Karuah River and Stroud Flood Study Update

Volume 1 - Final Report

Level 17, 141 Walker St
North Sydney NSW 2060
Australia

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Cover Photo: Floodwaters flowing across Cowper Street, Stroud on the morning of 21st April 2015 (*Source: Gloucester Advocate*)

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A	Draft Report – Issued for Council Review	LC L Collins	CRT C Thomas		5/02/2018
B	Draft Report for Public Exhibition	LC L Collins	CRT C Thomas	Chris Thomas	23/10/2019
C	Final Report	LC L Collins	CRT C Thomas	Chris Thomas	30/06/2020

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1 Introduction

The Karuah River Valley is located within the MidCoast Council Local Government Area (LGA) on the NSW mid-north coast. It drains a catchment area of approximately 1,460 km^2 from the Gloucester Tops in the north-west to Port Stephens in the south (*refer* **Figure 1-1**). The catchment has a history of flooding, with flooding occurring along the Karuah River and smaller local catchments and tributaries. Most notably, significant flood damage was sustained in the Stroud area in April 2015 due to intense rainfall and flooding of Mill Creek.

MidCoast Council (Council) is responsible for local planning and land management within its LGA, including the management of flood prone land. Council, with assistance from the NSW Office of Environment (OEH), engaged Advisian to prepare the *Karuah River and Stroud Floodplain Risk Management Study and Plan* (FRMS). The *Karuah River and Stroud Flood Study Update* forms part of the FRMS but is presented as separate report. *Volume 1* (*this report*) documents the work undertaken as part of the review of the existing flood study and the findings from that review. Volume 2 is a compendium of flood mapping developed from that review.

The objectives of the FRMS are to assess the potential impacts of flooding and to assess potential flood risk management measures and strategies. In order to do this it is necessary to understand the pattern of flooding in the valley which can readily be determined from reliable flood modelling outputs. The following flood models have previously been developed covering parts of the study area.

- *Karuah River Flood Study* (Paterson Consultants 2010)

  A RORB hydrologic model and a one-dimensional (1D) MIKE-11 hydraulic model were developed to define flood behaviour and design flood levels along the Karuah River from around 1.1 kms upstream of Stroud Road to the old Pacific Highway bridge at Karuah.

- *Stroud Flood Study* (WMAwater 2012)

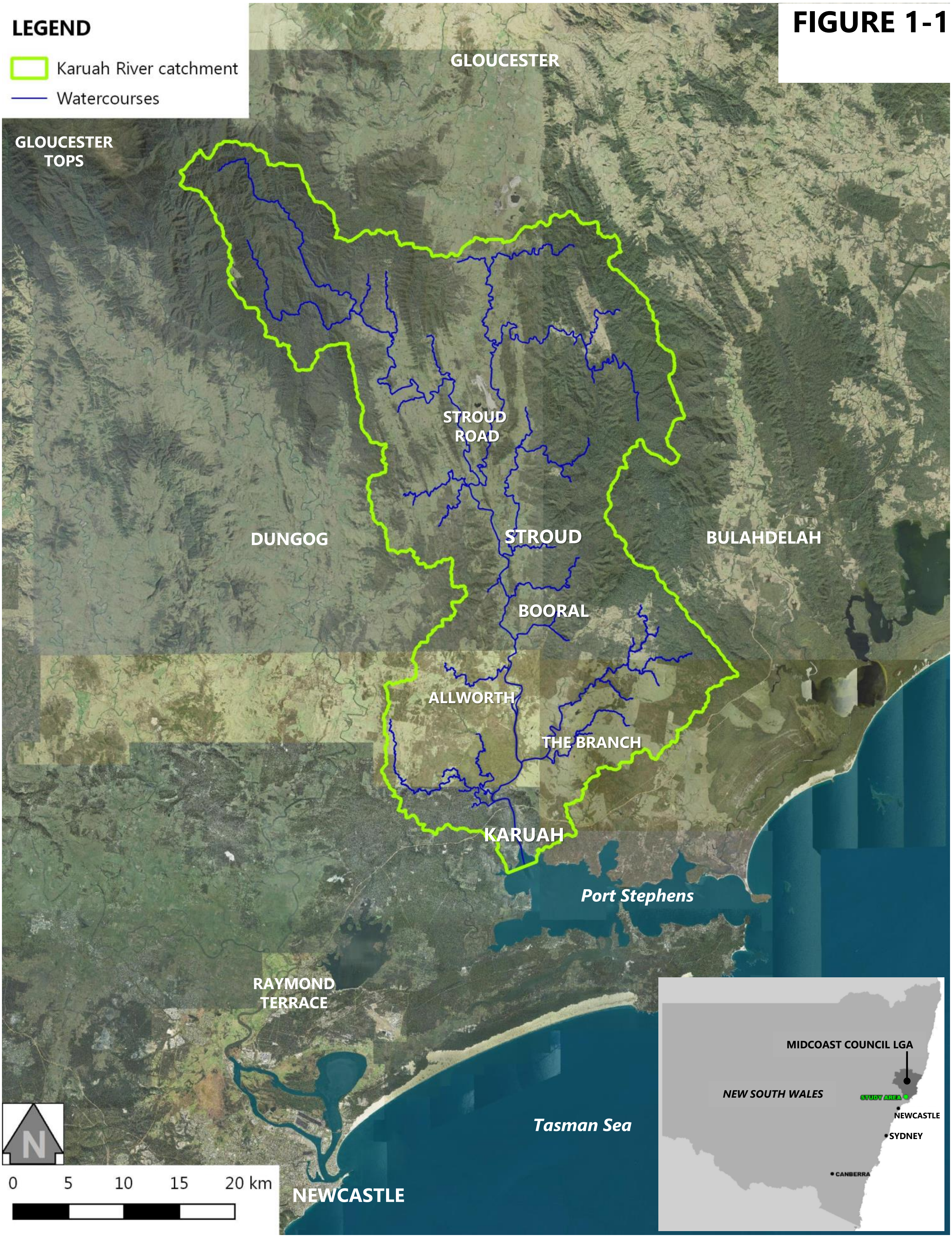
  A WBNM hydrologic model and a two-dimensional TUFLOW hydraulic model were established to simulate flood behaviour around the township of Stroud, considering flooding from Mill and Lamans Creeks as well as backwater flooding from the Karuah River.

For the purposes of the FRMS, it was considered that there would be considerable benefit in developing updated flood models and mapping using the latest guidelines, catchment data and technology. Accordingly, Advisian developed a WBNM hydrologic model for the entire Karuah River catchment, and a two-dimensional (2D) TUFLOW hydraulic model for the study area from Stroud Road to Port Stephens. Benefits of the model update include:

- Use of a single model software and approach, providing model results that are directly comparable throughout the study area and allow assessment of flood impacts, emergency management and potential mitigation works to be undertaken on a consistent basis.
- Improved resolution of flood behaviour in overbank / floodplain areas in 2D compared to 1D
- Provision of high resolution 2D temporal mapping outputs
- Use of the latest topographic LiDAR data
- Use of the April 2015 flood event to provide improved model calibration
- Use of *Australian Rainfall and Runoff: A Guide to Flood Estimation* (Geoscience Australia 2016) (ARR 2016) to define design flood conditions.

This report documents the *Flood Study Update* methodology and outcomes, with resulting flood mapping presented in a Compendium titled, *Karuah River and Flood Study Update: Volume 2 – Flood Mapping*.

FIGURE 1-1



STUDY LOCATION

2 Numerical Model Development

2.1 Available Data

A comprehensive compilation and review of background information and relevant available data is presented in Chapters 2 and 3 of the *Karuah River and Stroud Floodplain Risk Management Study and Plan* report. This includes review of flood history, previous studies, topographic data, hydrometric data, and historic flood data.

2.2 Modelling Approach

Numerical computer models have been adopted as the primary means of investigating flood behaviour for the Karuah River and Stroud study area. When used carefully, modern computer models allow simulation of flood behaviour over large areas in a cost efficient and reliable manner.

For this study, the WBNM hydrologic and TUFLOW 2D/1D hydraulic modelling software packages were selected. The hydrologic model simulates the catchment rainfall-runoff processes, with resulting flow hydrographs input to the hydraulic model. The hydraulic model simulates the physical behaviour of the flow as it passes through the catchment, producing information on flood levels, flood extents and flow velocities.

The WBNM and TUFLOW software were determined to be suitable tools for replicating the complex 2D nature of flooding in the study catchment based on consideration of the following.

- WBNM hydrologic modelling software:
  - WBNM is very robust and has been validated against numerous catchments in NSW
- TUFLOW hydraulic modelling software:
  - Allows accurate representation of catchment topography and bathymetry to be developed in 2D from various sources (e.g. a combination of LiDAR and detailed survey)
  - Allows integrated investigation and interaction of overland, mainstream and tidal and ocean driven components of flooding
  - Solves the full 2D surface water equations
  - Produces high quality, GIS compatible flood mapping outputs

2.3 Hydrologic Model Development

The WBNM2017 hydrologic modelling software was used to simulate rainfall-runoff and stream routing processes to determine flow hydrographs for input to the hydraulic model.

The extent of the 1,460 km^2 Karuah River catchment was determined from topographic data using the CatchmentSIM hydrologic and terrain analysis software. This was further delineated into 251 sub-catchments based on consideration of the catchment topography, location of stream gauges and hydraulic structures, and requirements for input to the hydraulic model (refer **Figure 2-1**). The sub-catchment delineation and linkage formed the basis for the development of the WBNM hydrologic model.

Parameters required by the WBNM model include sub-catchment area and linkage, percentage pervious / impervious, a runoff lag factor 'C', a stream routing lag factor 'F', rainfall hyetographs, initial loss and continuing loss. Adopted parameters were developed through the model calibration and verification process and are presented in **Table 3-3**.

2.4 Hydraulic Model Development

2D Model Domain

The 2D TUFLOW hydraulic model was developed with a focus on simulation of flooding at the settlements of Stroud Road, Stroud, Booral, Allworth, The Branch and Karuah North. Flooding along the Karuah River, Mammy Johnsons River, Mill Creek, Lamans Creek, The Branch River and Little Branch River, was specifically investigated using the model. Backwater flooding from the Karuah River was also considered along other tributaries such as Alderley Creek and Booral Creek.

The 2D hydraulic model domain covers an area of 147.6 km^2. A minimum model grid size of 5 m was adopted in order to adequately resolve flood characteristics in the Stroud area. This grid size would also be beneficial for representing narrower waterways such as Mammy Johnsons River. Each square grid cell contains information on ground surface elevation, hydraulic roughness and other parameters. The ground surface elevation is sampled at the centre, mid-sides and corners of each cell from a specified Digital Elevation Model (DEM). For a 5 m grid this results in DEM elevations being sampled every 2.5 m.

This model extent and grid size resulted in a computationally demanding 5.9 million grid cells. In order to reduce RAM requirements and run-time to manageable levels, a number of sub-models were developed to represent the overall hydraulic model extent, these being:

- M1: Model 1 extent from Stroud Road to upstream of Allworth => 5 m TUFLOW grid size
  - This model was used to determine design flood conditions from Stroud Road to downstream of the confluence of the Karuah River and Booral Creek including Stroud
- M2: Model 2 extent from upstream of Allworth to Port Stephens => 5 m TUFLOW grid size
  - This model was found to be excessively computationally demanding, and consequently was used only to confirm the suitability of the M3 8 m grid TUFLOW model to represent flood conditions from downstream of Booral Creek to Karuah
- M3: Model 3 extent from Stroud Road to Karuah => 8 m TUFLOW grid size
  - This model was used to determine design flood conditions from downstream of the confluence of the Karuah River and Booral Creek to Karuah, including The Branch.

The resulting hydraulic model extents are shown in **Figure 2-2**.

Topography and Bathymetry

The DEM used to sample TUFLOW model ground surface topography and waterway bathymetry was created from the following data sets:

- Airborne Light Detection and Ranging (LiDAR) survey data captured by NSW Lands and Property Information (LPI):
  - LPI Dungog 1m DEM, captured 19 January to 24 February 2016
  - LPI Raymond Terrace 1m DEM, captured 16 June to 21 September 2013
  - LPI Bulahdelah 1m DEM, captured 9 June to 8 December 2013
  - LPI Port Stephens 1m DEM, captured 15 December 2012 to 7 July 2013.
- Cross-sectional survey of the Karuah River obtained for the *Karuah River Flood Study* (Paterson Consultants 2010)
- Cross-sectional survey of Mill Creek and Lamans Creek obtained for the *Stroud Flood Study* (WMAwater 2012).

In waterways where bathymetric survey data was not available, estimates were made as follows:

- The Branch River

  A bed level of 0.59 mAHD was estimated at The Branch Lane crossing of The Branch River from measurements made on site and using LiDAR as a datum. This bed level was extended to a distance of about 800 metres downstream at the last of a series of rock bars. From this point the bed level decreased linearly to match the bed level of the Karuah River at the confluence with The Branch River.
- Little Branch River

  A bed level of 0.92 mAHD was estimated at The Branch Lane crossing of the Little Branch River from measurements made on site and using LiDAR as a datum. This bed level was extended to a distance of about 600 metres downstream where aerial photography appears to show a rock or gravel bar. From this point the bed level decreased linearly to match the bed level of the Karuah River at the confluence with The Branch River.
- Mammy Johnsons River

  Bed levels were estimated to be equivalent to those surveyed at similar chainages along the Karuah River, with checks made to confirm that channel depths were within the expected range.

The above estimates are expected to be appropriate for the purposes of this study as:

- Rock / gravel bars act as controls along significant portions of The Branch and Little Branch Rivers, reducing the influence of the bathymetric estimates in these areas. While lower in these rivers, backwater flooding from the Karuah River is the dominant flooding mechanism.
- Only rare flood events pose any significant flood risk along the Mammy Johnsons River. The influence of bathymetry on flood conditions during such events is relatively low as significant out of bank flow occurs. More frequent flood events such as the 20% AEP design event were found to remain largely in-bank using the estimated bathymetry, as may be expected.

Boundary Conditions

The hydraulic model boundary conditions consist of the following:

- M1:
  - 'Surface area' application of 'total' and 'local' flow hydrographs to the 2D model domain
  - A downstream water level boundary upstream of Allworth, placed immediately downstream of an s-bend in the Karuah River such that the influence on water levels upstream of the bend is reduced
- M2 and M3:
  - 'Surface area' application of 'total' and 'local' flow hydrographs to the 2D model domain
  - A downstream water level boundary at Port Stephens.

The locations of these boundary conditions are shown in **Figure 2-2**.

Hydraulic Structures

A number of hydraulic structures were included in the hydraulic model including culverts and bridges. Culverts were represented using 1D elements dynamically linked to the 2D grid. The influence of bridges on flood behaviour was represented in 2D using 'layered flow constrictions'.

The geometry of the bridges including pier arrangement, span, deck thickness and level, and detail of handrails was estimated from available survey, plans and site observations. Associated form losses were estimated using procedures from *Waterway Design* (*AustRoads 1994*).

Hydraulic Roughness

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

Spatial variation in hydraulic roughness is represented in TUFLOW by delineating the catchment into zones of similar hydraulic properties. The hydraulic roughness zones adopted in this study have been delineated based on consideration of aerial photography, Council LEP zoning and cadastral data, as well as site observations. Manning's 'n' values assigned to each zone were determined based on site observations and previous experience, with reference to values recommended in the literature (*e.g. Chow 1959*). As resistance to flow due to surface and form roughness varies with depth (*e.g. Chow 1959, Institution of Engineers Australia 1987*), variable depth-dependent hydraulic roughness values were adopted for this study.

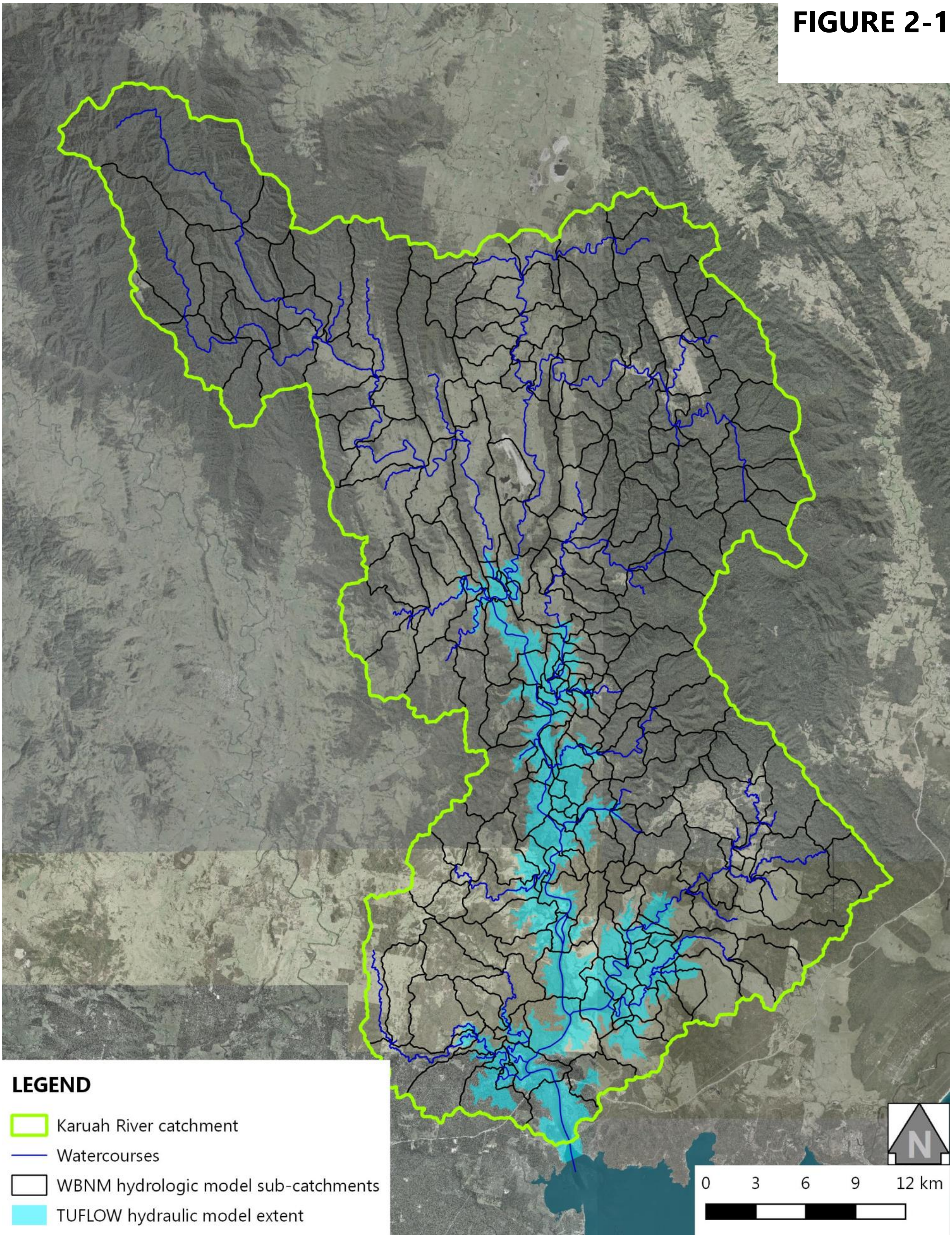
Manning's 'n' roughness coefficients applied in the TUFLOW model are listed in **Table 2-1**, with the delineation of hydraulic roughness zones shown in **Figure 2-3**. The higher Manning's values are applied at shallow depths below the specified range of depth variable roughness, while the lower Manning's values are applied at depths above the specified depth range.

At depths within the range of depth variable roughness, applied Manning's values are determined by linear interpolation.

