MID-WESTERN REGIONAL COUNCIL

MUDGEE FLOOD STUDY

FINAL REPORT

FEBRUARY 2021

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Project Mudgee Flood Study	**Project Number** 118033
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LIST OF ACRONYMS

AEP	Annual Exceedance Probability
AHD	Australian Height Datum
AR&R	Australian Rainfall and Runoff
BoM	Bureau of Meteorology
CSIRO	Commonwealth Scientific and Industrial Research Organisation
EY	Exceedances per Year
GSAM	General Southeast Australia Method
GSDM	Generalised Short Duration Method
IFD	Intensity, Frequency and Duration of Rainfall
IPCC	Intergovernmental Panel on Climate Change
LGA	Local Government Area
LiDAR	Light Detection and Ranging (also known as ALS)
LPI	Land and Property Information
LP3	Log Pearson III probability distribution
m	metre
m^3/s	cubic metres per second (flow measurement)
m/s	metres per second (velocity measurement)
MWRC	Mid-Western Regional Council
NOW	NSW Office of Water
OEH	Office of Environment and Heritage
PINNEENA	Database of water resources information
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
TUFLOW	one-dimensional (1D) and two-dimensional (2D) flood and tide simulation software program (hydraulic computer model)
WBNM	Watershed Bounded Network Model (hydrologic computer model)
1D	One dimensional hydraulic computer model
2D	Two dimensional hydraulic computer model

TERMINOLOGY USED IN REPORT

Australian Rainfall and Runoff have produced a set of draft guidelines for appropriate terminology when referring to the probability of floods. In the past, AEP has generally been used for those events with greater than 10% probability of occurring in any one year, and ARI used for events more frequent than this. However, the ARI terminology is to be replaced with a new term, EY.

Annual Exceedance Probability (AEP) is expressed using percentage probability. It expresses the probability that an event of a certain size or larger will occur in any one year, thus a 1% AEP event has a 1% chance of being equalled or exceeded in any one year. For events smaller than the 10% AEP event however, an annualised exceedance probability can be misleading, especially where strong seasonality is experienced. Consequently, events more frequent than the 10% AEP event are expressed as X Exceedances per Year (EY). Statistically a 0.5 EY event is not the same as a 50% AEP event, and likewise an event with a 20% AEP is not the same as a 0.2 EY event. For example an event of 0.5 EY is an event which would, on average, occur every two years. A 2 EY event is equivalent to a design event with a 6 month average recurrence interval where there is no seasonality, or an event that is likely to occur twice in one year.

While AEP has long been used for larger events, the use of EY is to replace the use of ARI, which has previously been used in smaller magnitude events. The use of ARI, the Average Recurrence Interval, which indicates the long term average number of years between events, is now discouraged. It can incorrectly lead people to believe that because a 100-year ARI (1% AEP) event occurred last year it will not happen for another 99 years. For example there are several instances of 1% AEP events occurring within a short period, for example the 1949 and 1950 events at Kempsey.

The PMF is a term also used in describing floods. This is the Probable Maximum Flood that is likely to occur. It is related to the PMP, the Probable Maximum Precipitation.

This report has adopted the approach of the ARR draft terminology guidelines and uses % AEP for all events greater than the 10% AEP and EY for all events smaller and more frequent than this.

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

FOREWORD

The NSW State Government's Flood Prone Land Policy provides a framework to ensure the sustainable use of floodplain environments. The Policy is specifically structured to provide solutions to existing flooding problems in rural and urban areas. In addition, the Policy provides a means of ensuring that any new development is compatible with the flood hazard and does not create additional flooding problems in other areas.

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

The Policy provides for technical and financial support by the Government through five sequential stages:

1. ***Data Collection***
   - Compilation of existing data and collection of additional data.
2. ***Flood Study***
   - Determine the nature and extent of the flood problem.
3. ***Floodplain Risk Management Study***
   - Evaluates management options for the floodplain in respect of both existing and proposed development.
4. ***Floodplain Risk Management Plan***
   - Involves formal adoption by Council of a plan of management for the floodplain.
5. ***Implementation of the Plan***
   - Construction of flood mitigation works to protect existing development, use of Local Environmental Plans to ensure new development is compatible with the flood hazard.

EXECUTIVE SUMMARY

WMAwater has been engaged by Mid-Western Regional Council (MWRC) to undertake an investigation on flood behaviour in Mudgee and provide an improved understanding of flood behaviour and impacts in the area, in order to better inform the management of flood risk for the community. Mudgee is located in the Macquarie River Basin on the banks of the Cudgegong River. The Cudgegong River has a wide floodplain at Mudgee with the majority of the town built on higher ground on the southern bank of the river.

The town is subject to flooding from the following sources:

- riverine flooding from Cudgegong River and Lawsons Creek, with their confluence on the north western edge of town;
- flash flooding from multiple smaller creeks that originate on the south western edge of Mudgee and traverse the town until their confluence with the Cudgegong River, and
- local urban stormwater flooding.

Major flood events over the last 70 years have occurred in 1955, 1969, 1971, 1974 and 1990. The town also experienced major flooding in February 2003 and December 2010. Recent flood events of lesser magnitude have occurred in 2016 and 2017.

MWRC has previously completed a number of studies to investigate floodplain management in Mudgee. The 1998, 2002 and 2008 studies separately consider flooding in Cudgegong River, Lawsons Creek and the local creeks that traverse Mudgee. As development pressure in the town continues, MWRC wishes to develop a single flood study that provides an improved understanding of flood behaviour and flood consequences in Mudgee. This study will focus on the February 2003, December 2010 and September 2016 events for model calibration as these events were recent and provide the best opportunity to obtain information from the community.

The primary objectives of this study are to:

- prepare a suitable hydrologic and hydraulic modelling system that defines flood behaviour for the 20%, 10%, 5%, 2%, 1%, 0.5%, 0.2% AEP and the Probable Maximum Flood (PMF) design events for the town of Mudgee and the surrounding floodplain.
- provide results for flood behaviour in terms of flood risk, peak flood levels and inundation extents within the study area.
- Prepare maps of flood behaviour results in order to provide MWRC with the planning tools necessary to mitigate flood risk for current and future development.

Based on the analysis undertaken the following has been identified:

- In a1% AEP riverine flood event there is significant flood impacts present both within the township and on the roadways connecting the town to the surrounding region. During a riverine flood only the Castlereagh Highway running south is flood free. In this event all other routes out of the town have the potential to be closed in excess of 24 hours;
- During a local (flash flood) 1% AEP storm event at Mudgee there is a high likelihood that property flooding and damage will occur. With the exception of Redbank Creek most other overland flow paths through the township do not have sufficient capacity to safely contain

flow through the township;

- Sensitivity analysis shows that in general the floodplain is not sensitive to changes in hydrologic or hydraulic modelling parameters which would still be in accordance with best practice. The catchment is sensitive to increases in rainfall intensity due to climate change however, with level increases in the 1% AEP event in excess of 0.50 m in the 1% AEP event within the Cudgegong River. These increased levels increases the risk of flooding on property and further reduces the evacuation capacity of the township.

1. INTRODUCTION

1.1. Background

Mudgee is situated in the Macquarie River Basin on the banks of the Cudgegong River, approximately 261 kilometres north-west of Sydney and is located within the Mid-Western Regional Council (MWRC) Local Government Area (LGA) as shown on Figure 1. The town is subject to flooding from the following sources:

- riverine flooding from Cudgegong River and Lawsons Creek with their confluence on the north western edge of town;
- flash flooding from multiple smaller creeks that originate on the south western edge of Mudgee and traverse the town until their confluence with the Cudgegong River, and
- local urban stormwater flooding.

MWRC has previously completed a number of investigations to determine flood behaviour and investigate floodplain management in Mudgee. The 1998, 2002 and 2008 studies separately consider flooding in Cudgegong River, Lawsons Creek and the local creeks that traverse Mudgee. As development pressure in the town continues and development begins to occur at the fringe of the available flood information, MWRC wishes to develop a single flood study that provides an improved understanding of flood behaviour and flood consequences in Mudgee. This study covers all urban areas of Mudgee and the surrounding floodplain, considering flooding from all sources and mechanisms.

1.2. Objectives

The primary objective of this Flood Study is to develop a robust hydrologic and hydraulic modelling system that defines flood behaviour for the 20%, 10%, 5%, 2%, 1%, 0.5%, 0.2% AEP and the Probable Maximum Flood (PMF) design events for the town of Mudgee and the surrounding floodplain. This will be used to assist MWRC in determining existing flood risk, peak flood levels and inundation extents within the study area. Given a history of flooding and recent development within the catchment, there is a strong need to define and map flood behaviour in the catchment in order to provide MWRC with the planning tools necessary to mitigate flood risk for current and future development. The tools developed may subsequently be used within a Floodplain Risk Management Study and Plan to assess the effectiveness and suitability of potential flood risk mitigation measures.

2. BACKGROUND

2.1. Study Area

Mudgee is located in the Macquarie River Basin on the banks of the Cudgegong River. The Cudgegong River rises in the Great Dividing Range within Wollemi National Park and follows a generally north westerly direction as it bypasses the town of Mudgee until its confluence with the Macquarie River at Burrendong Dam approximately 80 km downstream of Mudgee. The Cudgegong River has a wide floodplain at Mudgee with the majority of the town built on higher ground on the southern bank of the river. At Mudgee, the catchment area of the Cudgegong River and Lawsons Creek is approximately 1820 km². There are several water storage features in the catchment including the Windemere Dam, Kandos Weir and Rylstone Dam. Windamere Dam is located approximately 25 km upstream of Mudgee and has a contributing catchment area of 1,070 km^2 and a storage capacity of 368,120 ML. Windamere Dam operates in conjunction with Burrendong Dam to supply water for irrigation, stock and household needs in the Cudgegong and Macquarie Valleys, as well as providing environmental flows.

Lawsons Creek with a catchment area of 543 km² is the main tributary of the Cudgegong River rising 30 km east of Mudgee with their confluence on the north western edge of town. The other main tributaries of Cudgegong River in the vicinity of Mudgee are Oaky Creek, Sawpit Gully and Redbank Creek which originate south west of Mudgee as shown on Figure 2, with their confluence with Cudgegong River adjacent to Mulgoa Way. The urban area is drained by a series of smaller creeks which rise in the lower hills south of Mudgee and traverse the town itself until they meet the Cudgegong River on the northern edge of town. Their catchments are generally small and steep with bed slopes ranging between 4% in the upper reaches and 1% closer to the Cudgegong River floodplain.

The land uses in the catchment range from agriculture including grazing and vineyards to forested slopes in the Wollemi National Park and Avisford Nature Reserve as well as urban and industrial areas in the town of Mudgee.

2.2. Historical Flooding

2.2.1. Flood Mechanisms

Flooding at Mudgee is influenced by the following flood mechanisms:

1. **Cudgegong River and Lawsons Creek** - The floodplain adjacent to the town of Mudgee is subject to flooding from Cudgegong River and Lawsons Creek. Most of the urban area is built on higher ground and is largely unaffected by flooding from this source, although there are a number of residences, sporting facilities, commercial and agricultural businesses located on the floodplain that are directly affected by flooding from this mechanism. The coincidence of peak flood levels from the Cudgegong River and Lawsons Creek is usually responsible for major flood events. Flooding on Cudgegong River and Lawsons Creek can occur independently of one another or concurrently depending on the distribution and intensity of rainfall across the catchment. This will have significant effect on peak flood levels in Cudgegong River and Lawsons Creek and on the floodplains

adjacent to Mudgee.

2. **Local Creeks and Stormwater Flooding** - Due to their steep catchments the smaller creeks respond quickly to intense bursts of rainfall, rising quickly after the commencement of heavy rainfall and often resulting in “flash flooding” through the urban areas of Mudgee. At their outlets, the creeks discharge to the Cudgegong River, with river levels only influencing peak flood levels in the lower reaches of the creeks. As in any urban environment intense rainfall will exceed the capacity of the local drainage network resulting in overland flow paths traversing the town of Mudgee until they discharge into the Cudgegong River.

2.2.2. Historical Events

Records of historical flood events in and around Mudgee date back to 1870. Major flood events over the last 70 years occurred in 1955, 1969, 1971, 1974, 1990, 2003 and 2010. Recent flood events of lesser magnitude have occurred in 2016 and 2017. This study will calibrate to three events focusing on the February 2003, December 2010 and September 2016 events. As these events were recent, they provide the best opportunity to obtain information from the community.

The February 1955 storm was the largest recorded flood event since 1870 and has been reported to have approached the 1% AEP flood event for Cudgegong River at Mudgee. Since the 1955 event however, Windamere Dam has been incorporated which has significantly altered the hydrologic and hydraulic characteristics of the catchment. While the incorporation of the Dam has the potential to reduce flood levels, as the system is uncontrolled there is no specific flood mitigation capacity.

The February 2003 event recorded a 24 hour rainfall total of 178 mm at the Mudgee gauge which exceeds the 1% AEP 24 hour duration of 144 mm. The December 2010 flood event while not as intense as the 2003 event recorded 175 mm over three days at the Mudgee gauge and was significant enough for Mudgee to be declared a Natural Disaster Zone, with damage costs exceeding $10 million. A historical image of the 1955 flood event is shown in Plate 1.

Image Source: http://www.frankavis.com/blog/238/mudgee-floods/

Plate 1 – Flooding in Mudgee during 1955 flood event

2.3. Changes to Catchment and Flood Behaviour

2.3.1. Windamere Dam

The most significant change in catchment conditions was the construction of Windamere Dam with construction commencing in 1974 and completing in 1984. The dam has a total storage capacity of 386,120 ML with the main function to provide regulated flows along the Cudgegong River. It is not designed to include reserve storage capacity for flood mitigation and since the dam has an ungated spillway, there is no means of controlling the release of major flood flows. Historical records indicate that dam storage will be below full supply level for extended periods of time, therefore there is the potential for the dam to provide flood mitigation in flood events, but it is not its primary purpose nor can it be managed. The magnitude of this potential mitigation will depend on dam level prior to a flood event.

It is important to note that upstream of the town of Mudgee that 44% of the catchment which includes Lawson's Creek is not controlled by Windamere Dam. Major flooding can occur from this area independently of the catchment upstream of the dam.

2.3.2. Development in Catchment

As development in the catchment increases so does the percentage of impervious land, which will increase runoff and overland flow. The additional volume of water will exacerbate the pressure on the existing drainage network especially in the urban areas of the catchment. This has the potential to increase peak flood levels in the urban areas and drainage channels especially downstream of any new development.

With the explosion of residential development in the catchment and the region at large the issue of flooding and additional runoff from these areas will need to be managed on a small development scale. Retention basins and wetlands are an example of mitigation measures that can capture additional runoff from development and provide controlled release into the existing rivers, creeks or drainage line. There is also the opportunity to create parklands and open space for the community around the basins or wetlands. There are already several basins in the area however the ad hoc nature of development and implementation means that there potential to improve the capability of the current systems utilising information generated from this study.

3. AVAILABLE DATA

3.1. Overview

Data collection is the first stage in the floodplain risk management process and is essential to gain an understanding of the flooding characteristics within the catchment, including the nature, size and frequency of the flood problem. The type of data that is collected for a flood study is as follows:

- Topographic – LiDAR, river bathymetry and site specific survey;
- Stream Level and Flow – permanent water level gauges and historical flood level survey;
- Rainfall – permanent rain gauges;
- Council – cadastre, zoning layers, pipes pits and hydraulic structures;
- Design Rainfall – design rainfall data from Bureau of Meteorology (BOM) and Australian Rainfall and Runoff (ARR2016) data hub; and
- Historical Catchment Conditions – previous reports, flood levels, flood behaviour.

3.2. Data Sources

The available data sets for this study are summarised in the following sections. Table 1 provides a summary of the type of data sources, the supplier, and its application in the study.

Table 1 - Data Sources

Type of Data	Format Provided (Source)	Application
LIDAR data (2017)	MWRC	To construct a Digital Elevation Model (DEM) of the study area
Pits, Pipes, Hydraulic Structures	DRAINS model (Reference 1), AutoCAD cross-sections (Reference 2)	To build drainage network and hydraulic structures in TUFLOW model
River channel cross-section data	AutoCAD cross-sections (Reference 2)	To redefine the river and creek channel bathymetry
GIS Information (Cadastre, Zoning)	MWRC	To assist with hydraulic and hydrologic model build
Intensity Frequency Duration (IFD)	BOM	Design Flood Estimation
Temporal Patterns, Rainfall Losses, Areal Reduction Factors	ARR 2106 Data Hub	Design Flood Estimation
Historical Flood Levels and Behaviour	MWRC / Community	Calibration of Modelling Package
Rainfall Gauge (Daily)	BOM	Calibration of Modelling Package
Rainfall Grids (Daily)	BOM	Calibration of Modelling Package
Pluviometer (Continuous)	BOM	Calibration of Modelling Package
Stream Gauge (Continuous)	Water NSW	Calibration of Modelling Package
Previous Reports	Council	Historical Catchment Conditions and Historical Flood Data.

3.3. Topographic Data

Light Detection and Ranging (LiDAR) survey of the study area and its immediate surroundings was obtained for the study with a Digital Elevation Model (DEM) developed to be used in the hydraulic model as shown on Figure 3. LiDAR is aerial survey data that provides a detailed topographic representation of the ground with a survey mark between 1 m and 5 m depending on the survey. The data has been obtained from NSW spatial services, with the location, resolution, date of survey and accuracy displayed in Table 2. The accuracy of the ground information obtained from LiDAR survey can be adversely affected by the nature and density of vegetation, the presence of steeply varying terrain, the vicinity of buildings and/or the presence of water.

Table 2 – LiDAR Data

Region	Resolution	Survey End	Spatial Accuracy Horizontal (+/- m)	Spatial Accuracy Vertical (+/- m)
Euchareena	2 m	09/02/2017	0.8	0.3
	5 m	29/09/2014	1.25	0.9
Gulgong	2 m	30/11/2015	0.8	0.3
Mudgee	2 m	22/01/2017	0.8	0.3
Orange	2 m	09/02/2017	0.8	0.3

Surveyed river and creek cross sections for the Cudgegong River and Lawson Creek floodplain were obtained for a previous study to define the river and creek channel bathymetry. The cross sections were surveyed in June 1995 by a local surveyor, Land & Engineering Surveyors, and have been partially updated in 2002 and 2004.

3.4. Stream Gauges

The presence of water level recorders (stream gauges) in a catchment will assist in the calibration of the hydrologic and hydraulic modelling package. For this study five gauges are located in or adjacent to the study area and are listed in Table 3 with their locations shown on Figure 4.

Table 3 – Stream Gauges

Station ID	Station Name	Opened	Closed	Gauge Zero (AHD)
421019	Cudgegong River at Yamble Bridge	Aug-39	Current	379.071
421079	Cudgegong River at D/S Windamere Dam	Feb-70	Current	490.424
421149	Cudgegong River at Rocky Water Hole	Oct-94	Current	458.371
421150	Cudgegong River at Wilbertree Road	Aug-87	Current	427.134
421184	Cudgegong River at Upstream Rylstone	Jun-09	Current	580.817

The flow corresponding to a given water level is estimated from a rating curve which provides a relationship between the water level and flow at each gauge. This relationship is derived from velocity measurements (using a current meter) at a known water level and cross-sectional water area (obtained by survey). Many of these velocity readings are taken over a period of years at different water levels (termed gaugings) and in this way a rating curve is developed as a "line of best fit" between the gaugings. It is relatively easy to obtain "low flow" gaugings as small rises in water levels occur frequently and the gauging party has therefore ample opportunity to undertake them. It is much harder to obtain "high flow" gaugings as they can only be obtained during large floods (which occur infrequently) and it may be that the gauging party cannot get access to the site or are otherwise engaged. Safe access to the site can also be an issue. Thus, all rating curves generally have few "high flow" gaugings and the rating curve must be extrapolated. A review of the gaugings indicates how many "high flow" gaugings were undertaken and the height at which they were taken, this in comparison to peak recorded flood levels can provide an estimate of the accuracy of the rating curve for high flows. Generally, there are few gaugings taken at the peak of a flood and thus the highest gaugings may be several metres below the highest recorded flood levels.

All five gauges used for this study are controlled by Water NSW and have available rating curves. The rating curves are shown on Figure 5 to Figure 9. A review of the gauges within the study area indicates that Cudgegong River at D/S Windamere Dam has some high flow ratings present (approximately a 10% AEP event) but no other gauges have recorded flows above a 20% AEP level. At these locations the flows are derived using an extrapolated rating curve which must be used with caution.

3.4.1. Analysis of Stream Gauge Records

The gauge with the longest record is the Yamble Bridge gauge at Cudgegong River. The top ten annual maximums recorded at the gauge are shown in Table 4 with the 1956 event recording the largest stage height. It should be noted that the stage height at the gauge was not available for the 1955 event.

Table 4 – Top Ten Annual Maximum at Yamble Bridge Gauge (Gauge zero - 379.071 mAHD)

421019 Cudgegong River at Yamble Bridge	
Year	**Annual Max Level (m)**
1956	8.36
2010	7.61
1979	7.33
2000	7.04
1971	6.88
1990	6.58
1998	5.99
2012	5.85
2003	5.19
1996	4.86

The stream gauge records were analysed for two significant historical events mentioned in Section 2.2. The recorded peak stage heights for the Cudgegong River for the 2003 and 2010 events are shown in Table 5 and the stage hydrographs are shown on Figure 10 and Figure 11.

Table 5 – Peak Stage Heights (m)

Event	Station Name	Cudgegong River Stage Height (m)
Feb 2003	Cudgegong River at Yamble Bridge	5.19
	Cudgegong River at D/S Windamere Dam	1.48
	Cudgegong River at Rocky Water Hole	4.52
	Cudgegong River at Wilbertree Road	5.80
Dec 2010	Cudgegong River at Yamble Bridge	7.61
	Cudgegong River at D/S Windamere Dam	2.16
	Cudgegong River at Rocky Water Hole	5.32
	Cudgegong River at Wilbertree Road	5.76
	Cudgegong River at Upstream Rylstone	2.39

3.5. Rainfall Stations

3.5.1. General

There are a number of rainfall stations within a 100 km radius of the study area. These include daily read stations and continuous pluviometer stations.

The daily read stations record total rainfall for the 24 hours to 9:00 am of the day being recorded. For example, the rainfall received for the period between 9:00 am on 3 February 2008 until 9:00 am on 4 February 2008 would be recorded on the 4 February 2008.

The continuous pluviometer stations record rainfall in sub-daily increments (with output typically reported every 5 or 6 minutes). These records were used to create detailed rainfall hyetographs. A rainfall hyetograph is a graphical representation of how rainfall intensity or rainfall depth is distributed over time. The rainfall hyetographs are a model input for historical events against which the model can be calibrated. Table 6 and Table 7 present a summary of the continuous pluviometer and daily rainfall gauges available for use in this study. The locations of these gauges are shown on Figure 12 and Figure 13. These gauges are operated by the BOM and Water NSW.

Table 6 - Continuous read rainfall stations

Station Name	Agency	Station ID	Opened	Closed
Glen Alice	BOM	61334	07/1970	04/2014
Bylong (Montoro)	BOM	62020	02/1965	03/1991
Wellington Research Centre	BOM	65035	02/1961	02/2005
Bylong (Bylong Rd)	BOM	62102	05/1991	10/2016
Glen Alice (Eurella)	BOM	61149	01/1966	10/1967
Ben Bullen	BOM	563034	07/2005	Current
Rylstone (Marloo)	Water NSW	562101	22/6/1990	28/11/2011
Glenn Alice (Yandarra)	Water NSW	562102	22/6/1990	28/11/2011

Table 7 - Daily read rainfall stations

Station Name	Station ID	Opened	Closed
Rylstone (Kelgoola)	61215	30/10/1962	Current
Brogans Ck Cement Quarry	62001	29/09/1950	29/12/1978
Charbon Standard Portland Ceme	62006	29/06/1929	29/12/1978
Kandos	62016	30/07/1938	29/12/1967
Kandos Cement Works	62017	01/01/1951	Current
Springdale	62023	30-01-1898	29/12/1967
Ilford (Tara)	62029	01/01/1928	Current
Ilford (Warrangunyah)	62031	30-01-1896	Current
Leadville (Moreton Bay)	62035	01/01/1936	Current
Ulan Post Office	62036	27/02/1906	Current
Marsden Forest	62055	01/01/1948	01/01/1984
Wollar (Maree)	62056	29/09/1962	Current
Lue (Bayly St)	62062	30/10/1902	Current
Mudgee (Kemshall)	62075	01/01/1959	Current
Budgee Budgee (Botobolar Vineyard)	62084	29/04/1971	Current
Windamere Dam	62093	28/02/1976	Current
Mudgee Airport AWS	62101	30/10/1988	Current
Mudgee (Wandu-Too)	62104	08/09/1997	Current
Tallawang (Talinga)	62105	01/01/2003	Current
Tyar	63110	01/01/1935	01/01/1964
Goolma (Brooklyn)	62028	01/01/1919	Current
Wollar (Barrigan St)	62032	01/01/1901	Current
Weeroona	62033	01/01/1897	01/01/1971
Leadville (Daymar)	62068	01/01/2002	Current
Bylong (Heatherbrae)	62080	30/08/1968	Current
Geurie (Kurrabri)	65099	03/02/2003	Current
Hargraves (Edge Hill)	62089	01/01/1971	Current
Muronbung (Youralla)	65107	01/01/1948	01/01/1995
Muronbung (Youralla)	65107	29/09/2003	Current
Yarrabin (Osory)	62095	29/06/2002	25/08/2003
Bylong (Bylong Rd)	62102	30/05/1991	Current
The Gullies	63031	01/01/1940	01/01/1969
Hill end Post Office	63035	29/04/1880	Current
Dunedoo Post Office	64009	01/01/1912	Current
Elong Elong (Bendeela St)	64010	01/01/1926	Current
Sofala Old Post Office	63076	30/01/1892	Current
Paling Yards (Ulabri)	63085	01/01/1921	Current
Cobbora (Ellismayne)	64026	01/01/1887	Current
Wattle Flat General Store	63089	29/09/1889	Current
Wellington Research Centre	65035	01/01/1946	22/02/2005
Eurella	61149	30/01/1914	29/12/1969
Bodangora Post Office	65003	30/10/1899	29/12/1968
Geurie Post Office	65018	30/05/1910	Current
Hargraves (The Elders)	62014	30/05/1913	Current
Dunedoo Post Office	64009	01/01/1912	Current

3.5.2. Analysis of Daily Read Data

The selected daily rainfall gauges were analysed for the three significant events specified in Section 2.2.2. Each event was analysed for the maximum 1-day, 2-day, 3-day and entire event totals. The 2010 event was also analysed for the maximum 4-day entire event totals. The results of the analysis are shown in Table 8

The pluviometer gauges were also analysed for the historical events that had corresponding rainfall data. The rainfall hyetographs for the historical events are shown on Figure 14 to Figure 15.

The rainfall totals for each event at each available rain gauge were used to create rainfall isohyets for the entire catchment using the natural neighbour interpolation technique, whereby the recorded rainfall depth at each gauge is used to create a rainfall depth grid of the entire catchment, which are shown on Figure 16. They fundamentally show the variability in rainfall depth across the catchment which can then be used to determine rainfall depths for each individual sub catchment in the historical events in the hydrological model.

Table 8 – Highest Daily Read Rainfall Readings (mm) for 1955, 2003 and 2010 events

Event	Duration	Station ID	Station Name	Total Rainfall (mm)
1955	1-day	64009	Dunedoo Post Office	261.1
	2-day			326.1
	3-day			334.2
	entire event			334.2
2003	1-day	62014	Geurie (Kurrabri)	27
	2-day	62084	Budgee Budgee	213.2
	3-day			217.2
	entire event			217.2
2010	1-day	62102	Bylong (Bylong Rd)	53.4
	2-day	62032	Wollar (Barrigan St)	90.2
	3-day	62014	Hargraves (The Elders)	152
	4-day	64026	Cobbora (Ellismayne)	185.8
	entire event			185.8

3.6. Design Rainfall

The design rainfall intensities for the town of Mudgee obtained from the BOM website are shown in Table 9. Note the IFD values utilised in the study may vary as the IFDs are calculated at the centroid of each subcatchment.

Table 9 - IFD Table for Mudgee (location -32.597S, 149.5875E)

Storm Duration	1 EY	50% AEP	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP
1 min	1.79	2	2.66	3.13	3.6	4.25	4.76
2 min	2.97	3.31	4.39	5.15	5.92	6.92	7.7
3 min	4.13	4.6	6.11	7.16	8.23	9.63	10.7
4 min	5.18	5.77	7.67	9	10.3	12.1	13.5
5 min	6.12	6.82	9.07	10.7	12.2	14.4	16.1
10 min	9.62	10.7	14.3	16.8	19.4	22.9	25.7
15 min	11.9	13.3	17.7	20.9	24	28.4	31.9
30 min	16	17.8	23.7	27.9	32.1	38	42.6
1 hour	20.1	22.3	29.7	34.9	40.1	47.2	52.8
2 hour	24.6	27.4	36.2	42.4	48.6	56.9	63.4
3 hour	27.7	30.8	40.7	47.6	54.5	63.7	70.9
6 hour	34.3	38.2	50.4	58.8	67.2	78.5	87.4
12 hour	43	47.9	63.3	74	84.5	99.5	111
24 hour	53.6	59.8	79.5	93.2	107	127	144
48 hour	64.9	72.4	97.1	115	132	159	182
72 hour	71	79.3	107	126	146	177	203
96 hour	74.9	83.8	113	134	155	188	216
120 hour	77.8	87	117	139	161	195	223
144 hour	80.1	89.5	120	142	165	199	228
168 hour	82	91.7	123	145	167	202	231

3.7. Pits, Pipes and Hydraulic Structures

The 2008 Mudgee Local Creeks Floodplain Risk Management Study and Plan Volume 2 Flood Behaviour Studies (Reference 1) and the 2002 Mudgee Floodplain Management Study and Plan (Reference 2) established one dimensional (1D) flood models to define flood behaviour.

