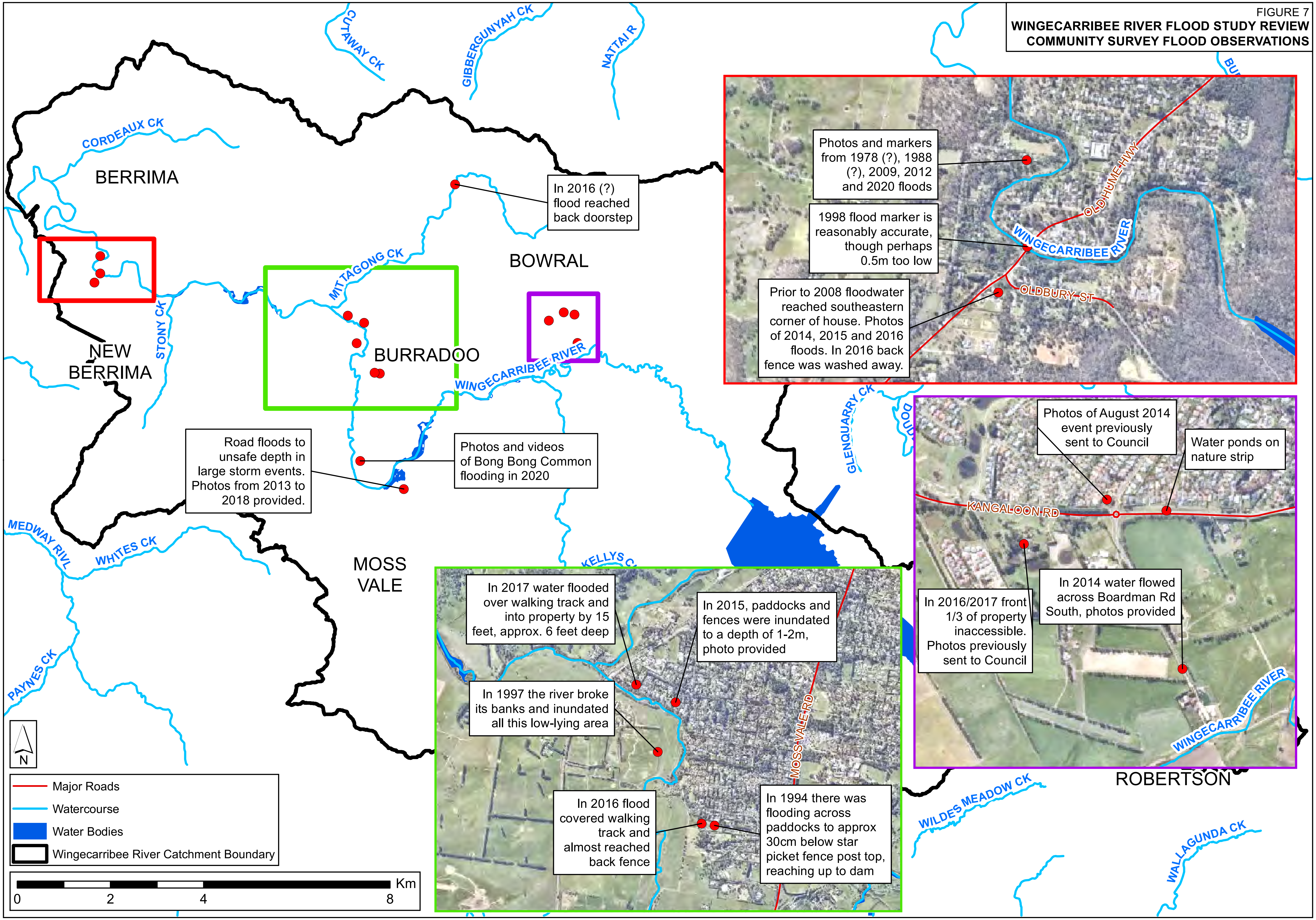
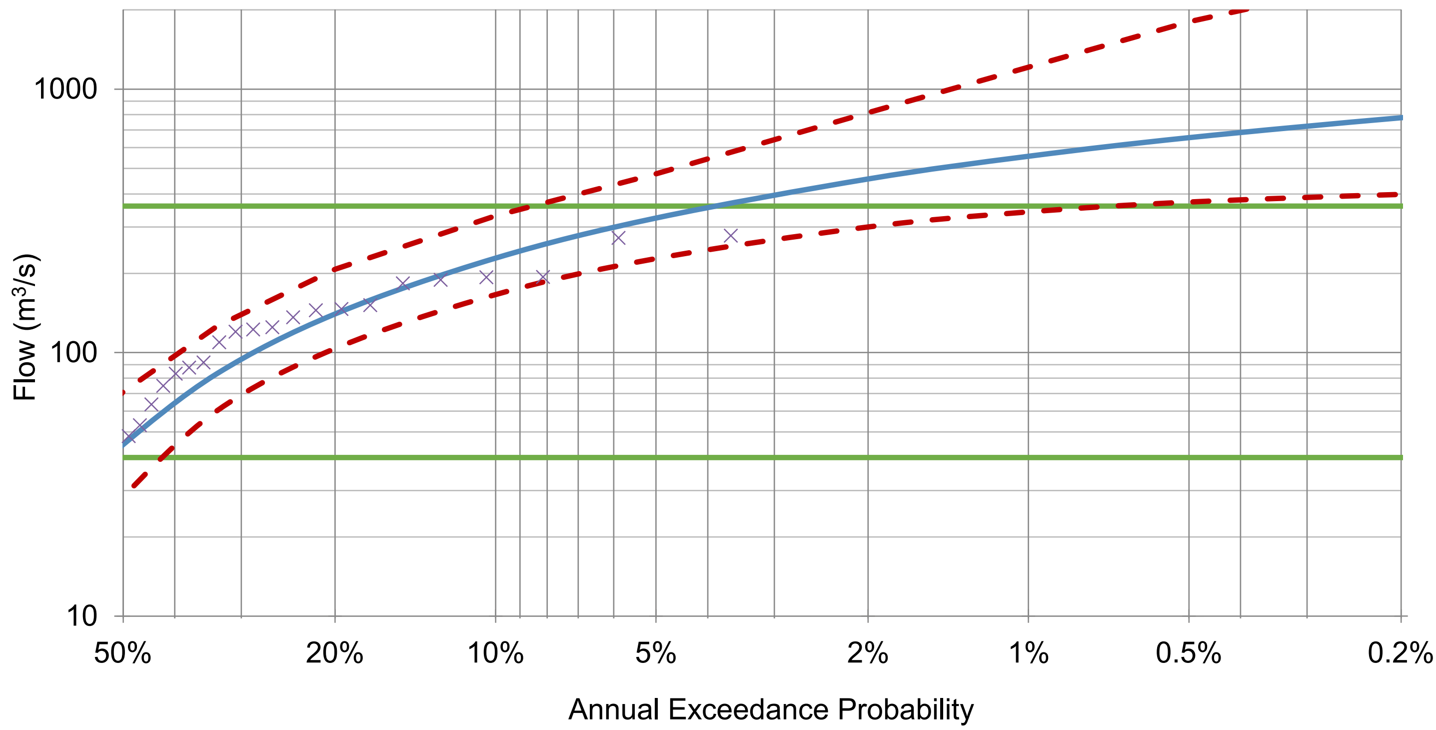