Table 2-1 Adopted Manning's 'n' hydraulic roughness coefficients

Material	Range of depth variable roughness (m)	Manning's 'n' Roughness Value
Buildings	-	2.0
Waterways	0.4–2.0	0.08-0.04
Open Space	0.15–0.45	0.1-0.05
Forest	0.3-0.9	0.2-0.12
Roads	0.05-0.15	0.08-0.03

FIGURE 2-1



HYDROLOGIC MODEL LAYOUT

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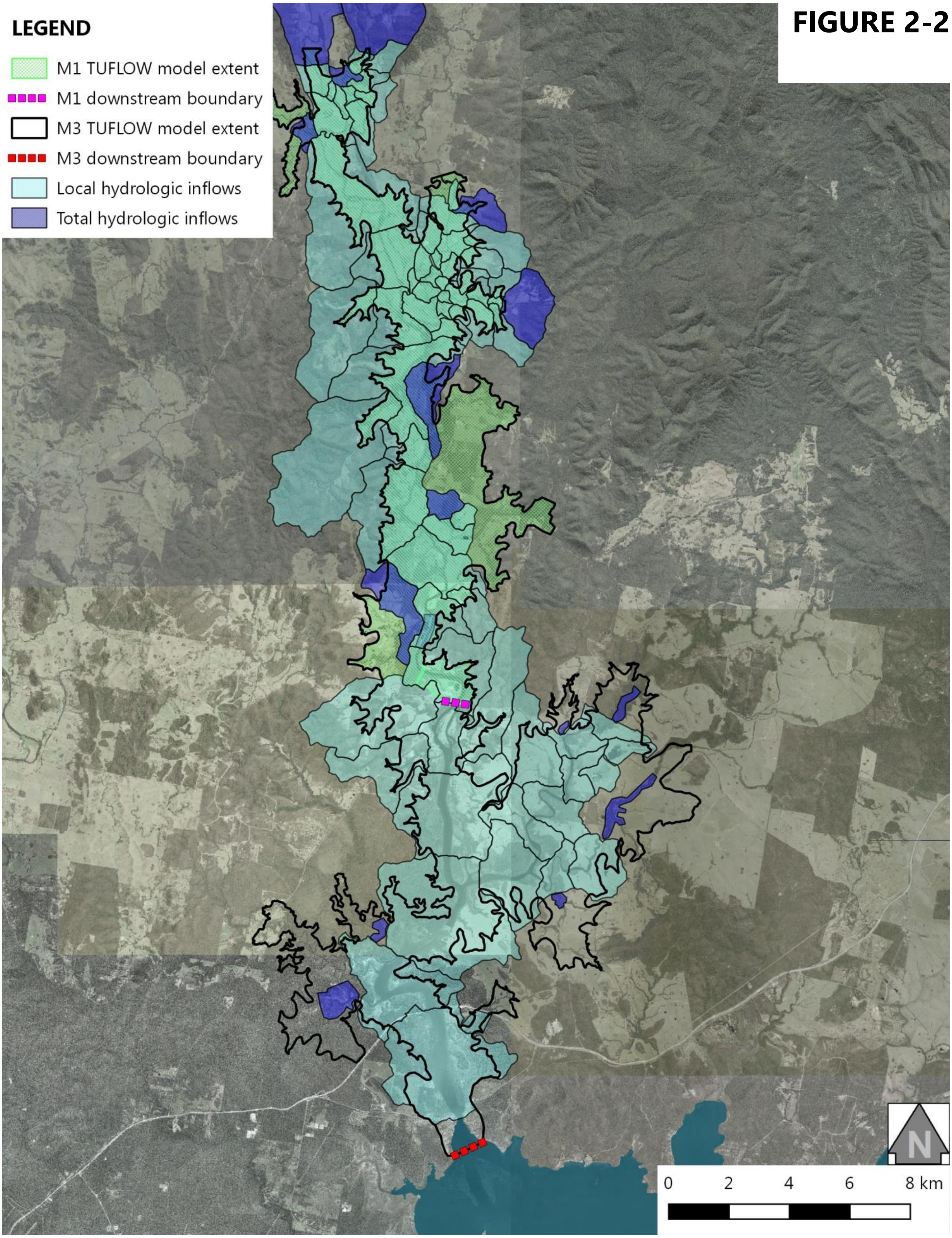
FIGURE 2-2



TUFLOW HYDRAULIC MODEL BOUNDARIES

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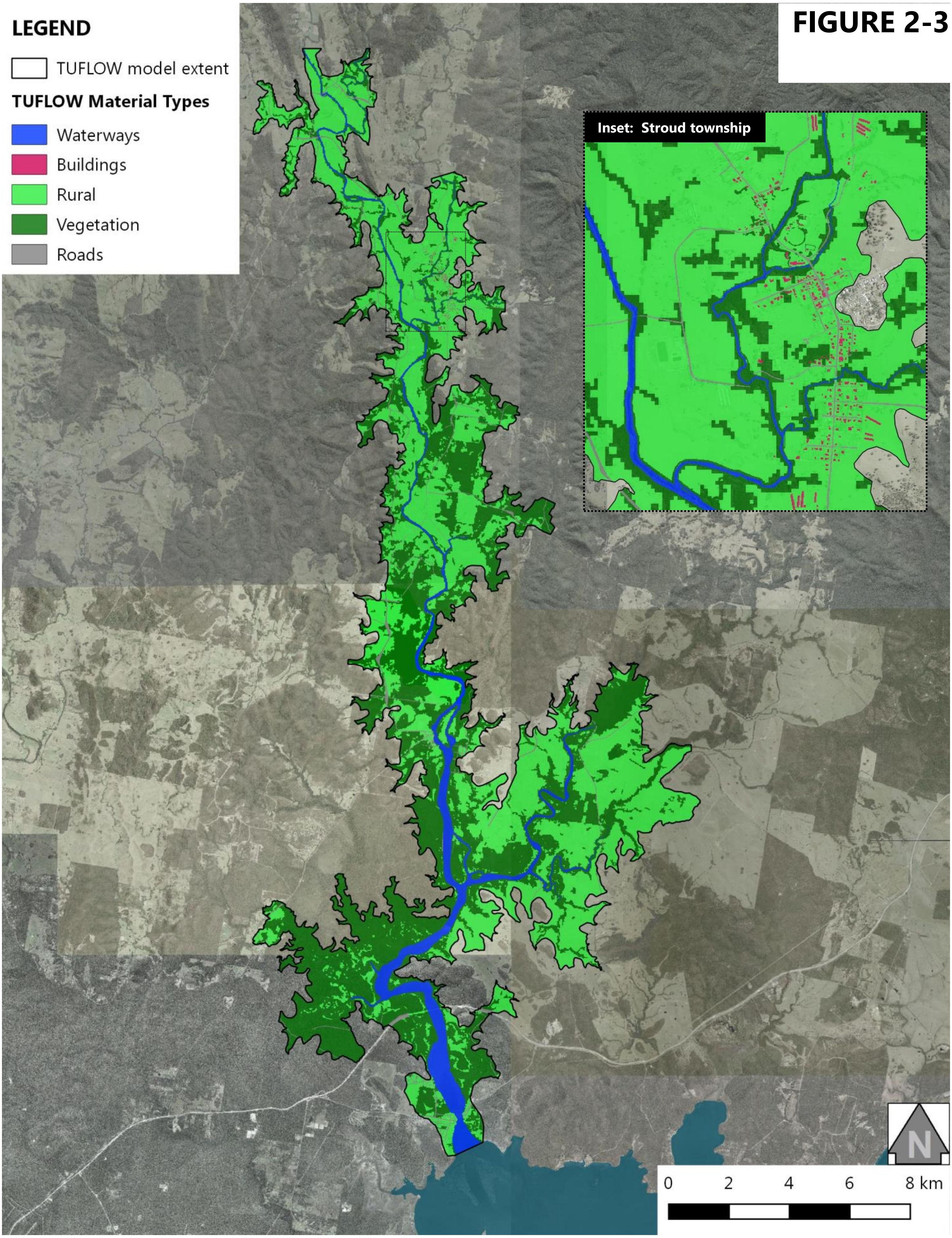
FIGURE 2-3



TUFLOW HYDRAULIC ROUGHNESS ZONES

3 Model Calibration and Verification

3.1 Overview of Model Calibration and Verification

Model calibration and verification is an essential step in the flood modelling process which is required to confirm that the model can reliably simulate historical flood events. The approach in the current study was to undertake model calibration and verification with reference to recorded data from flood events which occurred in April 2015 and June 2007.

The results provide confidence in the ability of the developed WBNM and TUFLOW models to realistically simulate flood behaviour across the study area. It is noted, however, that calibration focused on the localities of Stroud and Booral as little calibration data was available elsewhere. As a result, limited calibration has been undertaken of the remainder of the model, particularly downstream of Booral.

3.2 Selection of Model Calibration Events

The suitability of historical flood events for use in model calibration and verification is generally dependent on the availability, completeness and quality of recorded rainfall, flood level and stream flow data. It is also preferable to use a number of events of variable flood size.

The DPI Water stream gauge at Booral represents the best available continuous record of flood levels in the Karuah River catchment. Floods with peak recorded water levels above 9.0 mAHD at Booral since 1968 are listed in **Table 3-1**.

Table 3-1 Highest recorded flood levels for the Karuah River at the Booral gauge (since 1968)

Rank	Date	Peak Flood Level		Peak Flow (m^3/s)	
		Gauge Height (m)	Peak Elevation (mAHD)	2016 Rating Curve	Rating Curve at Time of Event
1	21 April 2015	9.32	10.37	1209	1164
2	21 January 1971	9.30	10.35	1203	2423
3	13 October 1985	8.86	9.91	1105	2088
4	4 February 1990	8.60	9.65	1048	1890
5	8 June 2007	8.42	9.47	1008	1761
6	20 March 1978	7.98	9.03	916	1506

From the flood events listed in **Table 3-1**, the 21 April 2015 flood is most suitable for use in model calibration. It is the largest flood recorded at Booral and, in addition to the gauge data, has various recorded flood mark levels available for use in calibration. It is also the most recent flood and is likely to have the best coverage of rainfall data. Similarly, the June 2007 flood has been selected for use in model verification due to the associated availability of rainfall and flood level data.

Also notable from **Table 3-1** is that there has been significant change in the Booral rating curve over time. This is indicative of the significant uncertainty in the rating curves and resulting flow estimates at elevated flood levels.

3.3 Model Calibration – 21 April 2015 Event

3.3.1 Event Overview

In April 2015 an intense East Coast Low formed off the NSW coast. The low initially moved in a northerly direction up until the evening of 19 April when it was centred approximately 250 km east of Port Macquarie. Over the period from Monday 20 to Tuesday 21 April, the system continued to intensify drawing more moist air inland, while moving south-west towards Newcastle and the Hunter Valley.

The system brought severe weather to the Lower Mid North Coast, Hunter, Central Coast and Sydney regions including intense rainfall, strong winds and large waves. In addition to the major flooding at Stroud, the rainfall caused widespread flooding in the Hunter region with devastating impacts suffered at Dungog including the loss of three lives and destruction of several houses.

An overview of the timing and intensity of rainfall in the Karuah River catchment as indicated by BoM rainfall radar imagery is presented in **Figure 3-1** and **Figure 3-2**. It can be seen that a band of moderate to heavy rainfall formed across the centre of the catchment in the vicinity of Stroud at around 10 pm on the evening of 20 April 2015. From then until about 12 am, rainfall in the catchment was generally of moderate intensity with heavier falls over The Branch River catchment.

From about 1 am on the morning of 21 April, heavy rainfall began to fall over Stroud. A north-west to south-east aligned band of high intensity rainfall formed, which affected the catchments of The Branch River, Mill and Lamans Creeks, and parts of the upper Mammy Johnsons River catchment through to about 3:30 am.

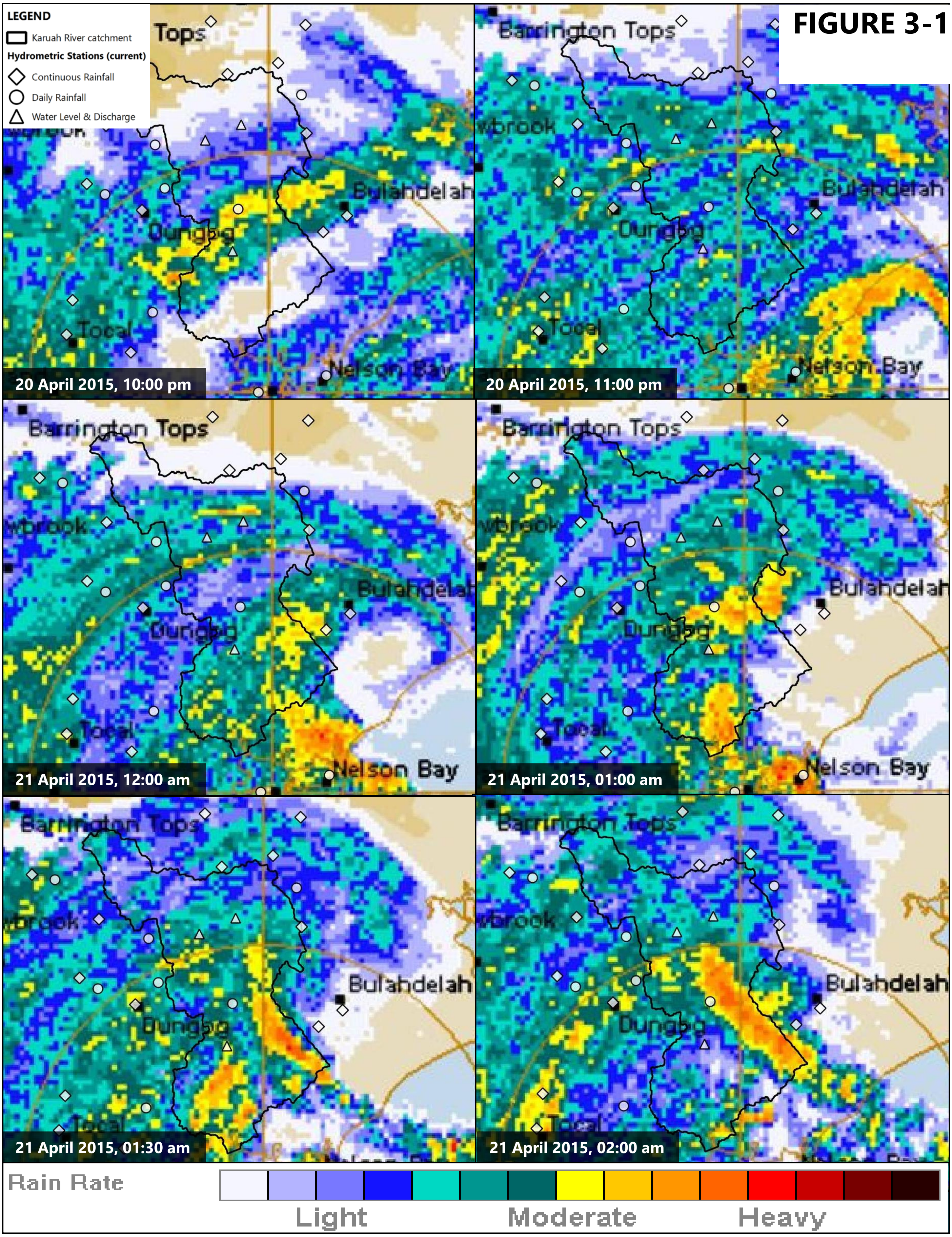
By 4 am this zone of heavy rainfall had largely disbanded, with the lower Karuah River catchment experiencing little rainfall by 5 am and the storm cell having largely moved on to the Williams River catchment by 6 am with heavy rainfall centred around Dungog.

The location of hydrometric data stations is also indicated in **Figure 3-1** and **Figure 3-2**. It is evident that there was significant spatial and temporal variation in rainfall intensity across the Karuah River catchment throughout the event which could not be fully captured by the available rainfall stations.

Rainfall totals for the 24 hour period from 9 am on 20th April to 9 am on 21st April 2015 at all stations from which data was acquired are presented spatially in **Figure 3-3**.

It is noted that the rainfall contours shown, as determined by inverse-distance-weighting from available rainfall stations, may not accurately reflect the true distribution of rainfall, as evident by comparison with radar rainfall rate imagery. In particular, it is evident from the radar imagery that rainfall over the upper Mill Creek, Lamans Creek, Alderley Creek and The Branch River catchments is likely to have been comparable to that recorded at the Crawford gauge.

FIGURE 3-1



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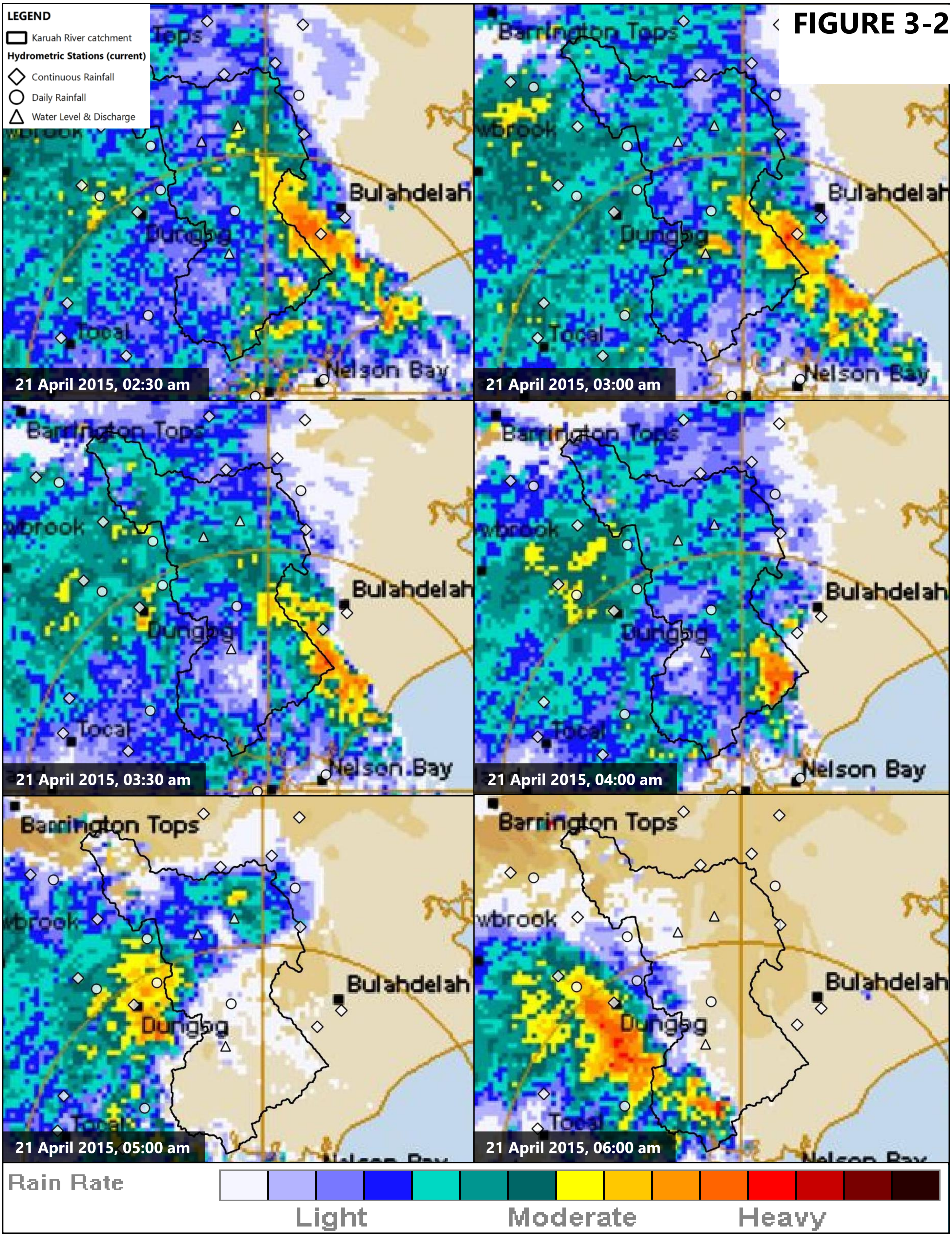
BOM RADAR RAINFALL RATE IMAGERY
21 APRIL 2015 EVENT

FIGURE 3-2



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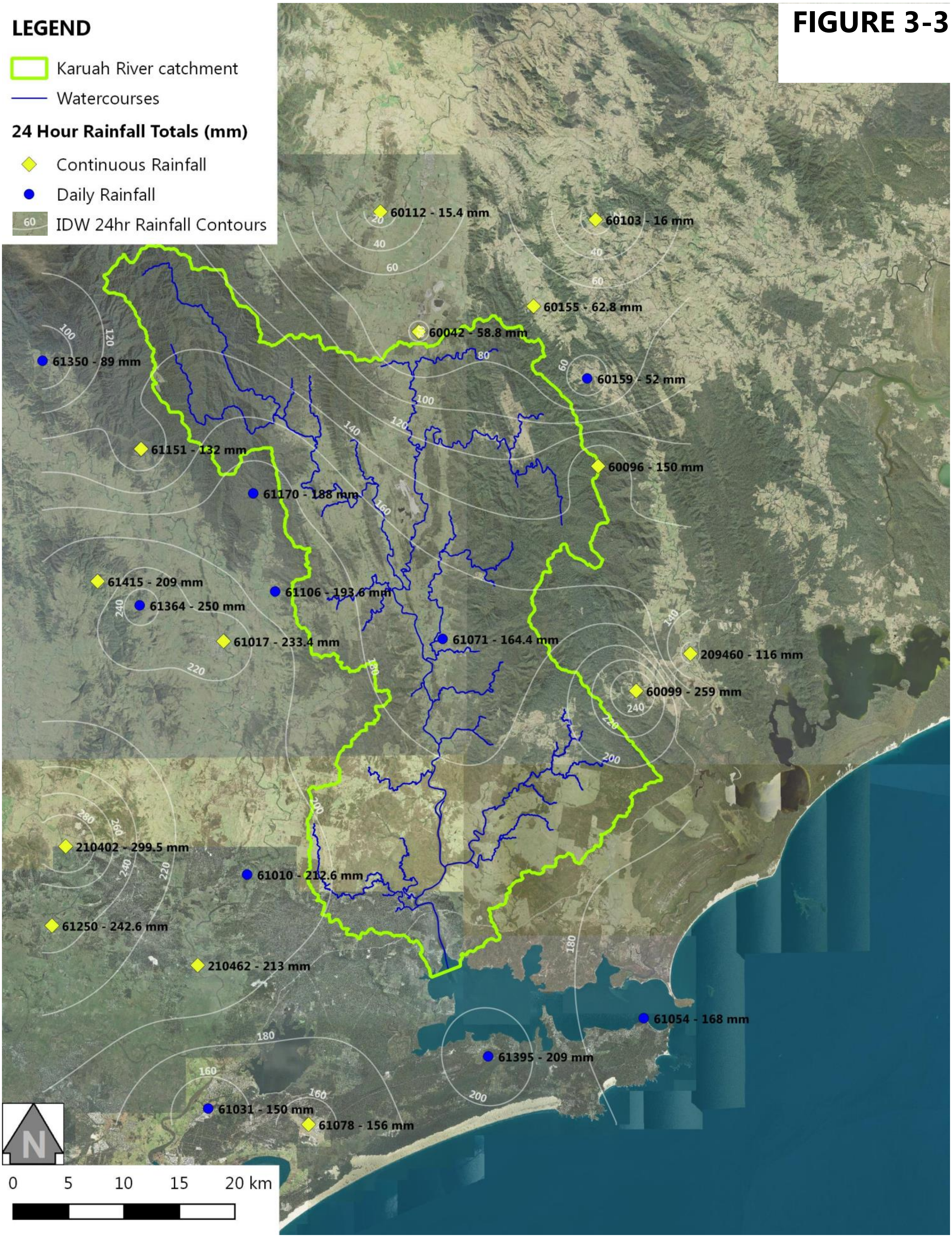
BOM RADAR RAINFALL RATE IMAGERY
21 APRIL 2015 EVENT



24 HOUR RAINFALL TOTALS
9 AM 20 APRIL TO 9 AM 21 APRIL 2015

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3.3.2 Rainfall Data

A cumulative rainfall plot for the period from 9 am 20 April to 9 am 21 April 2015 is presented in **Figure 3-4** including selected gauges most relevant to the Karuah River catchment.