These models were developed from cross section survey and information on hydraulic structures. Pits, pipes and hydraulic structure data from these studies were reviewed and the suitability for use in the current study determined. Missing data was identified and site visits undertaken by WMAwater on 23rd to 24th May 2018 and 20th to 22nd June 2018 to verify pit and pipe locations and obtain a more accurate understanding of the drainage network within the catchment. The site visits also included the inspection of other hydraulic controls within the catchment, such as detention basins, swales, bridges and open channels. The location of the hydraulic structures reviewed for inclusion in the hydraulic model to date are shown on Figure 17. A data gap analysis was undertaken for the hydraulic structures in the study area with details of this analysis provided to Council.

Due to limited availability of data some crossing structure details have been omitted. It is considered these omissions are unlikely to significantly affect the outcomes of the modelling however as better data becomes available this should be reviewed against the model setup to confirm reasonable correlation. Table 10 shows the locations of key structures where information is missing. Note that at Fairy Dale Lane the model DEM is out of date, once revised topographic information is present for this area the model setup should be reviewed to incorporate the data.

Table 10 – Key structures missing information

Location	X Coordinate	Y Coordinate	Assumed Dimensions
Sawpit Gully downstream of industrial area (under railway)	744626.008	6389176.200	4 x 1.2 m RCP
12 Castlereagh Hwy	743785.062	6389788.062	Assumed open bridge
63 Fairy Dale Lane	740661.658	6391515.777	Omitted (DEM outdated)

3.8. Previous Studies

3.8.1. Mudgee Reconnaissance Flood Study Report; Water Resource Commission 1985 (Reference 4)

The report has not been obtained by WMAwater but the following summary was taken from Reference 6. A reconnaissance flood study was undertaken in 1985 which documents flood data recorded during the February 1955 flood and produced a flood inundation map for Mudgee based on this event. Although a flood frequency analysis on the historical flood data was not carried out. The 1955 flood is reported as being a major event approaching the 1% AEP event the Cudgegong River at Mudgee. A preliminary assessment of the flood problem noted that flood damage to urban development at Mudgee was limited to about six dwellings on the floodplain and the local radio station.

3.8.2. Advice Concerning Flooding of the Cudgegong River and Lawsons Creek at Mudgee; Sinclair Knight & Partners 1983 (Reference 3)

The report has not been obtained by WMAwater but the following summary was taken from Reference 6. This advice is contained in a brief report that provides a flood assessment for land located between the Cudgegong River and Lawsons Creek, upstream of the confluence of both rivers.

Reported food conditions were based on flood heights that were observed in the vicinity of the site in 1969 and 1955. These floods were assessed to be equivalent to a 5% and 1% AEP event respectively, based on flood frequency analysis of available flood records at Yamble Bridge and the Windamere Dam site.

3.8.3. Redbank Creek Dam – Dambreak Study; Public Works Department 1992 (Reference 5)

The report has not been obtained by WMAwater but the following summary was taken from Reference 6. The study investigated the risk of flooding due to the possible failure of the Redbank Creek Dam wall. Various dambreak scenarios were investigated, with computer modelling simulating flood conditions in Redbank Creek, between the dam and the railway line.

Eleven cross sections of Redbank Creek, surveyed by Council of Redbank Creek were used in the analysis. Floor levels of low lying properties were also surveyed to help quantify the number of homes affected by flooding.

The report concludes that about fourteen dwellings would be at risk from a sunny day dam failure, upstream of the railway line. Dam failure during a PMF was estimated to result in additional inundation depths, but no increase to the number of dwellings affected by flooding. The dam was assessed as having a high flood hazard rating.

3.8.4. Mudgee Flood Study; Department of Land and Water Conservation 1998 (Reference 2)

The flood study was undertaken to define flood behaviour in the town of Mudgee and the rural surrounds. In this study, flood behaviour for Cudgegong River and Lawsons Creek was assessed using the hydrologic model (RORB) and hydraulic model (MIKE-11) software. Surveyed cross sections from the 1995 study were used to define the river system bathymetry. Flood levels and velocities were determined for the 5%, 2%, 1% AEP and PMF design events, with these results to be used to assess development applications. The models developed for this study were used in the subsequent Floodplain Risk Management Study and Plan.

3.8.5. Mudgee Floodplain Management Study and Plan – Redbank Creek Flood Investigations; Bewsher Consulting 2000 (Reference 7)

After considering the flooding issue on Redbank Creek the Floodplain Management Committee (FMC) decided to expand the Mudgee floodplain management study to include the Redbank Creek catchment. The objective of the study was to define flood behaviour for Redbank Creek so that management options could be considered in the subsequent management study. Flood behaviour of Redbank Creek was investigated using the hydrologic model RORB and the hydraulic model HECRAS. Flood levels and velocities were determined for the 5%, 2% and 1% AEP design events. The following issues were identified:

- potential for dam failure;
- houses subject to flooding;
- issues at Waterworks Road;
- culverts with inadequate capacity;
- high velocities, scour potential and potential infrastructure damage;
- Redbank Creek Dam operation options;
- recommended freeboard of 1.0 m, and
- suggested mitigation options.

3.8.6. Mudgee Floodplain Management Study and Plan; Bewsher Consulting 2002 (Reference 6)

The FRMS&P used the modelling package developed in the 1998 Flood Study (Reference 2). The objectives of the study included:

- a review of the existing flood study model and results;
- additional flood modelling of Redbank Creek (Reference 5);
- quantification of the flood problem in Mudgee and rural surrounds;
- assessment of potential flood mitigation options, and
- development of recommended floodplain management plan.

A review and investigation of potential planning instruments and measures was undertaken as well as the investigation of potential floodplain mitigation measures. Following this investigation the following measures were recommended in the Draft Floodplain Management Plan:

- High Priority Measures
    - planning and development controls – graded set of planning controls that recognises type of development and flood risk of that area;
    - improved public awareness – update Council's GIS with current flood information, issue of flood certificates, construction of flood markers;
    - improved emergency management plans – update SES local flood plan for Mudgee in conjunction with improvement to flood warning system;
    - flood action plan for the Short Street Caravan Park, and
    - remedial measures for Redbank Creek Dam (in 2008 1.6 m diameter outlet pipe was installed. In 2013 the upper section of the dam wall was demolished to create an 80 m wide spillway at a crest level of 531.1 mAHD and the 1.6 m diameter outflow pipe was reduce to 0.75 m in dimeter to convert the dam into a retarding basin).
- Medium Priority Measures
    - vegetation management study and plan – recommended for Cudgegong River and Lawsons Creek;
    - flood warning proposal and implementation, and
    - small landscaped levee in Mulgoa Robertson Street.
- Low Priority Measures
    - culvert amplifications under Waterworks Road;
    - channel works upstream of Waterworks Road;
    - voluntary house raising, and
    - flood proofing measures.

3.8.7. Redbank Creek Dam Flood Study, Department of Commerce 2006 (Reference 8)

The Hydrology Group of the NSW Department of Commerce (DOC) were engaged to provide specific flood estimates to assist with the concept work relating to the upgrading of the Redbank Creek Dam. The report summarizes the hydrologic investigations undertaken to provide estimates of 1 in 100000 AEP inflow hydrographs. The estimates were requested to be based on:

- using the RORB hydrological model for the Dam catchment;
- using suitable model parameter values based on the work of Dyer et al (1996) and the

regional relations in ARR87;
- determining design rainfall frequency curves, and
- using the RORB model to transfer the 1 in 100,000 AEP design rainfalls to provide 1 in 100,000 AEP flood inflow hydrographs.

The study recommended that flood estimates should be reviewed for future design purposes and consideration should be given to reviewing the flood frequency estimates when CRC Forge rare rainfall estimates becomes available for NSW.

3.8.8. Mudgee Local Creeks Floodplain Risk Management Study and Plan Volume 1&2; Lyall and Associates 2008 (Reference 1)

The Floodplain Risk Management Study and Plan consisted of two volumes:
- Volume 1 – Draft Floodplain Management Study and Plan
- Volume 2 – Flood Behaviour Studies

The overall objectives of the study were to define and assess the impacts of flooding in the local creeks catchments, review policies and options for management of flood affected land and to develop a draft Floodplain Risk Management Plan which:
- proposes modifications to existing Council policies to ensure that the development of flood affected land adjacent to the creeks in undertaken so as to be compatible with the flood risk;
- proposes flood planning levels for various land uses in the floodplains;
- sets out the recommended program of works and measures aimed at reducing over time, the social, environmental and economic impacts of flooding, and
- provides a program for implementation of the proposed works and measure.

<u>Volume 1 – Study and Plan</u>
The proposed measures in Volume 2 were refined and an investigation undertaken into planning, policy, emergency response and a flash flood early warning system. The recommended measures for the draft floodplain risk management plan are:
- investigation/concept design study to confirm the feasibility of structural drainage works;
- depending on results of above undertake detailed design and construction of drainage works program;
- application of existing policy document "Managing Our Flood Risks" to control development in the floodplains of the Mudgee Local Creeks;
- undertake investigation of feasibility of a flash flood warning system;
- implementation of flash flood warning system;
- ensure flood data in this FRMS&P are available to SES for inclusion in flood emergency response procedures, and
- implement flood awareness and education program for residents bordering the creek system and owners industrial developments adjacent to Sawpit Gully.

<u>Volume 2 – Flood Behaviour Studies</u>
Volume 2 of the study defines flood behaviour for seven of the eight drainage lines running through the town of Mudgee excluding Redbank Creek which was investigated in Reference 6. The

drainage lines were given the following names:

- Catchment A, also known as Saleyards Creek
- Catchment B
- Catchment C
- Catchment D
- Catchment E
- Catchment F
- Sawpit Gully

The study used a hydrological model (DRAINS) and a one-dimensional hydraulic model (HEC-RAS, Reference 5) to estimate design flood behaviour in the study area for the 20%, 5%, 1% AEP and PMF events. A broad scale investigation of structural measures was undertaken to mitigate flooding in residential areas bordering the Mudgee Creek system and is summarised below:

- Catchment A
    - channel enlargement from Wallerang – Gwabegar Railway embankment to Lang Street;
    - channel enlargement from on Southern side of Galdstone Street from Fairy Dale Lane to Bell Street;
    - improve capacity of Rifle Range Road culvert;
    - detention basin d/s Bellevue Road (constructed in 2013), and
    - reconstruct Farm Dam (as a dual purpose flood mitigation/water conservation dam).
- Catchment B
    - detention basin u/s Railway (constructed in 2017), and
    - improve hydraulics of intake pit to relief pipeline in Cox Street.
- Catchment C
    - improve capacity of Mortimer Street culvert;
    - detention basin Victoria Park area and improve inlet to Perry Street culvert, and
    - remove brick wall across channel south side Gladstone Street
- Catchment D
    - no improvements proposed
- Catchment E
    - increase culvert capacity and/or lower road level at Mortimer Street crossing
- Catchment F
    - improve capacity of George Street culvert;
    - convert golf course dam to dual purpose storage basin;
    - improve capacity of Inglis Street culvert, and
    - improve capacity of Mortimer Street culvert
- Sawpit Gully
    - reduce capacity of detention basin low level outlets (short-term measure);
    - raise level of embankment and spillway of detention basin (long term measure), and
    - improve capacity of Industrial Avenue culverts, plus channel improvements.

3.8.9. Stormwater and Flood Investigation – Byron Place/Church Street Mudgee Town

Centre; Wallis and Moore Insites 2009 (Reference 10)

Stormwater and flood behaviour were investigated in the Mudgee town centre to provide options and advice to Council on works in the catchment to reduce potential flooding in Byron Place car park through to Market Street, Mortimer Street in front of Woolworths and the corner of Gladstone and Church Streets. The hydrologic and hydraulic modelling package XP storm was used to model the 20%, 5% and 1% AEP events. The following options were investigated with specific recommendations provided in the report:

- Church Street drainage extension;
- Mortimer Street drainage upgrade and extension;
- Perry Street;
- Intersection of Perry Street and Gladstone Street; and
- Mortimer Street Low Point.

3.8.10. Spring Flat Drainage Study Report, Mudgee – Wallis and Moore Insites 2010 (Reference 11)

WMAwater has not obtained this report, with this brief description provided in the project brief document. The study assesses flooding/drainage problems within the Spring Flat catchment of Mudgee.

3.8.11. Glen Willow Master Plan – Glen Willow Regional Sporting Complex – Mid-Western Council 2016 - Amended in 2018 (Reference 12)

The master plan outlines MWRC proposal to establish a sporting complex around the main one thousand seat stadium located at Pitts Lane Mudgee. The objective is to establish a number of multi-use fields for both summer and winter competitions including soccer, AFL, rugby league, rugby union, touch football, cricket, junior league, hockey, softball, baseball and netball.

The proposed site is Council owned land that is bounded by Lawson Creek to the north, Pitts Lane to the south and farm land to the east and west. The site area is approximately 40 hectares. The site level is below the 1% AEP flood level and is located in an area designated as a high hazard flood zone. Significant vegetation exists along Lawsons Creek and there are a few native trees along the southern boundary. The remaining site is grassed and generally flat with a gentle fall to the west.

The overall vision is for the following:

- three major fields
- nine other fields
- one cricket oval
- two artificial fields
- up to 24 netball hardcourts
- 9 netball grass courts
- associated grandstands, amenities, club rooms and storage sheds
- extended off leash dog park
- cycleways and walkways

- lighting, signage, fencing and irrigation

As the site is located within a floodplain it is proposed to raise all buildings onto berms. The report states that the intention of the plan is to not raise the entire site as this would have detrimental effects on adjoining properties due to floodwaters and that flood analysis work is being carried out to ensure that pre-development and post-development flood levels both upstream and downstream are maintained.

Council's vision has already commenced with the development of the six existing fields, 12 netball courts and development of main field and stadium. Council proposes to develop the Glen Willow Regional Sporting Complex over a number of stages in the coming years.

3.8.12. Mudgee and Gulgong Urban Release Strategy – Hill PDA Consulting 2014 (Reference 13)

Council and the NSW Department of Planning and Environment identified the need to prepare an Urban Release Strategy for the towns of Mudgee and Gulgong. This is due to strong population growth driven by the expansion of the local coal mining industry and the sustained pressure for residential development. To date the majority of housing growth has occurred in Mudgee however nearby Gulgong has also been impacted in recent years by shifts in the housing market.

The Urban Release Strategy addresses the following:

- Strategy timeframe and review
- Land Supply Monitor
- Planning Framework and Strategy
- Mid-Western Local Environment Plan 2012
- Development Servicing Plans
- Urban Release Strategy
- Demographic Trends
    - Population Projections
    - Resident and Dwelling Characteristics
- Residential Market Snapshot
- Supply and Demand Analysis
    - Supply Factors
    - Demand Factors
    - Mudgee – Supply and Demand
- Land Release Strategy
- Recommendations
    - Mudgee Land Release Recommendations
    - Gulgong Land Release Recommendations

4. COMMUNITY CONSULTATION

4.1. Information Brochure and Survey

In collaboration with MWRC an information brochure with community survey was distributed to residents within the study area. The function of this was to describe the role of the Flood Study in the floodplain risk management process and to request records of historical flooding. Coupled with updates on Council's social media and online survey eighteen responses were received from the survey. From the survey 94% of respondents are aware of flooding issues in the catchment, with eleven respondents having had their properties affected by flooding.

4.2. Community Responses

The responses are summarised in graphs on Figure 18 and the properties identified as flood affected are shown on Figure 19. The following issues were raised by the respondents:

- the majority of respondents are acutely aware of flooding risks. Most respondents remember the flood events in February 2010, September 2016 and March 2017 causing limited access to or isolation in their properties. For most of the affected properties flood water took longer than 1 day to drain away or had to be pumped out;
- some residents are concerned about the impact of flooding on local tourism for caravan parks or hotels;
- some respondents feel that new residential buildings and unit development and changes to the drainage system in their local area have significantly changed the overland flow path in recent years, making their properties more vulnerable to flooding;
- some respondents observed that the general watercourse from the airport and Henry Lawson Drive through to Putta Bucca Road has been significantly changed, making parts of Putta Bucca Road completely unusable and inaccessible;
- according to some respondents, improvements in the management of Windamere Dam could reduce the risk of flooding downstream of the dam;
- some respondents feel that the current flood situation causes a threat to children, animals and more vulnerable people that rely on medical care and assistance;
- a respondent feels that the flood problem is being neglected by the Council with regard to the redirection of a watercourse through their property, and
- some respondents are concerned about future development in areas that are isolated during flood events. They are concerned that the development will be dangerous to new residents and stretch the resources of community and emergency services during flood events.

A selection of flood images provided by MWRC and the community is shown in Plate 2 to Plate 15.

Plate 2– Lawsons Park 2003

Plate 3 – Lawsons Park 2003

Plate 4 - Lawsons Park 2003

Plate 5 – Wilbertree Road 2003

Plate 6 – Ulan Road 2003

Plate 7 – Jubilee Park after 2003 flood

Plate 8 – Mudgee, 2010 flood

Plate 9 – Mudgee, 2010 flood

Plate 10 – Mudgee, 2010 flood

Plate 11 – Mudgee, 2010 flood

Plate 12 – 17 Mortimer Street Mudgee

Plate 13 - 17 Mortimer Street Mudgee

Plate 14 – Glen Willow Sports Complex

Plate 15 – Glen Willow Sports Complex

5. STUDY METHODOLOGY

The approach adopted in flood studies to determine design flood levels largely depends upon the objectives of the study and the quantity and quality of the data (survey, flood, rainfall, flow etc.). There is a thorough record of daily rainfall data for the catchment and some sub-hourly rainfall data from pluviometer gauges and stream gauges with sufficient record length, which can be used for event-based model calibration. For this study, a rainfall-runoff approach was adopted, using a hydrologic model to estimate the runoff flows from rainfall, and a detailed hydraulic model to determine the flood levels, depths, velocities and extents produced by the runoff flows throughout the study area. A diagrammatic representation of the flood study process undertaken in this manner is shown below.

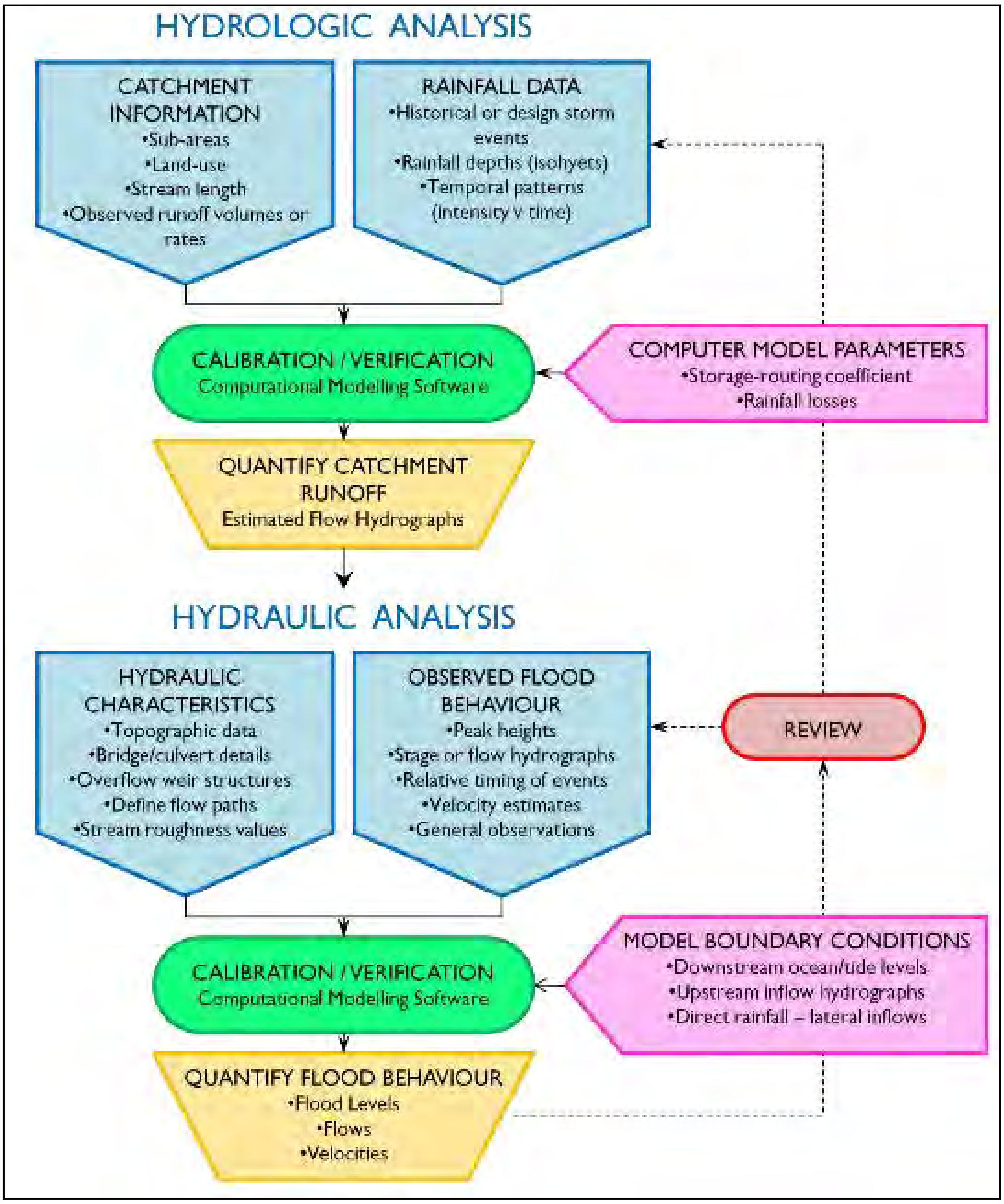

Diagram 1: Flood Study Process

6. HYDROLOGIC MODEL

6.1. Introduction

Inflow hydrographs serve as inputs at the boundaries of the hydraulic model. In a flood study where long-term gauged streamflow records are not available at the point of interest, or other flood mechanisms exist, a rainfall-runoff hydrologic model (converts rainfall to runoff) is generally used to provide these inflows. A range of runoff routing hydrologic models are available as described in Australian Rainfall and Runoff (ARR2019) 2019. These models allow the rainfall depth to vary both spatially and temporarily over the catchment and readily lend themselves to calibration against recorded data. While there is long term data available for

The WBNM hydrologic run-off routing model was used to determine flows from each sub-catchment. The WBNM model has a relatively simple but well supported method, where the routing behaviour of the catchment is primarily assumed to be correlated with the catchment area. If flow data is available at a stream gauge, then the WBNM model can be calibrated to this data through adjustment of various model parameters including the stream lag factor, storage lag factor, and/or rainfall losses.

A hydrological model for Cudgegong River and Lawsons Creek catchment was created and used to calculate the flows for each individual sub-catchment and tributary creek for inclusion in the TUFLOW hydraulic model. A detailed hydrological model which covers the Mudgee Township has also been developed to assess the local runoff characteristics of the area.

6.2. Sub-catchment delineation

The catchment boundary was determined by the ridges that create the natural drainage division. Precipitation falling on the other side of these boundaries would flow into other catchments and so was not modelled within this study area. Lawson creek catchment has been combined with the adjacent Cudgegong river catchment, both adding up to a total catchment size of approximately 1800 km^2 to the downstream of Mudgee Township. Within these catchments, smaller sub catchment areas were derived from LiDAR topographic data and consideration of hydraulic controls such as bridge crossings and rail/road embankments. Figure 20 shows the sub catchment delineation for the study area.

The catchment in general has been considered to be pervious in the majority of areas. The township of Mudgee and surrounding suburbs have been assessed on a land use scale for the application of effective fraction impervious parameters.

The catchment model extends significantly further downstream than the study boundary to allow for the inclusion of the Wilbertree Road flow gauge. This is to enable two calibration points within the hydrology and hydraulic models.

6.3. Adopted Hydrologic Model Parameters

The model input parameters for each sub catchment are:

- A lag factor (termed C), which can be used to accelerate or delay the runoff response to rainfall (Section 6.4);
- A stream flow routing factor, which can accelerate or decelerate in-channel flows occurring through each sub catchment (Section 6.4);
- An impervious area lag factor (Section 6.5);
- An areal reduction factor (Section 6.7);
- The percentage of catchment area with a pervious/impervious surface (Section 6.5); and
- Rainfall losses calculated by initial and continuing losses to represent infiltration (Section 6.6).

6.4. Lag and Routing Factors

A typical regional value of 1.8 for the lag factor ‘C’ hydrologic model parameter which is in range rec by WBNM was found to be appropriate which is within the range of values recommended by WBNM. This was based on the calibration of the flood models, discussed in Section 8. A value of 1.45 was used for the stream flow routing which is based on the calibration undertaken (Refer Section 8). The C value was modified from the default to account for the flat nature of the floodplain in the Mudgee region. This characteristic alters the response of the catchment lag. The value is still close to the default and is well within the bounds of the variation identified within WBNM runoff routing parameters for south and eastern Australia (Reference 24). The impervious area lag factor is set to 0.1, which is the default set by WBNM.

6.5. Impervious Surface Area

Runoff from connected impervious surfaces such as roads, gutters, roofs or concrete surfaces occurs significantly faster than from vegetated surfaces. This results in a faster concentration of flow within the downstream area of the catchment and increased peak flow in some situations. This is less important in rural studies as they consist of relatively few impervious areas, and those areas are typically not hydraulically connected to the waterway (i.e. the water flows across pervious areas on the route between the impervious surface and the receiving waterway). Mudgee, on the other hand has a number of commercial impervious areas such as the CBD and the industrial precinct south east of the township.

Land use information and aerial photography was utilised to estimate the effective impervious surface area for each sub-catchment. For each of the land use types, an impervious percentage was assigned. The assumed effective imperviousness of each sub-catchment varied from 0 to 90%, depending on the land use. A large majority of the catchment is undeveloped and has an imperviousness of 0% to 5%. Slightly higher values were applied where there was low-density development, whilst higher imperviousness percentages were applied in the urban area of Mudgee. Table 11 provides a summary of the fraction impervious and the effective fraction impervious utilised for each associated land use. Effective fraction impervious differs from fraction impervious as it aims to estimate the proportion of the total impervious area that results in runoff.

Based on aerial photography the medium density and general residential have been deemed to have the same effective fraction impervious as both still contain significant regions of green space.

Table 11 - Summary of the Effective Fraction Impervious Utilised

Land Use	Fraction Impervious (%)	Effective Fraction Impervious (%)
Rural / Primary Production	0	0
Commercial	90-100	90
Medium Density Residential	40-50	30
General Residential	30-40	30
Recreation	0-10	0

6.6. Rainfall Losses

Methods for modelling the proportion of rainfall that is "lost" to infiltration are outlined in ARR2019 (Reference 15). The intent of the approaches is to provide a reasonable estimate of loss in the catchment based on the best available information. The methods are of varying degrees of complexity, with the more complex options only suitable if sufficient data is available. The method most typically used for design flood estimation is to apply an initial and continuing loss to the rainfall. The initial loss represents the wetting of the catchment prior to runoff starting to occur and the filling of localised depressions, and the continuing loss represents the ongoing infiltration of water into the saturated soils while rainfall continues. The rainfall losses adopted as a result of the calibration process are discussed in Section 8 and the loss values used in design flood estimation are discussed in Section 9.

6.7. Areal Reduction Factor

Areal reduction factors (ARF) convert design point rainfall intensities (IFD) into areal-averaged rainfall estimates. The ARF provides a correction factor between the catchment rainfall depth (for a given combination of AEP and duration) and the mean of the point rainfall depths across a catchment. The ARF applied to design rainfall is a function of the total area of the catchment, the design rainfall duration and the AEP. Applying an ARF is a necessary input to computation of design flood estimates from a catchment model that preserves a probability neutral transition between the design rainfall and the design flood characteristics. The ARF merely influences the average depth of rainfall across the catchment, it does not account for variability in the spatial and/or space-time patterns of its occurrence over the catchment.

The method adopted for the derivation of areal reduction factors is based on ARR 2019 (Reference 16). Local rainfall areal reduction factors were applied to short duration burst events that may affect the town centre rather than the regional areal reduction factor. This ensures the correct volume of rainfall is considered for events in the area of interest.

7. HYDRAULIC MODEL

7.1. Introduction

The availability of high quality LiDAR as well as detailed aerial photographic data enables the use of 2D hydraulic modelling for the study. Various 2D software packages are available (SOBEK, TUFLOW, RMA-2) and the TUFLOW package was adopted as it is the most widely used model of this type in Australia for riverine and property scale flood modelling.

Recent developments to the TUFLOW engine have enabled the utilisation of high powered graphics cards to improve the run times associated with large model domains. Given the large area present in this study area, it was deemed necessary to utilise this technology, known as TUFLOW HPC GPU.

The TUFLOW model version used in this study was 2018-03-AE-iSP and further details regarding TUFLOW software can be found in the User Manual (Reference 20)

In TUFLOW the ground topography is represented as a uniform grid with a ground elevation and Manning's 'n' roughness value assigned to each grid cell. The size of grid is determined as a balance between the catchment features, model result definition required, and the computer processing time needed to run the simulations. The greater the definition i.e. the smaller the grid size the greater the processing time needed to run the simulation. A cell size of 3 m by 3 m was adopted as it provided an appropriate balance between providing sufficient detail for the river channels and bridges, while still resulting in workable computational run times.