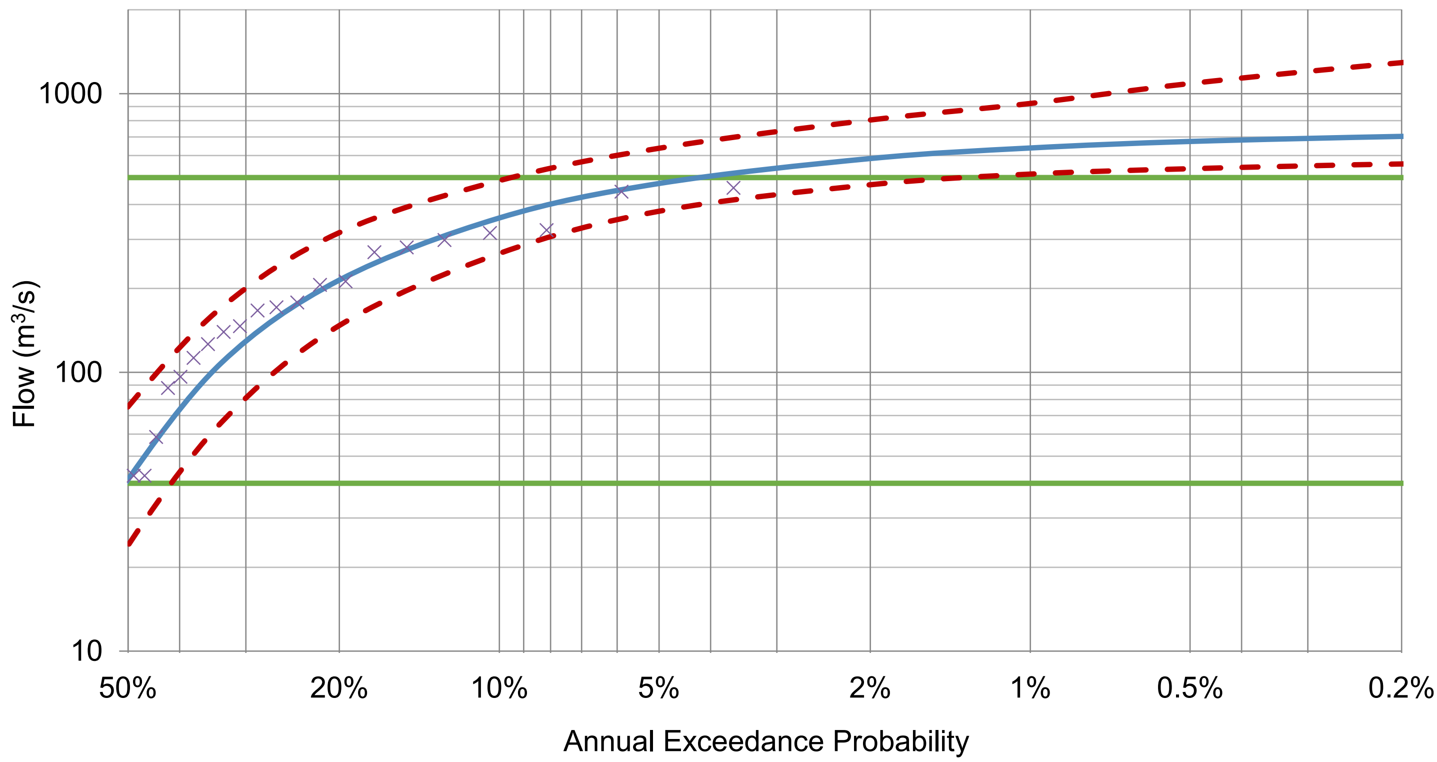
FIGURE 7
WINGECARRIBEE RIVER FLOOD STUDY REVIEW
COMMUNITY SURVEY FLOOD OBSERVATIONS