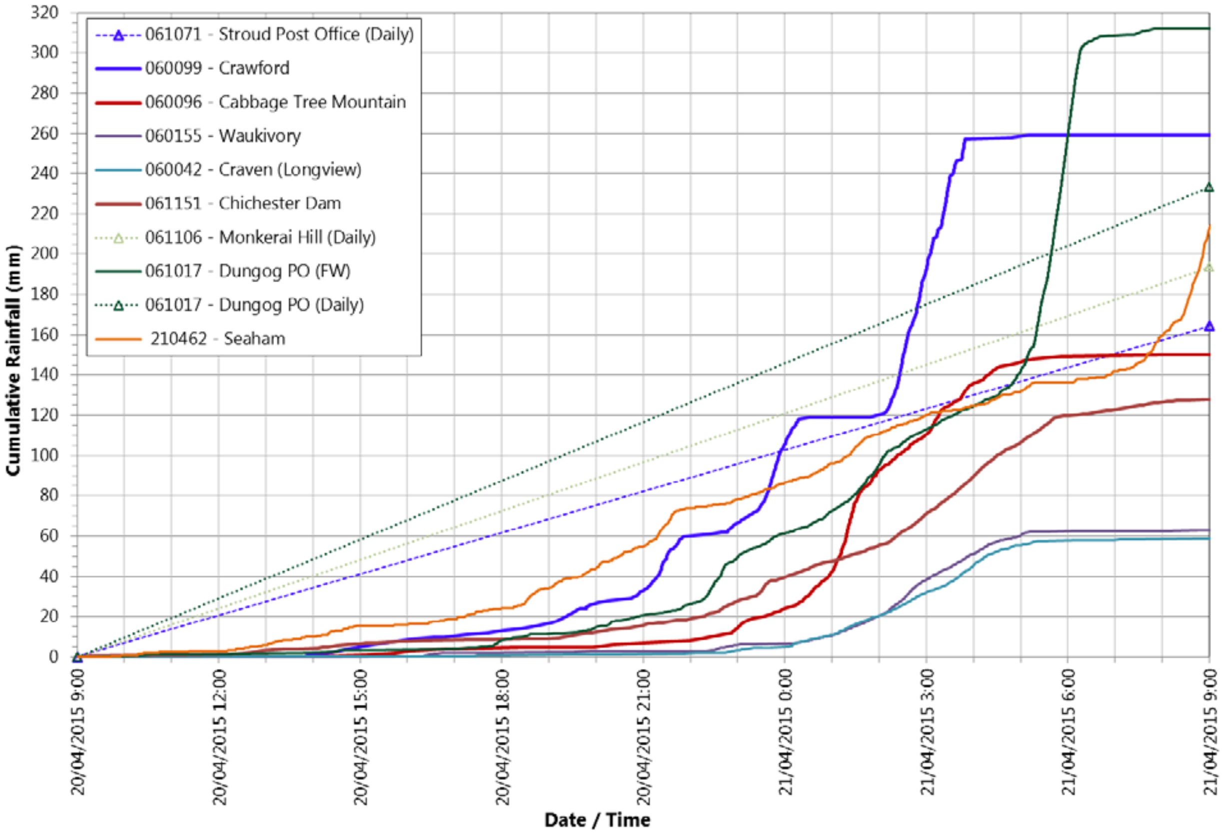


Figure 3-4 Cumulative rainfall plot for the period 9 am 20 April to 9 am 21 April 2015

The BoM daily rainfall station at Stroud is the only rainfall station located within the Karuah River catchment. It recorded a 24 hour rainfall total of 164.4 mm for the 24 hour period to 9 am on 21st April 2015. The nearest pluviometer gauges at Cabbage Tree Mountain and Crawford recorded 24 hour totals of 158 mm and 259 mm, respectively.

The Crawford gauge is most representative of the heavy rainfall band that formed over the south-east of the catchment. Rainfall over the upper catchment was generally lower with 24 hour totals of 62.8 mm, 58.8 mm and 127.6 mm recorded at the Waukivory, Craven and Chichester Dam stations, respectively.

3.3.3 Assessment of Rainfall Return Period

In order to assess the relative intensity and return period of rainfall during the April 2015 event, maximum recorded rainfall depths over durations of one to 24 hours have been plotted against design ARR2016 Intensity-Frequency-Duration (IFD) curves for the catchment centroid (refer **Figure 3-5**). IFD curves for the 0.5% and 0.2% AEP events have been scaled from the 1% AEP event using 'growth factors' of 1.140 and 1.344 respectively, as specified in Book 8, Chapter 3 of ARR 2016.

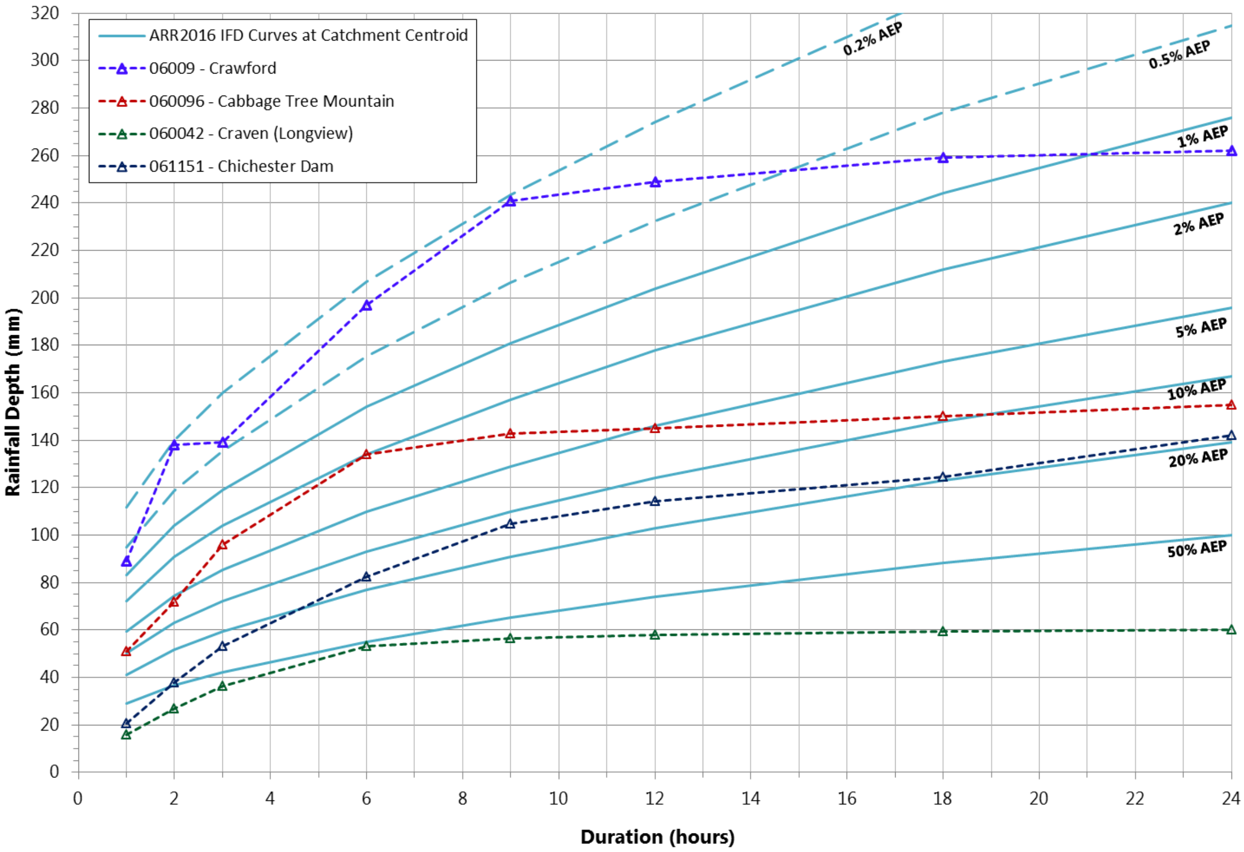


Figure 3-5 Comparison of recorded rainfall and design rainfall for 21 April 2015 event

The plot shows that rainfall at the Crawford gauge exceeded the 1% AEP design rainfall over durations from one hour to 18 hours, and was approximately equal to a 0.2% AEP event over durations of two and 9 hours.

Rainfall at Cabbage Tree Mountain gauge exceeded a 10% AEP design event for all durations except 24 hours, exceeded a 5% AEP for durations from 3 to 9 hours, and was as high as a 2% AEP event over a duration of 6 hours.

Rainfall at Chichester Dam exceeded a 20% AEP design event for durations of 6 to 24 hours, while rainfall at Craven did not exceed a 50% AEP design event over any duration.

3.3.4 Stream Gauge Data

Stream flow data downloaded from the DPI Water website for the three gauges within the Karuah River catchment is presented in **Figure 3-6**. As there has been considerable change in the discharge rating table for the Booral gauge over time, gauged flows as determined using both the 2016 and 2007 DPI Water rating tables are presented as well as flows determined using a rating table extracted from the developed TUFLOW model.

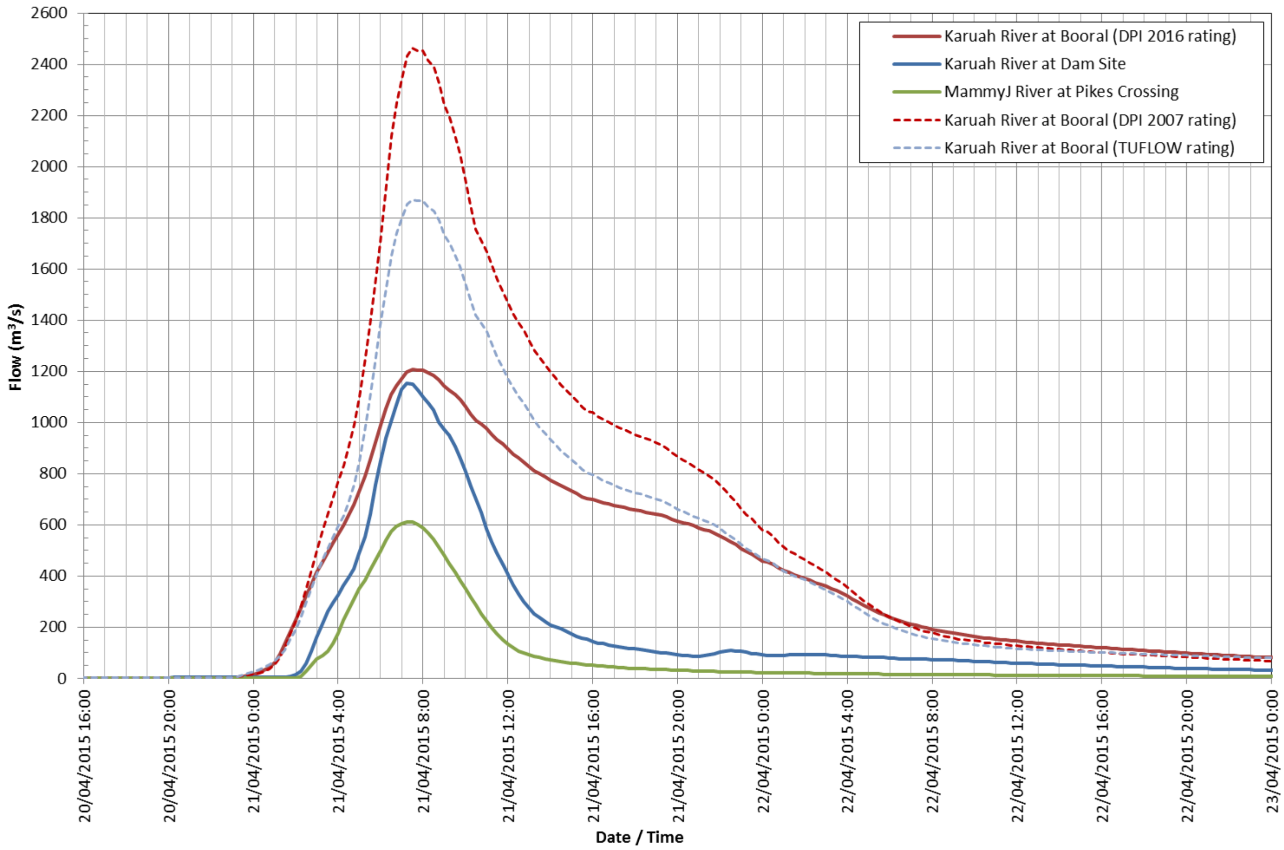


Figure 3-6 DPI Water streamflow data for 20 to 22 April 2015

Flows at the Karuah River at Dam Site and Mammy Johnson River at Pikes Crossing gauges peaked at 7:15 am, while flows at the Karuah River at Booral gauge peaked just 15 minutes later at 7:30 am. Given the significant length of river between the Dam Site and Pikes Crossing gauges and the Booral gauge (greater than 30 kilometres), this suggests that the flood peak at the Booral gauge was driven by flows from nearer catchments such as Alderley Creek, Lamans Creek, Mill Creek and perhaps Ram Station Creek, where observed rainfall was also more intense. The secondary “hump” in the Booral hydrograph at around 6 pm would then appear to relate to flows arriving from the upper Karuah and Mammy Johnsons River catchments.

3.3.5 Review of Stream Gauge Rating Tables

Due to the large difference between rating tables for the Booral gauge used during the 2007 and 2015 events a review of DPI rating tables was undertaken. There was little change in rating tables for the Karuah River at the Dam site or Mammy Johnsons River at Pikes Crossing gauges over this period, and the latest rating tables have therefore been adopted as appropriate.

As a first step, a sanity check of gauged flow volumes for the April 2015 event was undertaken considering the catchment area above each gauge, recorded rainfall throughout the catchment and the range of rainfall losses that may be expected (refer **Table 3-2**). Based on IL values (10 to 40 mm) and CL values (1 to 8 mm) presented in ARR 1987 and ARR 2016, total rainfall losses in the range of about 20 to 80 mm (considering that the full CL rate only applies during periods of sufficient rainfall) could have been expected over the duration of the event.

Table 3-2 Review of gauged flow volumes for the April 2015 event

	Location	Catchment Area (ha)	Event gauged flow volume (ML)	Indicated Excess Rainfall (mm)	Average event rainfall across catchment determined by IDW (mm)	Average losses across catchment to match gauged flow (mm)
	Karuah River at Dam Site	29217	30424	104.1	147.1	43.0
	Mammy Johnsons River at Pikes Crossing	15751	14452	91.8	119.5	27.8
2016 Rating	Karuah River at Booral	97901	74924	76.5	142.9	66.4
2016 Rating	Booral excluding catchment above Dam Site and Pikes Crossing gauges	52933	30048	56.8	147.7	**90.9**
2007 Rating	Karuah River at Booral	97901	114850	117.3	142.9	25.6
2007 Rating	Booral excluding catchment above Dam Site and Pikes Crossing gauges	52933	69974	132.2	147.7	**15.5**

The analyses presented in **Table 3-2** show that for the gauged flow volume at Booral using the 2016 rating table to be correct, total rainfall losses of over 90 mm would need to have occurred over the mid to lower catchment, equating to IL/CL values which are very much at the upper end of or above those recommended in ARR 2016 for the east coast of NSW.

Conversely, for the gauged flow volume at Booral using the 2007 rating table to be correct, total rainfall losses of less than 16 mm would need to have occurred over the mid to lower catchment, equating to IL/CL values which are low compared to those recommended in ARR2016 for the east coast of NSW. This suggests that a rating somewhere in between DPI Water's 2016 and 2007 rating tables is likely to be more appropriate.

The rating tables applied by DPI Water are derived by fitting a curve to field gaugings that have been undertaken at the station location during its period of record. **Figure 3-7** presents results from field gaugings at Booral against the 2016 and 2007 rating curves.

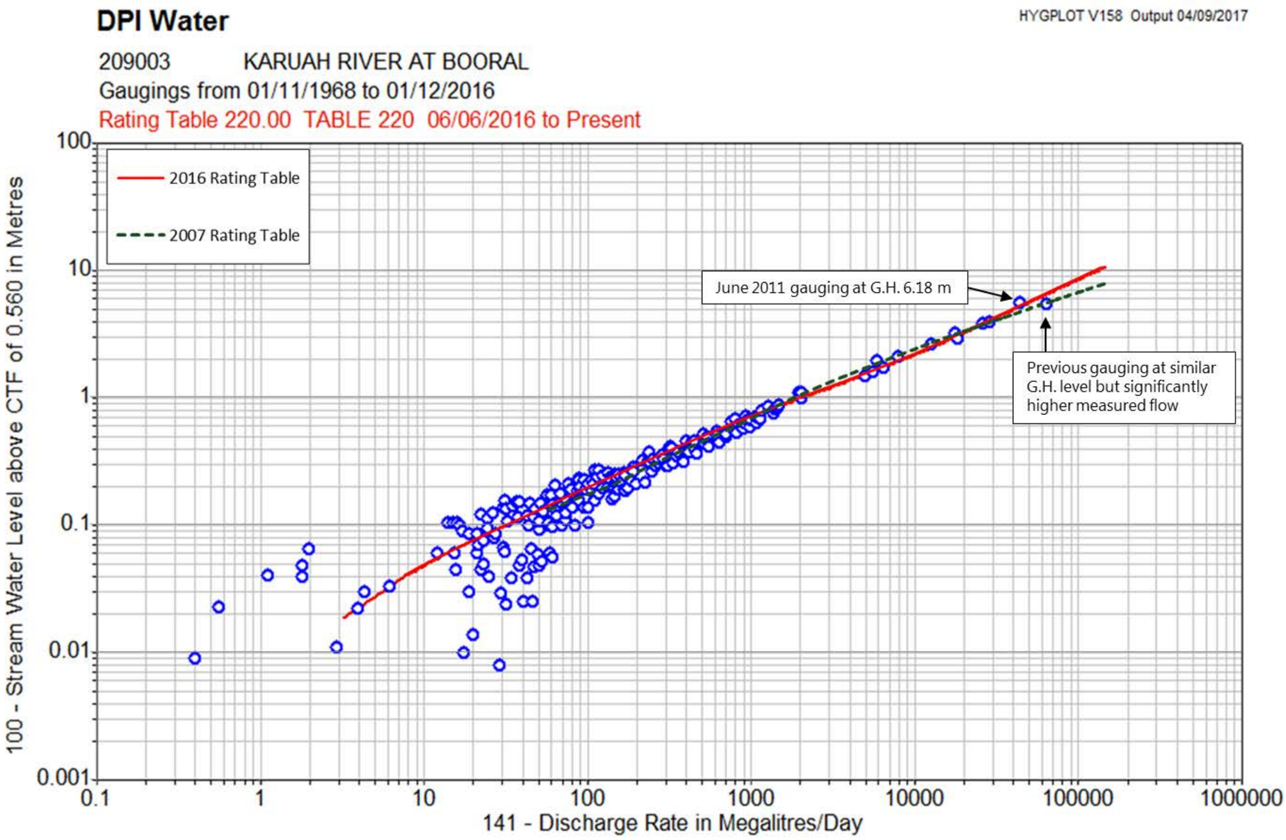


Figure 3-7 Analysis of Rating Curves for the Karuah River at Booral Gauge

While on the logarithmic scale of the plot presented in **Figure 3-7** there may not appear to be a significant difference between the 2016 and 2007 rating curves, their deviation at higher gauge levels (above about 5 m on the chart) represents a large percentage difference in flow. Given that there are fewer field gaugings completed at high stream levels, the results of a single gauging can have a large influence on the upper section of the rating curve. The June 2011 gauging resulted in a significant difference in the upper parts of the 2016 and 2007 rating curves and, based on the above review of April 2015 flow volume, it is considered likely to be unreliable.

Further evidence of the probable unreliability of the June 2011 field gauging and resulting 2016 rating table is evident in the shape of the 2016 rating curve. The curve inflects upwards from around the 2 metres above zero flow level meaning that the rate of flow increase decreases with increasing flood level. This is counter to the behaviour that would generally be expected whereby the channel cross-section increases in width with increasing stream level resulting in an increasing rate of increase in cross-sectional area that would typically be expected to result in a similar increasing rate of increase in flow.

On this basis, it is considered that a rating somewhere in between DPI Water's 2016 and 2007 rating tables is likely to be appropriate.

Accordingly, a rating curve was extracted from the developed TUFLOW hydraulic model for comparison and found to lie in the expected range.

3.3.6 Ocean and Port Stephens Estuary Water Levels

Data from MHL's three water level stations in Port Stephens and the lower Karuah River for the April 2015 event is presented in **Figure 3-8**.

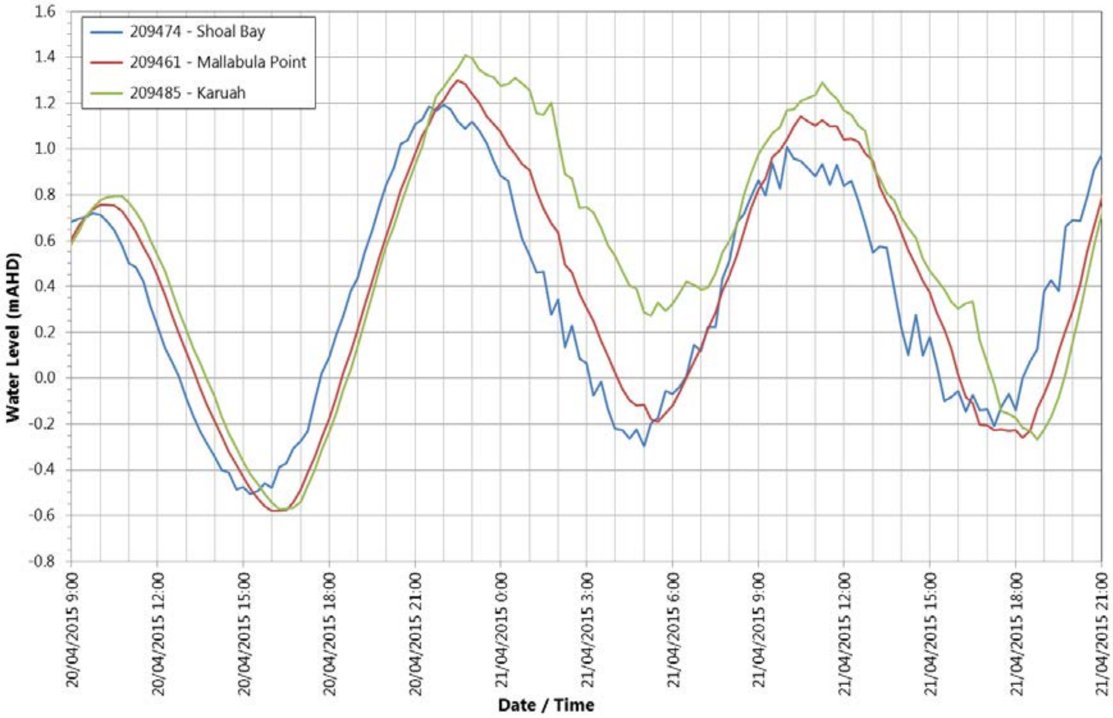


Figure 3-8 MHL ocean and estuary water level data for 20 and 21 April 2015

Given its similarity to the Karuah River gauge in terms of timing and peak tidal levels prior to the flood event, and its greater proximity to the downstream model boundary than the Shoal Bay gauge, data from the Mallabula Point gauge would provide the most appropriate downstream boundary condition for use in the model calibration.

It is also evident from **Figure 3-8** that the Karuah River gauge recorded higher water levels than at Mallabula Point. Given the location of the gauge close to Port Stephens and the results of subsequent hydraulic modelling, it appears that other factors such as wind setup are likely to have contributed to this difference more so than catchment flows.

3.3.7 Hydrologic Model Calibration

Rainfall Data

Recorded rainfall from the Crawford, Cabbage Tree Mountain, Waukivory, Craven, Chichester Dam and Seaham stations was applied in the WBNM hydrologic model for the April 2015 calibration. Data from the Stroud daily rainfall station was also included by adopting a temporal pattern averaging those recorded at the Crawford and Cabbage Tree Mountain gauges, and a duplicate of the Crawford gauge was placed near the top of the Mill Creek catchment to replicate heavy rainfall observed in BoM radar imagery in this area.