7.2. TUFLOW Hydraulic Model

The Digital Elevation Model (DEM) for use in TUFLOW was generated from a triangulation of filtered ground points from the LiDAR dataset and surveyed cross sections as discussed in Section 3.3. The DEM is shown on Figure 3. The model extent for the catchment was determined in conjunction with MWRC based on where development is occurring and flood information is required. The upstream boundaries are Cudgegong River upstream of Rocky Water Hole gauge and Lawsons Creek upstream of Mudgee. The downstream boundaries are located on the Cudgegong River downstream of the Wilbertree Road gauge. The model extent is shown Figure 21.

7.3. Boundary Locations

7.3.1. Inflows

Figure 22 shows the locations of the flow and downstream boundaries of the flood model. For sub-catchments within the TUFLOW model domain, local runoff hydrographs were extracted from the WBNM model (see Section 6). These were applied to the downstream end of the sub-catchments within the 2D domain of the Mudgee Flood Study hydraulic model. The hydraulic model also has several inflows which utilise hydrologic routing in upstream catchments to reduce the overall footprint of the hydraulic model.

The inflow hydrographs for the design events were taken from the calibrated WBNM model utilising information from the ARR data hub (refer Section 9). The inflow hydrographs for the calibration events were also taken from the WBNM model, based on the parameters selected for each event (refer Section 8).

7.3.2. Downstream Boundary

The hydraulic model has one downstream boundary condition which is located downstream of Wilbertree Road gauge on Cudgegong River. This has been set as a constant slope boundary of 0.1% consistent with the gradient of the River at this location. The location is set sufficiently far downstream of the gauge to allow calibration of the model to occur at the gauge.

7.4. Mannings ‘n’ Roughness

Roughness, represented by the Manning’s ‘n’ coefficient, is an influential parameter in hydraulic modelling. The hydraulic reference book Chow provides the definitive reference work in regard to the setting of roughness values for hydraulic calculations. A range of standard hydraulic roughness examples are provided within the text book which allow the selection of parameters. These parameters form the initial basis of the assessment, with further refinement of the values undertaken during the calibration component of the study to ensure good replication of known events. As part of the calibration process roughness values are adjusted within ranges defined in industry guidance so that the model may match observed peak flood levels at a variety of locations. The calibration process is discussed in Section 8.

Henderson (Reference 14) also provides roughness values for various land use and flow conditions. Table 4-2 of Henderson (Reference 14) states that for a natural channel, roughness may vary between 0.025 to 0.03 for a clean and straight channel, from 0.033 to 0.04 for a winding channel with pools and shoals, and from 0.075 to 0.15 for a very winding and overgrown channel.

The main channel of Cudgegong River and Lawsons Creek are earth channels with several meanders. There are some riparian sections of dense weeds and shrubs on each channel which require consideration of vegetation in the hydraulic roughness selected. In some locations the banks of the channels are heavily treed, which is vastly different compared to the in-bank channel. Separate values were chosen for the river channels and the riparian edge.

The in-bank section of each river was modelled using a Manning's 'n' value of 0.04 and the dense riparian vegetation was modelled using a Manning's 'n' value of 0.08, recognising that some of the vegetation on the banks will be knocked flat in a major flood event. Figure 23 shows the roughness values within the model.

The Manning's 'n' values adopted are shown in Table 12.

Table 12 – Adopted Manning's *n* values – TUFLOW model

Surface	Manning's *n*
Road	0.02
Farmland	0.04
Township (Excluding Buildings)	0.04
River	0.04
Riparian Vegetation	0.08
Forest	0.10

7.5. Rivers

The river channels were defined in the 2D grid domain. The channels represent the key conveyance system in the study area and thus appropriate representation is required. The DEM was modified to provide a continuous flow path with gradient determined from available data. The LiDAR was able to provide topographic information of the river channels above the water level on the day of the survey. The low water level channel information for Cudgegong River was based on the available cross section survey (Refer section 3.3) for the River. This was incorporated through the use of a z shape layer within TUFLOW which enables the interpolation of the information along the channel alignment.

7.6. Roads and Railway

The roads and railway were all modelled using break lines which alter the topography of the DEM. The elevations of the road and railway system were determined using the LiDAR survey. It is noted that in several locations the top of the Cudgegong River channel is above the surrounding flood plain, acting as a form of levee to the system. The use of a 3 m grid resolution ensures that, where present, these features, along with all other local hydraulic features, are picked up.

7.7. Hydraulic Structures

7.7.1. Bridges and Large Culverts

Throughout the study area there are several bridges that cross Cudgegong River and Lawsons Creek (Reference 2). These include:

- Rocky Water Hole Road over Cudgegong River. This is a bank of 7 culverts that has limited hydraulic capacity. The causeway serves as a hydraulic control for the upstream river gauge;
- Railway Crossing upstream of Mudgee Township over Cudgegong River;
- Ulan Road over Cudgegong River (Holyoake Bridge). A 60 m long bridge with 3 piers in

the waterway has a concrete railing approx. 1 m high on both sides. An additional pedestrian lane is present upstream of the original bridge which has an open metal handrail approx. 1.4 m high;
- Ulan Road over Lawsons Creek (Neville H Paine Bridge). A short span bridge with full concrete barriers on each side. An additional pedestrian lane is present upstream of the original bridge which has an open metal handrail approx. 1.2 m high;
- Putta Bucca Road over Cudgegong River. Short span bridge (approx. 21 m) with a single concrete buttress in the waterway. Metal posts and rails approx. 0.7 m high on both sides of the road;
- Railway Crossing downstream of Mudgee Township over Cudgegong River; and
- Wilbertree Road over Cudgegong River.

It is noted that there are also several structures also along Redbank Creek. Where information is available these structures have been incorporated. Where no data is present structural information has been estimated from photography.

The hydraulic model has utilised 1D elements and 2D layered flow constrictions to represent the structures as appropriate. Figure 17 shows the locations of the structures present in the model.

7.7.2. Detention Storage and Dams

The Mudgee Flood Study hydraulic investigation area has several detention basins and dams present. The largest system is the Redbank Creek Dam. Within the hydraulic model the dam crest, based on the information present in the Redbank Creek Dam Stabilisation Works Design Report and on Mid Western Regional Council's website (http://www.midwestern.nsw.gov.au/resident-services/Water-Services/stormwater/Redbank-Creek-Dam/) will be modelled in the 2D domain. The information provides detail on the Dam crest levels and the initial water level (assumed empty).

7.7.3. Buildings

All buildings within the Mudgee Township were digitised as separate elements for consideration within the hydraulic model. The buildings have been considered as full blockages to flow within the model.

7.7.4. Pit and Pipe Network

The stormwater drainage network within Mudgee has been incorporated into the model as 1d elements. The pipe and pipe network information is based upon the data that council supplied (Refer Section 3.7) and infilled where information was missing. Visual inspection of the alignment was also undertaken to inform appropriate network connectivity where data was missing.

8. CALIBRATION

8.1. Objectives

The objective of the calibration process is to build a robust hydrologic and hydraulic modelling system that can replicate historical flood behaviour in the catchment being investigated. If the modelling system can replicate historical flood behaviour then it can more confidently be used to estimate design flood behaviour. The resulting outputs from design flood modelling are used for planning purposes and for infrastructure design. For this study, due to limited historical data for the area the historical events chosen for calibration were:

- February 2003;
- December 2010; and
- September 2016.

The events were selected based on the magnitude of the event and the availability of data. It is noted that the largest event on record, the 1955 event has not been modelled. This is due to no information with regards to flow or river being present at any stream flow, rainfall gauge within the study area available and Windamere Dam not being present in the catchment during the event. It is difficult to replicate conditions prior to the construction of Windamere Dam with the available information.

The 1998 Flood Study provides some advice with regards to the magnitude of the 1955 event and some limited flood level information. The report notes the event was in the order of a 1% AEP event when Windamere Dam is present. It should be noted during the 1998 Flood Study that validation of the model to recorded levels alongside Mudgee was unsuccessful (Reference 2, pg. 28). This was generally attributed to the passing of time and the limited data available of earlier conditions. The three events selected have information that is relevant to current catchment conditions and have sufficient information to inform at least a partial calibration.

8.2. Stream Gauge information

Within the study area downstream of Windamere Dam there are three flow gauges present. Due to the hydraulic control of Windamere Dam, which will attenuate all upstream flow from that portion of the catchment into the dam and in many cases result in no downstream flow, no calibration of gauges upstream of the dam has been undertaken. Table 13 provides a summary of the gauges selected for review within the calibration. Figure 4 shows the locations of these gauges within the study area.

Table 13 – Stream Gauges

Station ID	Station Name	Opened	Closed
421079	Cudgegong River at D/S Windamere Dam	Feb-70	Current
421149	Cudgegong River at Rocky Water Hole	Jul-85	Current
421150	Cudgegong River at Wilbertree Road	May-85	Current

8.3. Methodology

A joint calibration of the hydrologic and hydraulic model was chosen as the best approach for the study area for the following reasons:

- While there are two flow gauges present within the hydraulic study area, there is limited confidence on the flow rating curves present. More emphasis will therefore be placed on the recorded levels than the recorded flows during the assessment.
- There is very sparse rainfall pluviograph information for the region which results in large data gaps for historical events. A review of level and extent rather than flow in most cases will be the only available data to verify the system is responding appropriately to lived experience.

The approach to model calibration was to adjust the rainfall loss parameters and the stream routing parameter in the WBNM (hydrologic) model and adjust the Manning's 'n' roughness values in the TUFLOW hydraulic model. Multiple combinations of these parameters were investigated until the best fit to the recorded water levels and description of flood behaviour in the study area could be achieved across the whole range of calibration events.

For the three events, the adopted rainfall depths (obtained from AWAP, Reference 23) and temporal patterns (obtained from local pluviography information) were found to have the most influence on the calibration results. The levels obtained at the three gauges in the study area were more sensitive to the rainfall assumptions than to the other model parameters available for tuning the model calibration. Since the available rainfall data is inherently unable to reflect the true spatial and temporal rainfall distribution across the catchment for the floods investigated due to limited availability, it is unreasonable to try and obtain a perfect fit in the model calibration results. It was however identified that due to the very flat nature of the catchment through the floodplain area (approximately 0.2% gradient through the floodplain) the stream routing parameter was required to be increased to develop a reasonable response.

8.3.1. Rainfall Losses (WBNM)

The initial loss / continuing loss model was used to estimate rainfall losses over the catchment. Due to the irrigated nature of the catchment and the presence of a dam which releases environmental flows, the initial losses estimated within catchment varied significantly event to event. Additionally, the antecedent conditions of the catchment, given the different times of year the events occurred were likely varied. The continuing losses however were generally consistent which indicates a generally homogenous infiltration rate once the soil is saturated. Table 14 provides a summary of the losses used in each calibration event.

Table 14 – Calibration Event Rainfall Losses

Event	Initial Loss	Continuing Loss
February 2003	130 mm	2.5 mm/h
December 2010	55 mm	3 mm/h
September 2016	10 mm	3 mm/h

As the three events modelled are relatively recent, it is likely that current catchment conditions are relatively consistent with the calibration findings.

8.3.2. Windamere Dam

Since the completion of construction of Windamere Dam in 1974 there has been only one event in which the full supply level was exceeded. This was in August 1990. Unfortunately, data is not present at any downstream gauges within the catchment for this event and thus calibration to the event could not be undertaken. In the calibration events modelled, no flows were present over the dam spillway and thus flows from the upstream catchment have not been considered. Some low flow releases are present during the calibration events however these have been considered to be negligible relative to the flood flows present.

8.3.3. Stream Routing Parameter (WBNM)

The typical stream routing value in WBNM is 1.0 for natural channels. An increase to this parameter will reduce stream velocity and a decrease will increase stream velocity. A stream routing value of 1.45 was applied to provide the best fit to historical events. This value can be justified by the very flat terrain of the floodplain and the meanders present. Preliminary hydraulic model runs indicate an average velocity of less than 0.7 m/s through the floodplain, consistent with this assumption.

8.3.4. Manning's 'n' Roughness

Multiple combinations of Manning's 'n' parameters were modelled in order to determine the values that provided the best fit to recorded water levels. The values modelled were justified in the literature discussed previously in Section 7.4. The Manning's 'n' values that provided the best fit are shown in Table 15 and were used in all three modelled events. These values are in line with standard industry guidance and are considered reasonable.

Table 15 – Adopted Manning's *n* values – TUFLOW model

Surface	Manning's *'n'*
Road	0.02
Rural farmland	0.04
Township (buildings Excluded)	0.04
River	0.04
Riparian Vegetation	0.08
Dense Vegetation	0.10

8.4. Calibration Results

8.4.1. Hydrologic Flow Comparison

The flow hydrographs for D/S Windamere Dam (421079), Rocky Water Hole (421149) and Wilbertree (421150) gauges from the modelled historical events are shown Figure 24 to Figure 26. The same rainfall loss and stream routing parameters that were used as part of the joint calibration were adopted.

A review of the rating curves provided indicates that there is little confidence in the rating curves generated due to limited to no gauging of major flood events.

As such the hydrologic validation primarily focussed on matching the event shape and timing. In general, the response of the model with regards to rate of rise is good however due to limited temporal rainfall information the distribution of flow was not able to be replicated. Similarly, in several instances the peak flow rate in the model is significantly different to the recorded flows. A review of the water levels generated within the hydraulic model is required to provide more confidence in the modelling systems developed. The peak flow summary is presented in Table 16.

Table 16 – Peak Flows Summary

Parameter	D/S Windamere Dam (421079)	Rocky Water Hole (421149)	Wilbertree (421150)
February 2003			
Recorded Flow (m^3/s)	20.6	97.4	430.8
Modelled Flow (m^3/s)	29.6	93.0	375.9
Difference (m^3/s)	9.0	-4.4	-54.9
Difference (%)	44	-5	13
December 2010			
Recorded Flow (m^3/s)	45.7	232.2*	391.8
Modelled Flow (m^3/s)	55.7	116.0	410.8
Difference (m^3/s)	10	-116.2	19
Difference (%)	22	-50	14
September 2016			
Recorded Flow (m^3/s)	30.9	34.9	192.5
Modelled Flow (m^3/s)	16.5	45.1	161.1
Difference (m^3/s)	14.4	10.2	-31.4
Difference (%)	-47	29	-16

* note – this flow greatly exceeds even the estimated flow rating curve and is likely to be highly erroneous.

8.4.2. Hydraulic Calibration

The hydraulic model was setup utilising the approach discussed in Section 7. The hydrologic inflows were incorporated into the model for each calibration event. Due to the long durations associated with the calibration events the model has been run on a 5 m x 5 m grid for the purposes of calibration.

8.4.2.1. FEBRUARY 2003

The February 2003 event was modelled over 4 days. BoM daily rainfall grids (http://www.bom.gov.au/climate/how/newproducts/IDCdrgrids.shtml) for the 4 days were developed and a variable rainfall depth for each subcatchment applied. A maximum rainfall total of 213 mm was applied to some subcatchments however there some subcatchments that were estimated to receive less than 120 mm. The temporal pattern from the Glen Alice pluviometer was utilised as best available temporal information. This pluviometer is located 70 km away from the Mudgee Township.

The results are shown Figure 24 and in Table 17. Due to the large variance in rainfall depth (and likely temporal variance) experienced over the catchment, a poor shape representation is present in the hydraulic model. Several variations of the model setup were utilised however the rainfall temporal shapes recorded at surrounding gauges do not match the shape of the recorded hydrographs. The closest pluviograph information recorded a multiple burst event with the highest intensity occurring in the second burst. Additionally, while the Windamere Dam did not overtop it is noted that in the recorded hydrographs a baseflow in the channel is present which may slightly affect the results. A review of the results and discussion is provided below.

During the event, Rocky Creek gauge recorded a single event peak (Chart 1) while Wilbertree Road gauge recorded a double peak event (Chart 2). This may be due to the timing of the rainfall event resulting in offset peaks between Pipeclay Creek and Cudgegong River. The pluviograph information available is too sparse to confirm however. It may also be due to the initial peak at Rocky Creek gauge being absorbed by the initial loss in the model. This is the assumption that was utilised in the calibration approach.

This assumption results in an offset of the peak flow recorded at Rocky Creek gauge but results in a very similar response shape and magnitude. It also results in a reasonably well timed double peak at Wilbertree Road gauge however the highest peak is predicted to be on the second burst event, while the gauge recorded the peak during the first event.

Due to the data limitations the calibration of stream flow records undertaken is deemed to be adequate however it is likely that improvements could be made if additional information on the rainfall event was avialable. At Wilbertree Road Gauge an over estimation of the volume is recorded.

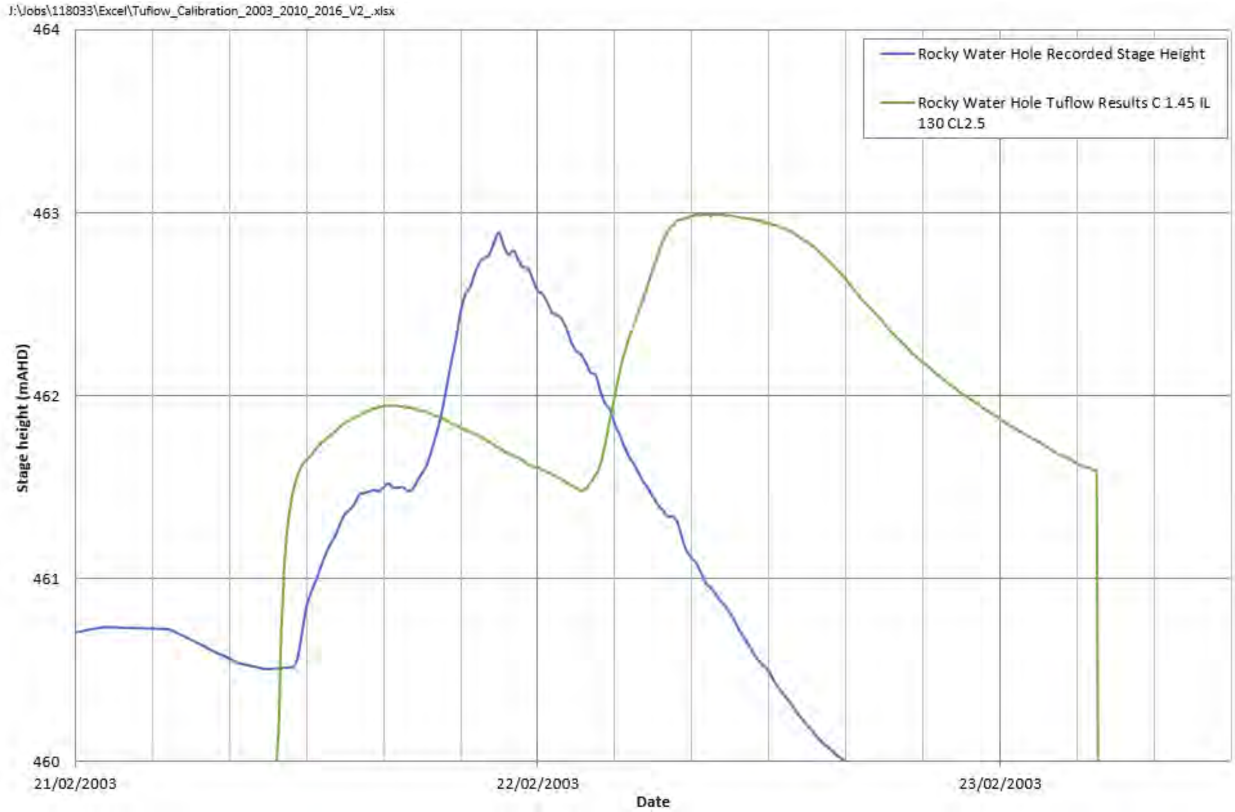

Chart 1: February 2003 Event – Rocky Creek Water Hole Results Comparison

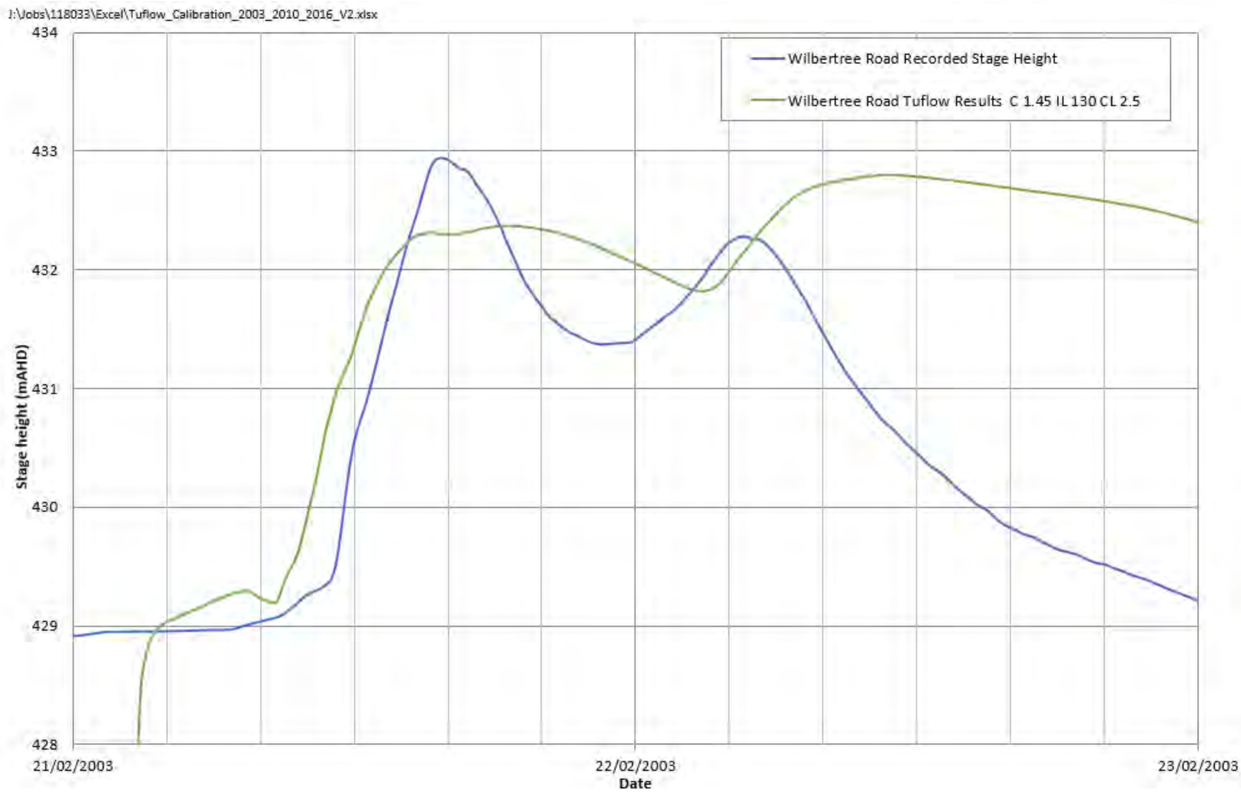

Chart 2: February 2003 Event –Wilbertree Road Gauge Results Comparison

While some difficulty was experienced in the development of hydrologic parameters, the developed flows utilised within the hydraulic model results in well matched peak flood levels at the two gauges present in the hydraulic model.

Table 17 – Peak Flood Levels January 2003

Gauge	Recorded (mAHD)	Modelled (mAHD)	Difference (m)	Calibration
Rocky Water Hole (421149)	462.9	463.0	0.1	Good
Wilbertree (421150)	432.9	432.8	-0.1	Good

To further validate the model, visual comparison of flood photography taken during the event to the modelled outputs has also been undertaken. Note that a significant amount of flood photography was provided however in general there was limited information available to georeference the photographs. The following locations were selected based on the ability to confidently locate the photograph to allow for a direct comparison with model results. The red "X" on each flood map indicates the estimated location the photograph was taken.

Jubilee Oval – The model results indicate depths in the range of 0.05 – 0.40 m present with the majority of the oval and surrounds inundated. Debris marks on the fence near the netball courts of similar depth (between 0.15 – 0.2 m).

Plate 16 –Inundated Jubilee Oval during February 2003 flood event

Plate 17 - Model result depth map around Jubilee Oval area

Lawson Park – Modelled depths of less than 0.1 m present at the location of the memorial, extent of flooding very similar to the photography supplied.

Plate 18 – Extent of February 2003 flood event at Lawson Park

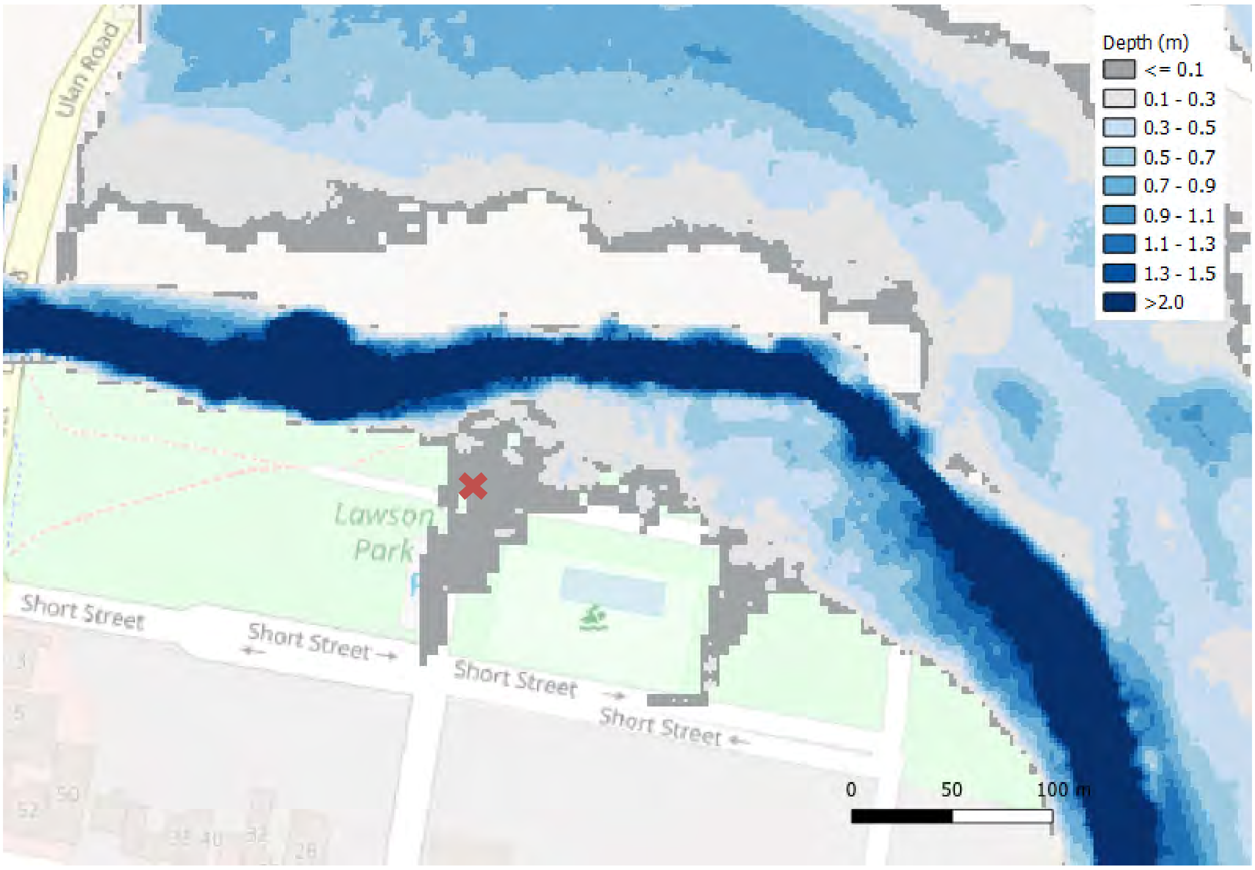

Plate 19 - Modelled result depth map at Lawson Park

32 Cox Street Mudgee – Modelled flood depths in the order of 0.15 – 0.30 m present on the roadway. Results look to be consistent with photography of debris marks.

Plate 20 –Debris marks of February 2003 flood event at 32 Cox Street Mudgee

Plate 21 - Modelled result depth map at 32 Cox Street Mudgee

Ulan Road Opposite the Racecourse – during the flood event Ulan Road was overtopped with fast flowing water from the racecourse passing over the road. The hydraulic model replicates a similar extent and depth of flooding as presented in the photography.