FIGURE 8

FLOOD FREQUENCY ANALYSIS AT BONG BONG WEIR 212031
AUGMENTED AND CENSORED AMS WITH DAM - LPIII



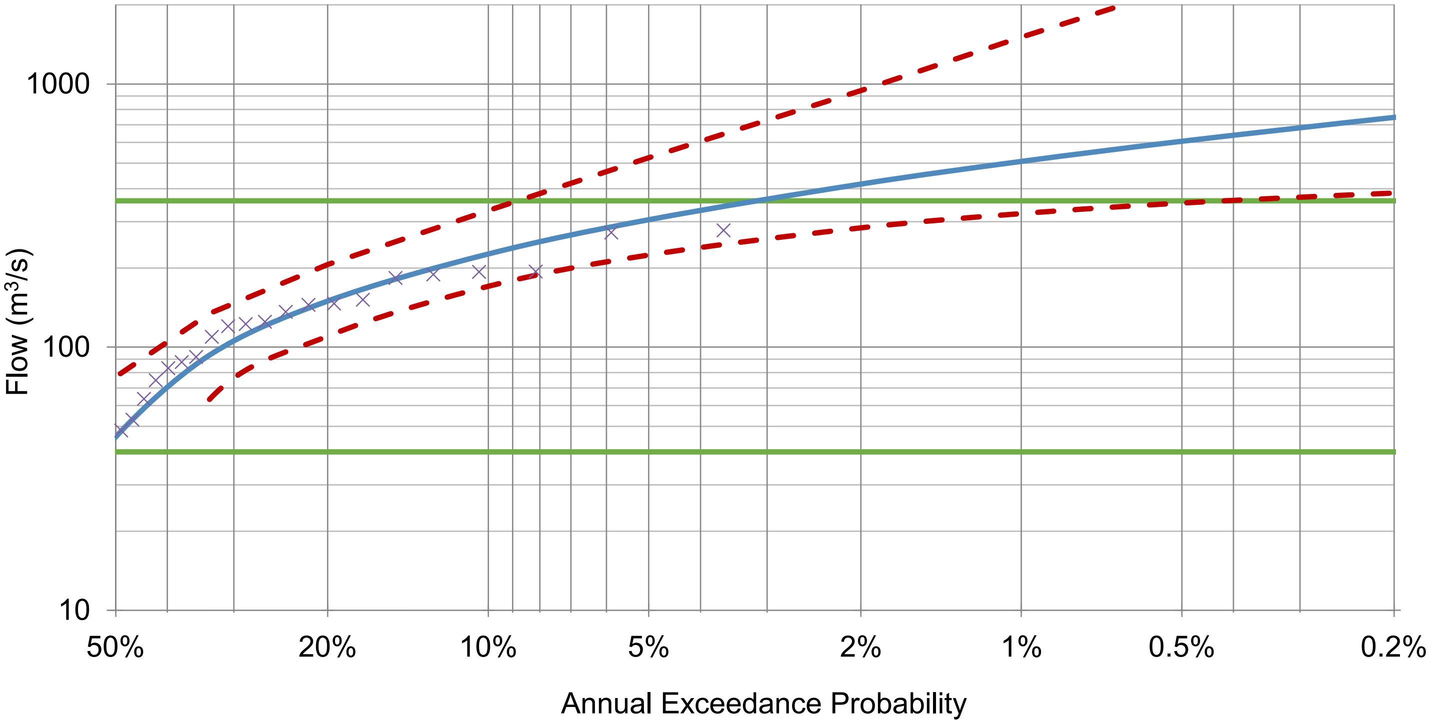
FLOOD FREQUENCY ANALYSIS AT BERRIMA WEIR 212272
CENSORED AMS WITH DAM - LPIII



Censoring threshold
Gauged annual maxima
Log Pearson III Distribution
90% Confidence Interval