The location of the Chichester Dam gauge was modified in order to increase its influence on simulated rainfall over the upper Karuah River catchment. Rainfall definition below Booral may be less reliable due to a lower density of pluviometers.

Recorded rainfall from the Chichester Dam gauge was applied to the upper Karuah River catchment with a 30 minute delay. This was considered appropriate for the following reasons.

- Review of BoM radar rainfall rate imagery shows bands of rainfall generally moving in a northerly direction across this part of the catchment, reaching its centre some time after passing the Chichester Dam gauge location.
- The simulated hydrograph had the desired shape but was arriving earlier than recorded. The desired lag could not be achieved by changes to model parameters as this would have had a negative impact on the already well calibrated June 2007 event.

The WBNM software determines rainfall depths across each model sub-catchment from the input rainfall gauges using an inverse-distance-weighting algorithm, and the temporal pattern across each sub-catchment is taken from the nearest input rainfall gauge.

Hydrologic Model Parameters

Calibration of the hydrologic model involved modification of the WBNM runoff lag factor ‘C’ and stream routing lag factor ‘F’, as well as initial loss (IL) and continuing loss (CL) rate. The model was first calibrated to the Karuah River at Dam Site and Mammy Johnsons River at Pikes Crossing gauges so that the remainder of the catchment could be calibrated with these known flows set in place.

Parameters in the Mill Creek catchment were adjusted to achieve a flood peak close to the anecdotally reported peak time of about 5:00 am on 21 April, and to produce appropriate peak flows such that observed flood levels were matched by the TUFLOW hydraulic model.

Estimates of impervious areas were made from aerial photography for each model subcatchment, with values ranging from 1% to 30%. A runoff lag factor of 0.2 was applied to impervious areas and zero rainfall losses.

Calibration to the April 2015 event was undertaken simultaneously with verification to the June 2007 event to ensure that any parameter changes were appropriate to represent behaviour from both floods. The calibration was found to be complex, with adoption of default parameters or even uniform parameters across the catchment generating poor results.

Final adopted parameters are presented in **Table 3-3**.

Table 3-3 Adopted WBNM hydrologic model parameters for the April 2015 calibration event

Catchment	Runoff Lag Factor 'C'	Stream Routing Lag Factor 'F'	Initial Loss (mm)	Continuing Loss (mm)	Comments
Mammy Johnsons River U/S of Pikes Crossing	1.6	1.4	35.0	2.5	In order to achieve calibration at Pikes Crossing a default runoff lag and high stream lag were adopted.
Wards River and Mammy J. R. U/S of Stroud Road	2.0	1.5	40.0	8.0	In order to achieve calibration at Booral high runoff and stream lag values were adopted.
Karuah River U/S of Dam Site	0.9	1.2	35.0	0.0	In order to achieve calibration at Dam Site a low runoff lag was adopted. A CL of 0 provided the best result indicating that applied rainfall may have been somewhat lower than actual rainfall.
Karuah River from Dam Site to Booral	1.8	1.2	40.0	8.0	In order to achieve calibration at Booral a high runoff lag and moderate stream lag were adopted.
Ram Station Creek	1.2	1.2	40.0	8.0	A moderately low runoff lag was adopted for consistency with values for other creeks in the study area.
Mill Creek U/S of Bucketts Way	0.9	1.0	1.0	2.0	A low runoff lag was adopted in order to calibrate to peak flood levels and time of flood peak at Stroud. Low IL and CL were required to achieve peak flood levels at Stroud.
Lamans Creek U/S of Bucketts Way	0.9	1.0	40.0	8.0	A low runoff lag was adopted per the Mill Creek catchment.
Lower Mill Creek and Alderley Creek	1.6	1.2	40.0	8.0	In order to achieve calibration at Booral a default runoff lag and moderate stream lag were adopted.
Karuah River from Booral to Karuah	1.6	1.0	37.5	6.0	In the absence of calibration data downstream of Booral, default runoff lag and stream lag values were adopted.

Comparison of Gauged and Simulated Flood Hydrographs

The ability of the developed WBNM hydrologic model to simulate the catchment response during the April 2015 flood event was assessed by comparing simulated flood hydrographs with DPI Water stream gauge hydrographs estimated from recorded water levels using rating tables. As there is significant uncertainty regarding available DPI Water rating tables for the Booral gauge, the calibration aimed to reproduce a hydrograph developed by extracting a rating curve from the TUFLOW hydraulic model. This was considered appropriate as it results in a peak flow approximately mid-way between the 2016 and 2007 DPI Water rating tables.

The results of the April 2015 hydrologic model calibration are presented in **Figure 3-9**.

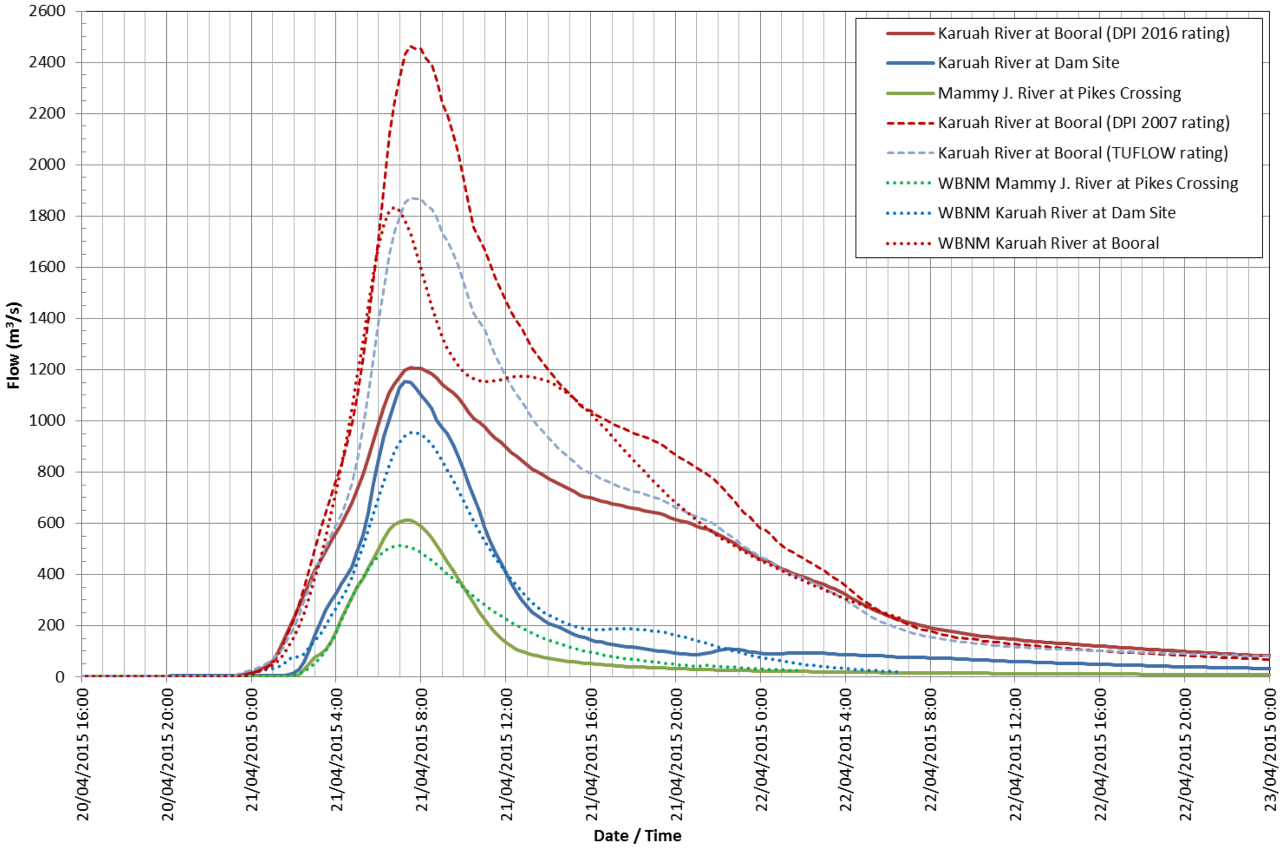


Figure 3-9 Comparison of gauged and simulated flows for the April 2015 event

The results of the calibration can be summarised as follows:

- Karuah River at Dam Site
  - The overall shape of the flood hydrograph is well represented including the timing of the flood peak.
  - The peak simulated flow is somewhat lower than the peak gauged flow, despite zero continuing rainfall losses being applied to this catchment. It is therefore considered that the difference in peak flow is attributable primarily to differences between the applied and actual rainfall, and / or inaccuracies in the DPI Water rating table. It was not practical to achieve a higher peak simulated flow as this would have required the use of parameters outside of recommended ranges and would have negatively impacted on other aspects of the model calibration and verification.
- Mammy Johnsons River at Pikes Crossing
  - The overall shape of the flood hydrograph is well represented including the timing of the flood peak.
  - The peak simulated flow is only slightly lower than the peak gauged flow.
- Karuah River at Booral
  - The overall shape of the flood hydrograph is reasonably well represented including the timing of the flood peak.

- The peak flood flow is well represented. It is noted that the peak flow at Booral was purposefully underestimated in the WBNM model as the resulting peak flow at this location in the TUFLOW model was found to be slightly higher.
- While there are differences evident between the simulated and gauged hydrograph shapes (as determined using the TFULOW derived rating table), for the purposes of the latter design flood modelling it was considered most important to replicate the timing and magnitude of the initial flood peak.
- Efforts were made to improve the shape of the falling limb of the simulated hydrograph, however the required parameter adjustments were found to have negative impacts on the initial flood peak and on the results of the June 2007 model verification.

Given the uncertainty in the distribution of rainfall across the catchment during the event, and in the reliability of the rating tables applied at the available stream gauges, the results are considered to constitute a successful calibration of the hydrologic model. It is noted that no calibration information was available below the Booral stream gauge and therefore default model parameters have been adopted for this area.

3.3.8 Hydraulic Model Calibration

The hydraulic model calibration was assessed through the comparison of flood levels simulated by the TUFLOW model with available recorded and observed flood levels. This included comparisons at the DPI Water Karuah River at Booral gauge, the MHL Karuah River at Karuah gauge, and at 28 flood mark levels in Stroud.

Comparison of Recorded and Simulated Flood Levels

A comparison of recorded and simulated water levels at the Karuah River at Booral gauge for the April 2015 flood event is presented in **Figure 3-10**, and a comparison of gauged and simulated flows presented in **Figure 3-11**. As with the WBNM hydrologic model, the timing and level of the flood peak is well represented. The peak simulated flood level is 0.17 m higher than that recorded and occurs 15 minutes earlier. Considering the significant flood depth of over 10 metres and that flood levels remain in-bank, the TUFLOW model simulation provides a very good representation of peak flood behaviour at this location. Peak flood flows at Booral from the TUFLOW model are slightly higher than those from the WBNM model, but the two models show good agreement in terms of stream routing behaviour.

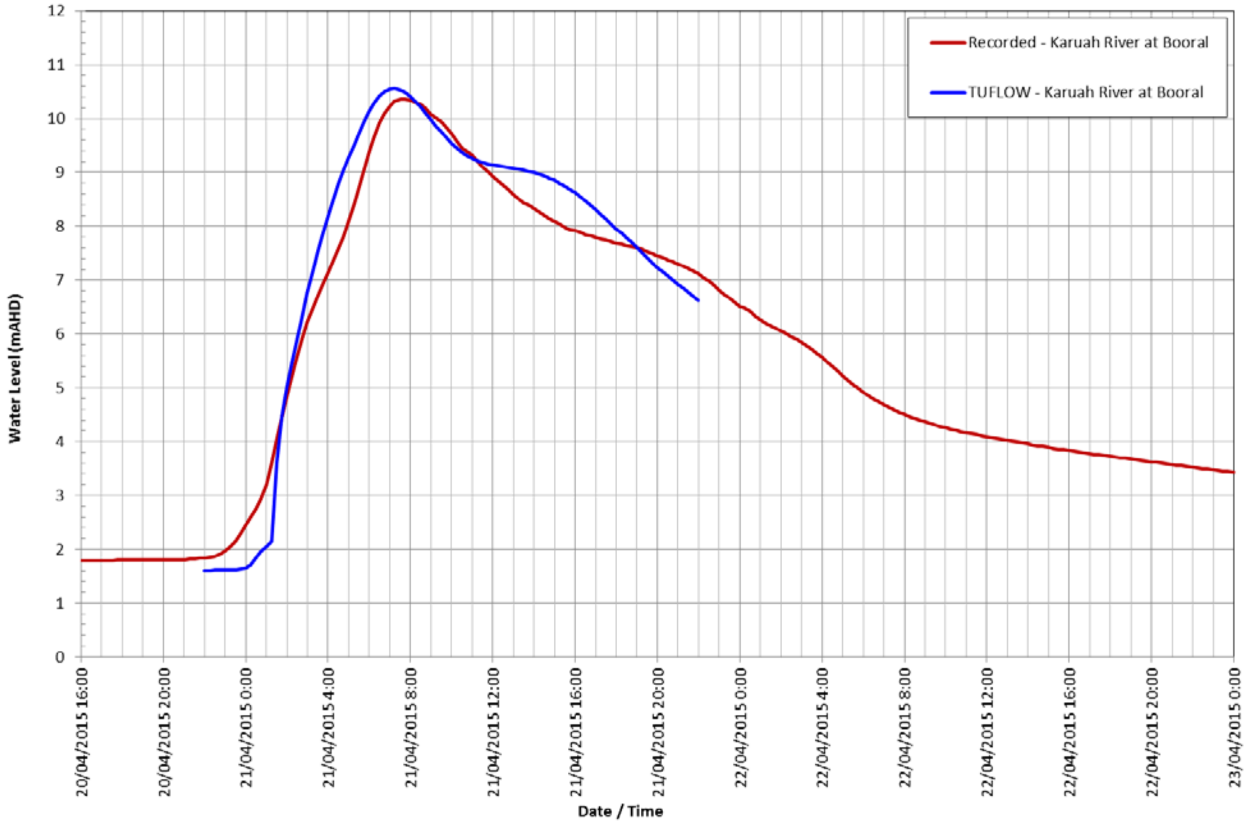


Figure 3-10 Comparison of recorded and simulated flood levels at the Booral gauge for the April 2015 event

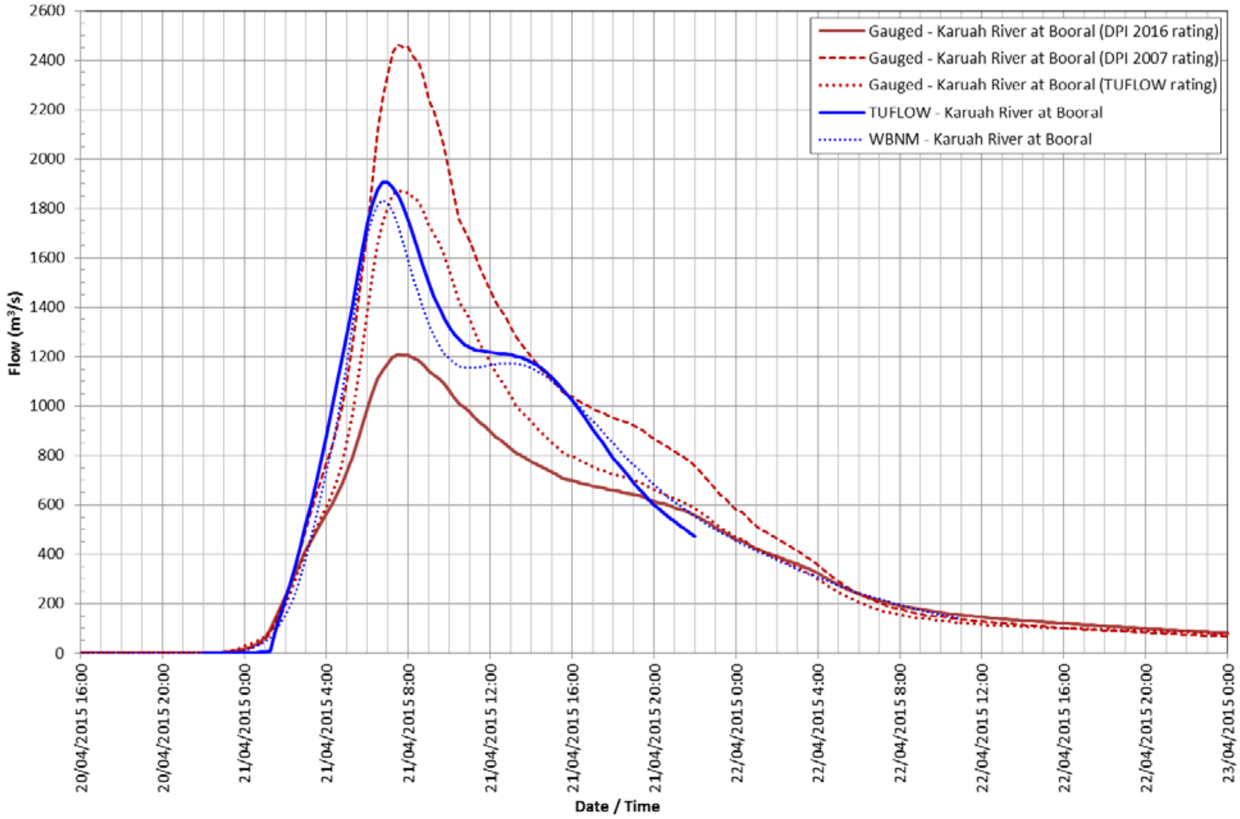


Figure 3-11 Comparison of gauged and simulated hydrographs at the Booral gauge for the April 2015 event

A comparison of simulated and recorded peak flood levels at the Booral and Karuah gauges for the April 2015 event is presented graphically in **Figure 3-12**. Peak simulated flood levels are 0.1 m lower than recorded at the Karuah gauge, and are similar to the Mallabula levels applied at the downstream boundary. This suggests that other factors such as wind setup may have contributed to peak flood levels at the Karuah gauge rather than catchment inflows.

Comparison of Simulated Peak Flood Levels to Flood Marks

A total of 28 flood marks were compiled for the April 2015 flood, all located in the vicinity of Mill Creek at Stroud. MidCoast Council surveyed 11 of the flood marks following the event, while 10 were extracted from *Flood Data Collection, Dungog and Stroud Flood Event 21 April 2015* (Paterson Consultants 2015), 5 from flood intelligence collected by the NSW SES, and 2 from the community questionnaire issued as part of this study. Total flood levels were derived from the observations contained in the Paterson Consultants and SES reports using detailed floor level survey or 2016 LiDAR as a datum.

Results of the comparison of flood mark levels and peak simulated flood levels are summarised in **Table 3-4**and presented graphically in **Figure 3-13**. Differences between peak simulated flood levels and flood mark levels range from +0.05 m to -0.25 m, with an average difference of -0.05 m indicating that the simulated flood levels are, on average, slightly lower than observed levels. The simulated flood peak occurred at 5:00 am on 21 April, which agrees well with observations from residents as reported in the SES flood intelligence.

Community consultation regarding the April 2015 flood event found that blockage, particularly of the old timber bridge, was believed to have contributed to the severity of the flooding. In light of this, a second calibration scenario was simulated with a blockage factor of 20% applied to the old and new Mill Creek bridges as determined in consideration of ARR 2016 guidance.

Results of the comparison of flood mark levels and peak simulated flood levels with structural blockages are summarised in **Table 3-5**and presented graphically in **Figure 3-14**. Differences between peak simulated flood levels and flood mark levels range from +0.16 m to -0.17 m, with an average difference of +0.02 m indicating that the simulated flood levels are, on average, slightly higher than observed levels. In general, application of the 20% blockage factor at the Mill Creek bridges resulted in higher flood levels and improved calibration at locations upstream of The Bucketts Way / Cowper Street but resulted in levels that were higher than observed elsewhere, particularly at the Stroud Community Lodge.

Overall the comparison indicates that the TUFLOW model and associated WBNM hydrologic model are able to provide a good representation of observed flood conditions along Mill Creek at Stroud for the April 2015 flood event. Peak flood levels better matching flood mark levels may have been achieved through further modification of a number of parameters; however, this was not considered appropriate as changes that may benefit the calibration at one location were likely to have a negative impact at others.

Additionally, it is considered likely that very localised hydraulic effects occurring on a scale not resolved by the TUFLOW model (for example local super elevation on the upstream face of structures, trees and posts in flowing water) may contribute to some of the larger observed discrepancies. This possibility appears to be reinforced by the significant variation in observed flood mark levels at points in quite close proximity to one another.