Plate 22 –Inundated Ulan Road Opposite the Racecourse during February 2003 flood event

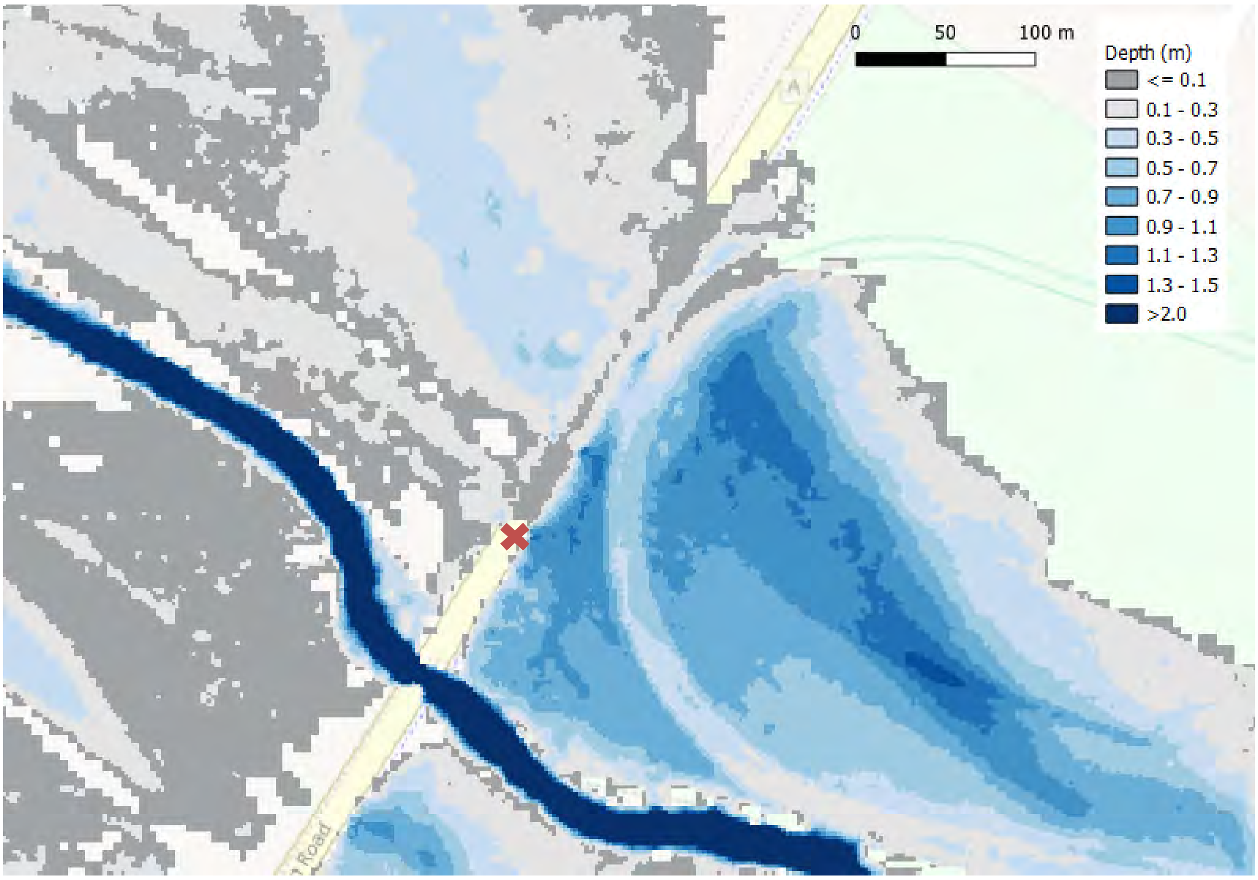

Plate 23 Modelled result depth map at Ulan Road Opposite the Racecourse

8.4.2.2. DECEMBER 2010

The December 2010 event was modelled over 9 days. BoM daily rainfall grids (http://www.bom.gov.au/climate/how/newproducts/IDCdrgrids.shtml) for the 9 days were developed and rainfall for each subcatchment applied a maximum rainfall total of 202 mm was present, consistent with local rainfall station recordings. Rainfall looked to be generally consistent across the catchment with a minimum in the order of 180 mm recorded in the grids. The temporal pattern from the Glen Alice pluviometer was utilised as best available temporal information. The results are shown in Figure 25 and Table 17.

For the primary peak in the rainfall events a good match of rise and fall is present however at the Rocky Water Hole gauge there looks to be a burst rainfall period which was not captured in the temporal pattern applied, this has resulted in a slightly lower peak. This is not present at Wilbertree which shows a good match between rising limbs, falling limbs and the peak water level achieved.

Table 18 – Peak Flood Levels December 2010

Gauge	Recorded (mAHD)	Modelled (mAHD)	Difference (m)	Calibration
Rocky Water Hole (421149)	463.7	463.1	-0.6	Average
Wilbertree (421150)	432.9	432.9	0.0	Good

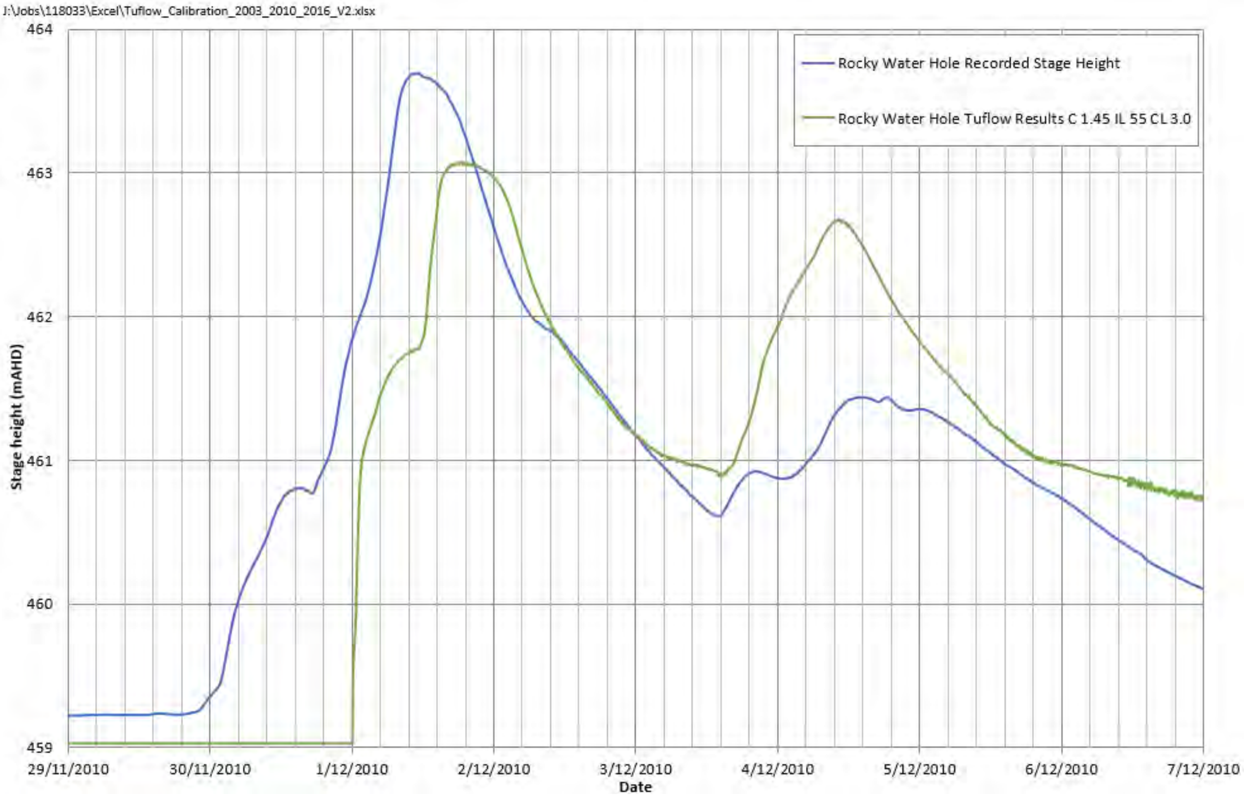

Chart 3: December 2010 Event – Rocky Creek Water Hole Results Comparison

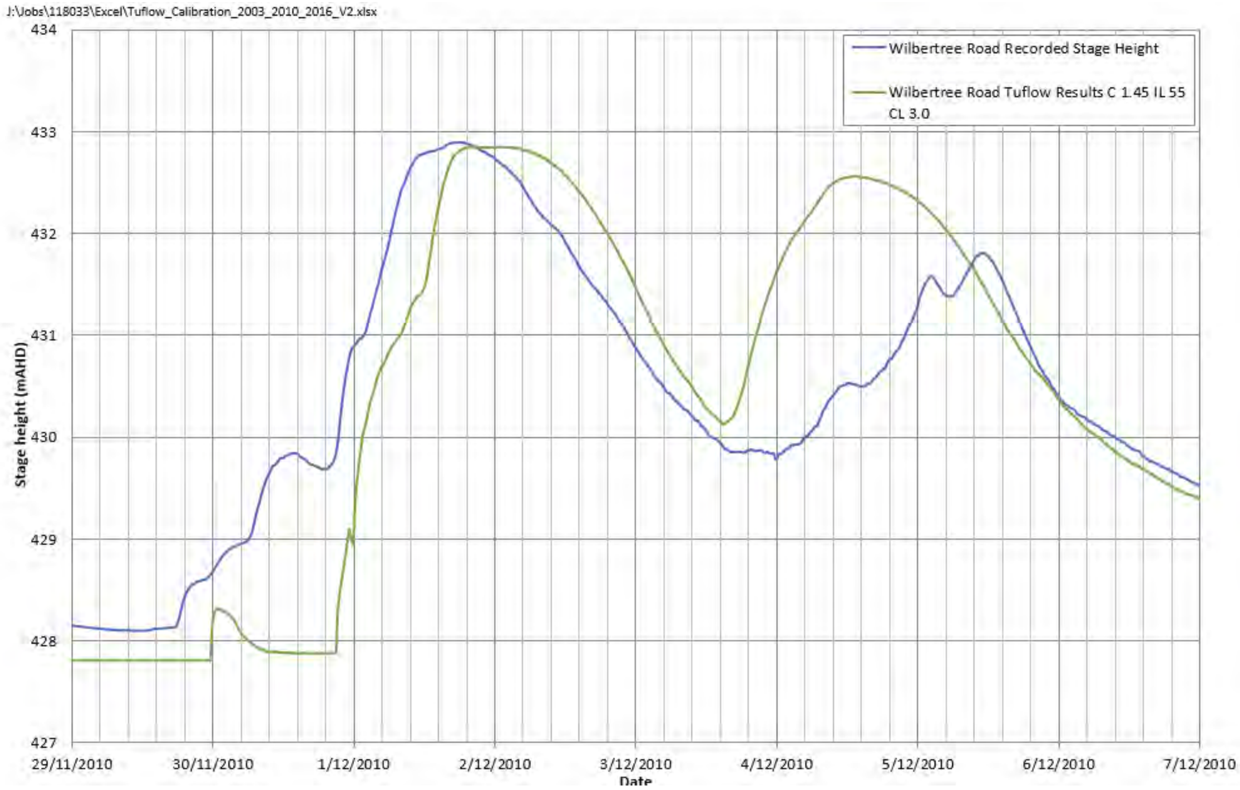

Chart 4: December 2010 Event –Wilbertree Road Gauge Results Comparison

While some photography was provided for the 2010 event, there was no indicator of location and thus limited information could be inferred. An aerial photo of the flood however is available. Comparison of the extents shows a good correlation, with very similar levels present on the racecourse. Additionally, at Glen Willow Sports

Plate 24 – Aerial Image of Flooding December 2010

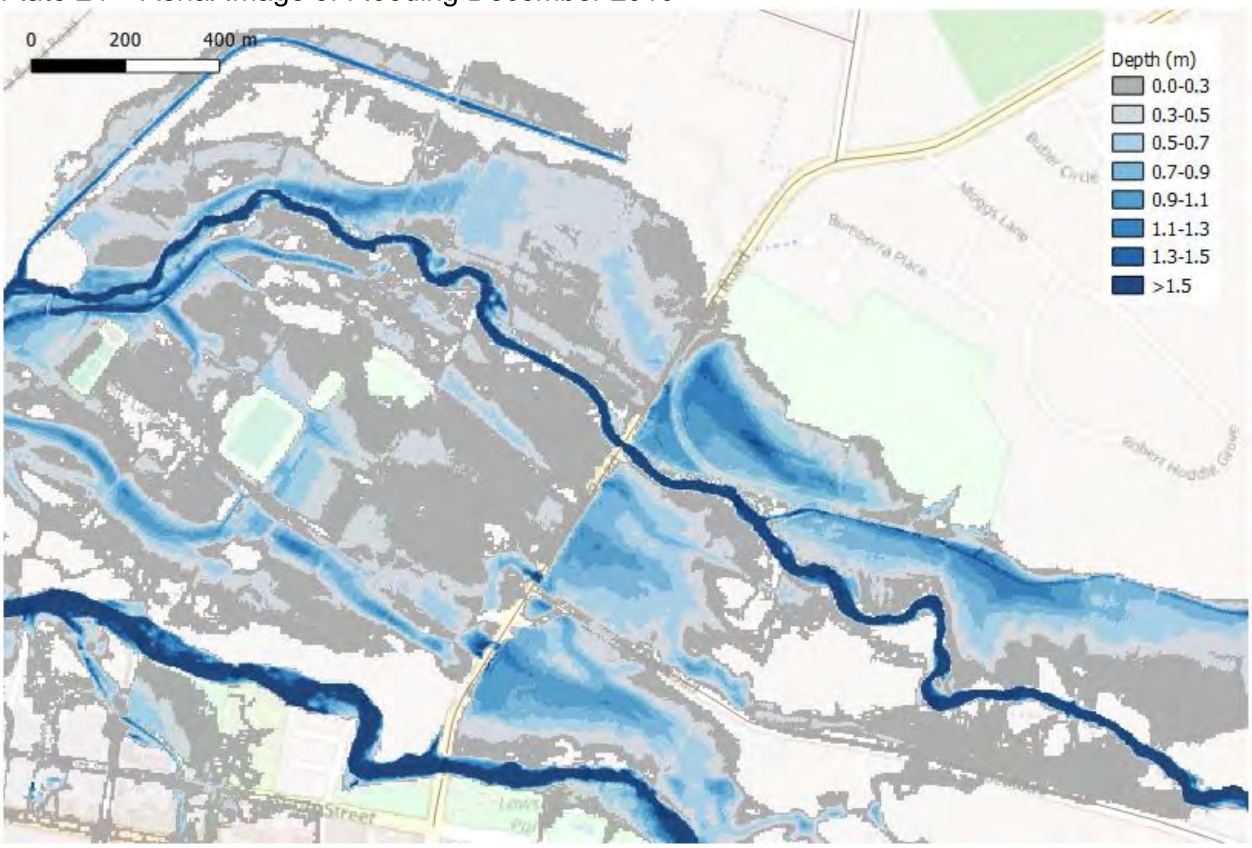

Plate 25 – December 2010 Modelled Flood Extent

Plate 26 – Glen Willow Sports Field Netball Court Flooding December 2010

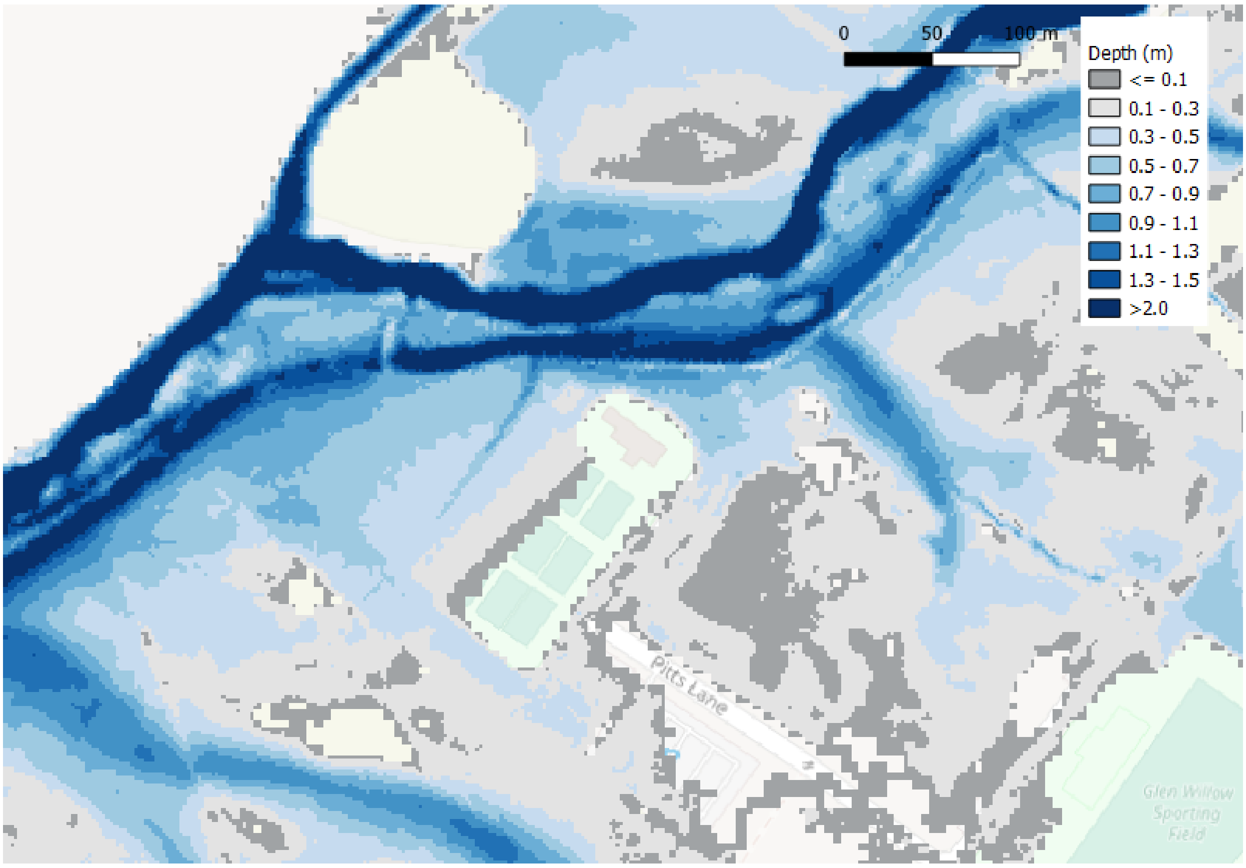

Plate 27 – December 2010 Modelled Flood Extent

8.4.2.3. SEPTEMBER 2016

The September event was modelled over 4 days. BoM daily rainfall grids (http://www.bom.gov.au/climate/how/newproducts/IDCdrgrids.shtml) for the 4 days were developed and rainfall for each subcatchment applied a maximum rainfall total of 91 mm was present, consistent with local rainfall station recordings. Rainfall looked to be generally consistent across the catchment with a minimum in the order of 72 mm recorded in the grids. The temporal pattern from the Windamere Dam pluviometer was utilised as best available temporal information. The results are shown in Figure 26 and Table 19.

The calibration for this event is based on a best fit outcome for both gauges. As Wilbertree Road was indicating higher levels and Rocky Water Hole lower, a compromise between the two locations within the hydrology model was required. Independent calibration at each gauge would result in a more accurate calibration at one gauge at the expense of accuracy at the other.

For the rainfall events a good match of rise and fall is present however the event in the model starts earlier. At Rocky Water Hole the tail of the modelled event falls more sharply than the recorded event in the hydrology model while a slower fall is recorded in the flood model . No flood photography was present to further verify this event.

Table 19 – Peak Flood Levels September 2016

Gauge	Recorded (mAHD)	Modelled (mAHD)	Difference (m)	Calibration
Rocky Water Hole (421149)	462.7	462.3	-0.4	Good
Wilbertree (421150)	431.9	432.2	0.3	Good

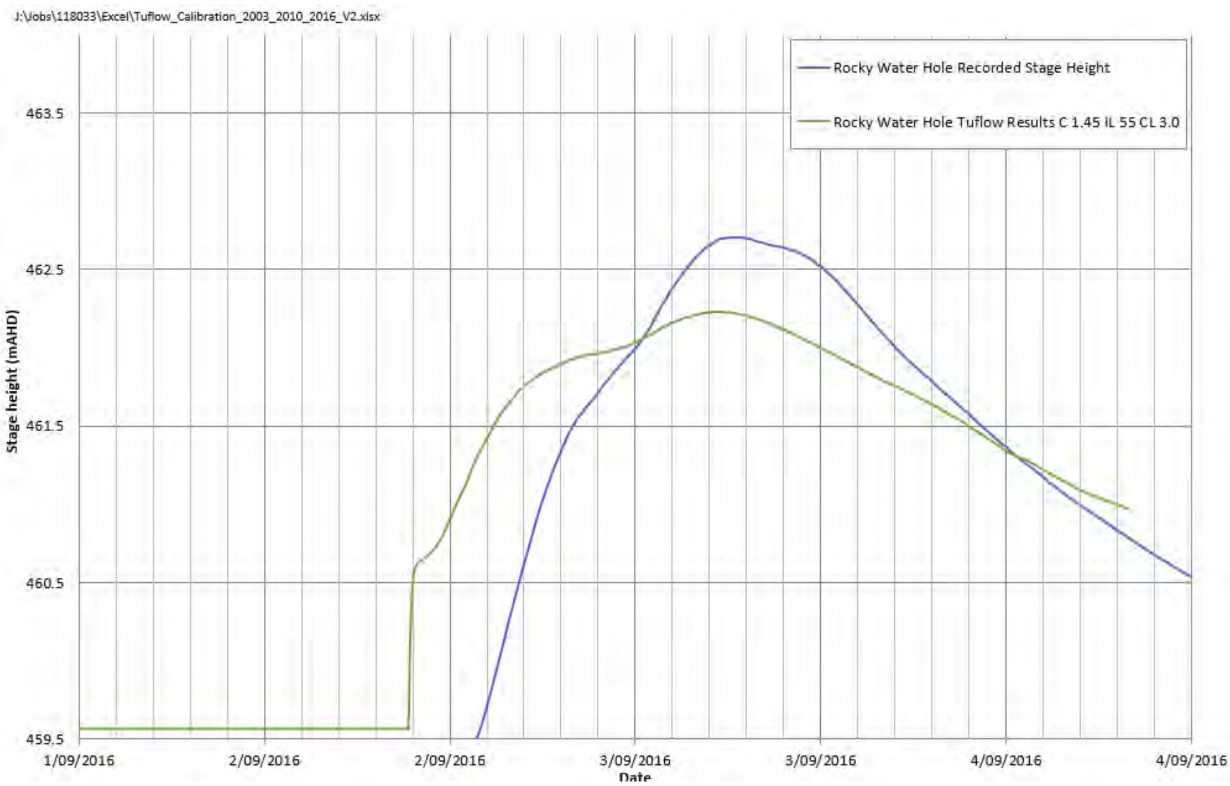

Chart 5: September 2016 Event – Rocky Creek Water Hole Results Comparison

Chart 6: September 2016 Event –Wilbertree Road Gauge Results Comparison

8.5. Discussion

A calibration of the flood model has been undertaken to determine the validity of the model setup for both the hydrologic and hydraulic models. Due to limited recorded data in the area the development of good calibration was difficult. Through a mix of gauge readings and visual inspection of flood photography however a good correlation between recorded events and the model outputs has been achieved.

Due to the limited data, it is recommended that during future rainfall events flood levels through the township are recorded to enable the verification of the flood model. The installation of a pluviograph and flow gauge in closer proximity to the township would also enable a review of levels in critical locations during flood events.

9. DESIGN EVENT SETUP

9.1. Design Losses

NSW Office of Environment and Heritage has developed a guide to assist councils and consultants undertaking studies under the NSW Floodplain Management Program to transition to Australian Rainfall and Runoff 2019.

As part of this transition a study (Review of ARR Design Inputs for NSW report) was undertaken to review and advise on addressing under-estimation bias being experienced when using standard ARR2019 design event methods with default data available from the ARR data hub.

The outcomes of this study indicated that there is significant bias in the standard ARR2019 design event method with default ARR data hub losses and pre-burst.

It identified that default continuing losses available from the ARR data hub over-estimated losses and therefore were not fit for purpose and should only be used where better information was not available. If default continuing losses from the ARR datahub are to be used these should only be used with a multiplier of 0.4 applied.

9.1.1. Initial Loss Rate

The calibration undertaken for the study area utilised a range of initial losses from 130 – 10 mm. Due to the large variance, it is deemed unreasonable to utilise an average of the losses as the design loss. Instead it is proposed to utilise losses based on the ARR2019 Data hub. This provides an initial burst loss of 10 mm. This value is consistent with the lowest calibrated design loss and thus conservative.

9.1.2. Continuing Loss Rate

Based on the calibration undertaken, a continuing loss of between 2.5-3 mm/hr provides a good correlation to the events modelled. As such it is reasonable to utilise a loss rate of 2.8 mm/hr for the purposes of design modelling. This is consistent with ARR2019 advice which suggests the average of the calibrated losses should be utilised where possible. This is slightly lower than the ARR2019 Data hub estimate of 3.6 mm/hr.

9.2. Flood Frequency Analysis

Flood Frequency Analysis (FFA) estimates the magnitudes of flood peaks based on the statistical analysis of recorded data at specific locations. In order to develop confidence design flows produced using the calibrated hydrology model and the ARR2019 design flood approach.

Some advantages of FFA are:

- No assumptions are required regarding the relationship between probabilities of rainfall and runoff;
- All factors affecting flood magnitude are already integrated into the data;
- Estimation of rainfall losses is not required;
- Confidence limits can be estimated; and
- Historical rainfall data is not required.

The FFA approach also has several limitations:

- The data cannot be easily adjusted to account for catchment modifications or the change in climatic conditions;
- The data available is relatively short (compared to the correspondent design event) for which there is considerable uncertainty; and
- Gauges generally present issues with the accuracy of rating curves, especially at high flows.

As per the ARR2019 recommendation, a Bayesian approach in the software Tuflow Flike was applied to perform the current FFA. It must be highlighted that the results of the FFA are estimates only, and therefore, they must be used accordingly to guide engineering design.

9.2.1. Stream gauges

Three gauges are present downstream of Windamere Dam within close proximity to the study area. Table 20 lists the gauges and their locations.

Table 20 - Stream Gauges

Station ID	Station Name	Opened	Closed
421079	Cudgegong River at D/S Windamere Dam	Feb-70	Current
421149	Cudgegong River at Rocky Water Hole	Oct-94	Current
421150	Cudgegong River at Wilbertree Road	Aug-87	Current

Station 421079 is located immediately downstream of Windamere Dam. It has 50 years of records in total from 1970 until 2019. As Windamere Dam is a major hydraulic control however, it is necessary to omit the record of data that occurred prior to the completion of the dam, which was 1984. This reduces the relevant, useful data size to 35 years. Stations 421149 and 421150 have less than 30 years of records. This limited dataset present at all sites results in limited confidence in the estimated peak flows for major flood events however provides a reasonable estimation of peak flows for more frequent flow events.

Table 21 shows the results of the FFA completed at all stations, the confidence limits are presented to highlight the uncertainty present in the outcomes. As a consequence of this uncertainty, the results of the FFA must be used very carefully and interpreted as guide estimations only.

Table 21 - Peak flows determined by FFA for gauges within or adjacent to the Study Area

Station	Event	FFA (m^3/s)	90% Quantile Probability Limits (m^3/s)	
421149	20% AEP	**49**	31	85
	10% AEP	**87**	51	178
	5% AEP	**140**	76	352
	2% AEP	**237**	114	826
	1% AEP	**338**	144	1510
	0.5% AEP	**465**	175	2699
421150	20% AEP	**142**	65	326
	10% AEP	**333**	139	1142
	5% AEP	**687**	242	3910
	2% AEP	**1577**	396	19805
	1% AEP	**2774**	493	65824
	0.5% AEP	**4685**	600	212461
421079 (1985-current)	20% AEP	**31**	22	46
	10% AEP	**51**	34	87
	5% AEP	**77**	48	156
	2% AEP	**123**	68	317
	1% AEP	**166**	84	528
	0.5% AEP	**220**	100	859

9.3. Windamere Dam Design Water Level

Windamere Dam is the largest hydraulic control present upstream of Mudgee and has the potential to greatly influence the design peak flow rate estimates for Mudgee. The full supply level (FSL) of the Windamere Dam is 552 mAHD. Once this level is reached the spillway which passes flow to Cudgegong River is activated. During these events the Dam acts as a large hydraulic control with the spillway capacity limiting the flow into the Cudgegong River.

The historical records at the site show that this level has been exceeded once, in August 1990. A flood on the Cudgegong River was recorded in August 1990, preceded by significant rainfalls in April and July of that year.

Based on this information alone it may be reasonable to suggest that a level lower than full supply level is appropriate to incorporate into design event analysis. This information however does not consider peak levels in the dam over the known historical period, just the time it has overtopped. In order to determine the appropriate level to set the initial water level in Windamere Dam for design runs a review of the historical levels present in the dam has been undertaken.

The development of a Water Level Frequency Assessment is difficult as it takes into account the maximum water level achieved in any year. In years that had a major rainfall event, this would be at the end of the event rather than the beginning. As the purpose of this assessment is to determine design levels however it is considered that a conservative approach to the dam level, noting there is no controls in place to release water in advance of a large rainfall event, is appropriate. Table 22 presents the results of the Water Level Frequency Assessment.

Based on the analysis undertaken, in events greater than a 10% AEP the analysis indicates a dam level of FSL or greater. A review of the analysis undertaken within the 1998 Mudgee Flood Study confirms a similar outcome. For conservatism and consistency with the previous flood study it is proposed to utilise the FSL as the initial level for all design events.

Table 22 - Water Levels determined by the Frequency Assessment

Event	WLFA (mAHD)	90% Quantile Probability Limits (mAHD)	
20% AEP	548	546	550
10% AEP	551	548	>552
5% AEP	>552	551	>552
2% AEP	>552	>552	>552
1% AEP	>552	>552	>552
0.5% AEP	>552	>552	>552

9.4. Design Event Temporal Pattern Selection

Temporal patterns for this study were obtained from ARR2016 (Reference 1615). ARR 1987 provided a single temporal pattern for events more and less frequent than a 30 year ARI for each storm duration. The ARR 2016 attempts to provide several temporal patterns and recommends an approach where an ensemble of different temporal patterns are investigated. This addresses the potential inaccuracies with adopting a single pattern in ARR 1987. It is widely accepted that there are a wide variety of temporal patterns possible for rainfall events of similar magnitude. This variation in temporal pattern can result in significant effects on the estimated peak flow.