FIGURE 9

FLOOD FREQUENCY ANALYSIS AT BONG BONG WEIR 212031
AUGMENTED AND CENSORED AMS WITH DAM - GEV



FLOOD FREQUENCY ANALYSIS AT BERRIMA WEIR 212272
CENSORED AMS WITH DAM - GEV

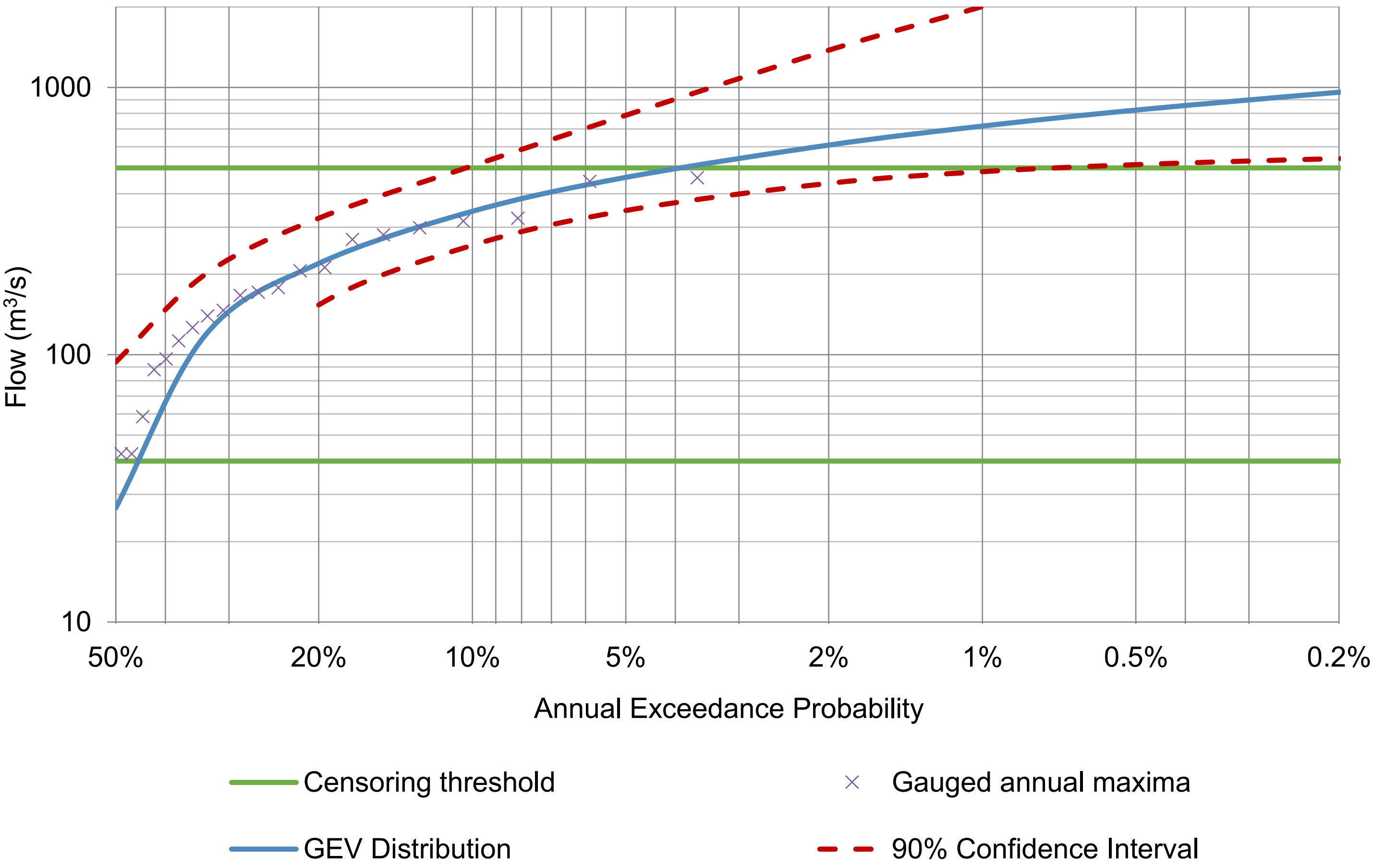
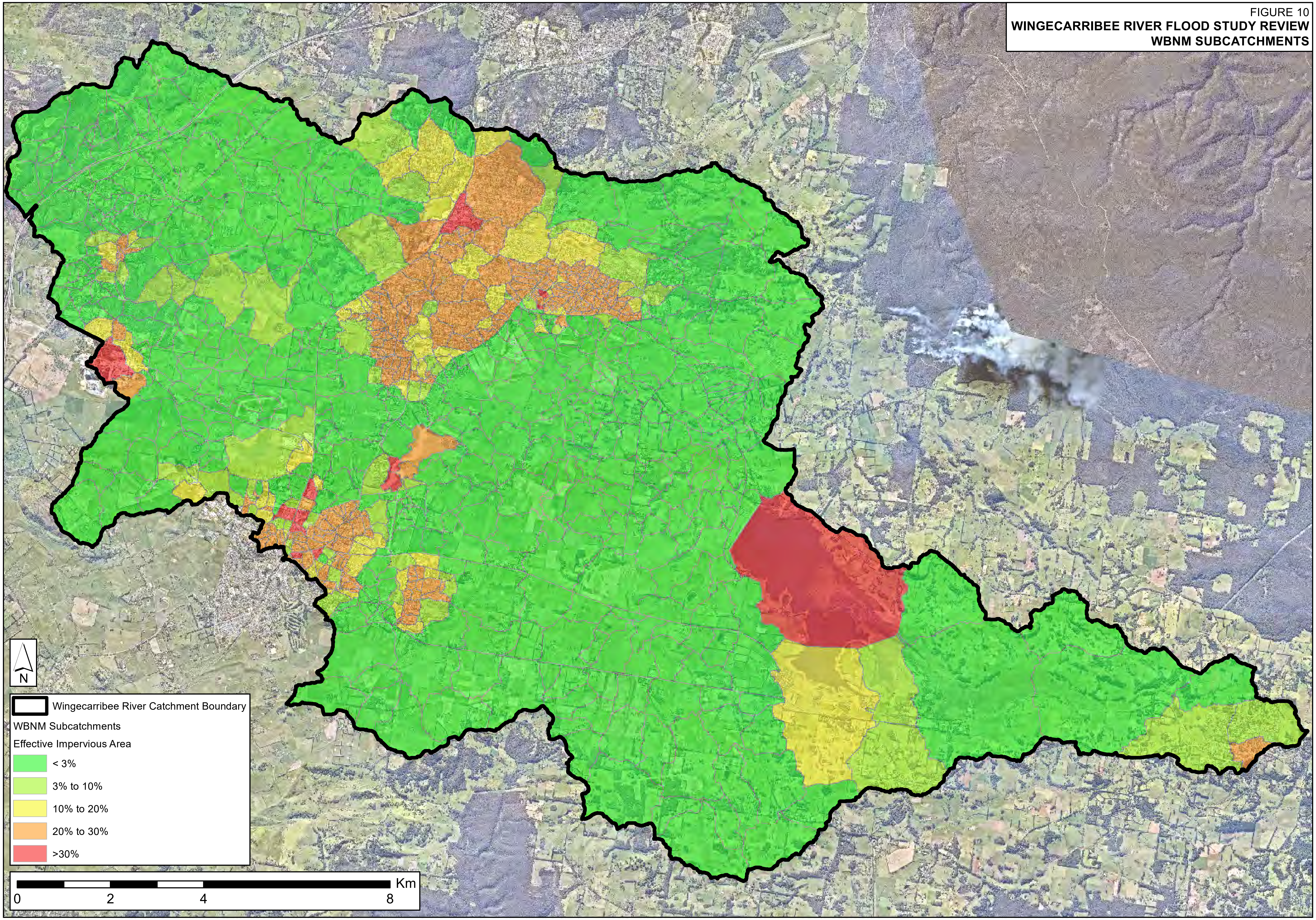