Table 3-4 Comparison of simulated peak flood levels with flood marks at Stroud for the April 2015 event, unblocked scenario

Location	Easting	Northing	Flood Mark Level (mAHD)	Peak Simulated Flood Level (mAHD)	Difference (m)	Source of Flood Mark
Mill Creek bridge (U/S)	402502	6414805	31.19	31.19	0.00	MidCoast Council survey
Mill Creek bridge (D/S)	402496	6414795	31.17	31.08	-0.09	MidCoast Council survey
Stroud Showground	402578	6414795	32.01	31.77	-0.24	MidCoast Council survey
Stroud Showground	402637	6414724	31.87	31.63	-0.25	MidCoast Council survey
Near Mill Brook culverts	402763	6414625	32.19	32.10	-0.09	MidCoast Council survey
Stroud Community Lodge	402665	6414616	31.39	31.40	0.01	MidCoast Council survey
Stroud Community Lodge	402692	6414618	31.41	31.41	-0.01	MidCoast Council survey
Fence post U/S of Cowper Street	402679	6414688	31.69	31.62	-0.07	MidCoast Council survey
Near Mill Brook culverts	402766	6414619	32.10	32.11	0.01	MidCoast Council survey
Near Mill Creek bridge (U/S)	402514	6414793	31.74	31.72	-0.02	MidCoast Council survey
Near Mill Creek bridge (U/S)	402466	6414872	31.73	31.71	-0.02	MidCoast Council survey
37 Cowper Street	402399	6414968	32.01	31.97	-0.04	SES flood intelligence [1]
41 Cowper Street	402413	6414934	32.01	31.99	-0.02	SES Flood Intelligence [1]
14 Britton Court Road	402317	6414885	30.42	30.47	0.05	SES Flood Intelligence [1]
9 Britton Court Road	402344	6414858	30.69	30.65	-0.04	SES Flood Intelligence [1]
39 Cowper Street	402381	6414949	31.85	31.83	-0.02	SES flood intelligence [1]
Showground - laundry block	402638	6414935	32.20	31.99	-0.20	Paterson Consultants [2]
Showground - shower block	402630	6414934	32.04	31.98	-0.06	Paterson Consultants [2]
Erin Street sewer vent marker	402335	6414292	28.67	28.63	-0.05	Paterson Consultants [2]
Stroud Community Lodge	402657	6414621	31.37	31.39	0.02	Paterson Consultants [2]
113 Millbrook Road	403026	6415632	34.07	34.04	-0.03	Paterson Consultants [1]
83 Millbrook Road shed	403069	6415424	33.36	33.36	0.00	Paterson Consultants [2]
Showground - Luncheon Room	402585	6414866	31.83	31.77	-0.06	Paterson Consultants [2]
Showground - Kiosk	402566	6414793	31.77	31.70	-0.07	Paterson Consultants [2]
Swimming Pool	402733	6414708	31.93	31.79	-0.14	Paterson Consultants [2]
49 Cowper Street	402589	6414694	31.58	31.55	-0.03	Paterson Consultants [1]
7 Britton Court - inside	402379	6414883	30.90	30.94	0.04	Community Survey [1]
7 Britton Court - outside	402385	6414884	31.30	31.25	-0.05	Community Survey [1]

1 - 2009 floor level survey used as datum for derivation of flood mark level

2 - 2016 Dungog LiDAR used as datum for derivation of flood mark level

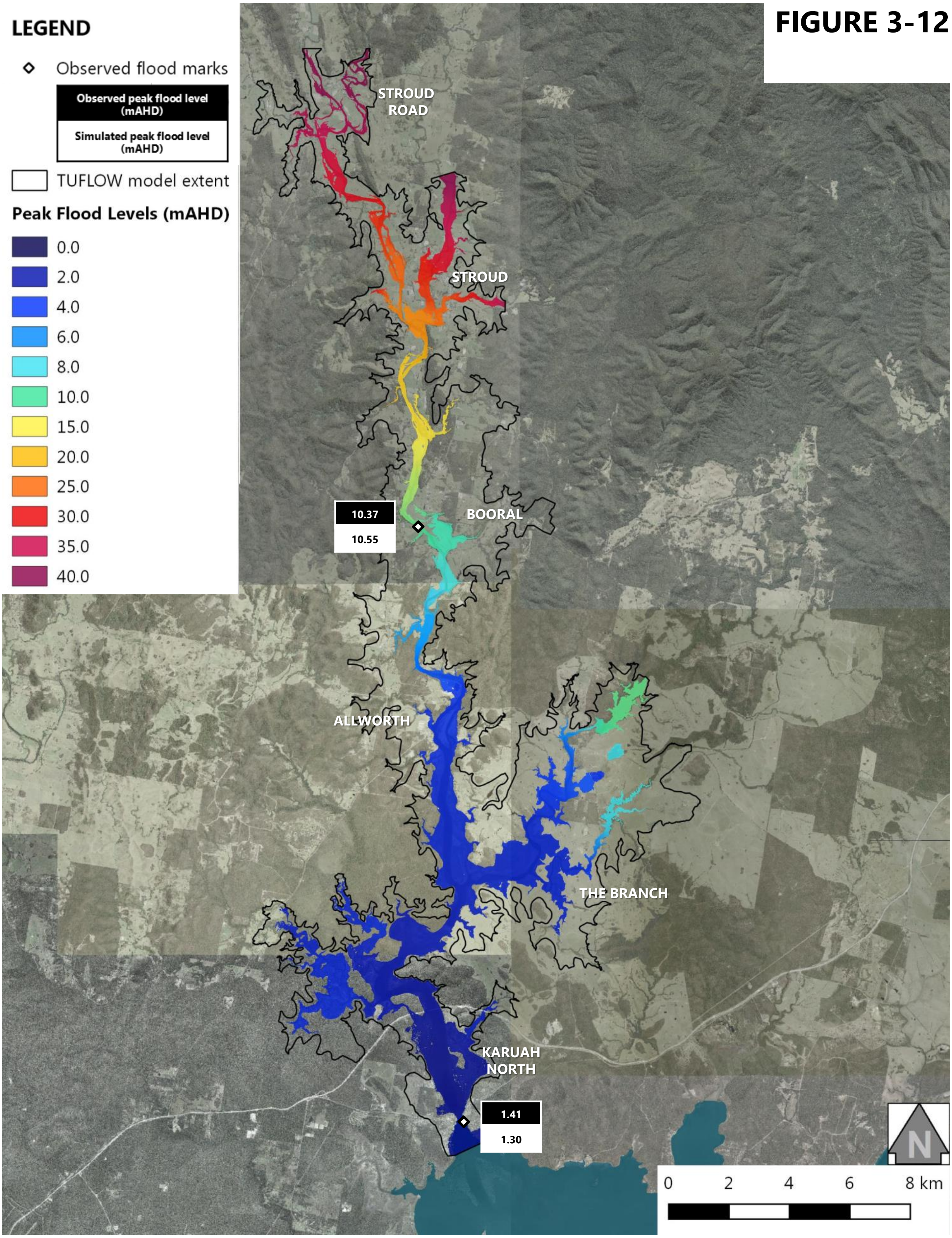
Table 3-5 Comparison of simulated peak flood levels with flood marks at Stroud for the April 2015 event, with 20% blockage of Mill Creek bridges

Location	Easting	Northing	Flood Mark Level (mAHD)	Peak Simulated Flood Level (mAHD)	Difference (m)	Source of Flood Mark
Mill Creek bridge (U/S)	402502	6414805	31.19	31.25	0.06	MidCoast Council survey
Mill Creek bridge (D/S)	402496	6414795	31.17	31.05	-0.12	MidCoast Council survey
Stroud Showground	402578	6414795	32.01	31.85	-0.16	MidCoast Council survey
Stroud Showground	402637	6414724	31.87	31.70	-0.17	MidCoast Council survey
Near Mill Brook culverts	402763	6414625	32.19	32.14	-0.05	MidCoast Council survey
Stroud Community Lodge	402665	6414616	31.39	31.54	0.14	MidCoast Council survey
Stroud Community Lodge	402692	6414618	31.41	31.55	0.14	MidCoast Council survey
Fence post U/S of Cowper Street	402679	6414688	31.69	31.69	0.00	MidCoast Council survey
Near Mill Brook culverts	402766	6414619	32.10	32.16	0.06	MidCoast Council survey
Near Mill Creek bridge (LHS)	402514	6414793	31.74	31.82	0.08	MidCoast Council survey
Near Mill Creek bridge (RHS)	402466	6414872	31.73	31.83	0.10	MidCoast Council survey
37 Cowper Street	402399	6414968	32.01	32.05	0.04	SES flood intelligence [1]
41 Cowper Street	402413	6414934	32.01	32.07	0.06	SES Flood Intelligence [1]
14 Britton Court Road	402317	6414885	30.42	30.50	0.08	SES Flood Intelligence [1]
9 Britton Court Road	402344	6414858	30.69	30.70	0.01	SES Flood Intelligence [1]
39 Cowper Street	402381	6414949	31.85	31.90	0.05	SES flood intelligence [1]
Showground - laundry block	402638	6414935	32.20	32.08	-0.12	Paterson Consultants [2]
Showground - shower block	402630	6414934	32.04	32.07	0.03	Paterson Consultants [2]
Erin Street sewer vent marker	402335	6414292	28.67	28.63	-0.05	Paterson Consultants [2]
Stroud Community Lodge	402657	6414621	31.37	31.53	0.16	Paterson Consultants [2]
113 Millbrook Road	403026	6415632	34.07	34.05	-0.02	Paterson Consultants [1]
83 Millbrook Road shed	403069	6415424	33.36	33.38	0.02	Paterson Consultants [2]
Showground - Luncheon Room	402585	6414866	31.83	31.86	0.03	Paterson Consultants [2]
Showground - Kiosk	402566	6414793	31.77	31.79	0.02	Paterson Consultants [2]
Swimming Pool	402733	6414708	31.93	31.85	-0.08	Paterson Consultants [2]
49 Cowper Street	402589	6414694	31.58	31.64	0.06	Paterson Consultants [1]
7 Britton Court - inside	402379	6414883	30.90	30.99	0.09	Community Survey [1]
7 Britton Court - outside	402385	6414884	31.30	31.31	0.01	Community Survey [1]

1 - 2009 floor level survey used as datum for derivation of flood mark level

2 - 2016 Dungog LiDAR used as datum for derivation of flood mark level

FIGURE 3-12



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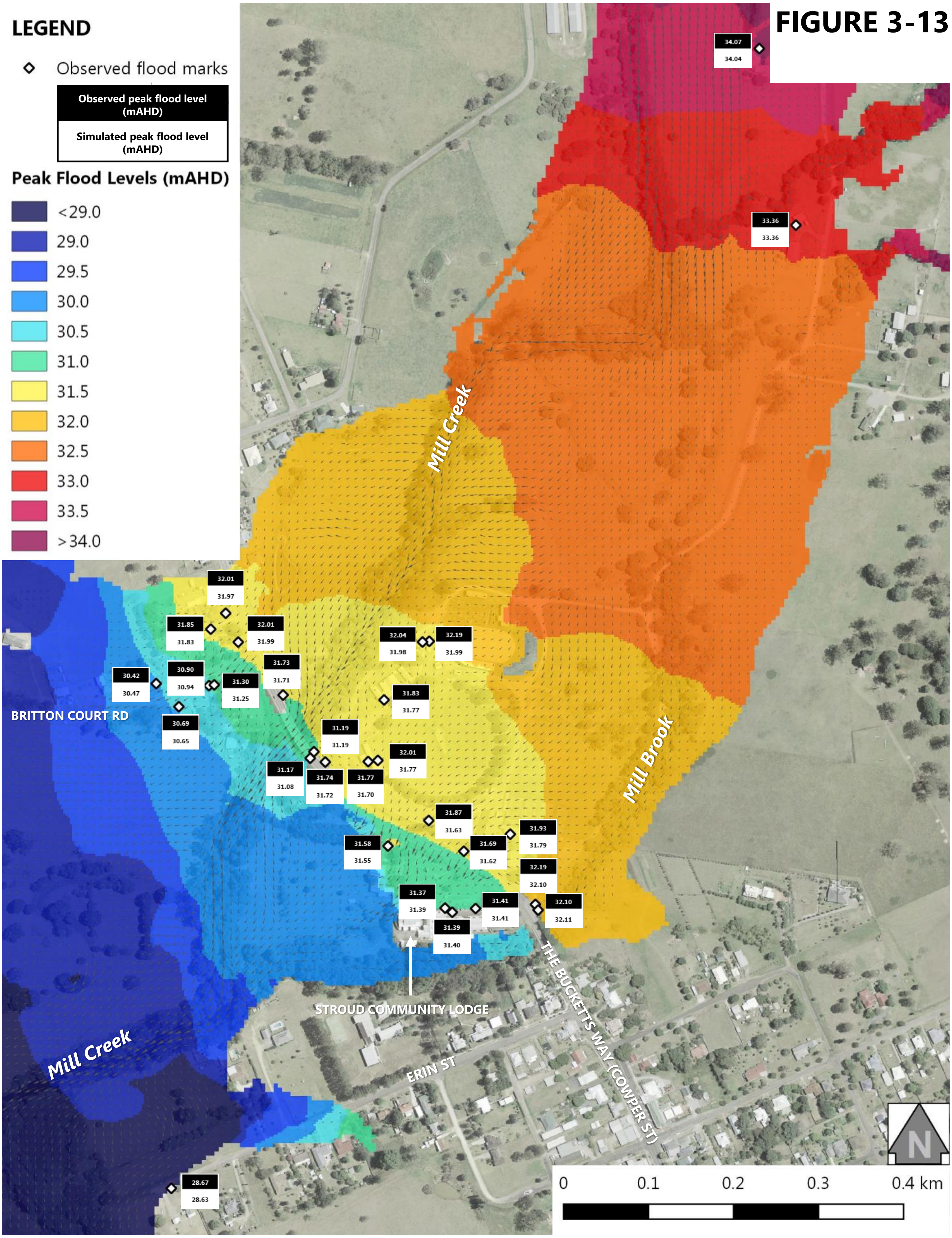
WorleyParsons Group

APRIL 2015 CALIBRATION SIMULATED PEAK FLOOD LEVELS

FIGURE 3-13



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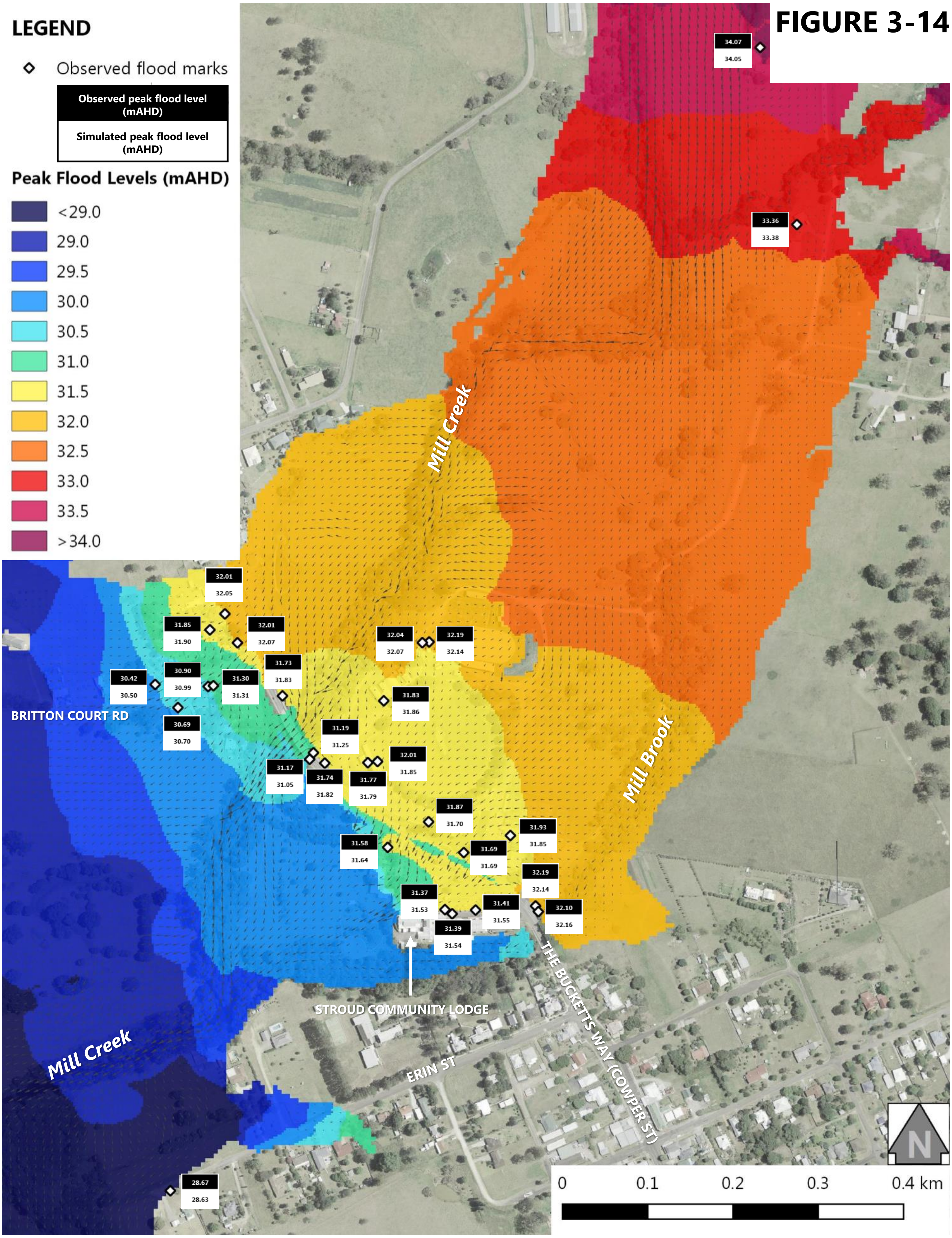
APRIL 2015 CALIBRATION
SIMULATED PEAK FLOOD LEVELS AT STROUD

FIGURE 3-14



APRIL 2015 CALIBRATION
SIMULATED PEAK FLOOD LEVELS AT STROUD
20% BLOCKAGE OF MILL CREEK BRIDGES

3.4 Model Verification – 8 June 2007 Event

3.4.1 Event Overview

The June 2007 storm event was associated with an East Coast Low that formed off the coast of NSW, just north of Newcastle. The storm produced strong winds, elevated ocean levels and sustained heavy rainfall, and caused widespread damage across the Central Coast and Hunter regions (Bureau of Meteorology, 2007). Significant flooding occurred in the Hunter, with minor flooding observed along the Karuah River.

3.4.2 Rainfall Data

A cumulative rainfall plot for the period from 9 am 7 June to 9 am 9 June 2007 is presented in **Figure 3-15** including selected gauges most relevant to the Karuah River catchment.

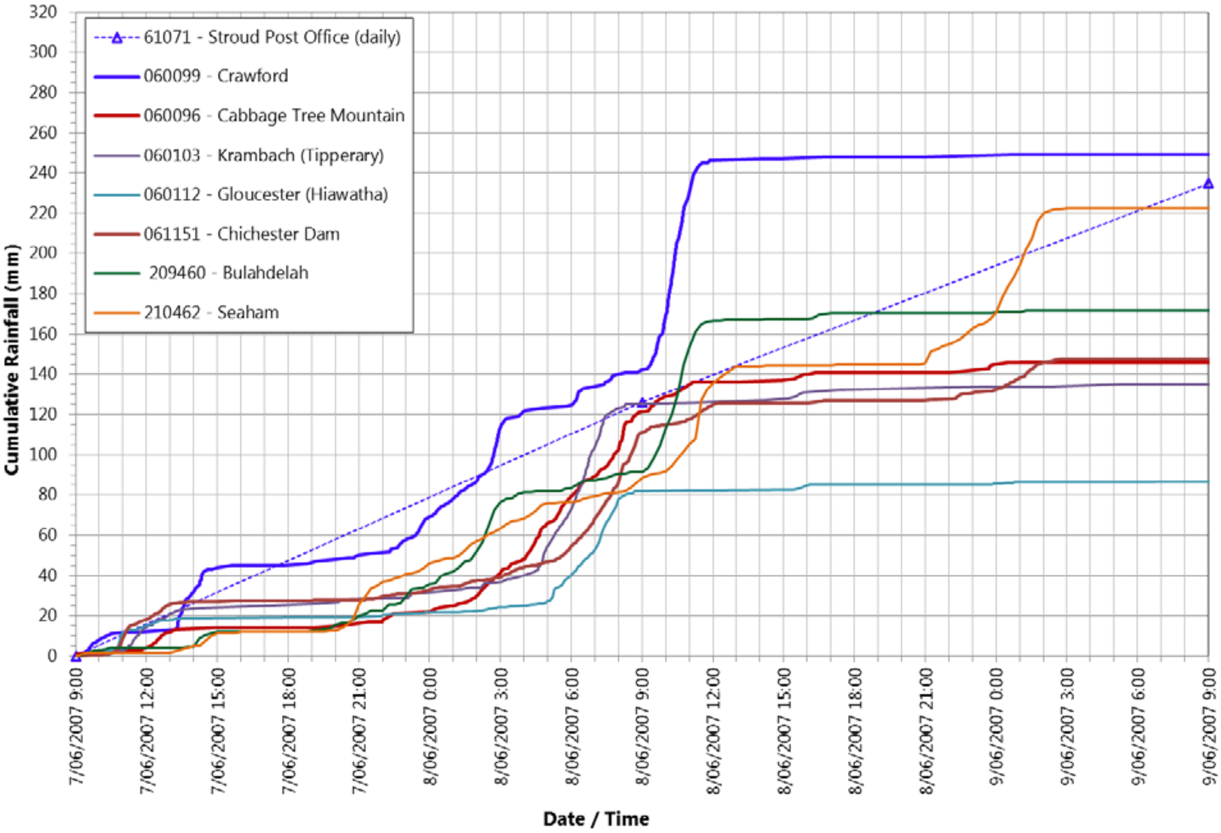


Figure 3-15 Cumulative rainfall plot for the period 9 am 7 June to 9 am 9 June 2007

The BoM daily rainfall station at Stroud is the only rainfall station located within the Karuah River catchment and recorded a 48 hour rainfall total of 235 mm. The Crawford pluviometer gauge recorded a 48 hour rainfall total of 249 mm with a period of sustained heavy rainfall evident between about 9 am and 11 am on 8 June. A number of other pluviometers recorded 48 hour totals in the order of 140 mm, while rainfall at the Hiawatha gauge was lower with a total of about 86.6 mm recorded.

3.4.3 Stream Gauge Data

Stream flow data for June 2007 downloaded from the DPI Water website for the three gauges within the Karuah River catchment is presented in **Figure 3-16**. As there has been considerable change in the discharge rating table for the Booral gauge over time, gauged flows as determined using the 2016 and 2007 DPI Water rating tables, and the rating table extracted from the TUFLOW hydraulic model are presented.