To determine the critical storm duration for various parts of the catchment, modelling of the 0.2%, 0.5%, 1%, 2%, 5%, 10%, 20% AEP events from separate temporal pattern bins was undertaken for a range of design storm durations from 15 minutes to 24 hours for local catchments and from 24 hours to 168 hours for local catchments. Ensembles of 10 temporal patterns were run for each storm duration as per recommendations in ARR 2016. Temporal patterns for each duration are analysed for one regional subcatchment at Mudgee, downstream of the confluence of Cudgegong River and Lawsons Creek (M7). In addition to the regional analysis, this study will also assess flood impacts on Mudgee Town Centre based on overland flooding from the local subcatchment upstream of the Township. This area will likely be subject to flash flooding from short duration storm events. Three local catchments within the Mudgee town (J6, C10 and B14) have be selected for this purpose. The subcatchment outlet locations for C10, B14 and M7 are shown in Figure 4.

Due to the nature of Mudgee and the presence of a large hydraulic control on the primary creek running through the Township validation of flows from the hydrology model will provide little value.

Instead during the hydraulic modelling phase WMAwater will liaise with Council to confirm the flooding extent predicted is consistent with historical issues present in the township.

The temporal pattern selected to represent the ensemble is the pattern just above the mean peak flood level within the ensemble. Critical durations of 1.5 to 6 hours have been selected for the local catchments while critical durations in order of 36 to 72 hours have been used for the catchments in regional area. The selected critical events are presented in Table 23. For each AEP, the critical event that creates the higher flow has been selected for each critical duration among C10 and B14. The model has been also run for 7 more events for M7, and 4 more events for C10 which have similar mean flow values to the critical events presented in Table 23 to ensure the appropriate event is modelled.

Table 23 - Critical Events for Design Flow estimation

Catchment	Event	Critical Duration (hours)	Temporal Pattern
M7	0.2% AEP	36	ATP3879
	0.5% AEP	36	ATP3875
	1% AEP	72	ATP4057
	2% AEP	72	ATP4057
	5% AEP	72	ATP4057
	10% AEP	36	ATP3875
	20% AEP	36	ATP3878
C10	0.2% AEP	1.5	TP2220
	0.5% AEP	1.5	TP2220
	1% AEP	1.5	TP2220
	2% AEP	1.5	TP2220
	5% AEP	2	TP2266
	10% AEP	2	TP2234
	20% AEP	2	TP2277
B14	0.2% AEP	1.5	TP2220
	0.5% AEP	1.5	TP2220
	1% AEP	1.5	TP2220
	2% AEP	1.5	TP2220
	5% AEP	2	TP2266
	10% AEP	2	TP2234
	20% AEP	2	TP2277
J6	0.2% AEP	3	TP2283
	0.5% AEP	3	TP2283
	1% AEP	3	TP2282
	2% AEP	3	TP2282
	5% AEP	3	TP2282
	10% AEP	6	TP2367
	20% AEP	3	TP2300

9.4.1. Design Events

Chart A1 shows a boxplot of the design flow results for the 1% AEP for M7, C10, B14 and J6. The mean flow rates for the 36 and 72 hours events are approximately the same. These 2 durations have been run during the hydraulic analysis to ensure the appropriate event is modelled.

9.5. PMF Analysis

The probable maximum flood (PMF) is the largest flood that could reasonably be expected to occur for a catchment. For the purposes of floodplain management, and consistent with the NSW Government's Floodplain Development Manual, the PMF is estimated using the probable maximum precipitation (PMP) and a single temporal pattern. Due to the conservativeness applied to other factors influencing flooding, a PMP does not translate to a PMF of the same probability. But for the purposes of floodplain management, the probability of the PMP may be assigned to the PMF.

For Mudgee, two PMF analysis have been undertaken – a regional, taking into consideration the entire riverine catchment upstream of Mudgee, including Windamere Dam and a local assessment which considers only the area upstream of Mudgee Township. Similar to the design event process, this has been undertaken to ensure the correct rainfall depths have been assumed for each different flood scenario.

9.6. Review of Design Flow Estimates

9.6.1. Comparison to FFA Flows

Following the completion of the FFA analysis and the development of design model parameters, the WBNM model was run for a range of AEP and durations. Design events were then taken from a number of time varying flow hydrographs obtained from the WBNM model for 20, 10, 5, 2, 1, 0.5, 0.2 % AEP and Probable Maximum Flood (PMF). These inflow hydrographs were then applied to the calibrated TUFLOW hydraulic model to produce design flood levels.

Table 24 presents comparison between design flow estimates and FFA for three key locations in the regional area. At Rocky Creek Water Hole (421149) gauge the peak flow rates estimated from the hydraulic model are much greater than the FFA estimates however are still within the confidence intervals for the FFA. At Wilbertree Road gauge (421150) the estimates are closer to the flows produced by the FFA. At both locations however, in more frequent rainfall events the design flows are greater than those predicted in the FFA. This is primarily due to the catchment upstream of Windamere Dam providing runoff in the design events as the dam is assumed to be at full supply level. This outcome is consistent with the estimates of flow downstream of the Dam (421079) which are markedly higher in the design events.

Table 24 – Design flow estimate and critical durations

Station	Event	FFA (m^3/s)	Design Flow Estimate, (m^3/s)	Critical Duration (hours)
421149	20% AEP	**49**	**225**	**36**
	10% AEP	**87**	**281**	**72**

Station	Event	FFA (m³/s)	Design Flow Estimate, (m³/s)	Critical Duration (hours)
	5% AEP	**140**	**403**	**72**
	2% AEP	**237**	**590**	**72**
	1% AEP	**338**	**777**	**72**
	0.5% AEP	**465**	**975**	**36**
	0.2% AEP	**-**	**1258**	**72**
	PMF	**NA**	**7771**	**24**
421150	20% AEP	**142**	**364**	**36**
	10% AEP	**333**	**427**	**72**
	5% AEP	**687**	**615**	**72**
	2% AEP	**1577**	**913**	**72**
	1% AEP	**2774**	**1201**	**72**
	0.5% AEP	**4685**	**1514**	**36**
	0.2% AEP	**-**	**2033**	**36**
	PMF	**NA**	**12550**	**24**
421079 (1985-current)	20% AEP	**31**	**225**	**36**
	10% AEP	**51**	**280**	**72**
	5% AEP	**77**	**400**	**72**
	2% AEP	**123**	**589**	**72**
	1% AEP	**166**	**762**	**72**
	0.5% AEP	**220**	**965**	**36**
	0.2% AEP	**-**	**1234**	**36**
	PMF	**NA**	**7217**	**24**

9.6.2. Comparison to 1998 Flood Study

To further confirm the flow rates are within the order of reasonable representation, a review of the peak flows from the 1998 Flood Study (Post Dam scenario) has been undertaken. This is presented in Table 13. The peak flow rates at Mudgee, downstream of the confluence of Cudgegong River and Lawsons Creek, are within 10% for the 2% and 1% AEP events. In the 5% AEP the flow is 39% higher. A review of losses used in the 1998 flood study indicates an initial loss of 35 mm was utilised. To determine the sensitivity of the model to this parameter, the calibrated model was run with this initial loss assumption.

The current model utilising 35 mm initial loss resulted in a flow rate of 450 m³/s in the 5% AEP. This flow rate is generally consistent with the 1998 flood study flow rate. The 2% and 1% AEP flow rates dropped slightly however the changes are minor due to the greater storm volumes present. This review confirms the analysis is consistent with previous studies, with the 5% AEP predicted to be higher than the previous assessment.

Table 25 - Comparison to previous flood study

AEP (%)	1998 Flood Study Peak Flow (m³/s)	ARR2019 Selected Losses - Peak flow rate (m³/s)	Difference (m³/s)	ARR2019 35 mm IL - mean flow rate (m³/s)	Difference (m³/s)
5	425	**591**	166	450	25
2	800	**873**	73	765	-35
1	1120	**1146**	26	995	-125

10. DESIGN FLOOD MODELLING RESULTS

10.1. Design Flood Results

The Peak flood depths and levels for the 0.2%, 0.5%,1%, 5%, 10% and 20% AEP and Probable Maximum Flood (PMF) design events are presented in Figure 27 to Figure 34. As a summary, peak flood depths and levels at key locations are detailed in Table 26. The results shown are the combined results of the range of critical durations that impact the study area.

The following sections provides and overview of observed flood impacts in the 1% AEP design event.

10.1.1. Cudgegong River and Lawsons Creek

In a 1% AEP event the Cudgegong River and Lawsons Creek floodplain through Mudgee exceeds 1 km in width. All roads to the township from the north are cut with Putta Bucca Road over the river experiencing depths in excess of 2 m. Ulan Road is also completely inundated with depths exceeding 0.5 m. The Castlereagh Highway north west of the township towards Gulgong is also cut with depths of approximately 0.5 m experienced. Road closures have the potential to exceed 24 hours.

The area to the north of Mudgee is also impacted in the 1% AEP event, specifically the caravan park and surrounding area. It is noted that there is recent development on the land adjacent to the caravan park, it is unclear if the topography in the flood model is accurately reflecting the levels of the development.

In a major riverine flood event, the township would be reliant on the Castlereagh Highway running south for evacuation and supplies. This route may be impacted by local overland flooding however and thus there is a risk that during a major flood event the township is isolated.

10.1.2. Local Creeks and Stormwater Flooding

In a 1% AEP event the Mudgee township suffers from significant overland flooding. The area around Third Street and Gladstone Street has significant areas where property inundation is present. The area north of Mudgee Showgrounds also experiences significant flooding with a large flow path, impacting several properties.

The Castlereagh Highway is also inundated in the 1% AEP east of the township. The levels are generally lower than 0.2 m but this would likely result in a closure of the road.

In general, the majority of stormwater channels and creeks are unable to manage a 1% AEP storm event. Redbank Creek flooding however is well contained along the length of the creek with breakout flow only occurring once downstream of Castlereagh Highway.

Table 26 – Peak Flood Depths (m) and Levels (mAHD) at key Locations for all Design Events and PMF

ID	Location	0.2% AEP		0.5% AEP		1% AEP		2% AEP		5% AEP		10% AEP		20% AEP		PMF	
		Depth	Level	Depth	Level	Depth	Level	Depth	Level	Depth	Level	Depth	Level	Depth	Level	Depth	Level
1	Ulan Road at Lue Road	0.59	449.7	0.47	449.6	0.37	449.5	0.26	449.4	0.09	449.2	-	-	-	-	3.5	452.4
2	Denison Street at Perry Street	0.02	462.7	0.01	462.7	0.01	462.7	0.01	462.7	0.01	462.7	0.01	462.7	0.01	462.7	0.6	463.2
3	Charles Lester Place	0.94	470.7	0.88	470.6	0.83	470.5	0.83	470.6	0.73	470.4	0.55	470.3	0.43	470.2	2.0	471.6
4	Robertson Street at Trefusis Avenue	0.28	481.6	0.17	481.4	0.11	481.4	0.10	481.4	-	-	-	-	-	-	2.5	483.3
5	Madeira Road at Mudgee Showground	0.05	477.8	0.04	477.8	0.03	477.8	0.04	477.8	0.04	477.8	0.02	477.8	0.02	477.8	0.3	478.1
6	Nicholson Street at Atkinson Street	0.40	469.6	0.37	469.6	0.32	469.5	0.27	469.5	0.25	469.4	0.22	469.4	0.21	469.4	0.9	470.1
7	Industrial Avenue	0.30	465.6	0.24	465.5	0.21	465.5	0.20	465.5	0.14	465.4	0.08	465.3	0.02	465.3	1.3	466.5
8	Castlereagh Hwy at Bunnings Mudgee	0.08	470.5	0.06	470.4	0.05	470.4	0.05	470.4	0.04	470.4	0.03	470.4	0.02	470.4	0.5	470.9
9	Waterworks Road at Redbank creek	0.28	510.4	0.25	510.4	0.23	510.3	0.23	510.3	0.20	510.3	0.17	510.3	0.14	510.3	1.3	511.4
10	Putta Bucca Road over Cudgegong River	3.15	446.2	2.88	446.0	2.66	445.8	2.42	445.5	2.09	445.2	1.81	444.9	1.68	444.8	6.1	449.2
11	Lawsons Creek near Lue Road	2.71	454.2	2.70	454.2	2.67	454.1	2.64	454.1	2.59	454.1	2.52	454.0	2.49	454.0	5.9	456.2
12	Oaky Creek near Cudgegong River	6.09	451.9	5.82	451.6	5.61	451.4	5.36	451.2	5.03	450.8	4.72	450.5	4.55	450.4	9.0	454.8

10.2. Sensitivity Analysis

Sensitivity analyses are typically used to evaluate the effect of variations in the assumptions and boundary conditions on the modelling results. The following sensitivity analyses were undertaken for the 0.2%, 1%, 5% AEP design events to obtain an understanding of the variability of design flood levels that may occur if different conditions or parameters were adopted. The variability presented would still fall within what would be deemed good modelling practice and thus acts as a mechanism to ensure the model in itself is not suspectable to large changes with only minor input changes.

Table 27 – Overview of Sensitivity Analyses

Scenario	Description
Initial Loss (IL and CL)	The catchment initial and continues losses were reduced by 20%.
Catchment Lag Factor (C)	The catchment lag factor value was increased and decreased by 20%.
Manning's (n)	The hydraulic roughness value was increased and decreased by 20%.
Culvert, Pipes, Pits and Bridges Blockage	Sensitivity to blockage of all structures was assessed for 100% blockage.

Tables C1, C2 and C3 (APPENDIX C) present the impacts of the change in the flood levels at key locations due to change in initial and continuous losses, catchment lag factor (C), Manning's (n) and blockage.

The peak flood levels are shown to be relatively insensitive to variation. Some local locations, such as Olan Road are sensitive to blockage assumptions however these impacts are localised to around where these structures are present. The Cudgegong River was also sensitive to the change in C factor with level variances in the order of 200 mm. This result is unsurprising as the variation of this parameter alters the peak flow rates generated by the hydrology model. In general however, the model is not considered sensitive to the parameters reviewed.

10.3. Climate Change

The 2005 Flood Development Manual (Reference 17) recommends that Flood management studies consider the impact of climate change on flood behaviour. Based on recommendations outlined in Floodplain Risk Management Guideline (Reference 18), rainfall intensity has been increased by 20%. This value is slightly lower than the 22.8% presented in the interim climate change factors on ARR datahub for RCP 8.5 but generally consistent. For information purposes, the 1% AEP average rainfall depth increases have been compared to other AEPs for critical duration of 1.5, 36, and 72 hours in Table 28.

Table 28 – Rainfall Depth Comparison

Duration	1% AEP	1%AEP plus 10%	1%AEP plus 20%	1% AEP plus 30%	0.5% AEP	0.2% AEP
1.5	58	64	70	76	66	77
36	173	190	207	224	198	231
72	217	239	261	283	245	284

Table 28 indicates that for the 1% AEP:

- A 10% increase in rainfall is approximately equivalent to a 0.5% AEP event
- A 30% increase in rainfall is approximately equivalent to a 0.2% AEP event.

Comparison of these flood levels would provide further insight (presented in Table 26) into the implications of various rainfall intensity increases.

The hydrologic and hydraulic model have been run for 1% AEP considering a 20% rainfall increase. Table 29 presents the changes in flood level after 20% rainfall increase for 1% AEP design event at key locations. The results show that a 20% increase in rainfall intensity has increased flood levels by over 0.5 m within the Cudgegong River floodplain. In the urban areas the increased levels are less dramatic. This is to be expected as these areas are generally impacted by short duration rainfall events. In these events there is less total volume and thus the increase in total runoff is not as great as within the floodplain.

Table 29 – Results of Climate Change for 1% AEP (20% Rainfall increase)

ID	Location	1% AEP Peak Flood Level (mAHD)	Change in Peak Flood level (m)
1	Ulan Road at Lue Road	449.5	0.25
2	Denison Street at Perry Street	462.7	0.00
3	Charles Lester Place	470.5	0.06
4	Robertson Street	481.4	0.06
5	Madeira Road at Mudgee Showground	477.8	0.01
6	Nicholson Street at Atkinson Street	469.5	0.05
7	Industrial Avenue	465.5	0.03
8	Castlereagh Hwy at Bunnings Mudgee	470.4	0.01
9	Waterworks Road at Redbank creek	510.3	0.02
10	Putta Bucca Road near Cudgegong River	445.8	0.57
11	Lawsons Creek near Lue Road	454.1	0.05
12	Oaky Creek near Cudgegong River	451.4	0.56

10.4. Glen Willow Sporting Fields

As part of the study, a review of potential upgrades to the Glen Willlow Sporting Field was undertaken. The base hydraulic model was updated with a revised sports field topography for the site based on preliminary concept sketches for stage 2. The revised surface included the following features:

- A bund up to the 1% AEP Flood Level for a new sporting field west of the existing stadium;
- A bund to allow for an elevated playing shed area in the north of the site;
- Some earthworks and drainage in the north of the site to manage flows from the site back to Lawsons Creek.

The design was run within the flood model to determine the impact the development would have on the floodplain. The analysis undertaken is concept only to review the potential impacts that an upgrade would pose.

Plate 1 shows the results of this assessment. The mitigation design modelled have resulted in impacts less than 50 mm offset to the west of the development and a reduction in levels on the property located on the corner of Pitts Road and Pitts Lane.

What is apparent is the inclusion of an additional bunded sports field in the south of the site has a marked impact on the floodplain, the location and ultimate design of this field, should it occur, should be undertaken with appropriate consideration of the potential impacts. The location is sensitive to changes and may result in adverse impacts if these risks are not appropriately managed.

Plate 1 – Glen Willow Stage 2 – Concept Level Impact Assessment 1% AEP Event.

10.5. Flood Hazard

Hazard classification plays an important role in managing floodplain risk in an area. The flood hazard has been defined using the Australian Disaster Resilience Handbook Collection (Reference 19). The supporting guideline 7-3 provides hazard categorisation based on velocity and depth of floodwater and its hazard to people, vehicles and buildings. The velocity/depth relationship for each of these categories is depicted in Diagram 2.

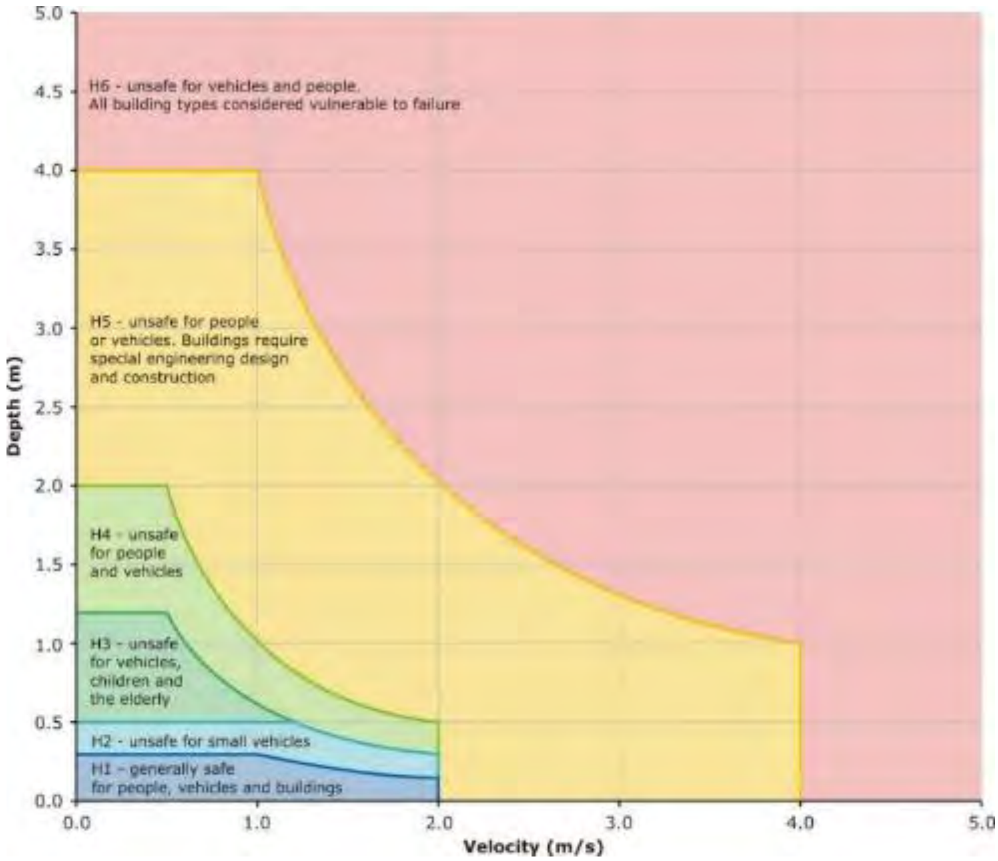

Diagram 2: Hazard Categorisation

The provisional hydraulic hazard categorisation based on Diagram 2 is shown in Figure 35 to Figure 37. The hazards are provisional because they only consider the hydraulic aspects of flood hazard and does not reflect other factors that influence hazard (such as warning time, flood readiness, rate of rise, duration of flooding, evacuation problems, effective flood access and the type of development). A review of the results indicates that a large proportion of Mudgee is classified as low hazard area while the high hazard areas are primarily located around the Cudgegong River on the northern edge of the town. Along the stormwater channels running through town there is areas where due to the channels having insufficient capacity, areas of moderate to high hazard are present.

11. INFORMATION TO SUPPORT DECISIONS ON ACTIVITIES IN THE FLOODPLAIN AND MANAGING FLOOD RISK

The following section of the report is provided as interim guidance in advance of a future flood risk management study (FRMS). An FRMS is a study in which the floodplain management issues confronting the study areas are assessed, management options investigated, and recommendations made. Specific objectives for this study include:

- Identifying innovative solutions to the management of flood hazards within the study area under current and future conditions,
- Emergency management planning for existing and future development,
- Strategic and development scale land-use planning to manage growth in flood risk,
- Review and discuss strategies for raising the awareness of flood risk and the level of flood preparedness in the catchment,
- Selection of practical, feasible and economic measures for treatment of risk.

A FRMS is a significant body of work and requires the development of a large amount of information to inform its decision making process.

The information provided in the following sections is based on the limited dataset of information that this flood study has developed. All information should be considered as high level guidance at this stage and will require review and revision as part of the future FRMS before the information is utilised to inform decision making processes.

11.1. Flood Function

Defining the floodway is a critical component of the flood risk management work carried out under the NSW Floodplain risk management program. This relates to the fact that the defined floodway extent will typically not be available for further residential development. As such it is imperative that the floodway definition is appropriate and not conservative.

Floodways are areas of the floodplain where a significant discharge of water occurs during floods and by definition if blocked would have a significant effect on flood flows, velocities or depths. Flood storage are areas of importance for the temporary storage of floodwaters and if filled would significantly increase flood levels due to the loss of flood attenuation. The remainder of the floodplain is defined as flood fringe.

The 2012 paper by Thomas et al. (Reference 21) presented an investigation which observed that "the 'corridor' required to convey approximately 80% of the peak 1% AEP flow correlated well with most of the other parameters that are relied upon to estimate the floodway extent" (e.g. the 0.1 m afflux approach described above).

Based on this approach a flood function map has been developed utilising the parameters presented in Table 30. The parameters were selected by reviewing cross sections through the floodplain to confirm the extent of the floodway carried approximately 80% of the total peak 1% AEP flow. Figure 38 presents the flood function map developed using these parameters.

Table 30 – Floodway Parameters

Waterway	Floodway Definition Parameters
Cudgegong River and Lawsons Creek	D > 0.65 m^2/s and V > 0.65 m/s; or V > 0.65 m/s
Local Creeks and Stormwater	VD > 0.15 m^2/s and V > 0.15 m/s; or V > 1.0 m/s

11.2. Flood Emergency Response Classifications for Communities

The Manual (Reference 17) requires flood studies to address the management of continuing flood risk to both existing and future development areas. As continuing flood risk varies across the floodplain so does the type and scale of the emergency response problem and therefore the information necessary for effective Emergency Response Planning (ERP). Classification provides an indication of the vulnerability of the community in flood emergency response and identifies the type and scale of information needed by the State Emergency Services (SES) to assist in ERP.

Criteria for determining flood ERP classifications and an indication of the emergency response required for these classifications are provided in the Australian Disaster Resilience Handbook Collection, 2017 (Flood Emergency Response Planning: Classification of Communities). Reference 22 summarises the response required for areas of different classification. However, these may vary depending on local flood characteristics and resultant flood behaviour, i.e. in flash flooding or overland flood areas.

The ERP classifications within the hydraulic model extent have been defined for Mudgee and surrounds, as represented by the PMF flood extent and is shown in Figure 40. The classification has been undertaken on a precinct basis rather than lot-by-lot and is targeted at those areas which may require evacuation or assistance during a flood event. Classification of the floodplain is done by considering all design flood events and more importantly how each precinct of the floodplain floods.

11.3. Consequences of Flooding to the Community

Based on the findings of the flood study a preliminary consequences assessment has been undertaken. Given the limited information of impact to the community at this stage this is available, the consequence assessment has been based upon the potential consequences of flooding based on property flooding and the isolation of the community.

Figure 40 shows the properties flooded in the study area and the event in which the depths exceed 50 mm. In a 20% AEP event as expected significant areas of rural land is flood impacted. There are however still several areas in the township that are also subject to flooding. There is a large increase in the number of properties impacted in the 5% AEP and then again in the 0.2% AEP. Table 31 summarises the number of properties impacted.

Table 31 – Flood Affected Properties

AEP	Properties Affected
20% AEP	1341
10% AEP	1373
5% AEP	1567
2% AEP	1655
1% AEP	1659
0.2% AEP	1860
PMF	3046

The property figures above do not consider the amount of property flooded or the location on the property flooding occurs. The numbers are not representative of the likely number of dwellings that are subject to flooding. During the flood risk management study floor level survey of all potentially flood affected dwellings in the area should be undertaken to ensure accurate identification of at risk properties.

Figure 41 to Figure 43 show the road inundation at key locations within the study area for the 5%, 1% AEP and PMF flood events. Of note is that Ulan Road, Putta Bucca Road and Castlereagh Highway (north of Mudgee) are inundated in a 5% AEP Cudgegong River event. This means that the only means of evacuation may be via Castlereagh Highway south. The highway south is also subject to flooding however this flooding is due to local creek flooding and not a regional flood event. The reduced evacuation and supply capacity of the road network in a major regional flood is considered to be a key flooding issue that may have significant consequences to the Mudgee township economy and surrounds. In a PMF event the Highway is cut in all directions and thus presents a significant risk to the community.

Based on the preliminary information the following risk matrix has been developed. Note the economy consequences have been inferred from the closure of major routes and have not been quantified.

Likelihood of consequences	AEP range (%)	Level of Consequences				
		Insignificant	Minor	Moderate	Major	Catastrophic
Likely	>10		People	Economy		
Unlikely	1 to 10			People	Economy	
Rare to very rare	0.01 to 1			People	Economy	
Extremely rare	<0.01				People, Economy	

Risk Very Low Low Medium High Extreme

11.4. Flood Planning Area

The Flood Planning Area (FPA) is an area to which flood planning controls are applied. An FPA map is a required outcome of the FRMS.

The NSW Standard Instrument LEP does not include a specific land use zone classification for flood prone land, rather it permits a Flood Planning Area map to be included as a layer imposed across all land use zones.

A preliminary flood planning area has been developed for this study which has been based on the 1% AEP in areas where depths exceed 100 mm. Figure 44 presents the area developed. This flood planning area should be reviewed in the following FRMS to ensure appropriate freeboard considerations are applied where relevant.

11.5. Flood Risk Precincts

Based on the revised flood information that is now available for Mudgee and surrounds it is recommended that an investigation into the appropriate method of implementation of the data into the Council development control plans be undertaken.

A key component of the flood planning controls utilised by Council is the flood risk precincts, which define what development is allowable in various locations throughout the floodplain. The development and control plan currently relies on two matrixes (One for Urban Floodplains and one for Non Urban Floodplains) which use a 3 flood risk precinct (High, Medium and Low) system to inform development controls.

The revised flood study has developed a revised provisional flood hazard categorisation map (Section 10.5) which is based on the hazard categorisation presented in Australian Disaster Resilience Handbook Collection. Previous flood studies in the area have relied upon a three criteria system focussing on hazard criteria of the 1% AEP and the extent of the PMF event.

Table 32 – Flood Planning Zone Potential Revision

Flood Planning Zone	Previous Zone Definition (from Mudgee FRMS&P, 2002)	Potential Zone Definition
High Flood Risk	Land that is below the 100 year ARI flood that is subject to a high hydraulic hazard (ie provisional high hazard in accordance with the criteria outlined in the Floodplain Management Manual) or areas that are isolated in a 100 year ARI flood due to evacuation difficulties.	Land that is below the 100 year ARI flood that is subject to a high hydraulic hazard (ie hazard categories 4,5 and 6 in accordance with the criteria outlined in the AIDR guideline 7-3) or areas that are isolated in a 100 year ARI flood due to evacuation difficulties.
Medium Flood Risk	Land below the 100 year ARI flood level that is not subject to high hydraulic hazard and where there are no significant evacuation difficulties.	Land below the 100 year ARI flood level that is not subject to high hydraulic hazard and where there are no significant evacuation difficulties.
Low Flood Risk	All other land within the floodplain (i.e. within the PMF extent) but not identified as either in a high flood risk or medium flood risk precinct.	All other land within the floodplain (i.e. within the PMF extent) but not identified as either in a high flood risk or medium flood risk precinct.