FIGURE 10
WINGECARRIBEE RIVER FLOOD STUDY REVIEW
WBNM SUBCATCHMENTS



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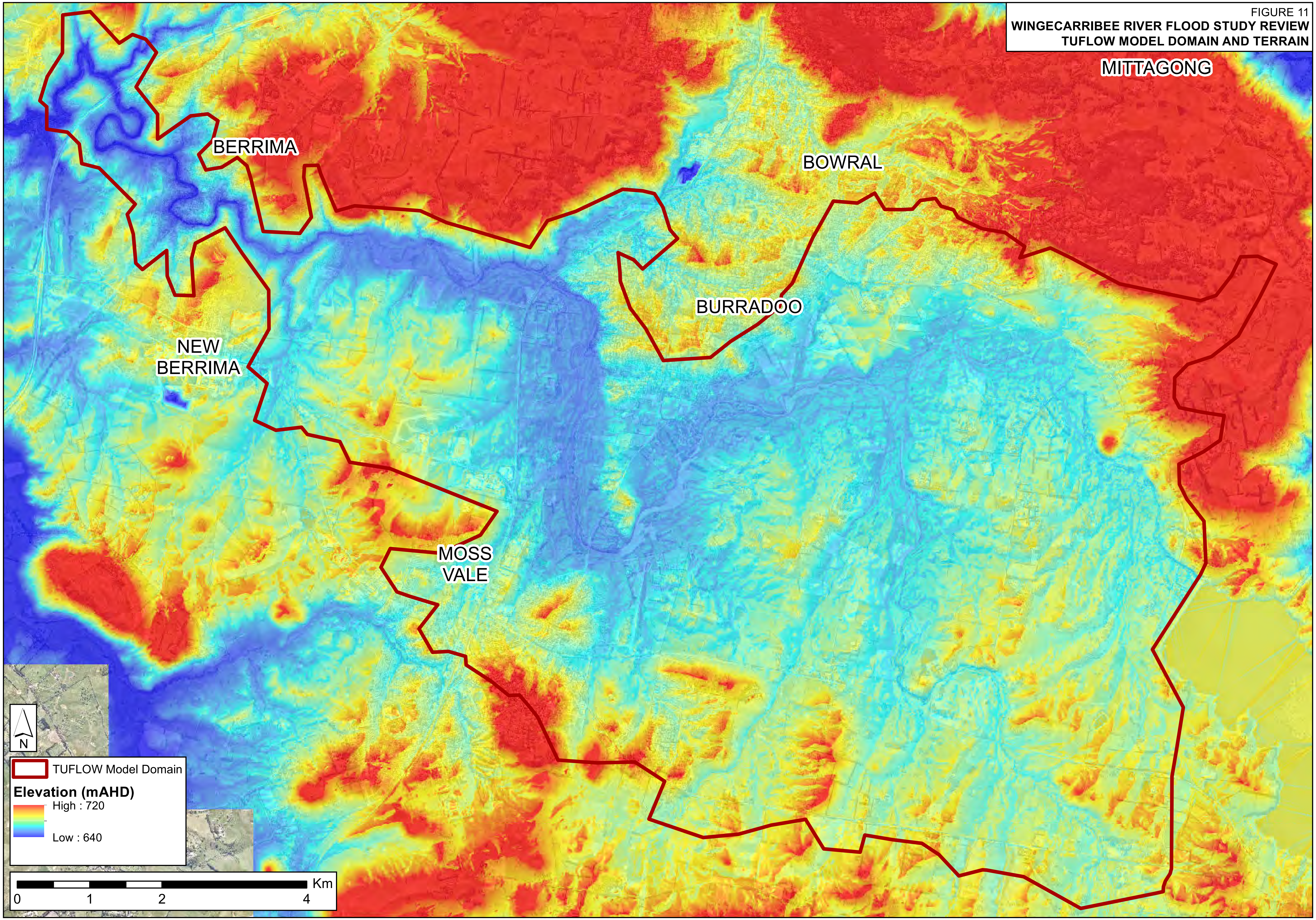