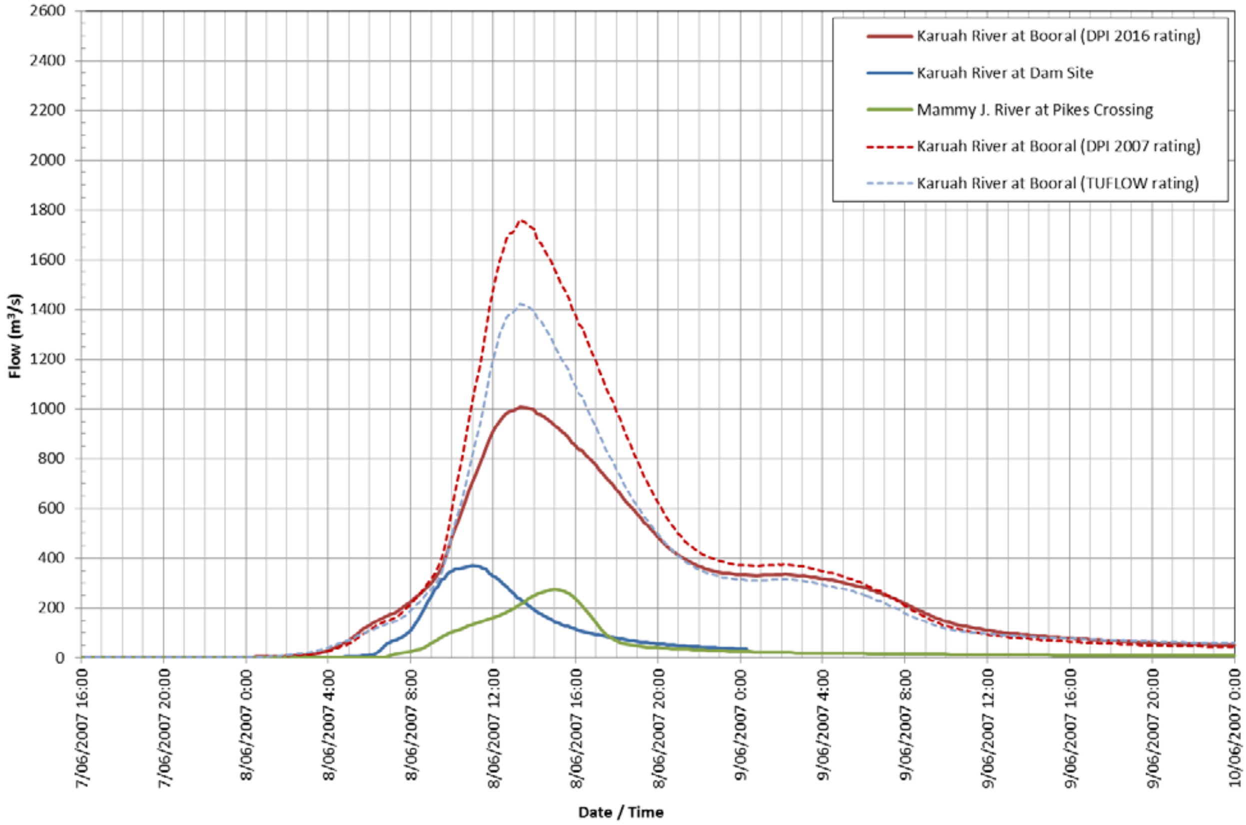


Figure 3-16 DPI Water streamflow data for 7 to 9 June 2007

3.4.4 Hydrologic Model Verification

Rainfall Data

Recorded rainfall from the Crawford, Cabbage Tree Mountain, Krambach, Hiawatha and Seaham stations was applied in the WBNM hydrologic model for the June 2007 verification. Rainfall definition below Booral may be less reliable due to a lower density of pluviometer gauges.

Hydrologic Model Parameters

The WBNM runoff lag factors 'C' and stream routing lag factors 'F' developed through the April 2015 calibration were also applied for the 8 June 2007 verification. Initial loss (IL) and continuing loss (CL) values were then adjusted within acceptable ranges to achieve the model verification.

The runoff and lag factors applied in the June 2007 model verification were per those presented in **Table 3-3**. Adopted initial loss values ranged from 10 to 60 mm and continuing loss values from 2 to 8 mm.

Comparison of Recorded and Simulated Flood Hydrographs

The ability of the developed WBNM hydrologic model to simulate the catchment response during the June 2007 flood event was assessed by comparing simulated flood hydrographs with DPI Water stream gauge hydrographs. The Booral rating curve extracted from the TUFLOW hydraulic model was considered appropriate for the model verification as it results in a peak flow approximately mid-way between the 2016 and 2007 DPI Water rating tables.

The results of the June 2007 hydrologic model verification are presented in **Figure 3-17**. The results of the calibration can be summarized as follows:

- Karuah River at Dam Site
  - The overall shape of the flood hydrograph is well represented including the timing of the flood peak, exhibiting only a slight delay from the recorded data
  - The peak flood flow is well represented.
- Mammy Johnsons River at Pikes Crossing
  - The overall shape of the flood hydrograph is not particularly well represented, however the overall volume is well represented.
  - The late peak in the gauged flow hydrograph would appear to be associated with a local, secondary burst of rainfall that was not captured in the recorded rainfall applied to the model.
- Karuah River at Booral
  - The overall shape of the flood hydrograph is well represented including the timing of the flood peak.
  - The peak flood flow is well represented. It is noted that the peak flow at Booral was purposefully underestimated in the WBNM model as the resulting peak flow at this location in the TUFLOW model was found to be slightly higher (refer **Figure 3-19**).
  - Efforts were made to improve the shape of the falling limb of the simulated hydrograph, however the required parameter adjustments were found to have a negative impact on the initial flood peak.

Given the uncertainty in the distribution of rainfall across the catchment during the event, and in the reliability of the rating tables applied at the available stream gauges, the results are considered to constitute a successful verification of the hydrologic model.

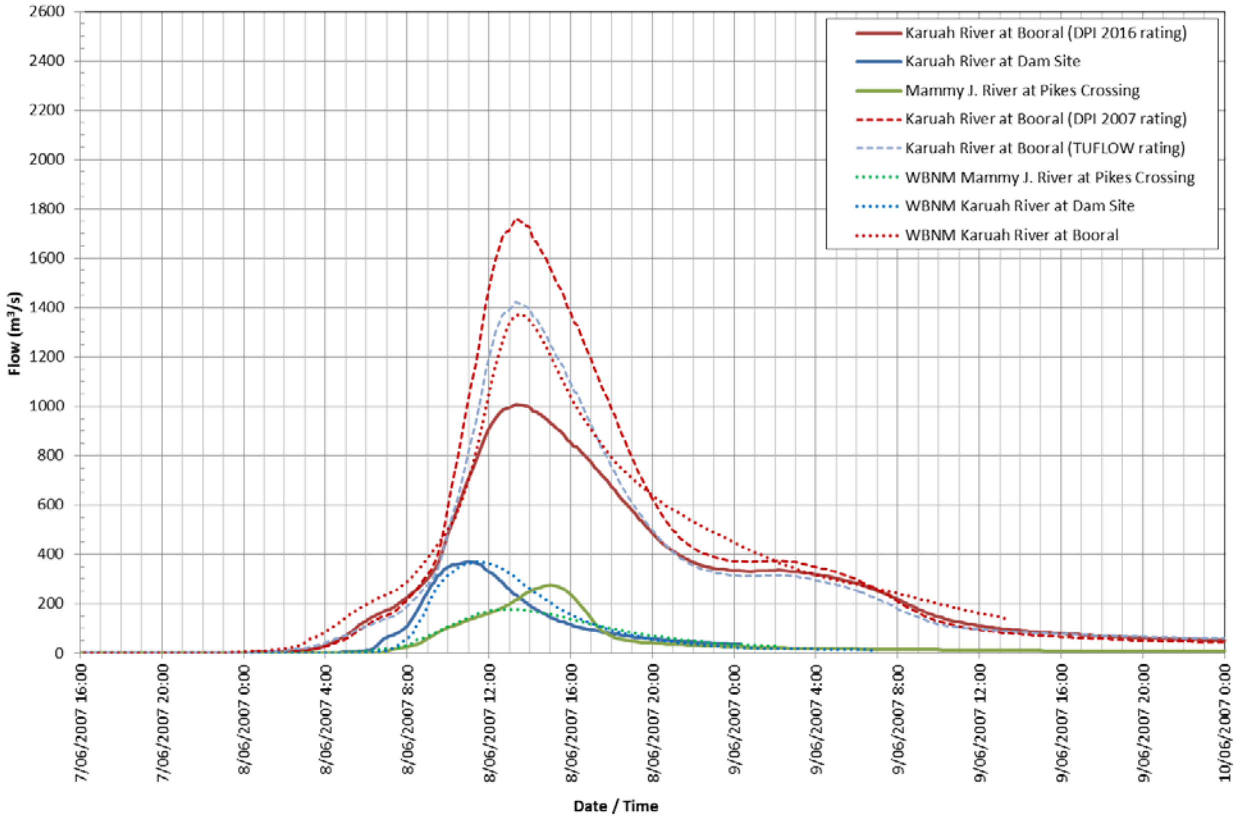


Figure 3-17 Comparison of gauged and simulated flows for the June 2007 event

3.4.5 Hydraulic Model Verification

The hydraulic model verification was assessed through the comparison of flood levels simulated by the TUFLOW model with available recorded flood levels. This included comparisons at the DPI Water Karuah River at Booral gauge and the MHL Karuah River at Karuah gauge. Five indicative flood levels observed by residents for the June 2007 event are presented in the *Karuah River Flood Study* (Paterson Consultants 2010) however they are vague in nature and not considered useful for model verification purposes.

Comparison of Recorded and Simulated Flood Levels

A comparison of recorded and simulated water levels at the Karuah River at Booral gauge for the June 2007 flood event is presented in **Figure 3-18**, and a comparison of gauged and simulated flows presented in **Figure 3-19**. As with the WBNM hydrologic model, the timing and level of the flood peak is well represented. The peak simulated flood level is 0.21 m higher than that recorded and occurs about 15 minutes later. Considering the significant flood depth of over 8 metres and that flood levels remain in-bank, the TUFLOW model simulation provides a very good representation of peak flood behaviour at this location. Peak flood flows at Booral from the TUFLOW model are slightly higher than those from the WBNM model, but the two models show good agreement in terms of stream routing behaviour.

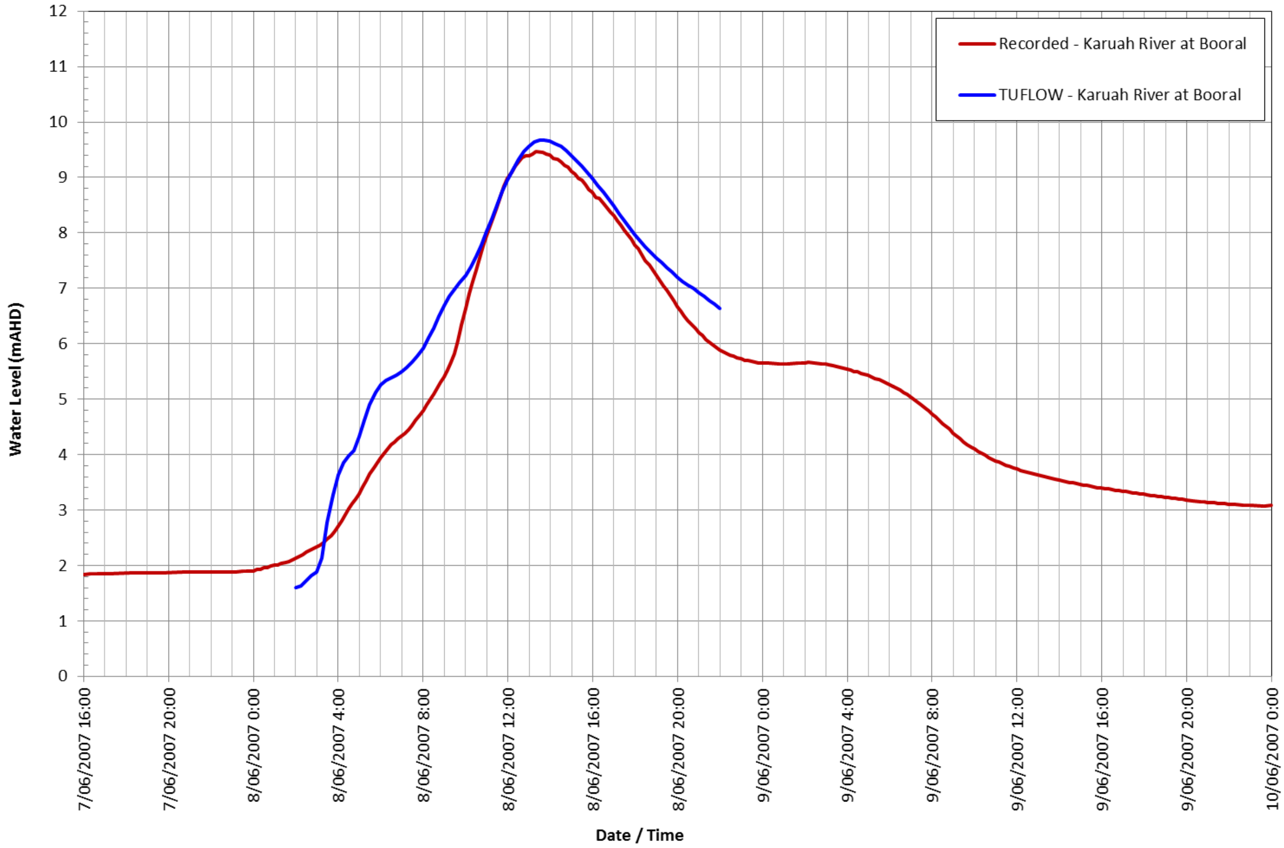


Figure 3-18 Comparison of recorded and simulated flood levels at the Booral gauge for the June 2007 event

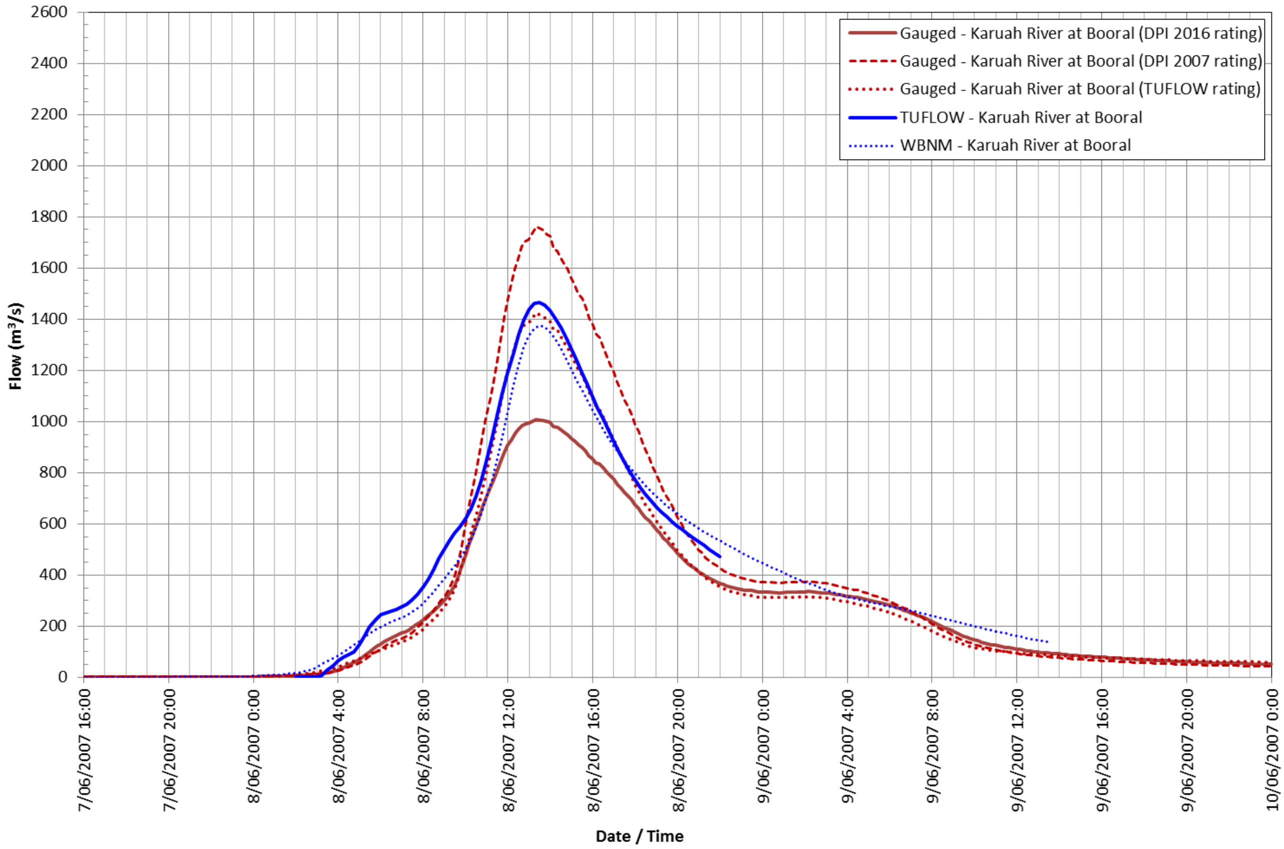


Figure 3-19 Comparison of gauged and simulated hydrographs at the Booral gauge for the June 2007 event

4 Design Flood Estimation

4.1 Introduction

Design flood conditions are estimated from hypothetical design rainfall events that have a particular statistical probability of occurrence. Guidance and data for the estimation of design flood conditions in Australia are provided in *Australian Rainfall and Runoff: A Guide to Flood Estimation* (Geoscience Australia 2016) (ARR 2016).

The probability of a design event occurring can be expressed in terms of percentage Annual Exceedance Probability (AEP), and provides a measure of the relative frequency and magnitude of the flood event. Flood conditions for the 20%, 5%, 2%, 1%, 0.5% and 0.2% AEP design events and the Probable Maximum Flood (PMF) have been investigated in this study.

4.2 Design Rainfall

4.2.1 Design Rainfall Depths

Design rainfall depths for the 20%, 5%, 2%, and 1% AEP events were obtained from the Bureau of Meteorology (BoM) online intensity-frequency-duration (IFD) data tool, as derived from standard procedures defined in ARR 2016. Design rainfall depths for the 0.5% and 0.2% AEP events were scaled from the 1% AEP event using 'growth factors' of 1.140 and 1.344 respectively, as specified in Book 8, Chapter 3 of ARR 2016. The Probable Maximum Precipitation (PMP), as used to determine the PMF, was calculated per the Generalised Short Duration Method (GSDM) as defined by BoM (2003).

4.2.2 Design Rainfall Spatial Pattern

As discussed in Book 2, Chapter 6 of ARR 2016, it is recommended that a non-uniform spatial pattern be applied to catchments with an area of greater than 20 km^2 to replicate the systematic spatial variability in rainfall that would be expected across the catchment during rainfall events of similar AEP to the design floods being estimated.

In order to assess the spatial variability of design rainfall depths across the Karuah River catchment, IFD data was extracted at some 36 locations across the catchment. It was found that there is significant spatial variation across the catchment. In general, design rainfall depths are higher nearer the coast and decrease moving in a northerly direction, reaching a minimum at the top of the catchment near the Barrington Tops. Design rainfall depths are also higher along the eastern boundary of the catchment than the centre or western boundary, characteristic of the orographic influence of the steep ridges rising in the east of the catchment. The spatial variation exhibited in the design rainfall depths is comparable to that observed for the April 2015 and June 2007 flood events.

An analysis was undertaken to select a number of point locations that would result in an appropriate representation of the spatial variation in design rainfall depths across the catchment using the 1% AEP 12-hour duration event as a guide. Design rainfall depths for the 1% AEP 12-hour duration event ranged from 171 mm in the north-west of the catchment near the Barrington Tops, to 236 mm in the south-east of the catchment along a ridgeline near Nerong. It was found that a minimum of 10 point locations were required to achieve an inverse-distance-weighted spatial pattern comparable to that for the full 36 points analysed and capture variation both across the overall Karuah River catchment and smaller local catchments such as that of Mill Creek. The resulting spatial pattern of design rainfall depth for the 1% AEP 12-hour duration event is presented in **Figure 4-1**.

4.2.3 Design Rainfall Temporal Patterns and Critical Storm Duration

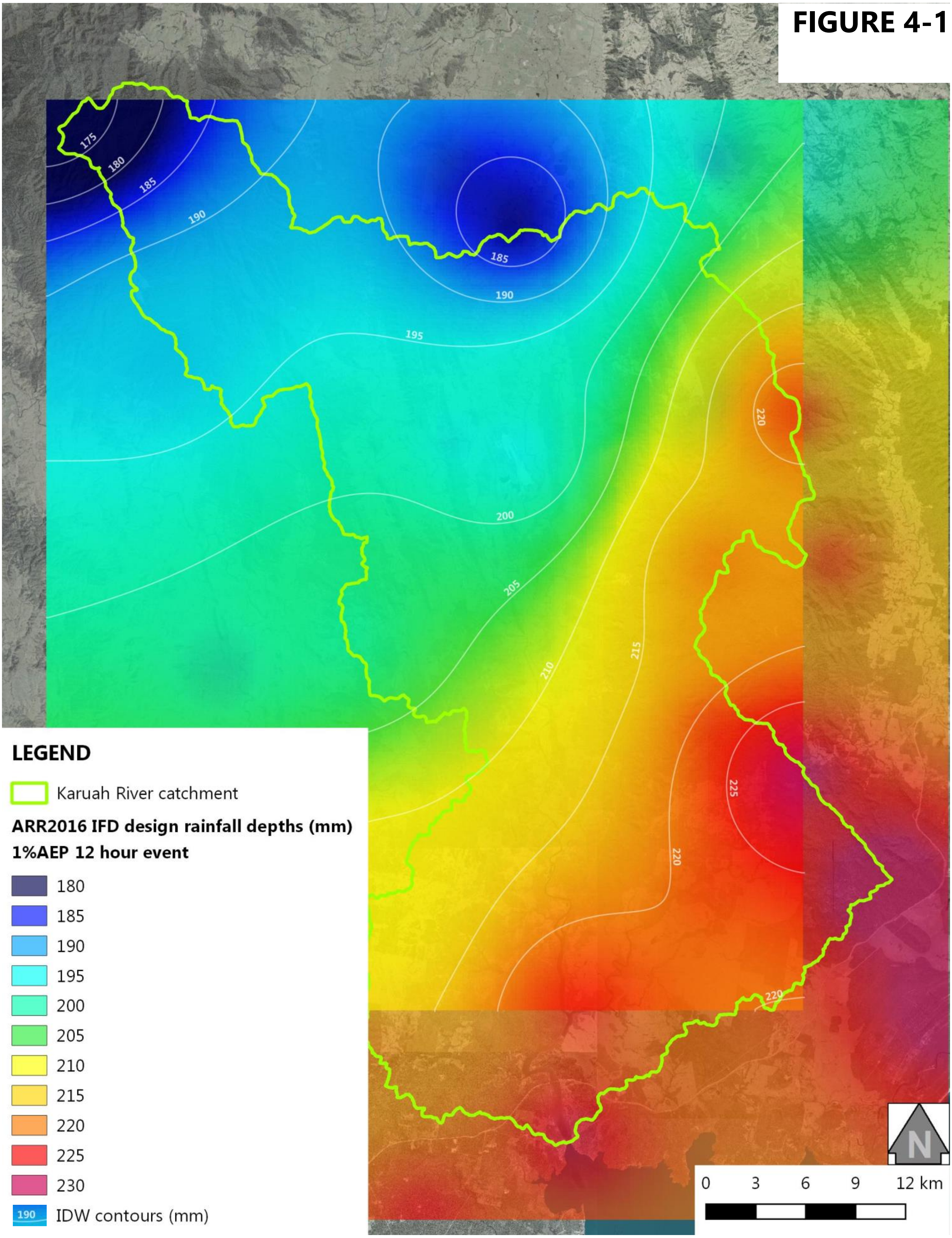
ARR 2016 Temporal Pattern Ensemble Approach

In order to estimate a design flood hydrograph, a temporal pattern must be applied to the design rainfall depths to describe how rain falls over time. Traditionally a single burst temporal pattern has been applied for each design rainfall event and duration; however, this approach has been questioned as a wide variety of temporal patterns is possible.