12. CONCLUSION

WMA water has undertaken a flood study for the Mudgee Township and surrounds, assessing both regional river flood impacts and local creek and stormwater impacts. The analysis undertaken has reviewed a range of design events and also tested the sensitivity of the area to various hydrologic and hydraulic parameters.

Based on the analysis undertaken the following has been identified:

- In a 1% AEP regional flood event there is significant flood impacts present both within the township and on the roadways connecting the town to the surrounding region. During a regional flood only the Castlereagh Highway running south is not inundated. In this event all other routes out of the town have the potential to be closed in excess of 24 hours;
- During a local 1% AEP storm event at Mudgee there is a high likelihood that property flooding and damage will occur. With the exception of Redbank Creek most other overland flow paths through the township do not have sufficient capacity to safely transfer flow through the township;
- Sensitivity analysis shows that in general the floodplain is not sensitive to changes in hydrologic or hydraulic modelling parameters which would still be in accordance with best practice. The catchment is sensitive to increases in rainfall intensity however, with level increases in the 1% AEP event in excess of 0.50 m in the 1% AEP event within the Cudgegong River.

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Appendix A

Appendix A- GLOSSARY of TERMS

Taken from the Floodplain Development Manual (April 2005 edition)

Annual Exceedance Probability (AEP)	The chance of a flood of a given or larger size occurring in any one year, usually expressed as a percentage. For example, if a peak flood discharge of 500 m^3/s has an AEP of 5%, it means that there is a 5% chance (that is one-in-20 chance) of a 500 m^3/s or larger event occurring in any one year (see ARI).
Australian Height Datum (AHD)	A common national surface level datum approximately corresponding to mean sea level.
Average Annual Damage (AAD)	Depending on its size (or severity), each flood will cause a different amount of flood damage to a flood prone area. AAD is the average damage per year that would occur in a nominated development situation from flooding over a very long period of time.
Average Recurrence Interval (ARI)	The long term average number of years between the occurrence of a flood as big as, or larger than, the selected event. For example, floods with a discharge as great as, or greater than, the 20 year ARI flood event will occur on average once every 20 years. ARI is another way of expressing the likelihood of occurrence of a flood event.
catchment	The land area draining through the main stream, as well as tributary streams, to a particular site. It always relates to an area above a specific location.
consent authority	The Council, Government agency or person having the function to determine a development application for land use under the EP&A Act. The consent authority is most often the Council, however legislation or an EPI may specify a Minister or public authority (other than a Council), or the Director General of DIPNR, as having the function to determine an application.
development	Is defined in Part 4 of the Environmental Planning and Assessment Act (EP&A Act). **infill development:** refers to the development of vacant blocks of land that are generally surrounded by developed properties and is permissible under the current zoning of the land. Conditions such as minimum floor levels may be imposed on infill development. **new development:** refers to development of a completely different nature to that associated with the former land use. For example, the urban subdivision of an area previously used for rural purposes. New developments involve rezoning and typically require major extensions of existing urban services, such as roads, water supply, sewerage and electric power. **redevelopment:** refers to rebuilding in an area. For example, as urban areas age, it may become necessary to demolish and reconstruct buildings on a relatively large scale. Redevelopment generally does not require either rezoning or major extensions to urban services.
disaster plan (DISPLAN)	A step by step sequence of previously agreed roles, responsibilities, functions, actions and management arrangements for the conduct of a single or series of connected emergency operations, with the object of ensuring the coordinated response by all agencies having responsibilities and functions in emergencies.
discharge	The rate of flow of water measured in terms of volume per unit time, for example, cubic metres per second (m^3/s). Discharge is different from the speed or velocity of flow, which is a measure of how fast the water is moving for example, metres per second (m/s).
effective warning time	The time available after receiving advice of an impending flood and before the floodwaters prevent appropriate flood response actions being undertaken. The

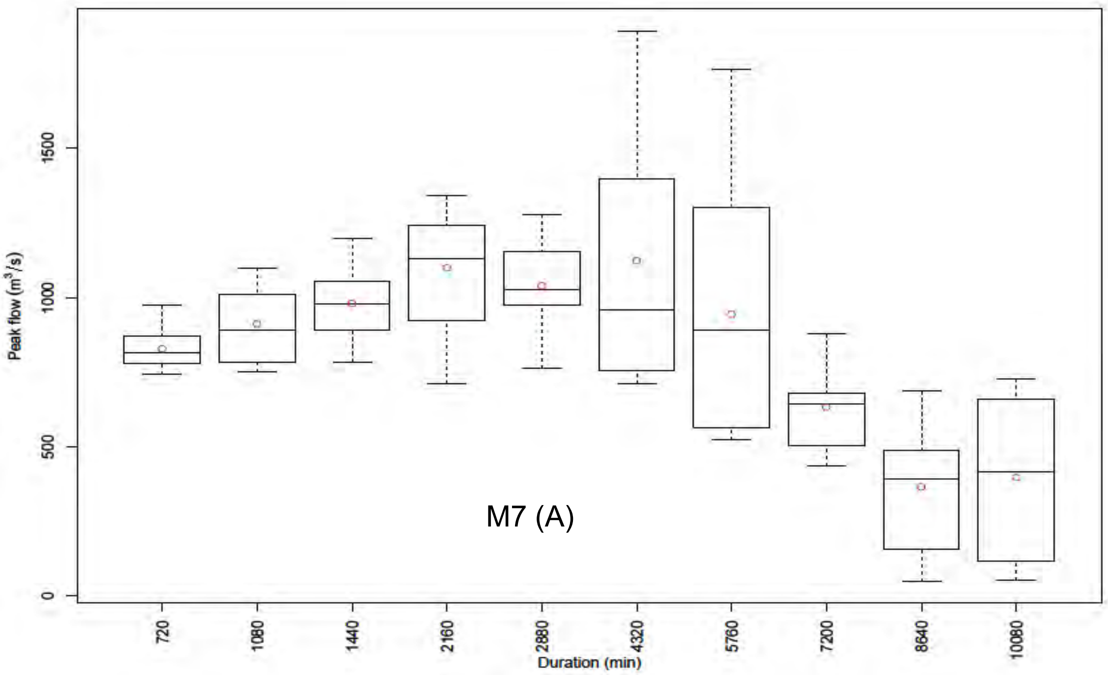
	effective warning time is typically used to move farm equipment, move stock, raise furniture, evacuate people and transport their possessions.
emergency management	A range of measures to manage risks to communities and the environment. In the flood context it may include measures to prevent, prepare for, respond to and recover from flooding.
flash flooding	Flooding which is sudden and unexpected. It is often caused by sudden local or nearby heavy rainfall. Often defined as flooding which peaks within six hours of the causative rain.
flood	Relatively high stream flow which overtops the natural or artificial banks in any part of a stream, river, estuary, lake or dam, and/or local overland flooding associated with major drainage before entering a watercourse, and/or coastal inundation resulting from super-elevated sea levels and/or waves overtopping coastline defences excluding tsunami.
flood awareness	Flood awareness is an appreciation of the likely effects of flooding and a knowledge of the relevant flood warning, response and evacuation procedures.
flood education	Flood education seeks to provide information to raise awareness of the flood problem so as to enable individuals to understand how to manage themselves an their property in response to flood warnings and in a flood event. It invokes a state of flood readiness.
flood fringe areas	The remaining area of flood prone land after floodway and flood storage areas have been defined.
flood liable land	Is synonymous with flood prone land (i.e. land susceptible to flooding by the probable maximum flood (PMF) event). Note that the term flood liable land covers the whole of the floodplain, not just that part below the flood planning level (see flood planning area).
flood mitigation standard	The average recurrence interval of the flood, selected as part of the floodplain risk management process that forms the basis for physical works to modify the impacts of flooding.
floodplain	Area of land which is subject to inundation by floods up to and including the probable maximum flood event, that is, flood prone land.
floodplain risk management options	The measures that might be feasible for the management of a particular area of the floodplain. Preparation of a floodplain risk management plan requires a detailed evaluation of floodplain risk management options.
floodplain risk management plan	A management plan developed in accordance with the principles and guidelines in this manual. Usually includes both written and diagrammatic information describing how particular areas of flood prone land are to be used and managed to achieve defined objectives.
flood plan (local)	A sub-plan of a disaster plan that deals specifically with flooding. They can exist at State, Division and local levels. Local flood plans are prepared under the leadership of the State Emergency Service.
flood planning area	The area of land below the flood planning level and thus subject to flood related development controls. The concept of flood planning area generally supersedes the "flood liable land" concept in the 1986 Manual.
Flood Planning Levels (FPLs)	FPL's are the combinations of flood levels (derived from significant historical flood events or floods of specific AEPs) and freeboards selected for floodplain risk management purposes, as determined in management studies and incorporated in management plans. FPLs supersede the "standard flood event" in the 1986 manual.
flood proofing	A combination of measures incorporated in the design, construction and alteration of individual buildings or structures subject to flooding, to reduce or eliminate flood damages.

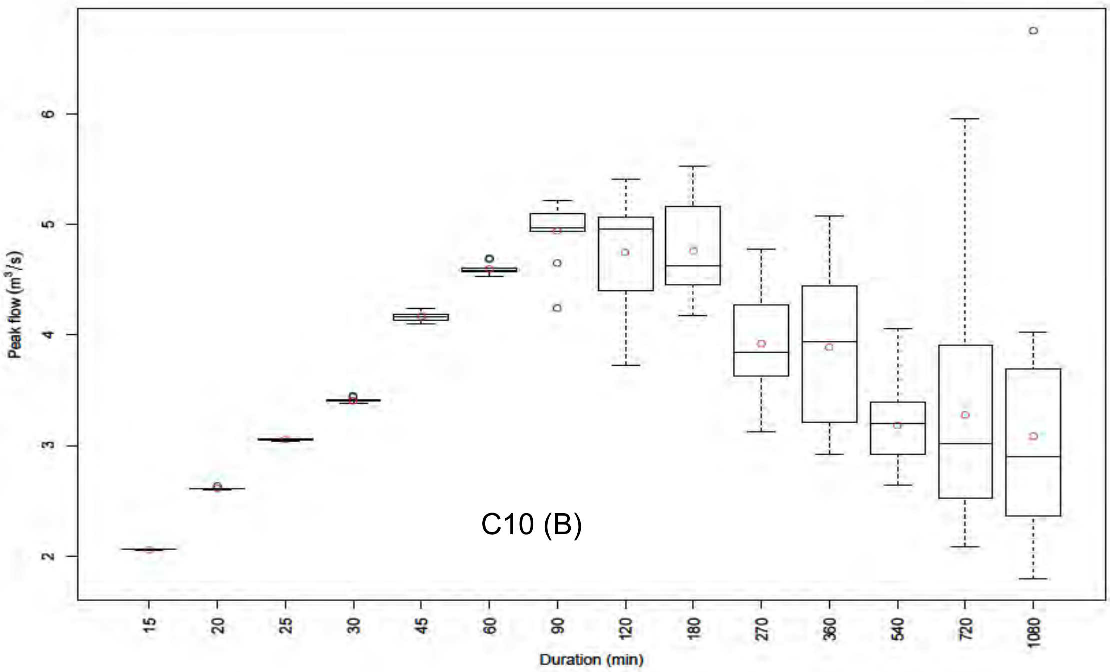
flood prone land	Is land susceptible to flooding by the Probable Maximum Flood (PMF) event. Flood prone land is synonymous with flood liable land.
flood readiness	Flood readiness is an ability to react within the effective warning time.
flood risk	Potential danger to personal safety and potential damage to property resulting from flooding. The degree of risk varies with circumstances across the full range of floods. Flood risk in this manual is divided into 3 types, existing, future and continuing risks. They are described below. **existing flood risk:** the risk a community is exposed to as a result of its location on the floodplain. **future flood risk:** the risk a community may be exposed to as a result of new development on the floodplain. **continuing flood risk:** the risk a community is exposed to after floodplain risk management measures have been implemented. For a town protected by levees, the continuing flood risk is the consequences of the levees being overtopped. For an area without any floodplain risk management measures, the continuing flood risk is simply the existence of its flood exposure.
flood storage areas	Those parts of the floodplain that are important for the temporary storage of floodwaters during the passage of a flood. The extent and behaviour of flood storage areas may change with flood severity, and loss of flood storage can increase the severity of flood impacts by reducing natural flood attenuation. Hence, it is necessary to investigate a range of flood sizes before defining flood storage areas.
floodway areas	Those areas of the floodplain where a significant discharge of water occurs during floods. They are often aligned with naturally defined channels. Floodways are areas that, even if only partially blocked, would cause a significant redistribution of flood flows, or a significant increase in flood levels.
freeboard	Freeboard provides reasonable certainty that the risk exposure selected in deciding on a particular flood chosen as the basis for the FPL is actually provided. It is a factor of safety typically used in relation to the setting of floor levels, levee crest levels, etc. Freeboard is included in the flood planning level.
habitable room	**in a residential situation:** a living or working area, such as a lounge room, dining room, rumpus room, kitchen, bedroom or workroom. **in an industrial or commercial situation:** an area used for offices or to store valuable possessions susceptible to flood damage in the event of a flood.
hazard	A source of potential harm or a situation with a potential to cause loss. In relation to this manual the hazard is flooding which has the potential to cause damage to the community. Definitions of high and low hazard categories are provided in the Manual.
hydraulics	Term given to the study of water flow in waterways; in particular, the evaluation of flow parameters such as water level and velocity.
hydrograph	A graph which shows how the discharge or stage/flood level at any particular location varies with time during a flood.
hydrology	Term given to the study of the rainfall and runoff process; in particular, the evaluation of peak flows, flow volumes and the derivation of hydrographs for a range of floods.
local overland flooding	Inundation by local runoff rather than overbank discharge from a stream, river, estuary, lake or dam.
local drainage	Are smaller scale problems in urban areas. They are outside the definition of major drainage in this glossary.

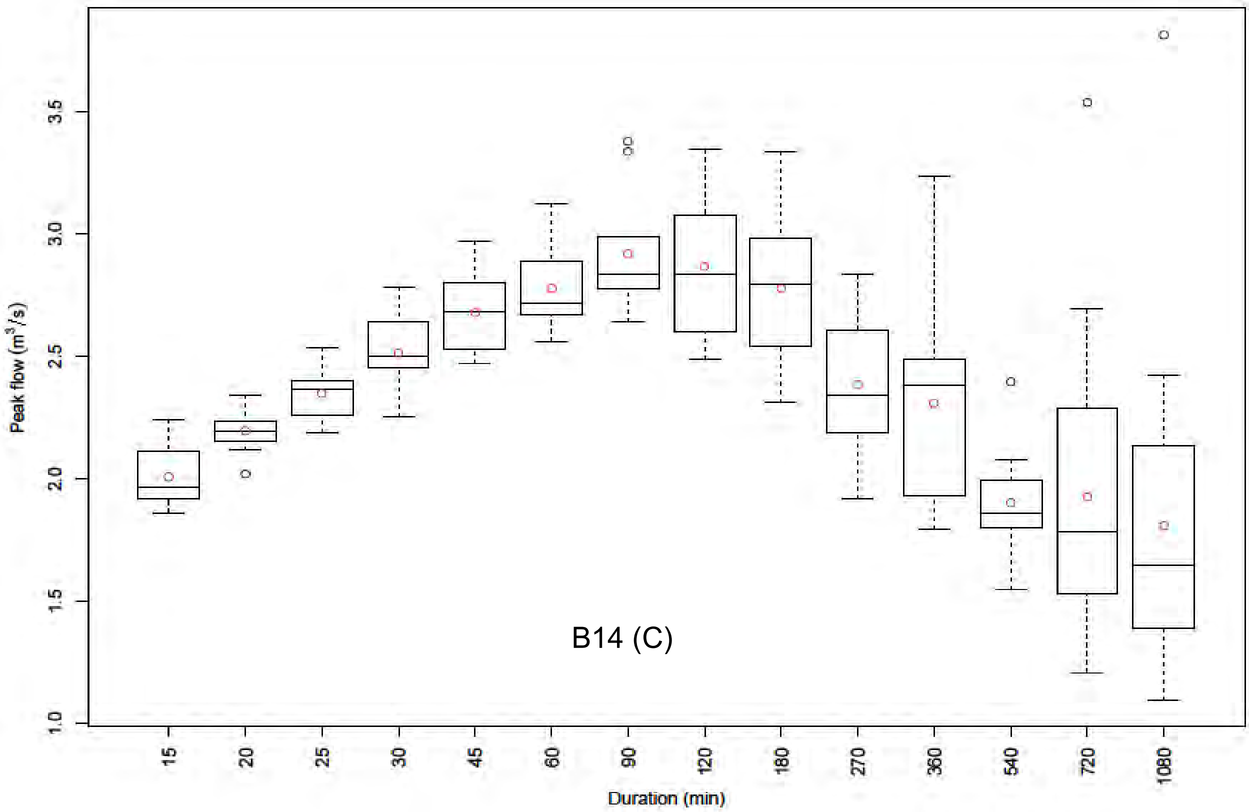
mainstream flooding	Inundation of normally dry land occurring when water overflows the natural or artificial banks of a stream, river, estuary, lake or dam.
mathematical/computer models	The mathematical representation of the physical processes involved in runoff generation and stream flow. These models are often run on computers due to the complexity of the mathematical relationships between runoff, stream flow and the distribution of flows across the floodplain.
minor, moderate and major flooding	Both the State Emergency Service and the Bureau of Meteorology use the following definitions in flood warnings to give a general indication of the types of problems expected with a flood: **minor flooding:** causes inconvenience such as closing of minor roads and the submergence of low level bridges. The lower limit of this class of flooding on the reference gauge is the initial flood level at which landholders and townspeople begin to be flooded. **moderate flooding:** low-lying areas are inundated requiring removal of stock and/or evacuation of some houses. Main traffic routes may be covered. **major flooding:** appreciable urban areas are flooded and/or extensive rural areas are flooded. Properties, villages and towns can be isolated.
modification measures	Measures that modify either the flood, the property or the response to flooding. Examples are indicated in Table 2.1 with further discussion in the Manual.
peak discharge	The maximum discharge occurring during a flood event.
Probable Maximum Flood (PMF)	The PMF is the largest flood that could conceivably occur at a particular location, usually estimated from probable maximum precipitation, and where applicable, snow melt, coupled with the worst flood producing catchment conditions. Generally, it is not physically or economically possible to provide complete protection against this event. The PMF defines the extent of flood prone land, that is, the floodplain. The extent, nature and potential consequences of flooding associated with a range of events rarer than the flood used for designing mitigation works and controlling development, up to and including the PMF event should be addressed in a floodplain risk management study.
Probable Maximum Precipitation (PMP)	The PMP is the greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends (World Meteorological Organisation, 1986). It is the primary input to PMF estimation.
probability	A statistical measure of the expected chance of flooding (see AEP).
risk	Chance of something happening that will have an impact. It is measured in terms of consequences and likelihood. In the context of the manual it is the likelihood of consequences arising from the interaction of floods, communities and the environment.
runoff	The amount of rainfall which actually ends up as streamflow, also known as rainfall excess.
stage	Equivalent to “water level”. Both are measured with reference to a specified datum.
stage hydrograph	A graph that shows how the water level at a particular location changes with time during a flood. It must be referenced to a particular datum.
survey plan	A plan prepared by a registered surveyor.
water surface profile	A graph showing the flood stage at any given location along a watercourse at a particular time.

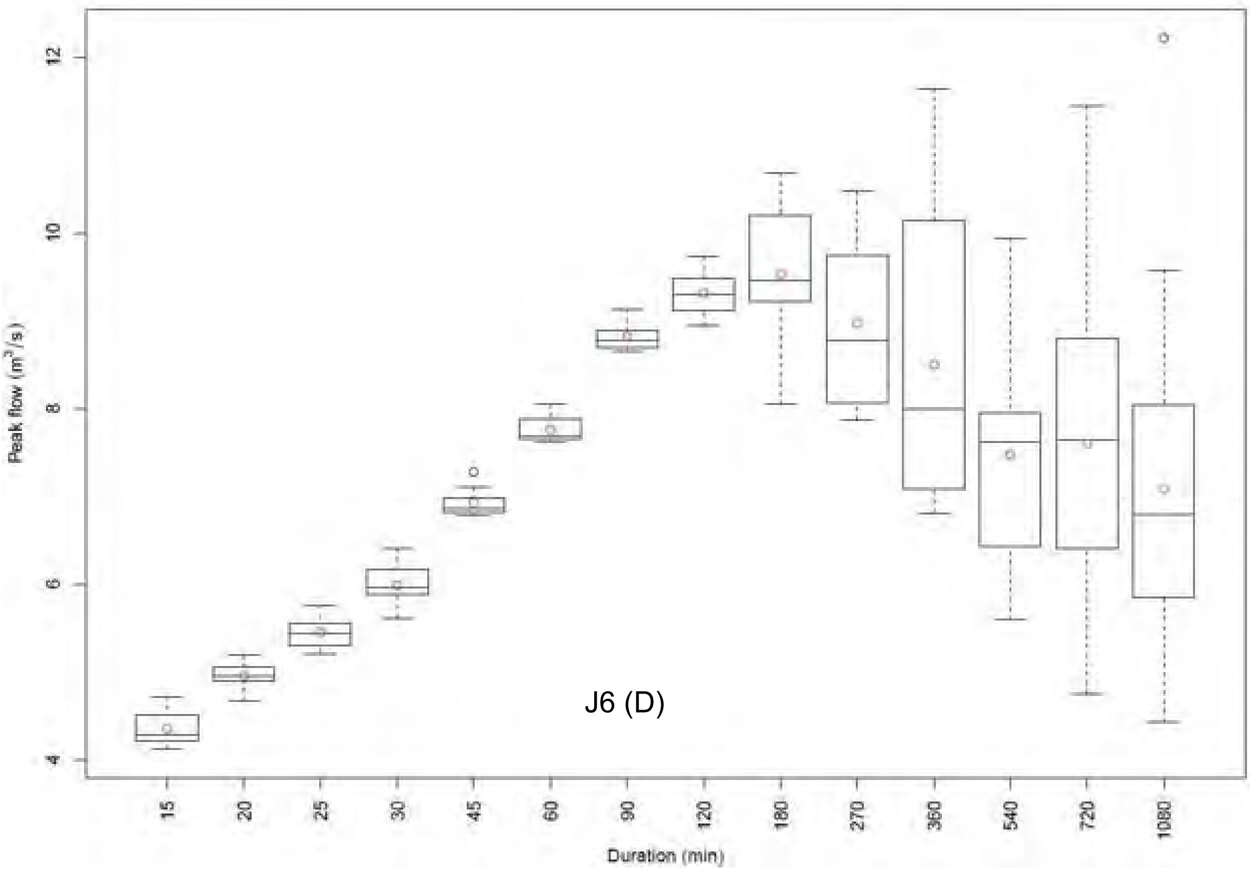
Appendix B

Appendix B - Chart B - 1% AEP Boxplot at M7 (A), C10 (B), B14 (C) and J6 (D) Subcatchments






B14 (C)
Peak flow (m^3/s)
Duration (min)
1.0
1.5
2.0
2.5
3.0
3.5
15
20
25
30
45
60
90
120
180
270
360
540
720
1080


J6 (D)
Peak flow (m^3/s)
Duration (min)
4
6
8
10
12
15
20
25
30
45
60
90
120
180
270
360
540
720
1080

Appendix C

Appendix C - Sensitivity Analysis Results

Table C 1 – Results of Sensitivity Analysis for 0.2% AEP

ID	Location	0.2% AEP Peak Flood Level (mAHD)	Change in Flood level (m)					
			Loss -20%	C -20%	C +20%	Manning's -20%	Manning's +20%	Blockage 100%
1	Ulan Road at Lue Road	449.7	0.00	0.08	-0.06	-0.02	0.06	0.13
2	Denison Street at Perry Street	462.7	0.00	0.00	0.00	0.02	-0.01	0.01
3	Charles Lester Place	470.7	0.00	0.04	-0.04	-0.04	0.04	-0.01
4	Robertson Street at Trefusis Avenue	481.6	0.00	0.03	-0.03	0.00	0.00	0.04
5	Madeira Road at Mudgee Showground	477.8	0.00	0.01	0.00	-0.01	0.01	0.01
6	Nicholson Street at Atkinson Street	469.6	0.00	0.01	-0.01	-0.01	0.01	0.01
7	Industrial Avenue	465.6	0.00	0.03	-0.03	-0.01	0.01	0.06
8	Castlereagh Hwy at Bunnings Mudgee	470.5	0.00	0.01	-0.01	-0.01	0.00	0.08
9	Waterworks Road at Redbank creek	510.4	0.00	0.01	-0.01	-0.02	0.00	0.00
10	Putta Bucca Road near Cudgegong River	446.2	0.00	0.16	-0.13	-0.12	0.12	0.01
11	Lawsons Creek near Lue Road	454.2	0.00	0.01	0.00	0.05	-0.03	0.00
12	Oaky Creek near Cudgegong River	451.9	-0.01	0.16	-0.13	-0.16	0.15	0.01

Table C 2 – Results of Sensitivity Analysis for 1% AEP

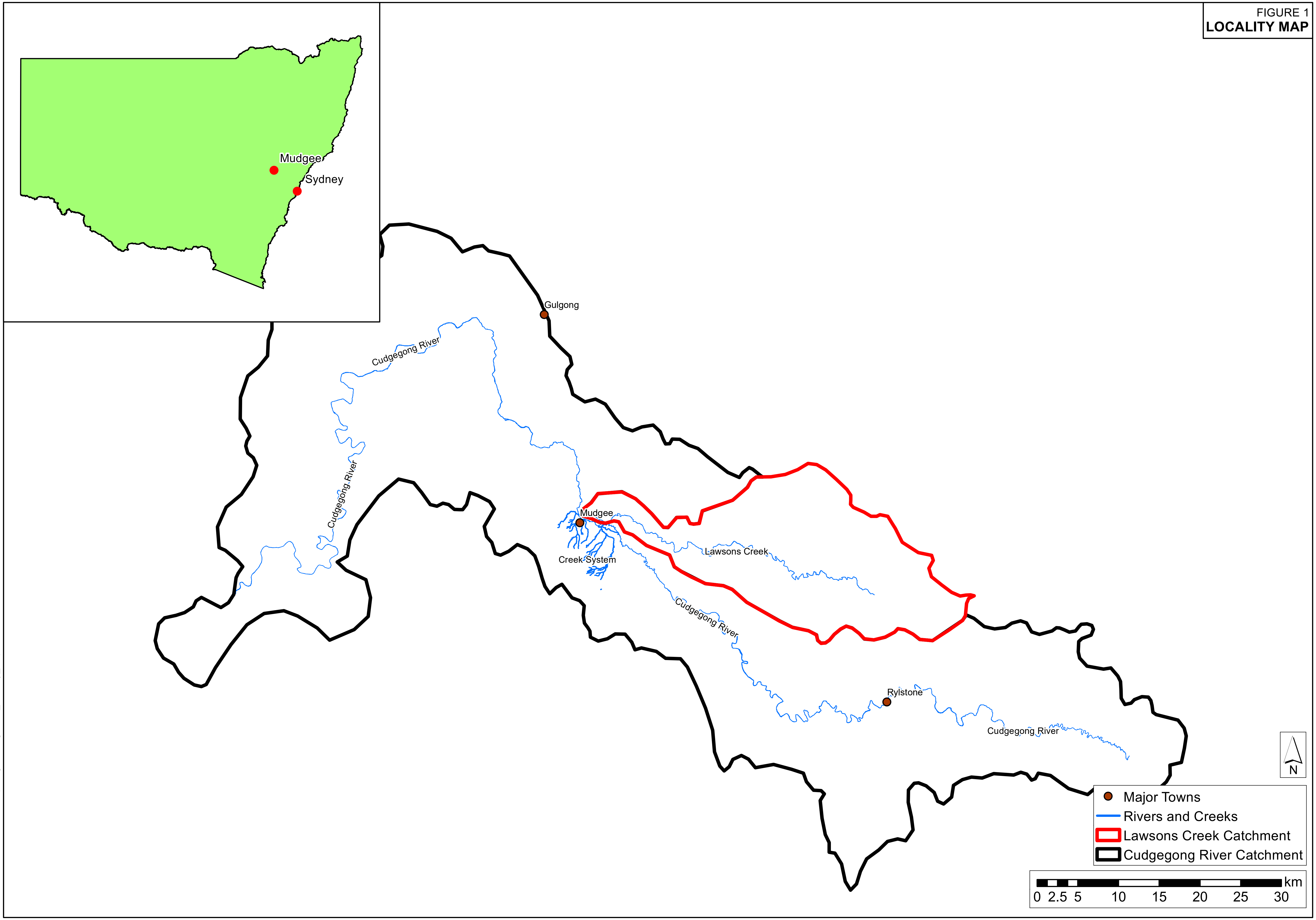
ID	Location	1% AEP Peak Flood Level (mAHD)	Change in Peak Flood level (m)					
			Loss -20%	C -20%	C +20%	Manning's -20%	Manning's +20%	Blockage 100%
1	Ulan Road at Lue Road	449.5	-0.01	0.08	-0.09	-0.03	0.01	0.15
2	Denison Street at Perry Street	462.7	0.00	0.00	0.00	0.01	-0.01	0.00
3	Charles Lester Place	470.5	0.00	0.04	-0.05	-0.05	0.04	0.00
4	Robertson Street at Trefusis Avenue	481.4	0.00	0.06	-0.05	0.00	0.00	0.08
5	Madeira Road at Mudgee Showground	477.8	0.00	0.01	0.00	0.00	0.01	0.01
6	Nicholson Street at Atkinson Street	469.5	0.00	0.01	-0.01	-0.01	0.01	0.03
7	Industrial Avenue	465.5	0.00	0.02	-0.01	-0.02	0.01	0.08
8	Castlereagh Hwy at Bunnings Mudgee	470.4	0.00	0.01	-0.01	0.00	0.00	0.08
9	Waterworks Road at Redbank creek	510.3	0.00	0.02	-0.02	-0.02	0.01	0.00
10	Putta Bucca Road near Cudgegong River	445.8	-0.03	0.18	-0.21	-0.14	0.07	-0.03
11	Lawsons Creek near Lue Road	454.1	0.00	0.03	-0.02	0.04	-0.03	0.00
12	Oaky Creek near Cudgegong River	451.4	-0.03	0.17	-0.21	-0.17	0.09	-0.02