FIGURE 11
WINGECARRIBEE RIVER FLOOD STUDY REVIEW
TUFLOW MODEL DOMAIN AND TERRAIN

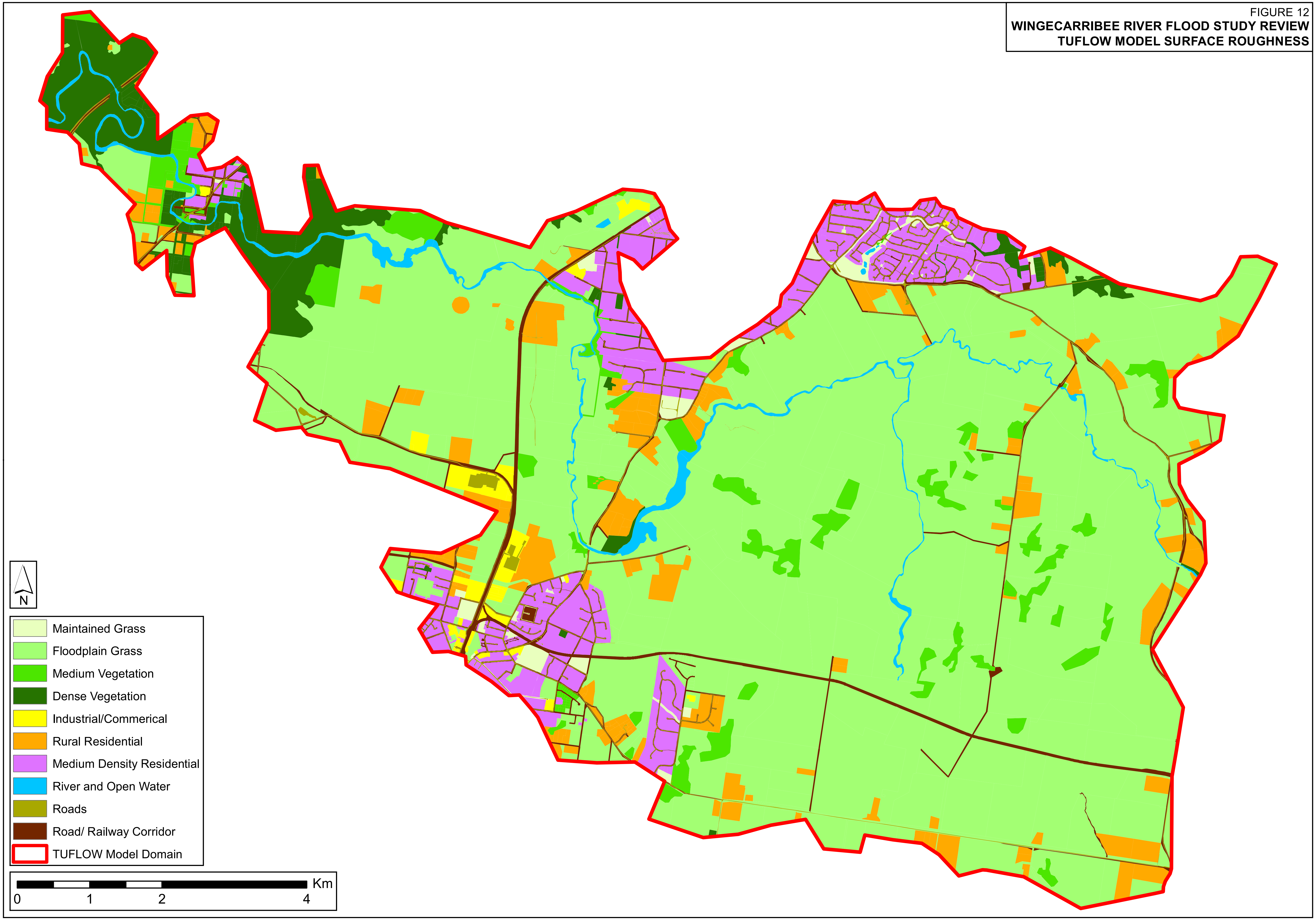

FIGURE 12
WINGECARRIBEE RIVER FLOOD STUDY REVIEW
TUFLOW MODEL SURFACE ROUGHNESS