The ARR 2016 guidelines now recommend that 'ensembles' of 10 temporal rainfall patterns that have been derived to represent variability in observed patterns be analysed for each design storm event. Further complicating this approach, the temporal pattern ensembles vary with catchment size, frequency of design event, and event duration; as do other parameters including Areal Reduction Factor (ARF), IL/CL, and pre-burst rainfall. 'Design Point Temporal Patterns' apply for catchments of less than 75 km^2, while 'Areal Temporal Patterns' apply for catchments of greater than 75 km^2 and include several temporal pattern ensembles that vary with catchment size.

ARR 2016 states that the 10 patterns within an ensemble provide a range of plausible answers, with testing demonstrating that on most catchments peak flows for a number of the patterns tend to cluster around the mean. For the purposes of selecting a single representative design rainfall pattern, the average of the 10 resulting peak flows is taken to be the actual peak design flood flow at a given location, and the temporal pattern resulting in a peak flow nearest to (but not less than) this average would typically be adopted to determine the design flood hydrograph.

FIGURE 4-1



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ARR 2016 IFD DESIGN RAINFALL DEPTH SPATIAL PATTERN, 1% AEP 12-HOUR EVENT

Areal Reduction Factors and Rainfall Losses

Areal Reduction Factors (ARF), initial losses (IL) and continuing losses (CL) were determined by the WBNM 2017 software per guidance and techniques presented in ARR 2016 (refer **Table 4-1**). Adopted IL values account for offsets associated with pre-burst rainfall.

ARR 2016 Critical Storm Duration and Temporal Pattern Assessment

For the purposes of the *Karuah River and Stroud Floodplain Risk Management Study & Plan*, definition of design flood conditions is required at various locations of interest that vary in terms of upstream catchment size and characteristics, and therefore critical storm duration and applicable temporal rainfall patterns.

Given the run time of the developed TUFLOW two-dimensional hydraulic model, it is not practical to simulate numerous temporal patterns for multiple durations for each design flood (i.e. AEP). A more practical approach was thus adopted, as follows:

- The WBNM2017 hydrologic model was used to determine critical storm durations and average peak design flows at 12 key locations, as calculated with temporal pattern ensembles, ARF and IL/CL values specific to each location (i.e. specific to the catchment size at each location)
- The number of required critical storm durations was identified, along with associated temporal patterns of interest, ARF and IL/CL values for each
- The selected rainfall hyetographs (i.e. specific combinations of design rainfall depth, duration and temporal pattern) were simulated across the entire catchment and assessed against actual average design peak flows at each location to verify their appropriateness.

From the results of the critical duration and temporal pattern assessment three design hyetographs (i.e. specific combinations of storm duration and temporal pattern) were selected for each design event (20%, 5%, 2% and 1% AEP), and their suitability to provide representative design flood hydrographs throughout the study area was reviewed. The selected critical storm durations, temporal patterns and parameters for each design event are presented in **Table 4-1**.

Table 4-1 Design event critical durations and selected representative temporal patterns

Design Event	Selected critical storm durations, representative temporal patterns & parameters			
	Event Duration (min)	**Pattern Set**	**Pattern No.**	**ARF / IL / CL**
20% AEP	360	Point - frequent	5	0.95 / 20.1 / 2.5
	720	Areal - 100 km^2	3	0.95 / 20.1 / 2.5
	1440	Areal - 1,000 km^2	9	0.94 / 27.1 / 2.5
5% AEP	360	Point - intermediate	2	0.94 / 10.9 / 2.5
	720	Areal - 100 km^2	3	0.93 / 20.5 / 2.5
	1440	Areal - 1,000 km^2	9	0.94 / 27.1 / 2.5
2% AEP	360	Point - rare	9	0.94 / 8.0 / 2.5
	720	Areal - 100 km^2	3	0.92 / 13.3 / 2.5
	1440	Areal - 1,000 km^2	9	0.92 / 13.3 / 2.5
1% AEP	360	Point - rare	9	0.93 / 5.8 / 2.5
	720	Areal - 100 km^2	3	0.91 / 7.9 / 2.5
	1440	Areal - 1,000 km^2	9	0.92 / 7.9 / 2.5
0.5% AEP	360	Scaled from 1% AEP hyetographs using growth factor of 1.14		0.93 / 5.8 / 2.5
	720			0.91 / 7.9 / 2.5
	1440			0.92 / 7.9 / 2.5
0.2% AEP	360	Scaled from 1% AEP hyetographs using growth factor of 1.344		0.93 / 5.8 / 2.5
	720			0.91 / 7.9 / 2.5
	1440			0.92 / 7.9 / 2.5
PMF	180	ARR 1987 / GSDM		1.0 / 10.0 / 2.5
	360			1.0 / 10.0 / 2.5

A comparison of peak design flood flows from the selected storm duration and temporal pattern combinations above with the average peak flow from the temporal pattern ensemble at each site are presented for the 20%, 5%, 2% and 1% AEP design events in **Table 4-2** to **Table 4-5**. It can be seen that the resulting peak flood flows are comparable to the averaged peak flood flows, within a range of percentage difference that is typical of the ARR 2016 temporal pattern ensemble technique. It is therefore considered that the selected design rainfall hyetographs and parameters are appropriate for determining design flood hydrographs for use in the *Karuah River and Stroud Floodplain Risk Management Study and Plan*.

Table 4-2 20% AEP comparison of peak design flood flows from average of temporal pattern ensemble and selected representative temporal pattern

			Design Flood Results - at site critical duration & temporal pattern assessment							Design Flood Results - selected durations & temporal patterns				
Location	WBNM sub-catchment	Upstream catchment area (km^2)	Critical Duration (min)	Averaged Peak Flow (m^3/s)	Av. Pattern Set	Av. Pattern No.	Av. Patt. Peak Flow (m^3/s)	% Diff. to Av.	ARF / IL / CL	Event Duration (min)	Pattern Set	Pattern No.	Peak Flow (m^3/s)	% Diff. to Av.
Stroud Road - Mammy Johnsons River inflow	16.13	312	720	277.8	Areal - 500 km^2	6	296.1	7%	0.95 / 27.1 / 2.5	720	Areal - 100 km^2	3	290.7	5%
Stroud Road - Karuah River inflow	1.11	337	720	467.7	Areal - 500 km^2	5	546.7	17%	0.90 / 27.1 / 2.5	720	Areal - 100 km^2	3	500.8	7%
Stroud Road - confluence	1.15	657	1440	640.9	Areal - 500 km^2	8	643.2	0%	0.94 / 27.1 / 2.5	1440	Areal - 1,000 km^2	9	633.0	-1%
Stroud - Mill Ck inflow	49.07	97	720	232.3	Areal - 100 km^2	3	242.8	5%	0.94 / 27.1 / 2.5	720	Areal - 100 km^2	3	247.3	6%
Stroud - Mill Ck bridge	49.11	112	720	255.5	Areal - 100 km^2	3	267.8	5%	0.93 / 27.1 / 2.5	720	Areal - 100 km^2	3	274.7	7%
Stroud - Lamans Ck bridge	65.05	20	360	73.7	Point - frequent	5	75.0	2%	0.95 / 20.1 / 2.5	360	Point - frequent	5	74.9	2%
Booral bridge	1.21	973	1440	844.5	Areal - 1,000 km^2	9	854.3	1%	0.93 / 27.1 / 2.5	1440	Areal - 1,000 km^2	9	881.1	4%
Allworth	1.25	1095	1440	914.64	Areal - 1,000 km^2	9	934.2	2%	0.92 / 27.1 / 2.5	1440	Areal - 1,000 km^2	9	965.9	6%
The Branch - properties	95.09	146	720	236.3	Areal - 200 km^2	3	243.4	3%	0.93 / 27.1 / 2.5	720	Areal - 100 km^2	3	254.2	8%
Little Branch - bridge	107.03	41	720*	91.7	Point - frequent	1	100.6	10%	0.96 / 27.1 / 2.5	360	Point - frequent	5	103.0	12%
The Branch - confluence	95.11	210	720	337.9	Areal - 200 km^2	5	391.7	16%	0.92 / 27.1 / 2.5	720	Areal - 100 km^2	3	346.9	3%
Karuah bridge	1.28	1455	1440	1196.7	Areal - 1,000 km^2	9	1233.2	3%	0.92 / 27.1 / 2.5	1440	Areal - 1,000 km^2	9	1275.2	7%

*360 minute duration averaged peak flow = 91.2 m^3/s

Table 4-3 5% AEP comparison of peak design flood flows from average of temporal pattern ensemble and selected representative temporal pattern

			Design Flood Results - at site critical duration & temporal pattern assessment							Design Flood Results - selected durations & temporal patterns				
Location	WBNM sub-catchment	Upstream catchment area (km^2)	Critical Duration (min)	Averaged Peak Flow (m^3/s)	Av. Pattern Set	Av. Pattern No.	Av. Patt. Peak Flow (m^3/s)	% Diff. to Av.	ARF / IL / CL	Event Duration (min)	Pattern Set	Pattern No.	Peak Flow (m^3/s)	% Diff. to Av.
Stroud Road - Mammy Johnsons River inflow	16.13	312	720	521.1	Areal - 500 km^2	6	523.2	0%	0.89 / 20.5 / 2.5	720	Areal - 100 km^2	3	520.6	0%
Stroud Road - Karuah River inflow	1.11	337	720	821.4	Areal - 500 km^2	5	916.7	12%	0.89 / 20.5 / 2.5	720	Areal - 100 km^2	3	843.6	3%
Stroud Road - confluence	1.15	657	1440	1163.3	Areal - 500 km^2	10	1190.1	2%	0.93 / 20.5 / 2.5	1440	Areal - 1,000 km^2	9	1164.5	0%
Stroud - Mill Ck inflow	49.07	97	720	386.9	Areal - 100 km^2	3	394.6	2%	0.93 / 20.5 / 2.5	720	Areal - 100 km^2	3	388.2	0%
Stroud - Mill Ck bridge	49.11	112	720	429.1	Areal - 100 km^2	3	441.7	3%	0.92 / 20.5 / 2.5	720	Areal - 100 km^2	3	435.6	2%
Stroud - Lamans Ck bridge	65.05	20	360	128.7	Point - intermediate	2	132.5	3%	0.94 / 10.9 / 2.5	360	Point - intermediate	2	138.5	8%
Booral bridge	1.21	973	1440	1571.4	Areal - 1,000 km^2	8	1577.6	0%	0.92 / 20.5 / 2.5	1440	Areal - 1,000 km^2	9	1636.1	4%
Allworth	1.25	1095	1440	1714.42	Areal - 1,000 km^2	9	1773.4	3%	0.92 / 20.5 / 2.5	1440	Areal - 1,000 km^2	9	1804.7	5%
The Branch - properties	95.09	146	720	431.9	Areal - 200 km^2	3	450.2	4%	0.92 / 20.5 / 2.5	720	Areal - 100 km^2	3	433.7	0%
Little Branch - bridge	107.03	41	360	172.9	Point - intermediate	5	181.7	5%	0.93 / 10.9 / 2.5	360	Point - intermediate	2	186.2	8%
The Branch - confluence	95.11	210	720	604.2	Areal - 200 km^2	5	677.0	12%	0.91 / 10.9 / 2.5	720	Areal - 100 km^2	3	598.0	-1%
Karuah bridge	1.28	1455	1440	2255.9	Areal - 1,000 km^2	9	2343.6	4%	0.92 / 20.5 / 2.5	1440	Areal - 1,000 km^2	9	2385.6	6%

Table 4-4 2% AEP comparison of peak design flood flows from average of temporal pattern ensemble and selected representative temporal pattern

Location	WBNM sub-catchment	Upstream catchment area (km^2)	Design Flood Results - at site critical duration & temporal pattern assessment							Design Flood Results - selected durations & temporal patterns				
			Critical Duration (min)	Averaged Peak Flow (m^3/s)	Av. Pattern Set	Av. Pattern No.	Av. Patt. Peak Flow (m^3/s)	% Diff. to Av.	ARF / IL / CL	Event Duration (min)	Pattern Set	Pattern No.	Peak Flow (m^3/s)	% Diff. to Av.
Stroud Road - Mammy Johnsons River inflow	16.13	312	720	698.5	Areal - 500 km^2	6	699.9	0%	0.88 / 13.3 / 2.5	720	Areal - 100 km^2	3	759.2	9%
Stroud Road - Karuah River inflow	1.11	337	720	1063.1	Areal - 500 km^2	5	1177.8	11%	0.88 / 13.3 / 2.5	720	Areal - 100 km^2	3	1176.2	11%
Stroud Road - confluence	1.15	657	1440	1568.3	Areal - 500 km^2	10	1587.0	1%	0.93 / 13.3 / 2.5	1440	Areal - 1,000 km^2	9	1551.3	-1%
Stroud - Mill Ck inflow	49.07	97	720	494.6	Areal - 100 km^2	3	496.5	0%	0.92 / 13.3 / 2.5	720	Areal - 100 km^2	3	494.7	0%
Stroud - Mill Ck bridge	49.11	112	720	549.7	Areal - 100 km^2	3	556.8	1%	0.92 / 13.3 / 2.5	720	Areal - 100 km^2	3	557.7	1%
Stroud - Lamans Ck bridge	65.05	20	360	162.3	Point - rare	9	170.1	5%	0.94 / 8.0 / 2.5	360	Point - rare	9	171.2	6%
Booral bridge	1.21	973	1440	2113.9	Areal - 1,000 km^2	9	2209.2	5%	0.92 / 13.3 / 2.5	1440	Areal - 1,000 km^2	9	2214.2	5%
Allworth	1.25	1095	1440	2340.1	Areal - 1,000 km^2	9	2441.7	4%	0.92 / 13.3 / 2.5	1440	Areal - 1,000 km^2	9	2451.2	5%
The Branch - properties	95.09	146	720	568.0	Areal - 200 km^2	9	587.1	3%	0.91 / 13.3 / 2.5	720	Areal - 100 km^2	3	601.0	6%
Little Branch - bridge	107.03	41	720*	222.2	Point - rare	8	226.5	2%	0.95 / 8.0 / 2.5	360	Point - rare	9	252.3	14%
The Branch - confluence	95.11	210	720	793.4	Areal - 200 km^2	5	885.4	12%	0.90 / 13.3 / 2.5	720	Areal - 100 km^2	3	840.9	6%
Karuah bridge	1.28	1455	1440	3106.5	Areal - 1,000 km^2	9	3252.6	5%	0.92 / 13.3 / 2.5	1440	Areal - 1,000 km^2	9	3240.0	4%

*360 minute duration averaged peak flow = 220.4 m^3/s

Table 4-5 1% AEP comparison of peak design flood flows from average of temporal pattern ensemble and selected representative temporal pattern

Location	WBNM sub-catchment	Upstream catchment area (km^2)	Design Flood Results - at site critical duration & temporal pattern assessment							Design Flood Results - selected durations & temporal patterns				
			Critical Duration (min)	Averaged Peak Flow (m^3/s)	Av. Pattern Set	Av. Pattern No.	Av. Patt. Peak Flow (m^3/s)	% Diff. to Av.	ARF / IL / CL	Event Duration (min)	Pattern Set	Pattern No.	Peak Flow (m^3/s)	% Diff. to Av.
Stroud Road - Mammy Johnsons River inflow	16.13	312	720	847.7	Areal - 500 km^2	6	849.5	0%	0.88 / 7.9 / 2.5	720	Areal - 100 km^2	3	907.3	7%
Stroud Road - Karuah River inflow	1.11	337	720	1257.2	Areal - 500 km^2	5	1387.9	10%	0.88 / 7.9 / 2.5	720	Areal - 100 km^2	3	1377.6	10%
Stroud Road - confluence	1.15	657	1440	1895.6	Areal - 500 km^2	10	1908.2	1%	0.93 / 7.9 / 2.5	1440	Areal - 1,000 km^2	9	1873.1	-1%
Stroud - Mill Ck inflow	49.07	97	720	583.1	Areal - 100 km^2	10	692.4	19%	0.92 / 7.9 / 2.5	720	Areal - 100 km^2	3	572.6	-2%
Stroud - Mill Ck bridge	49.11	112	720	648.9	Areal - 100 km^2	3	650.5	0%	0.91 / 7.9 / 2.5	720	Areal - 100 km^2	3	646.3	0%
Stroud - Lamans Ck bridge	65.05	20	360	191.6	Point - rare	9	199.0	4%	0.93 / 5.8 / 2.5	360	Point - rare	9	199.1	4%
Booral bridge	1.21	973	1440	2585.8	Areal - 1,000 km^2	9	2684.6	4%	0.92 / 7.9 / 2.5	1440	Areal - 1,000 km^2	9	2700.4	4%
Allworth	1.25	1095	1440	2846.3	Areal - 1,000 km^2	9	2974.9	5%	0.92 / 7.9 / 2.5	1440	Areal - 1,000 km^2	9	2997.2	5%
The Branch - properties	95.09	146	720	681.2	Areal - 200 km^2	9	697.6	2%	0.91 / 7.9 / 2.5	720	Areal - 100 km^2	3	712.1	5%
Little Branch - bridge	107.03	41	720*	265.6	Point - rare	5	300.7	13%	0.94 / 7.9 / 2.5	360	Point - rare	9	297.1	12%
The Branch - confluence	95.11	210	720	948.8	Areal - 200 km^2	5	1056.2	11%	0.89 / 7.9 / 2.5	720	Areal - 100 km^2	3	999.1	5%
Karuah bridge	1.28	1455	1440	3772.9	Areal - 1,000 km^2	9	3946.1	5%	0.92 / 7.9 / 2.5	1440	Areal - 1,000 km^2	9	4010.3	6%

*360 minute duration averaged peak flow = 262.7 m^3/s

4.2.4 Probable Maximum Precipitation

The Probable Maximum Precipitation (PMP), as used to determine the PMF, was calculated per the Generalised Short Duration Method (GSDM) as defined by BoM (2003). This method applies for catchment areas of up to 1,000 km^2 and storm durations of up to 360 minutes.

Across the vast majority of the study catchment including Stroud Road, Stroud, Booral and The Branch, the upstream catchment area at any given point is less than 1,000 km^2. The only area where this is not the case is along the Karuah River waterway from Allworth downstream to Port Stephens.

The GSDM was deemed appropriate for determining PMF conditions across the study area as; it is applicable to the majority of the study area, resulting peak flows are comparable to estimates from previous studies including at Karuah (refer **Table 5-2**), and use of the 360 minute event will also be more critical for the purposes of emergency response planning, for which the PMF is primarily used. The 180 minute duration event was found to be critical at Stroud and the Little Branch River, while the 360 minute duration event was critical at remaining locations of interest.

To determine design rainfall depths for the PMP, from which the PMF is determined, a single point location at Stroud was used. This was deemed appropriate as ARR 87 IFD data showed less variation in design rainfall depth across the catchment, and the variation observed was contrary to spatial patterns observed from ARR 2016 and recorded events.

4.3 Design Boundary Conditions at Port Stephens

Flood levels in the lower Karuah River may be influenced by the coinciding water level in Port Stephens, primarily due to the effect on available storage volume prior to the peak of a flood. While there are minor differences beyond Soldiers Point, water levels in Port Stephens are largely comparable with open ocean levels and consist of astronomical tide plus tidal anomalies, most notably storm surge (changes in ocean level driven by the combined effects of variations in air pressure and wind stress during storms).

The latest advice regarding the selection of ocean boundary conditions for use in studies under the NSW Floodplain Management Program is provided in *Floodplain Risk Management Guide - Modelling the Interaction of Catchment Flooding and Oceanic Inundation in Coastal Waterways* (OEH 2015). The Karuah River is classified as a semi-mature, tide-dominated, drowned valley estuary (Roy et al. 2001) with an open entrance condition, and is treated as a 'Type A' waterway entrance under these guidelines. For the purposes of this study the 'simplistic approach' has been adopted whereby static downstream boundary conditions are applied. This approach is conservative and would be expected have a small influence on peak flood level results in the lower Karuah River from approximately The Branch downstream.

Resulting water levels applied at the Port Stephens boundary for each catchment flood event investigated are presented in **Table 4-6**. It is noted that design flood levels for Port Stephens are available from *Port Stephens Design Flood Levels – Climate Change Review* (WMAwater 2010) which include the influence of elevated ocean levels, catchment runoff and local wind effects. These levels were considered overly conservative for the purposes of downstream boundary conditions for the current study, as their probability of coinciding with the peak of Karuah River catchment flooding may be low and a level of conservatism is already inherent in the adopted constant tailwater approach.

Table 4-6 Summary of adopted boundary conditions at Port Stephens

Karuah River Design Flood Event	Coinciding Port Stephens Event	Port Stephens Water Level (mAHD)	Source
20% AEP	HHWS(SS) at Mallabula Point	1.08	*OEH Tidal* Planes Analysis 1990-2012 Harmonic Analysis (MHL 2012)
5% AEP	HHWS(SS) at Mallabula Point	1.08	*OEH Tidal* Planes Analysis 1990-2012 Harmonic Analysis (MHL 2012)
2% AEP	5% AEP ocean level for south of Crowdy Head	1.40	*Modelling the Interaction of Catchment Flooding and Oceanic Inundation in Coastal Waterways* (OEH 2015)
1% AEP	1% AEP ocean level, south of Crowdy Head*	1.45	*Modelling the Interaction of Catchment Flooding and Oceanic Inundation in Coastal Waterways* (OEH 2015)
0.5% AEP	1% AEP ocean level, south of Crowdy Head	1.45	*Modelling the Interaction of Catchment Flooding and Oceanic Inundation in Coastal Waterways* (OEH 2015)
0.2% AEP	1% AEP ocean level, south of Crowdy Head	1.45	*Modelling the Interaction of Catchment Flooding and Oceanic Inundation in Coastal Waterways* (OEH 2015)
PMF	1% AEP ocean level, south of Crowdy Head	1.45	*Modelling the Interaction of Catchment Flooding and Oceanic Inundation in Coastal Waterways* (OEH 2015)

*Adopted in place of 1%AEP / 5%AEP and 5%AEP / 1%AEP ocean envelope approach as results are not sensitive to 0.05m difference in boundary level

5 Design Flood Results

5.1 Peak Design Flood Flows

Peak design flood flows at selected locations, as simulated using WBNM, are presented in **Table 5-1** for the full range of design events investigated. A comparison of these peak design flows with those estimated by previous studies is presented in **Table 5-2** for locations where relevant data was available.