Table C 3 – Results of Sensitivity Analysis for 5% AEP

ID	Location	5% AEP Peak Flood Level (mAHD)	Change in Peak Flood level (m)					
			Loss -20%	C -20%	C +20%	Manning's -20%	Manning's +20%	Blockage 100%
1	Ulan Road at Lue Road	449.2	-0.02	0.10	-0.09	-0.04	0.01	0.23
2	Denison Street at Perry Street	462.7	0.00	0.00	0.00	0.01	-0.02	0.00
3	Charles Lester Place	470.4	0.00	0.07	-0.06	-0.06	0.04	0.00
4	Robertson Street at Trefusis Avenue							
5	Madeira Road at Mudgee Showground	477.8	0.00	0.00	-0.01	-0.01	0.00	0.01
6	Nicholson Street at Atkinson Street	469.4	0.00	0.01	-0.01	-0.01	0.01	0.03
7	Industrial Avenue	465.4	0.00	0.03	-0.03	-0.01	0.01	0.06
8	Castlereagh Hwy at Bunnings Mudgee	470.4	0.00	0.01	-0.01	0.00	0.00	0.07
9	Waterworks Road at Redbank creek	510.3	0.00	0.02	-0.02	-0.02	0.01	0.00
10	Putta Bucca Road near Cudgegong River	445.2	-0.03	0.18	-0.20	-0.13	0.06	-0.02
11	Lawsons Creek near Lue Road	454.1	0.00	0.03	-0.05	0.01	0.00	0.00
12	Oaky Creek near Cudgegong River	450.8	-0.04	0.18	-0.22	-0.18	0.08	-0.03

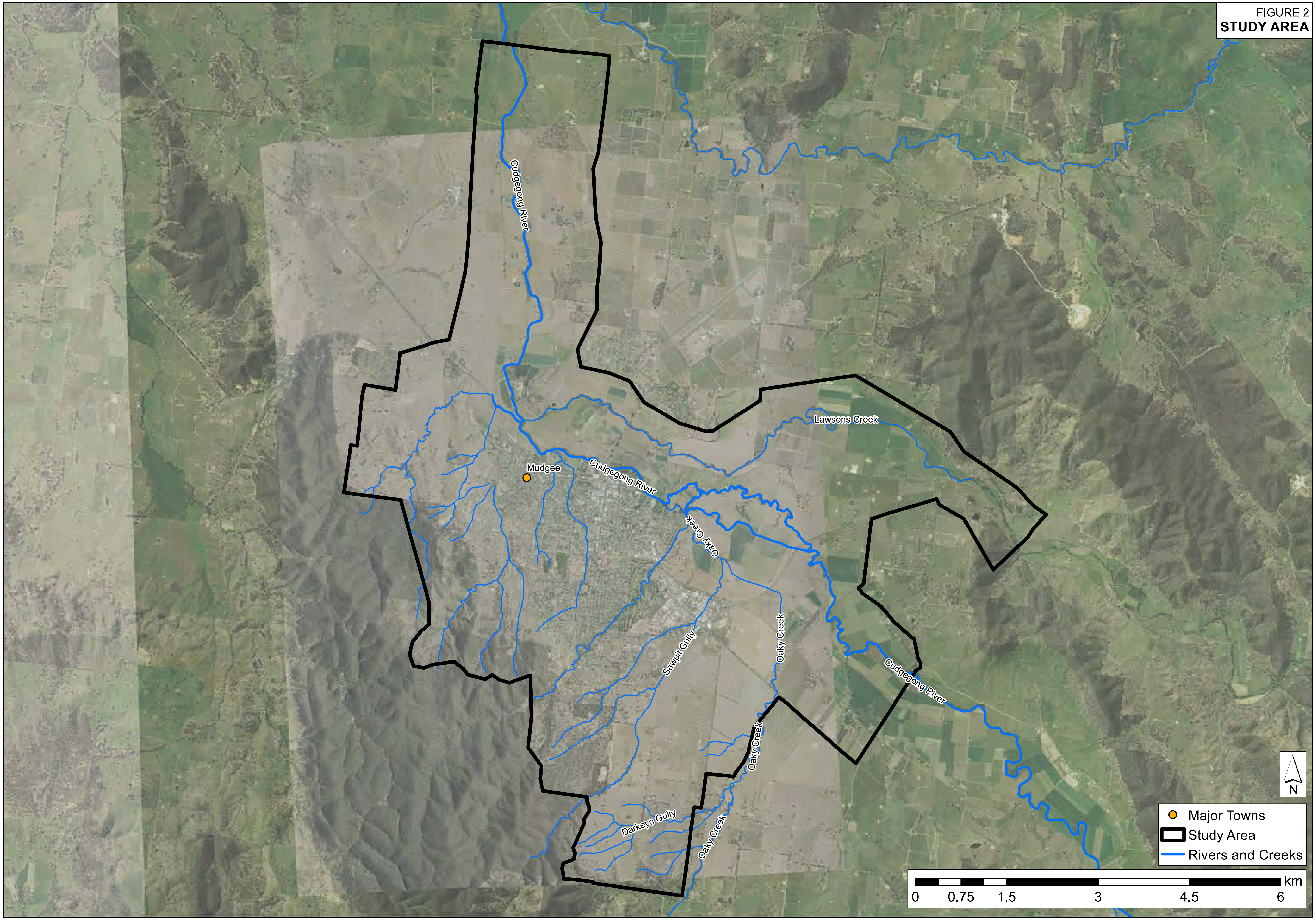
Figures

FIGURE 1
LOCALITY MAP



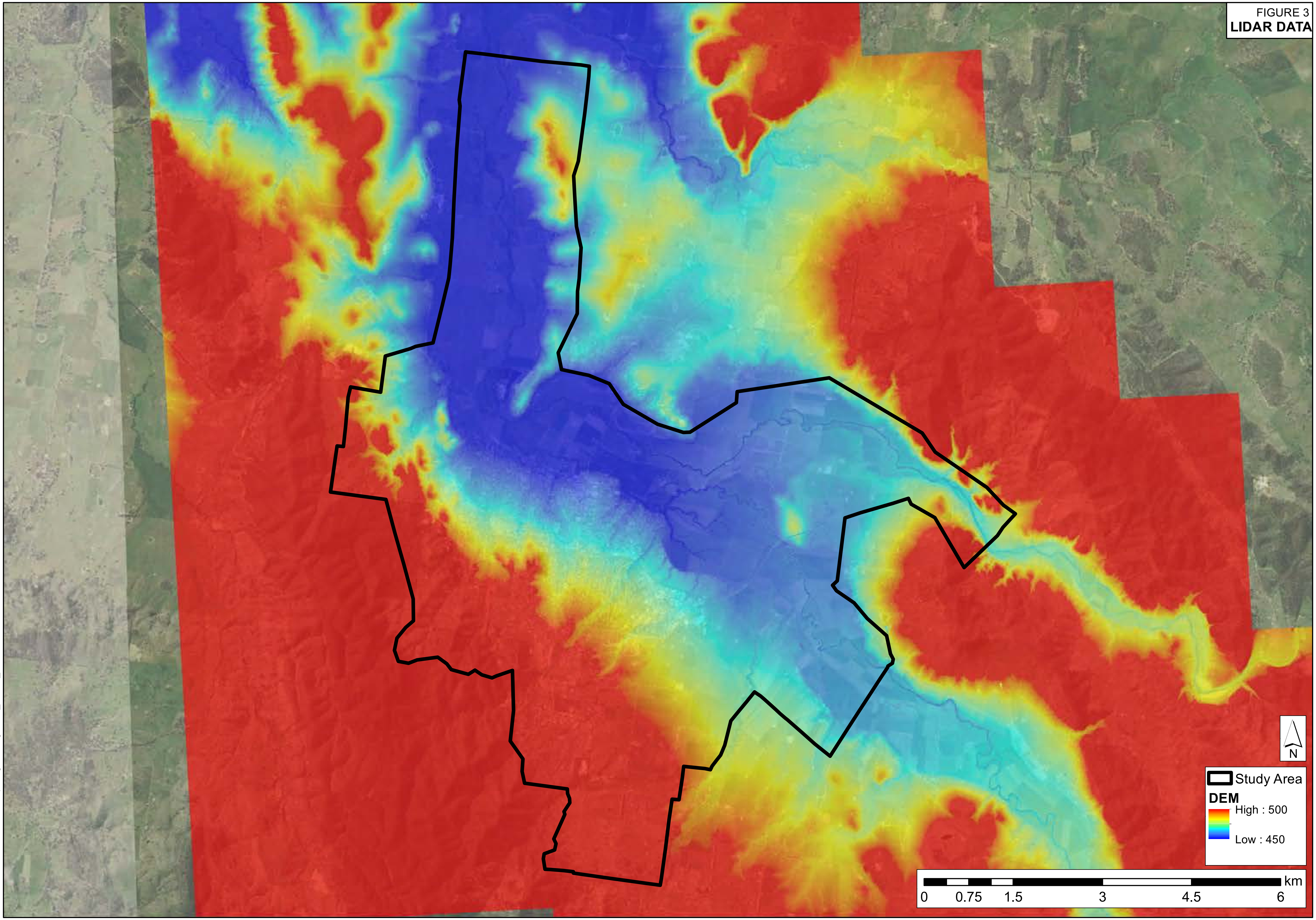
J:\Jobs\118033\Arcview\ArcMaps\Figures\Figure01_Locality_Map.mxd

FIGURE 2
STUDY AREA



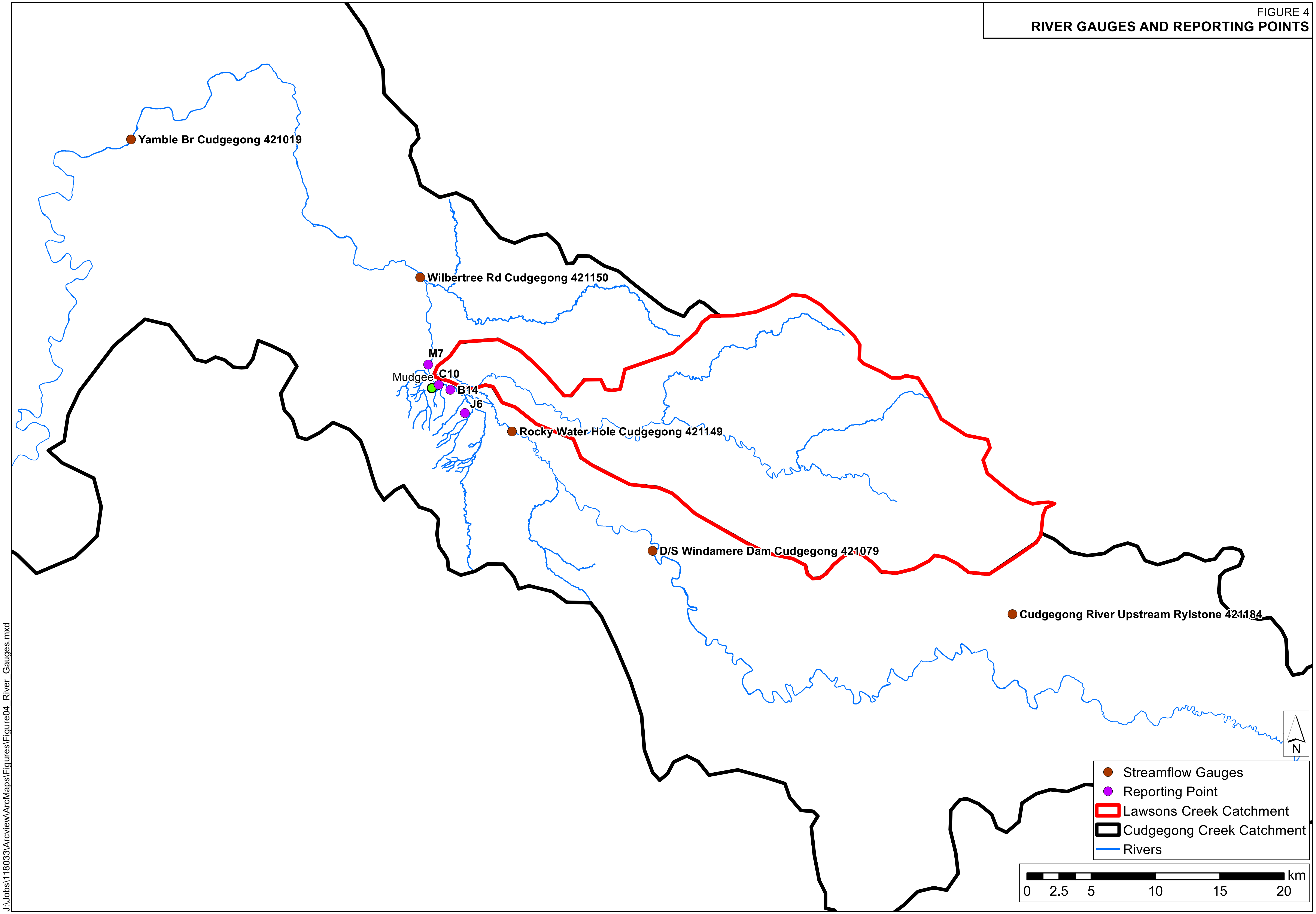
J:\Jobs\118033\Arcview\ArcMaps\Figures\Figure02_Study_Area.mxd

FIGURE 3
LIDAR DATA



J:\Jobs\118033\Arcview\ArcMaps\Figures\Figure03_LiDAR_Data.mxd

FIGURE 4
RIVER GAUGES AND REPORTING POINTS



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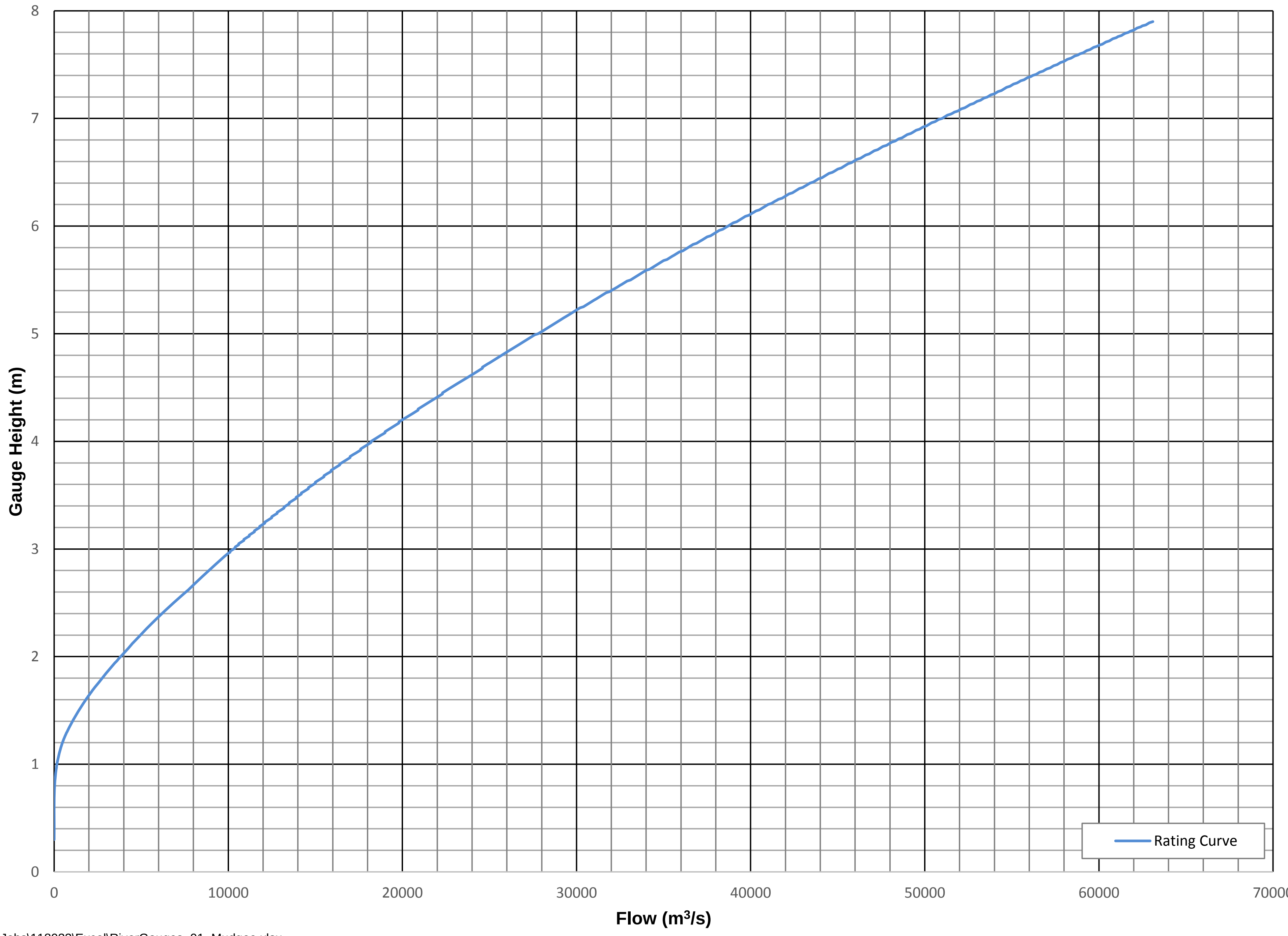


FIGURE 5

CUDGEGONG RIVER AT YAMBLE BRIDGE - 421019

RATING CURVE

J:\Jobs\118033\Excel\RiverGauges_01_Mudgee.xlsx

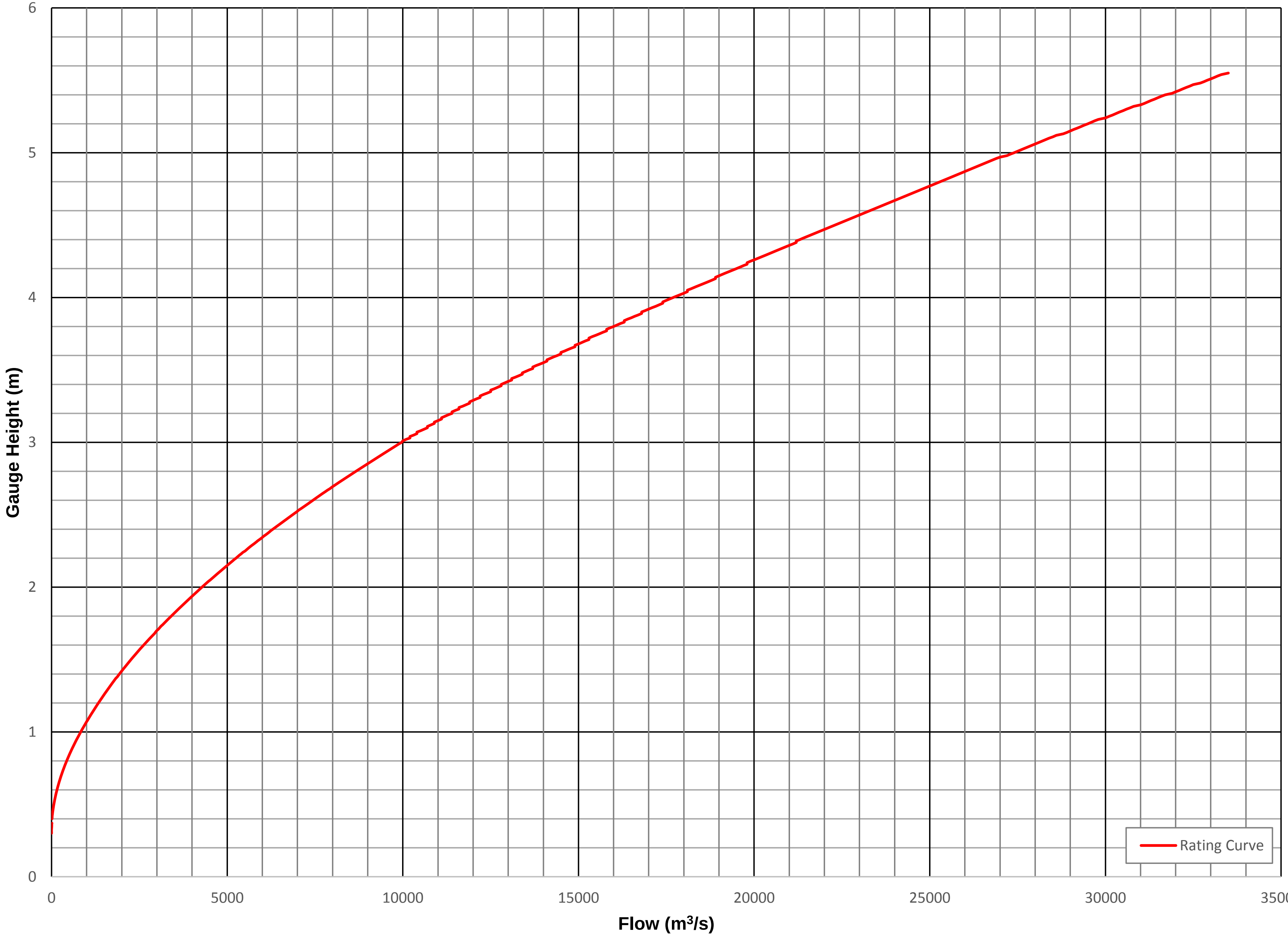


FIGURE 6
CUDGEGONG RIVER AT D/S WINDAMERE DAM - 421079
RATING CURVE

J:\Jobs\118033\Excel\RiverGauges_01_Mudgee.xlsx

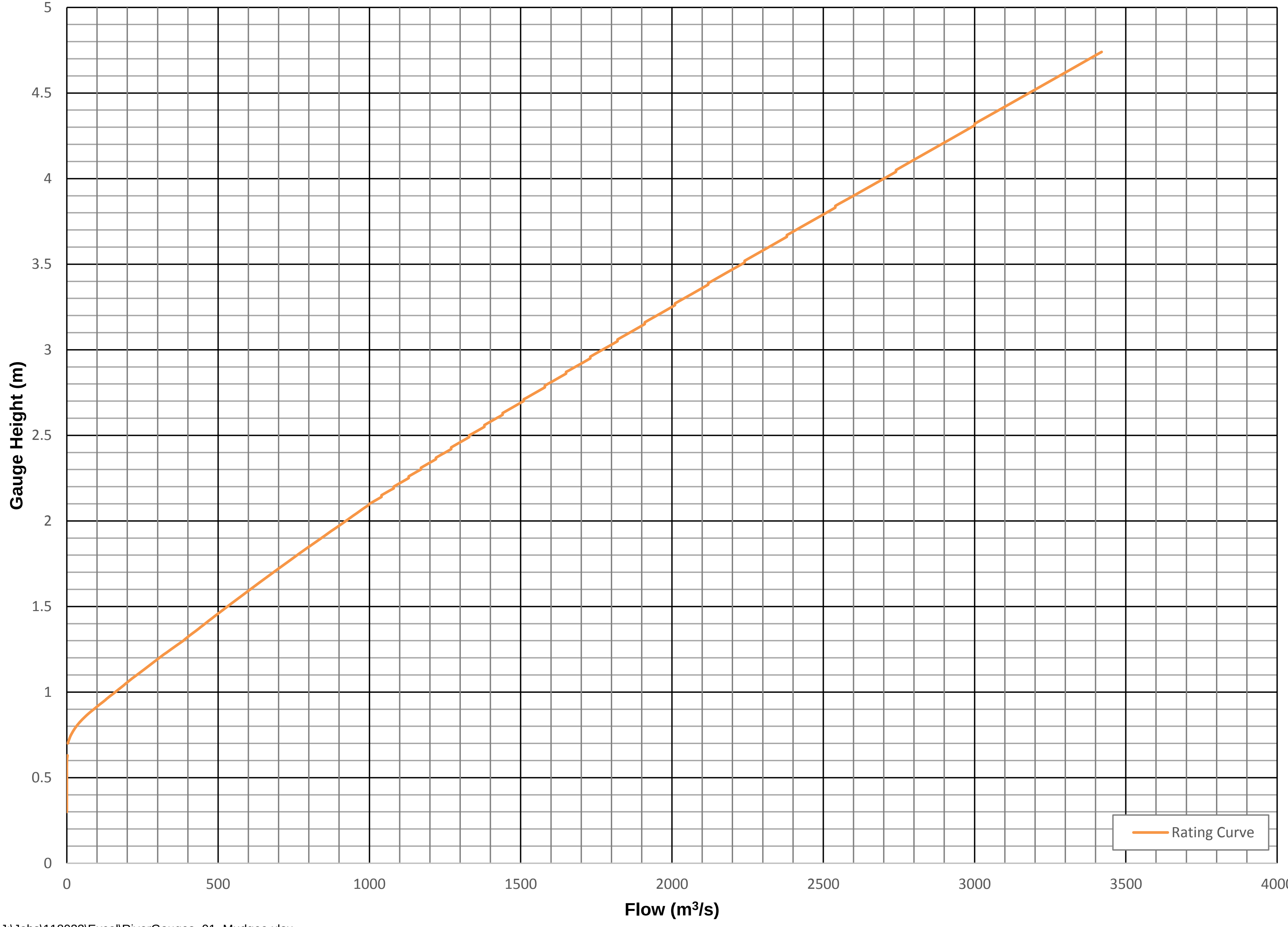


FIGURE 7

CUDGEGONG RIVER AT ROCKY WATER HOLE - 421149

RATING CURVE AND GAUGINGS

J:\Jobs\118033\Excel\RiverGauges_01_Mudgee.xlsx

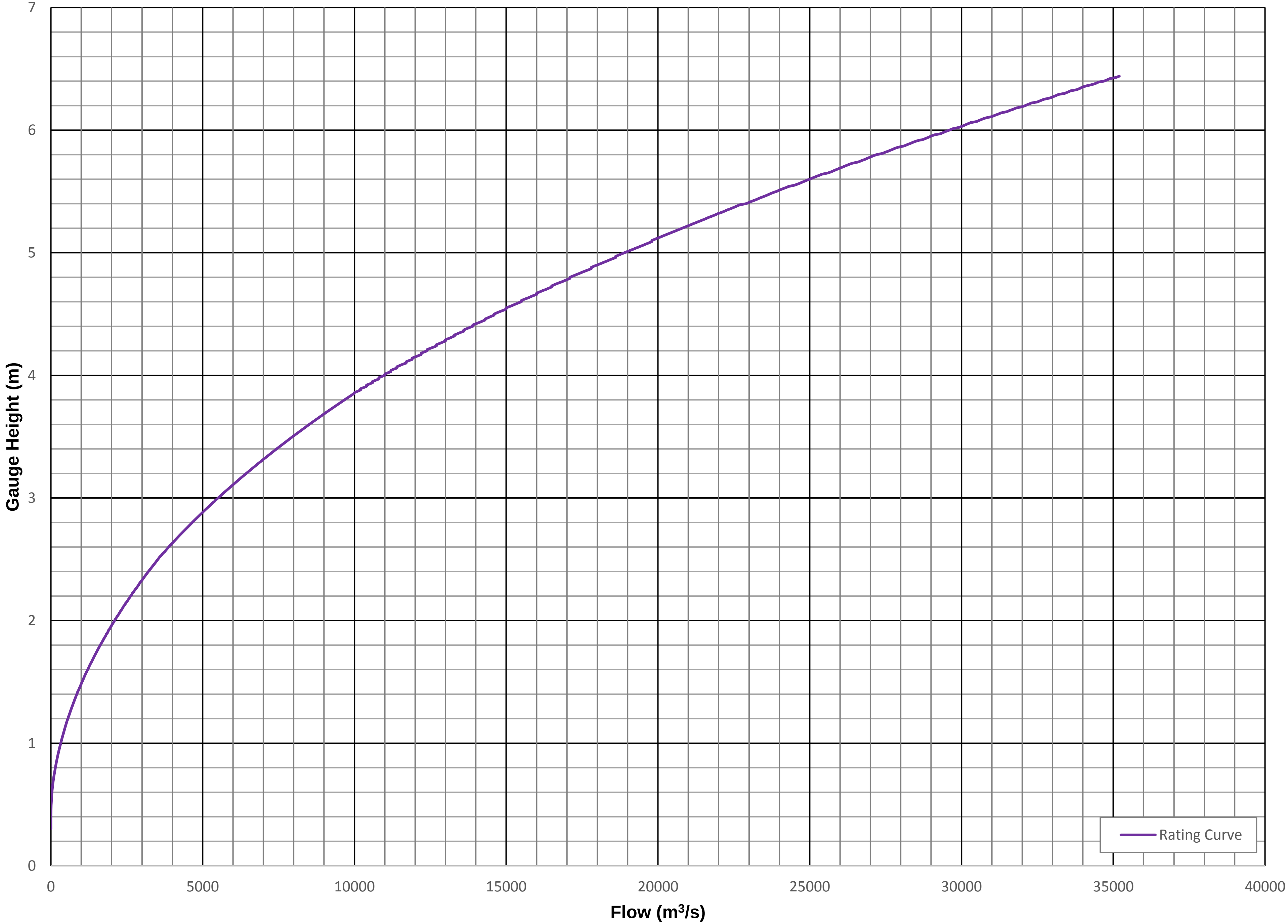


FIGURE 8

CUDGEGONG RIVER AT WILBERTREE ROAD - 421150

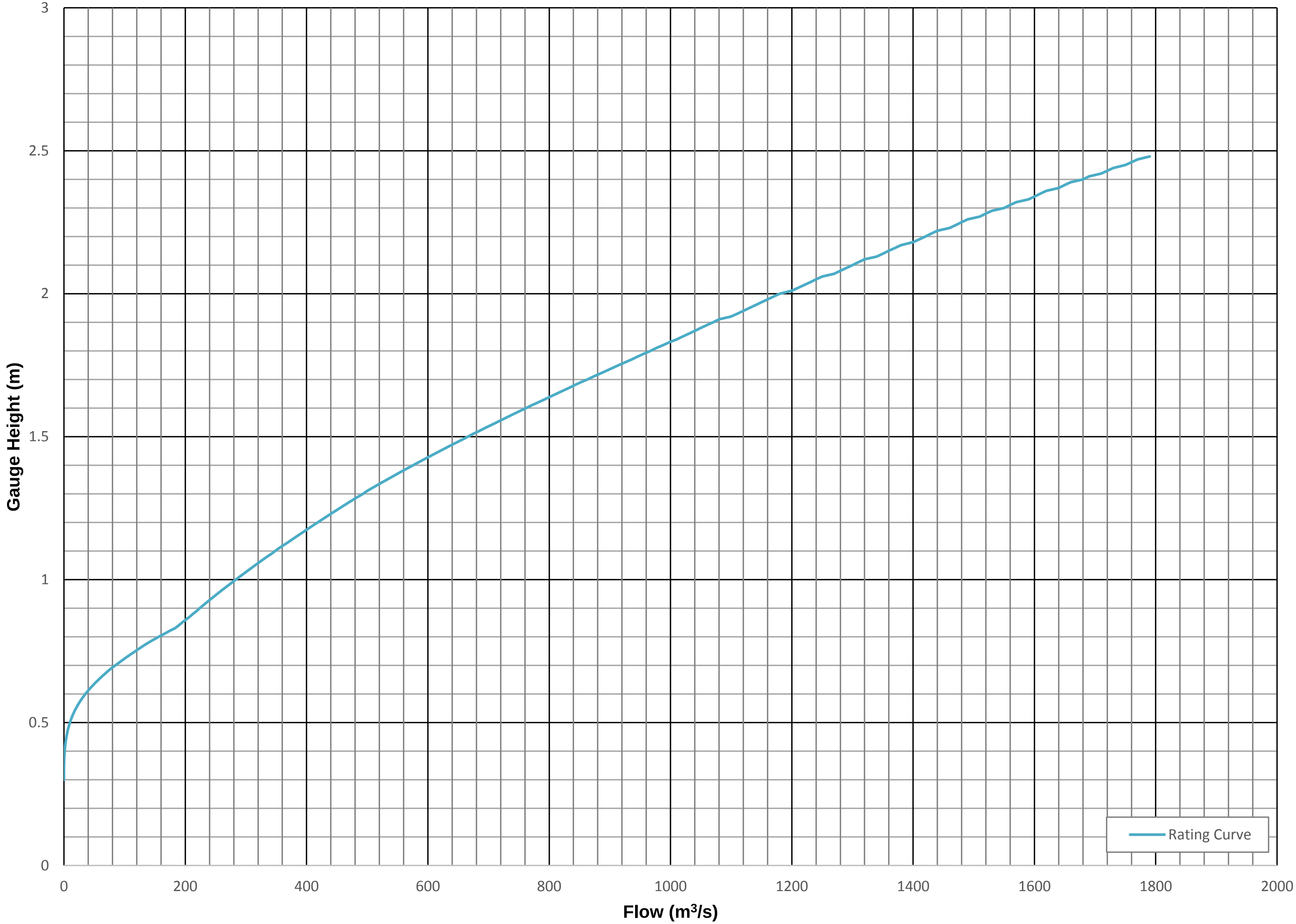
RATING CURVE

J:\Jobs\118033\Excel\RiverGauges_01_Mudgee.xlsx

FIGURE 9

CUDGEGONG RIVER AT UPSTREAM RYLSTONE - 421184

RATING CURVE



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J:\Jobs\118033\Excel\RiverGauges_01_Mudgee.xlsx