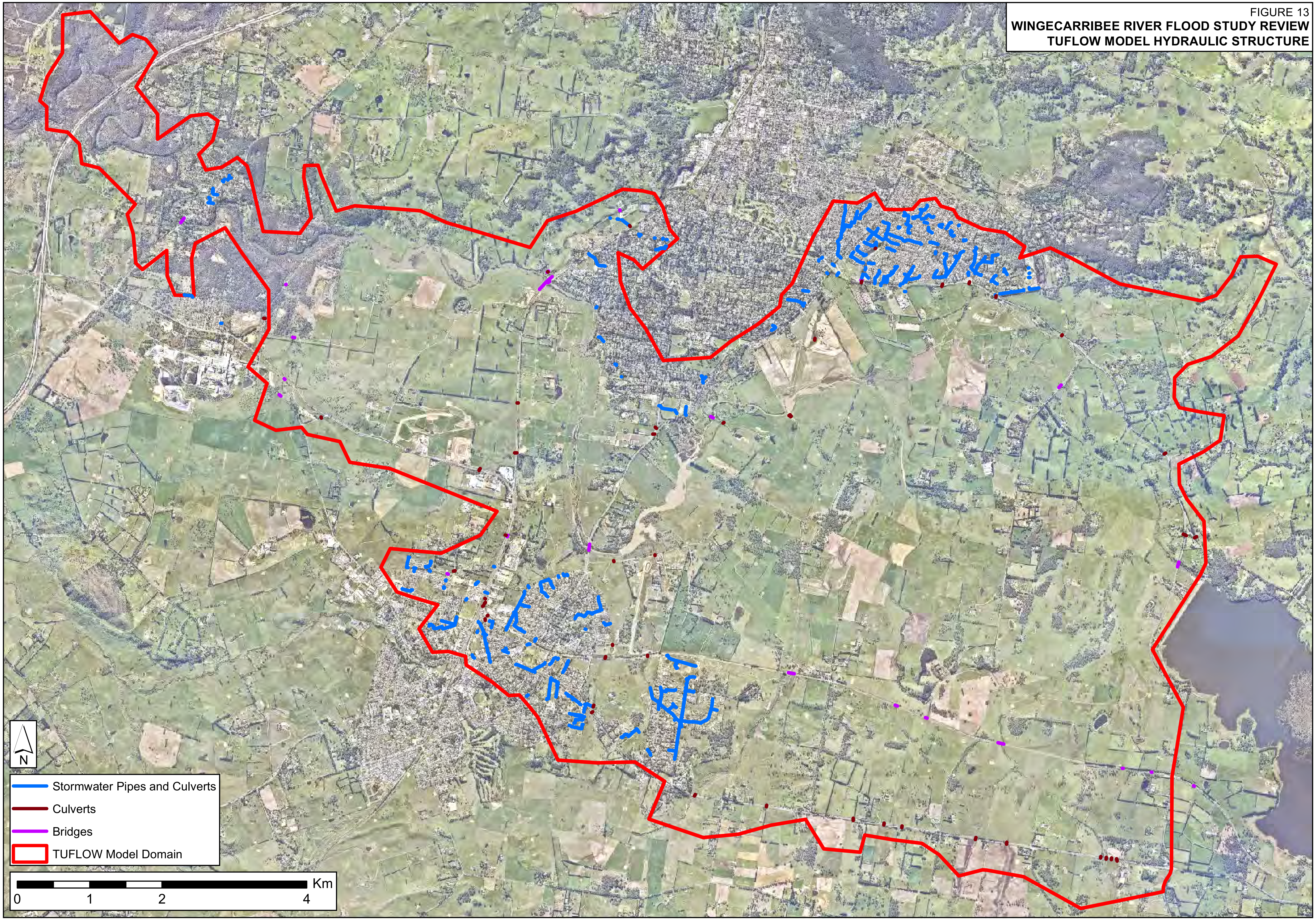

FIGURE 13
WINGECARRIBEE RIVER FLOOD STUDY REVIEW
TUFLOW MODEL HYDRAULIC STRUCTURE

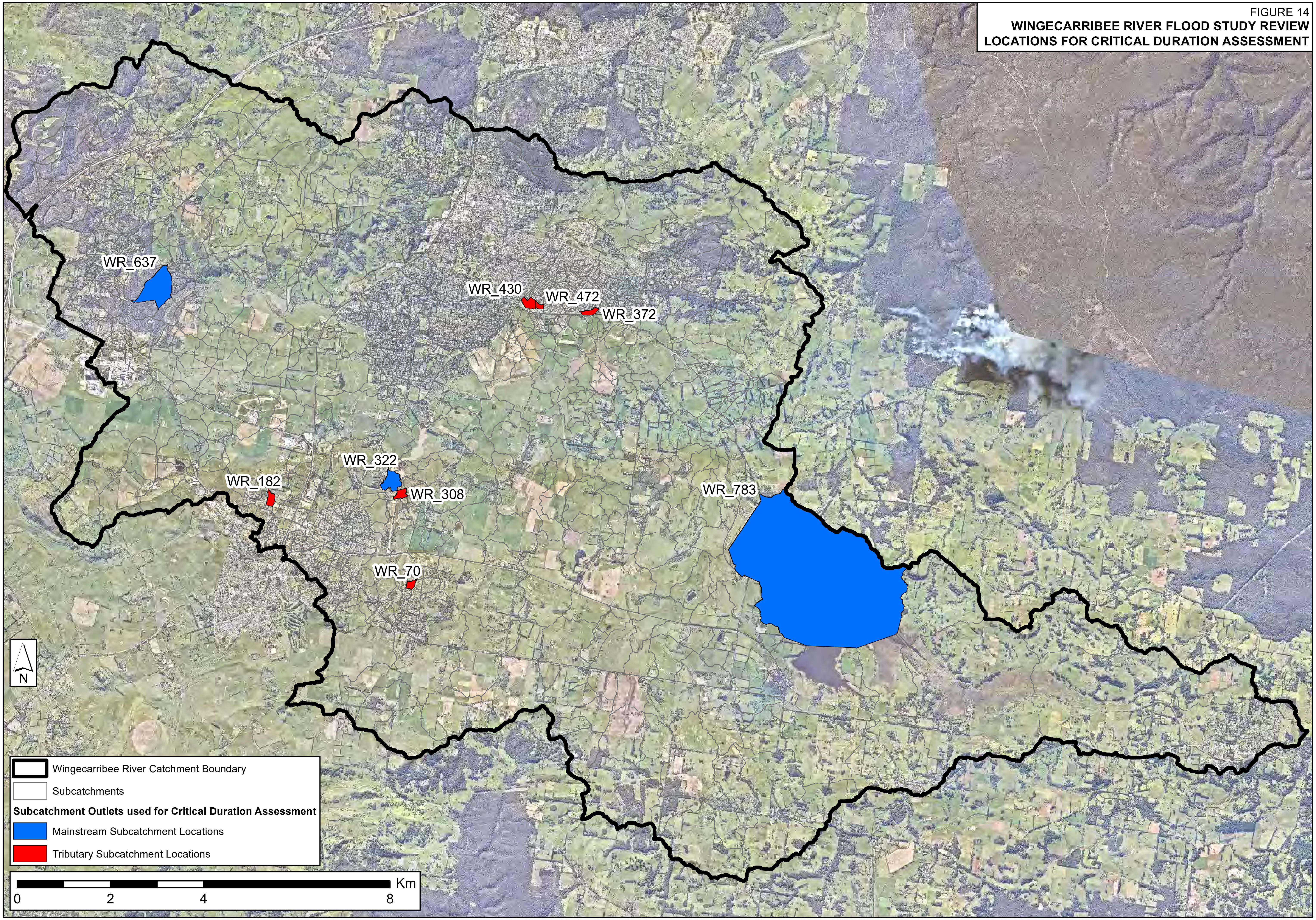

FIGURE 14
WINGECARRIBEE RIVER FLOOD STUDY REVIEW