Table 5-1 WBNM simulated peak flood flows for design events

Location	WBNM sub-catchment	Upstream catchment area (km^2)	Peak Design Flood Flows (m^3/s)						
			20% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP	PMF
Stroud Road - Mammy Johnsons River inflow	16.13	312	290.7	520.6	759.2	907.3	1094.1	1374.5	3221.7
Stroud Road - Karuah River inflow	1.11	337	500.8	843.6	1176.2	1377.6	1635.0	2016.7	5726.1
Stroud Road - confluence	1.15	657	633.0	1164.5	1551.3	1873.1	2233.4	2764.1	7050.5
Stroud - Mill Ck inflow	49.07	97	247.3	388.2	494.7	572.6	667.5	806.0	2604.8
Stroud - Mill Ck bridge	49.11	112	274.7	435.6	557.7	646.3	754.0	911.9	2906.3
Stroud - Lamans Ck bridge	65.05	20	74.9	138.5	171.2	199.1	232.3	281.5	622.3
Booral bridge	1.21	973	881.1	1636.1	2214.2	2700.4	3229.0	4006.3	9949.6
Allworth	1.25	1095	965.9	1804.7	2451.2	2997.2	3586.6	4455.0	10686.3
The Branch - properties	95.09	146	254.2	433.7	601.0	712.1	843.5	1037.9	2429.8
Little Branch - bridge	107.03	41	103.0	186.2	252.3	297.1	348.7	425.1	931.6
The Branch - confluence	95.11	210	346.9	598.0	840.9	999.1	1186.0	1462.6	3413.5
Karuah bridge	1.28	1455	1275.2	2385.6	3240.0	4010.3	4759.9	5928.8	13748.8

Table 5-2 Comparison of peak design flood flows from current and previous studies

Location	Peak Design Flood Flows (m^3/s)													
	20% AEP		5% AEP		2% AEP		1% AEP		0.5% AEP		0.2% AEP		PMF	
	Current	Previous	Current	Previous	Current	Previous	Current	Previous	Current	Previous	Current	Previous	Current	Previous
Stroud - Mill Ck bridge[1]	275	300	436	454	558	571	646	666	754	765	912	900	2906	2820
Stroud - Lamans Ck bridge[1]	75	64	139	95	171	119	199	138	232	169	282	186	622	589
Booral bridge[2]	881	1244	1636	2106	2214	2758	2700	3313	3229	3885	4006	-	9950	9669
Karuah bridge[2]	1275	1453	2386	2508	3240	3354	4010	4060	4760	4790	5929	-	13749	12713

1 - Source of 'previous' results: Stroud Flood Study (WMAwater 2012)

2 - Source of 'previous' results: Karuah River Flood Study (Paterson Consultants 2010)

The following results are notable from the comparisons presented in **Table 5-2**:

- PMF peak flows are comparable at all locations, with the current estimates consistently slightly higher than previous estimates
- Peak flows at the Mill Creek bridge are comparable for all design events
- Peak flows at the Karuah bridge (Tarean Road) are comparable for all design events
- Current peak flow estimates at the Lamans Creek bridge are higher than previous estimates for all design events
- Current peak flow estimates at the Booral bridge are lower than previous estimates for all design events.

Given that all current design flow estimates (with the exception of the PMF) were made using techniques and datasets recently introduced in the ARR 2016 guidelines, it is not surprising that there would be differences to previous estimates made using the ARR 1987 guidelines. In fact, it is perhaps encouraging that similar peak flows were estimated at some locations using these differing guidelines. There are various other factors contributing to the observed differences, including differences in hydrologic model software and / or configuration. Significant differences between the Karuah River at Booral rating tables adopted for model calibration in the current and 2010 studies may also contribute to differences in flow estimates at Booral bridge.

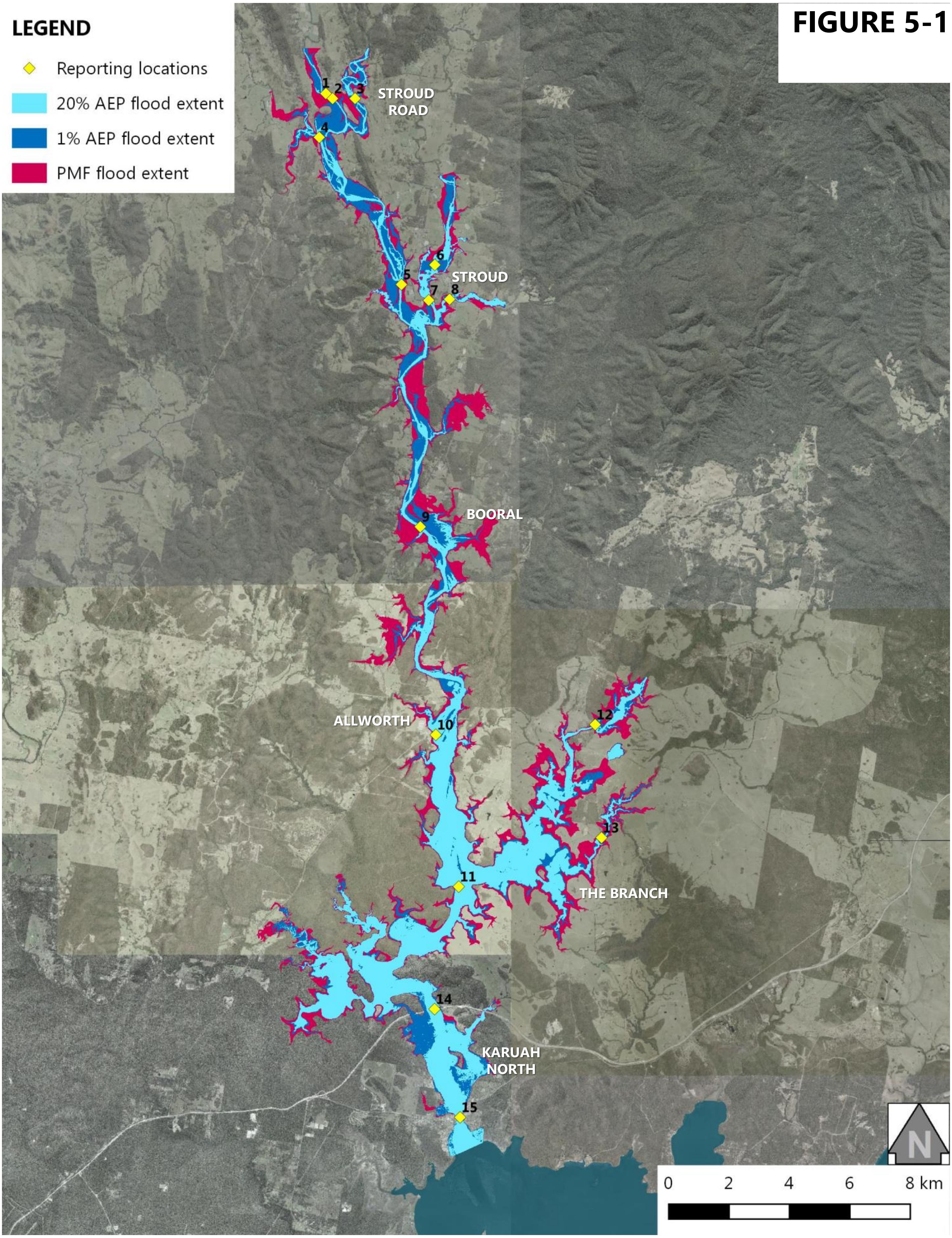
5.2 Peak Design Flood Levels

Simulated peak flood levels for the range of design flood events investigated are presented in **Table 5-3** for the locations shown in **Figure 5-1**.

Table 5-3 Simulated peak design flood levels (mAHD) at selected locations

ID	Location	PMF	0.2% AEP	0.5% AEP	1% AEP	2% AEP	5% AEP	20% AEP
1	Karuah River at Reisdale Rd Bridge	45.04	42.40	41.79	41.29	40.82	39.53	37.37
2	Karuah River at Railway Bridge	44.00	41.36	40.86	40.49	40.14	38.98	37.01
3	Mammy Johnsons River at The Bucketts Way	44.30	42.13	41.64	41.26	40.91	40.29	38.80
4	Karuah River at Washpool Bridge	41.56	38.42	37.70	37.09	36.44	35.57	34.13
5	Karuah River at Gorton's Crossing Rd Bridge	31.34	28.52	27.92	27.47	26.87	25.81	23.58
6	Mill Creek at The Bucketts Way	33.19	31.28	31.06	30.86	30.67	30.22	29.47
7	Mill Creek at Laman St Bridge	29.75	27.27	26.94	26.67	26.40	25.93	25.20
8	Lamans Creek at The Bucketts Way	29.59	26.76	26.54	26.37	26.11	25.92	25.32
9	Karuah River at Booral Gauge	18.47	13.23	12.27	11.73	11.09	10.10	8.39
10	Karuah River at Allworth (Karuah St)	10.09	6.46	5.54	4.88	4.21	3.29	2.17
11	Karuah River at The Branch	8.67	5.48	4.63	4.03	3.43	2.59	1.74
12	The Branch River at The Branch Lane	13.18	9.54	8.72	8.15	7.60	6.69	5.48
13	Little Branch River at The Branch Lane	8.79	7.06	6.66	6.34	6.04	5.46	4.66
14	Karuah River at Pacific Highway Bridge	4.03	2.68	2.35	2.14	1.91	1.44	1.22
15	Karuah River at Karuah Bridge	1.82	1.54	1.51	1.49	1.43	1.10	1.09

FIGURE 5-1



FLOOD LEVEL REPORTING LOCATIONS

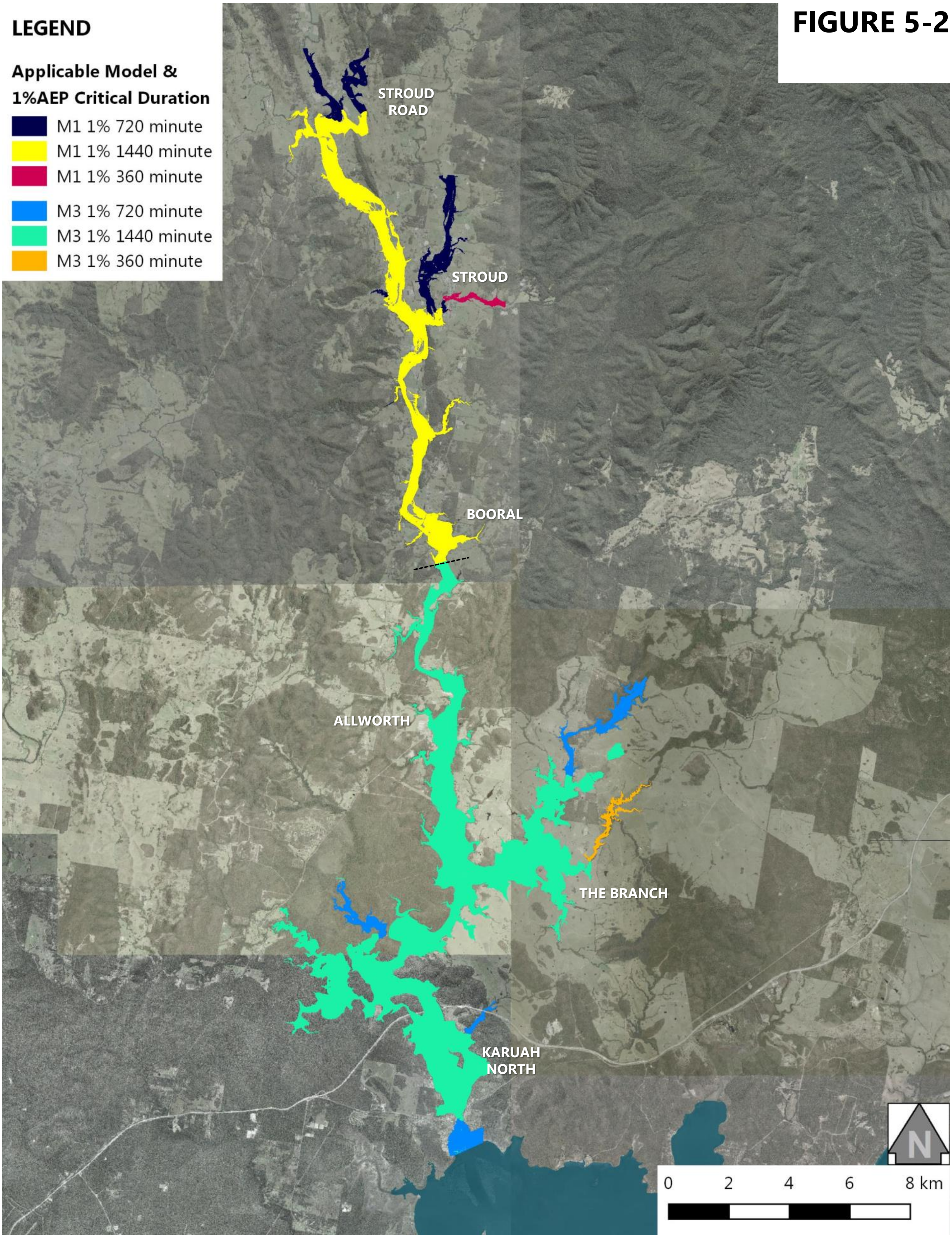
5.3 Design Flood Mapping

Design flood results are presented as A3 maps in Volume 2 of this report. This includes mapping of the following:

- 20% AEP design flood event: flood level, depth, velocity, NSW provisional flood hazard, ARR2016 general flood hazard
- 5% AEP design flood event: flood level, depth
- 2% AEP design flood event: flood level, depth
- 1% AEP design flood event: flood level, depth, velocity, NSW provisional flood hazard, ARR2016 general flood hazard
- 0.5% AEP design flood event: flood level, depth
- 0.2% AEP design flood event: flood level, depth
- PMF: flood level, depth, velocity, NSW provisional flood hazard, ARR2016 general flood hazard.

It is noted that results from the 'M1' TUFLOW model (refer to **Section 2.4**) were adopted upstream of the confluence of the Karuah River and Booral Creek, while results from the 'M3' TUFLOW model were adopted downstream of this point. Mapping presents maximums from peak flood conditions of all storm durations simulated for each design event. This approach is illustrated in **Figure 5-2**, which shows the extent over which results from each model were adopted, and the storm duration resulting in the maximum flood levels for the 1% AEP design event.

FIGURE 5-2



APPLICABLE MODEL RESULT EXTENTS AND 1% AEP CRITICAL STORM DURATIONS

5.3.1 Flood Hazard

Flood hazard provides a measure of the potential risk to life, well-being and property posed by a flood. The mapped 'NSW provisional flood hazard' and 'ARR2016 general flood hazard' categories are described in the following.

NSW Provisional Flood Hazard

The *NSW Floodplain Development Manual* (NSW Government, 2005) defines the following 'provisional flood hazard categories':

- High hazard – possible danger to personal safety; evacuation by trucks difficult; able-bodied adults would have difficulty in wading to safety; potential for significant structural damage to buildings.
- Low hazard – should it be necessary, trucks could evacuate people and their possessions; able-bodied adults would have little difficulty in wading to safety.

The hazard categories are determined according to relationships between flood depth and velocity as provided in the Manual and reproduced in **Figure 5-3**.

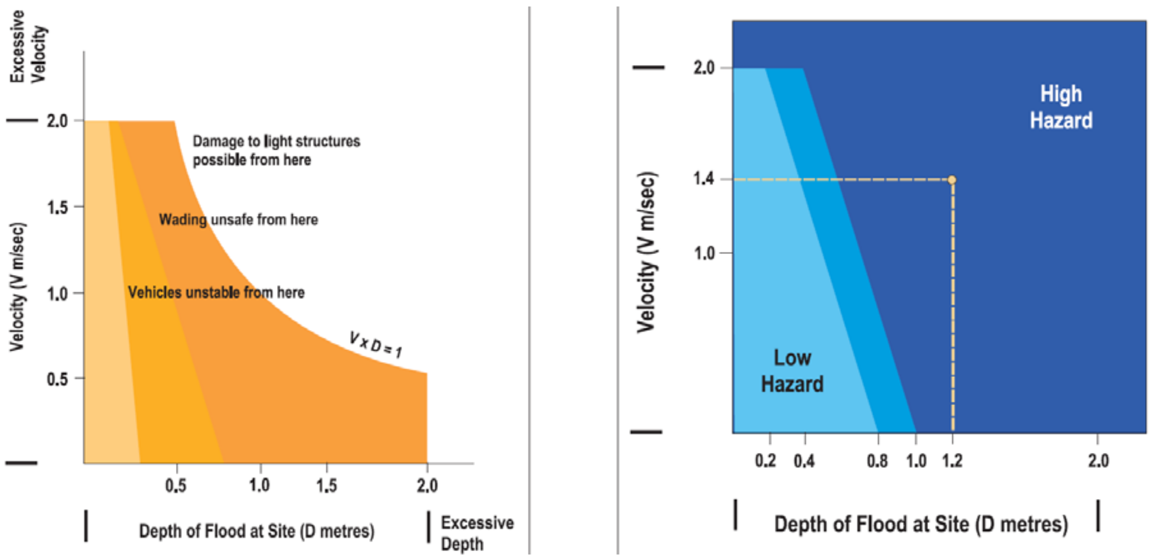


Figure 5-3 Provisional Flood Hazard Categories (Source: NSW Government 2005)

ARR 2016 General Flood Hazard

The 'general flood hazard' curves presented in Book 6, Chapter 7 of ARR 2016 are reproduced in **Figure 5-4**. The curves, derived through laboratory testing by Smith et al. (2014), set six hazard thresholds relating to the vulnerability of the community when interacting with floodwaters based on relationships between flood depth and velocity.

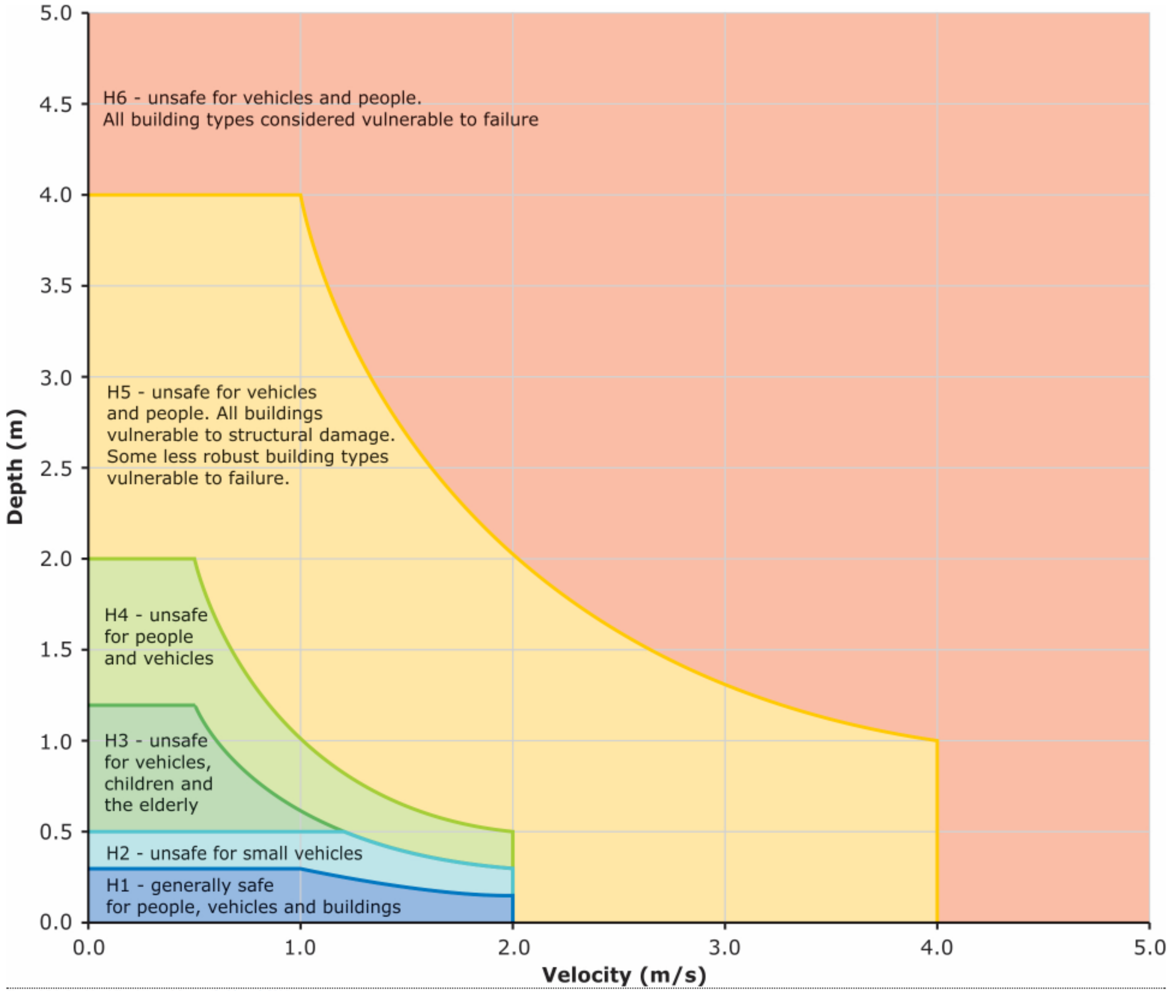


Figure 6.7.9. Combined Flood Hazard Curves (Smith et al, 2014)

Figure 5-4 General Flood Hazard Curves (Source: ARR 2016)

6 References

- AustRoads, 1994, *Waterway Design – A Guide to the Hydraulic Design of Bridges*
- Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors), 2016, *Australian Rainfall and Runoff: A Guide to Flood Estimation*, © Commonwealth of Australia (Geoscience Australia) (ARR 2016)
- Institute of Engineers Australia, 1998, *Australian Rainfall and Runoff: A Guide to Flood Estimation* (ARR 1987)
- Manly Hydraulics Laboratory (MHL), 2012, *OEH Tidal Planes Analysis 1990-2012 Harmonic Analysis*
- New South Wales Government, 2005, *Floodplain Development Manual: the management of flood liable land*, ISBN 07313 0370 9
- Office of Environment and Heritage (OEH), 2015, *Floodplain Risk Management Guide - Modelling the Interaction of Catchment Flooding and Oceanic Inundation in Coastal Waterways*
- Paterson Consultants, 2010, *Karuah River Flood Study*
- Paterson Consultants, 2015, *Flood Data Collection, Dungog and Stroud Flood Event 21 April 2015*
- Roy P, Williams R, Jones A, Yassini I. et al., 2001, *Structure and Function of South-east Australian Estuaries*, *Estuarine, Coastal and Shelf Science*. 53: 351–384
- Smith G P, Davey E K, and Cox R J, 2014, *Flood Hazard UNSW Australia Water Research Laboratory Technical Report 2014/07*, 30 September 2014.
- WMAwater, 2010, *Port Stephens Design Flood Levels – Climate Change Review*
- WMAwater, 2012, *Stroud Flood Study*