LOCATIONS FOR CRITICAL DURATION ASSESSMENT

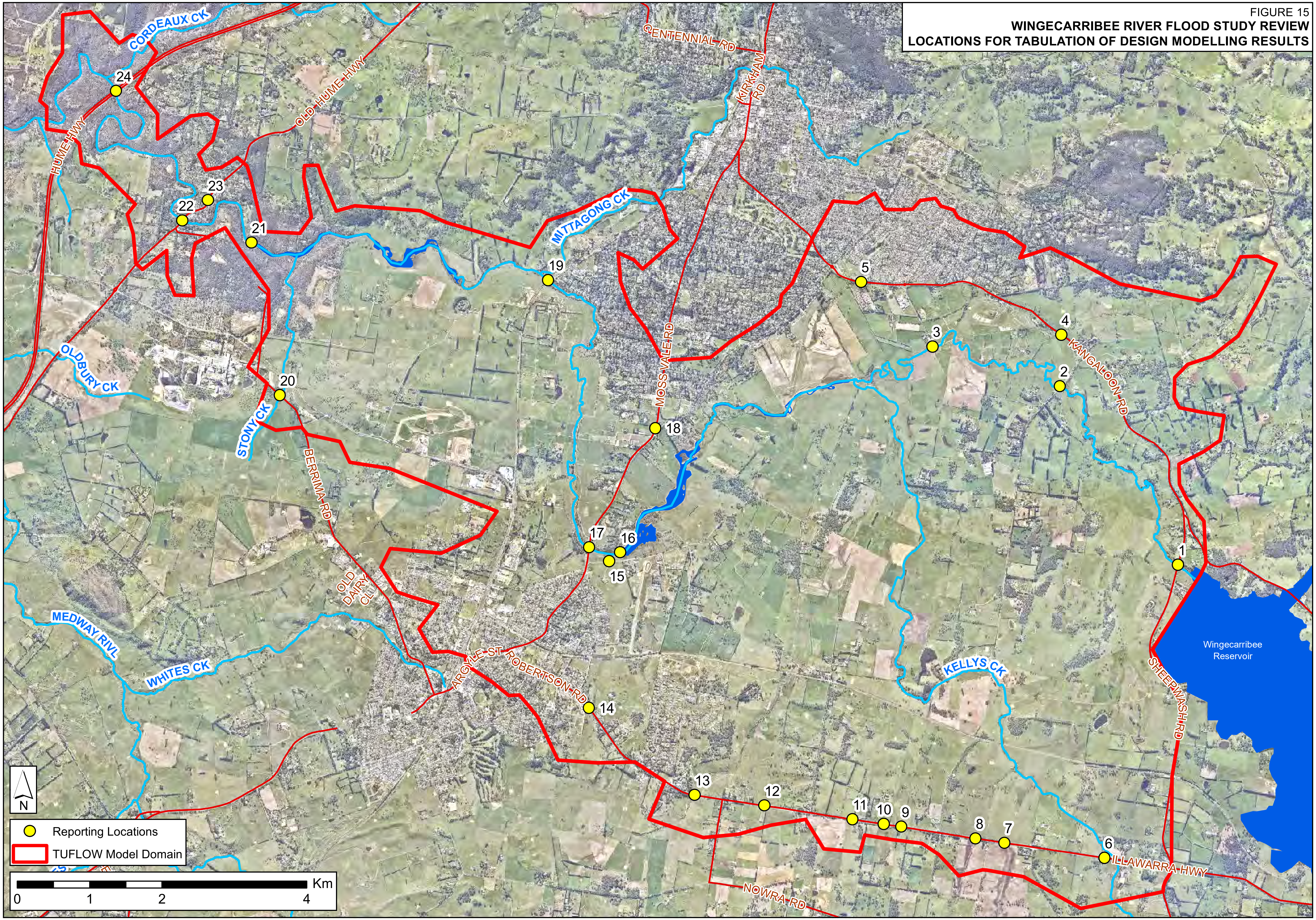

FIGURE 15
WINGECARRIBEE RIVER FLOOD STUDY REVIEW
LOCATIONS FOR TABULATION OF DESIGN MODELLING RESULTS