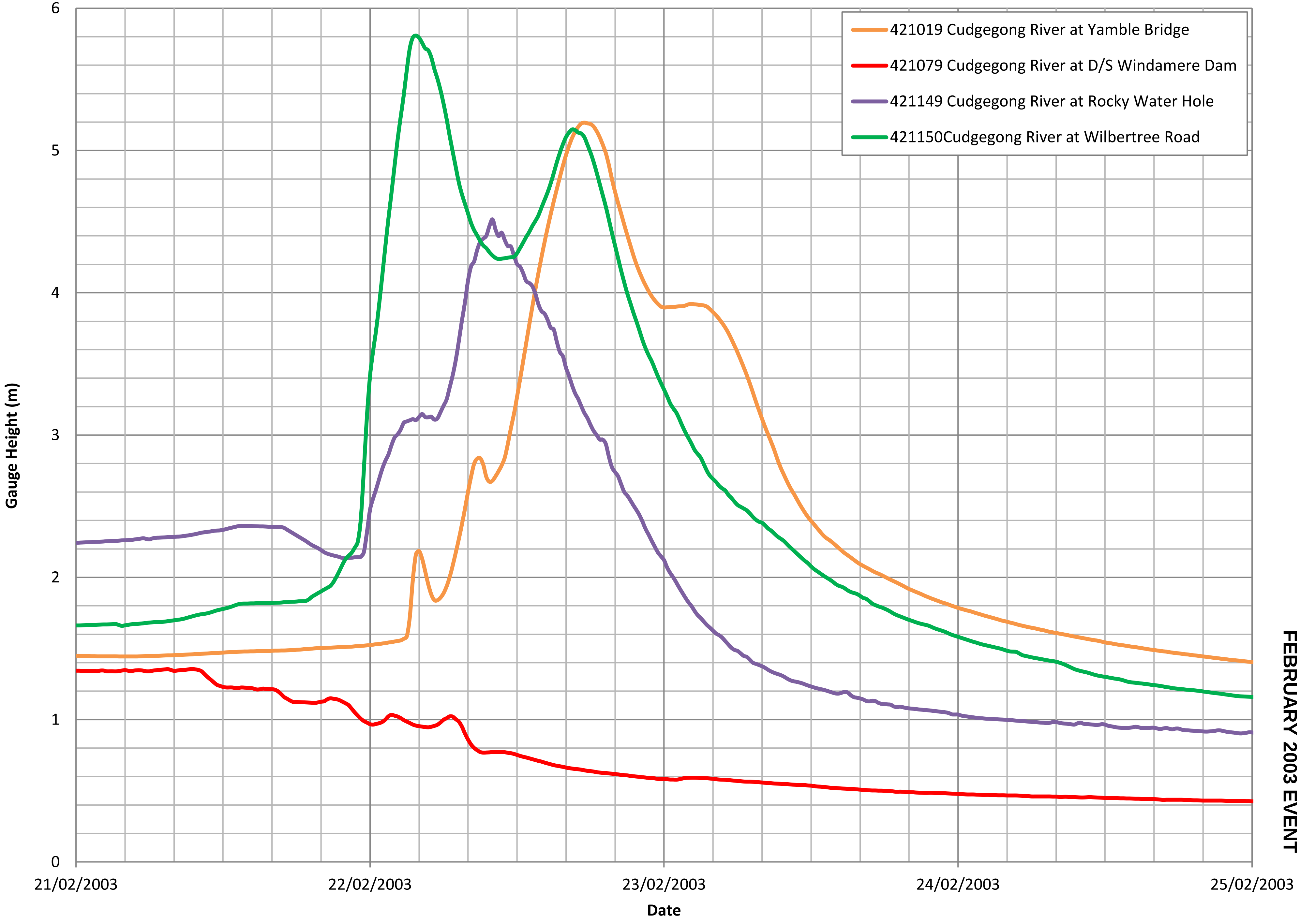


FIGURE 10
WATER LEVEL DATA
FEBRUARY 2003 EVENT

J:\Jobs\118033\Excel\RiverGauges_01_Mudgee.xlsx

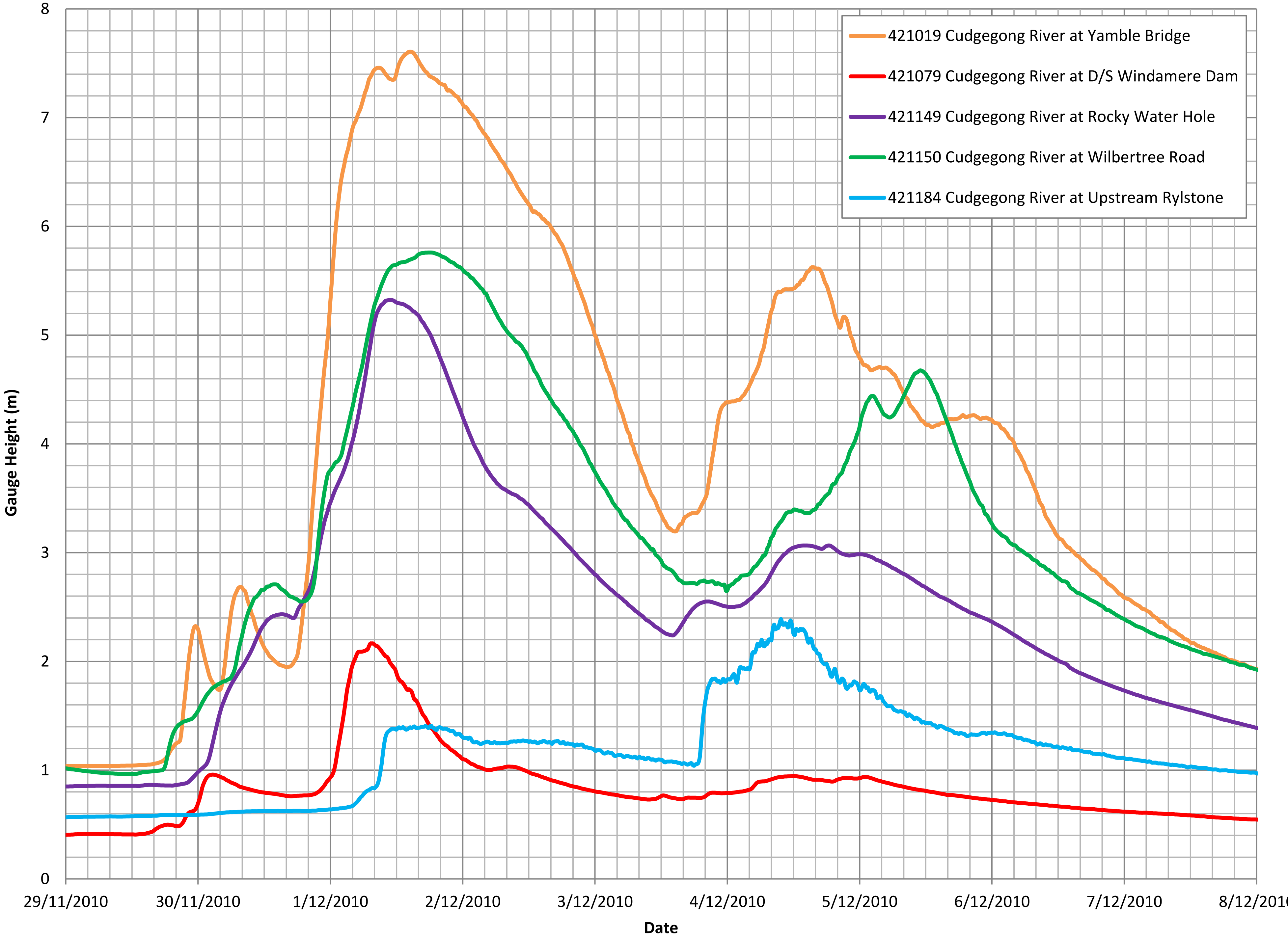
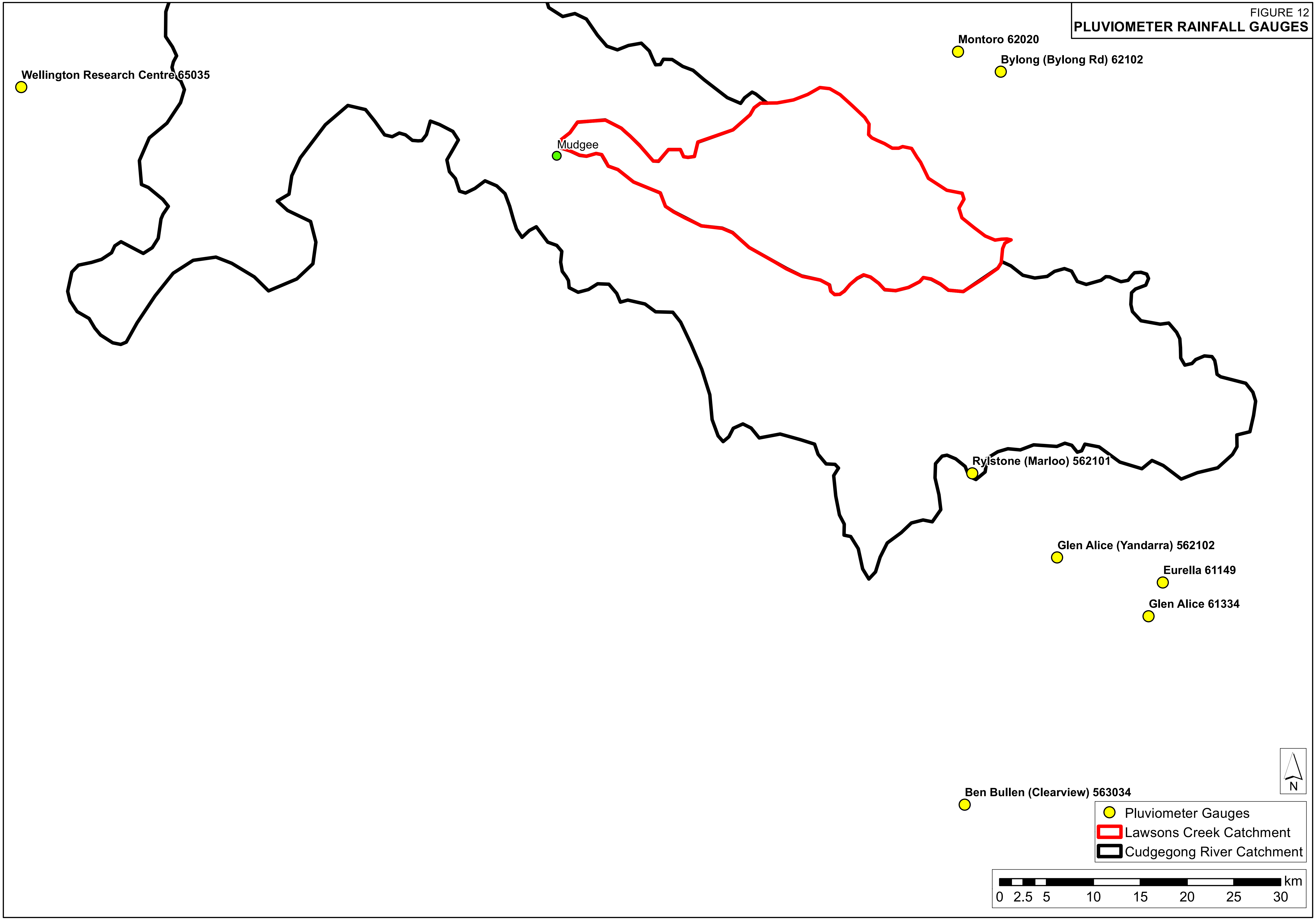


FIGURE 11
WATER LEVEL DATA
NOVEMBER / DECEMBER 2010 EVENT

FIGURE 12
PLUVIOMETER RAINFALL GAUGES



J:\Jobs\118033\Arcview\ArcMaps\Figures\Figure12_Pluviometer Rainfall Gauges.mxd

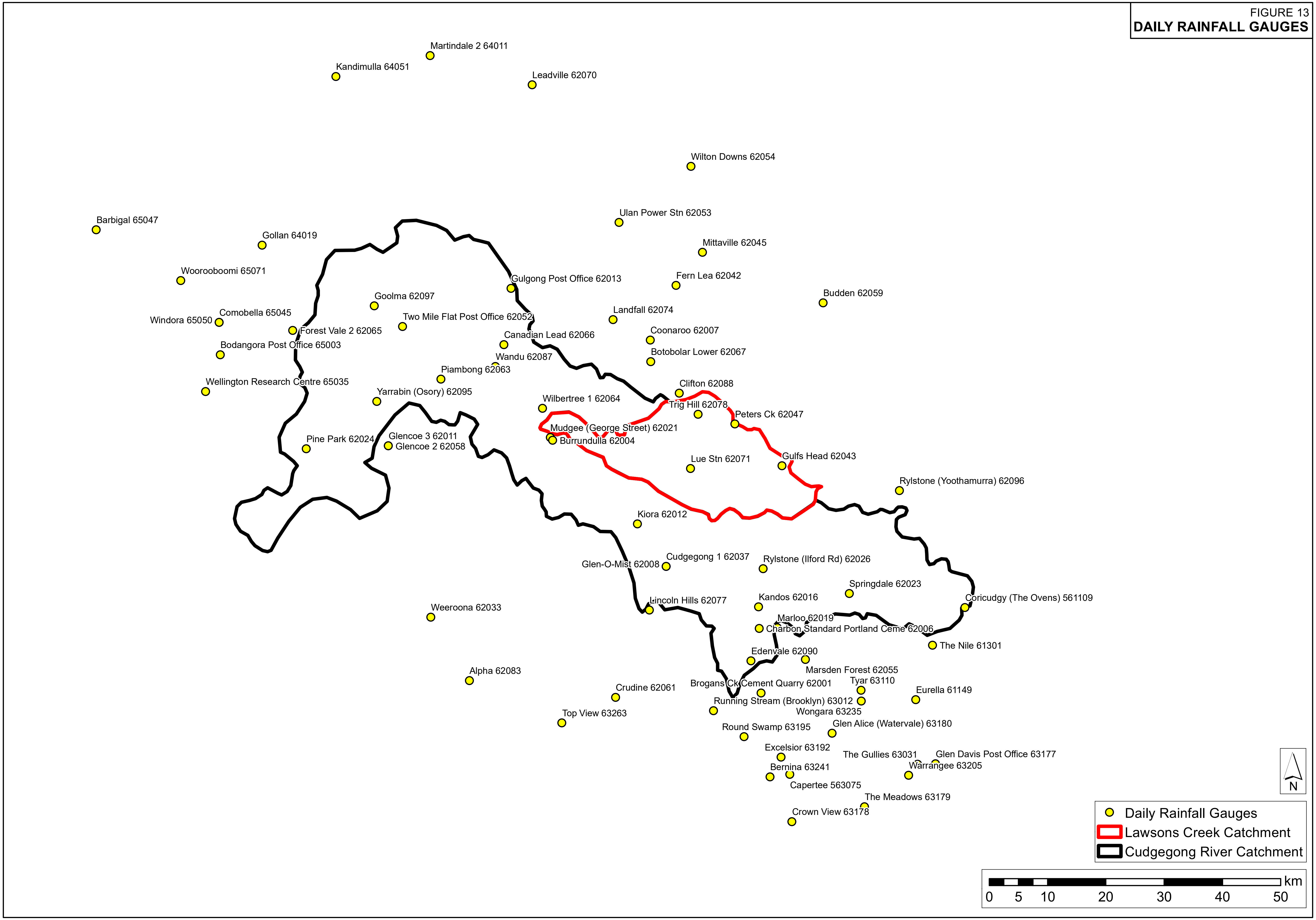
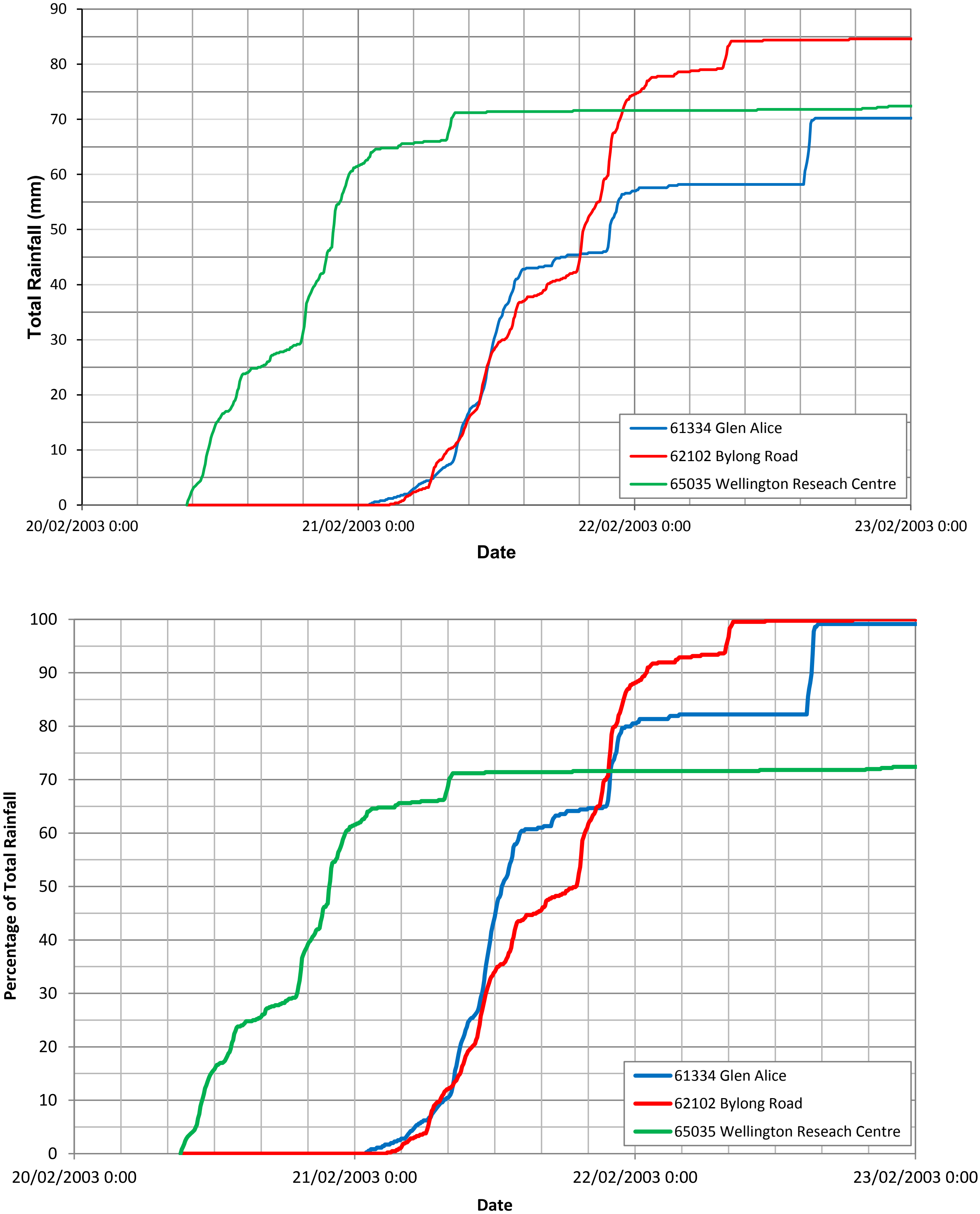


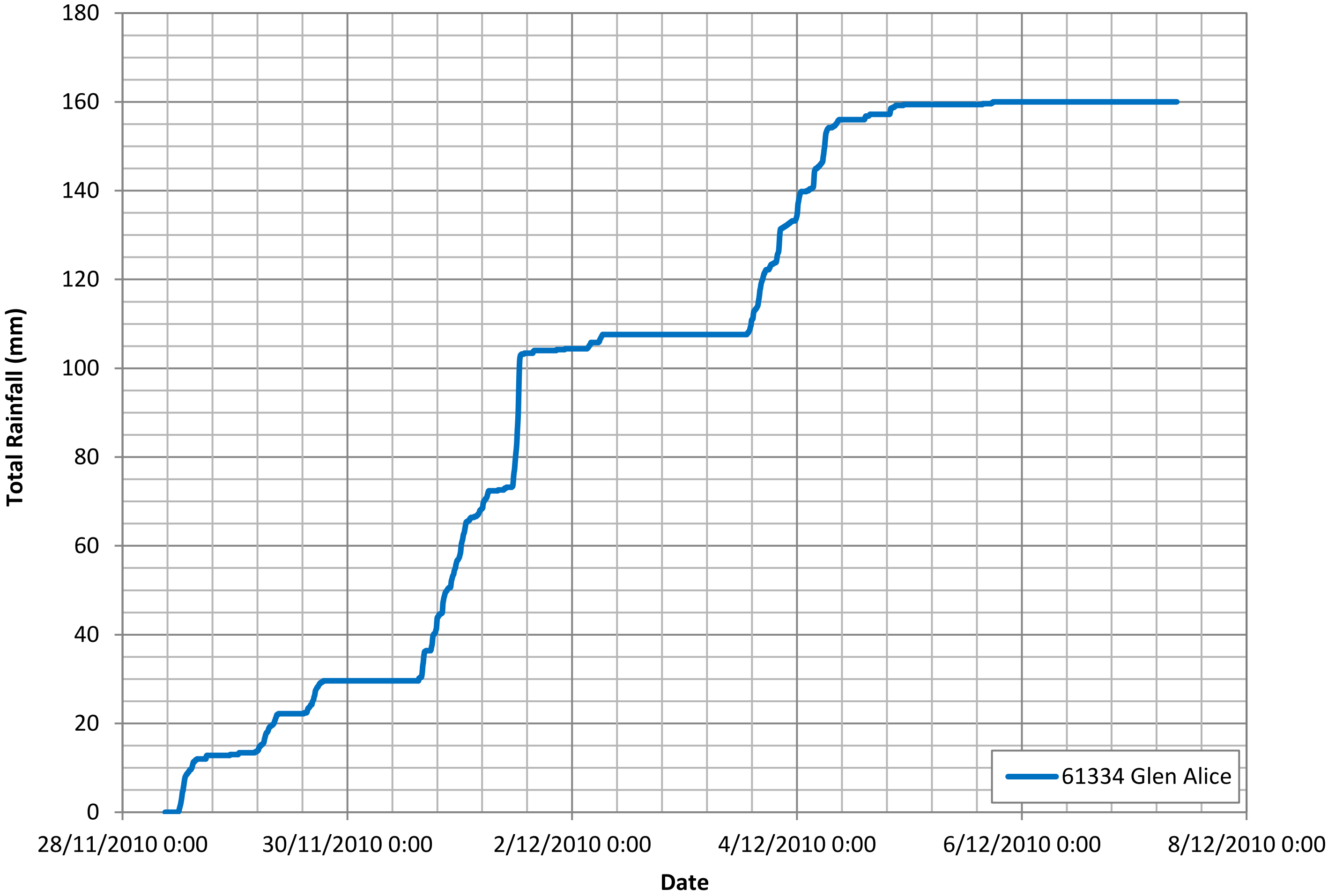
FIGURE 13
DAILY RAINFALL GAUGES
Martindale 2 64011
Kandimulla 64051
Leadville 62070
Wilton Downs 62054
Barbigal 65047
Ulan Power Stn 62053
Gollan 64019
Mittaville 62045
Wooroboomi 65071
Gulgong Post Office 62013
Fern Lea 62042
Budden 62059
Goolma 62097
Landfall 62074
Windora 65050
Comobella 65045
Two Mile Flat Post Office 62052
Forest Vale 2 62065
Coonaroo 62007
Canadian Lead 62066
Bodangora Post Office 65003
Botobolar Lower 62067
Wandu 62087
Piambong 62063
Wellington Research Centre 65035
Clifton 62088
Yarrabin (Osory) 62095
Wilbertree 1 62064
Trig Hill 62078
Peters Ck 62047
Mudgee (George Street) 62021
Burrundulla 62004
Pine Park 62024
Glencoe 3 62011
Glencoe 2 62058
Lue Stn 62071
Gulfs Head 62043
Rylstone (Yoothamurra) 62096
Kiora 62012
Cudgegong 1 62037
Rylstone (Ilford Rd) 62026
Glen-O-Mist 62008
Springdale 62023
Kandos 62016
Lincoln Hills 62077
Coricudgy (The Ovens) 561109
Weeroona 62033
Marloo 62019
Charbon Standard Portland Ceme 62006
The Nile 61301
Edenvale 62090
Alpha 62083
Marsden Forest 62055
Crudine 62061
Brogans Ck Cement Quarry 62001
Tyar 63110
Eurella 61149
Running Stream (Brooklyn) 63012
Wongara 63235
Top View 63263
Glen Alice (Watervale) 63180
Round Swamp 63195
Excelsior 63192
The Gullies 63031
Glen Davis Post Office 63177
Warrangee 63205
Bernina 63241
Capertee 563075
The Meadows 63179
Crown View 63178
N
Daily Rainfall Gauges
Lawsons Creek Catchment
Cudgegong River Catchment
km
0 5 10 20 30 40 50
J:\Jobs\118033\Arcview\ArcMaps\Figures\Figure13_Daily_Rainfall_Gauges.mxd

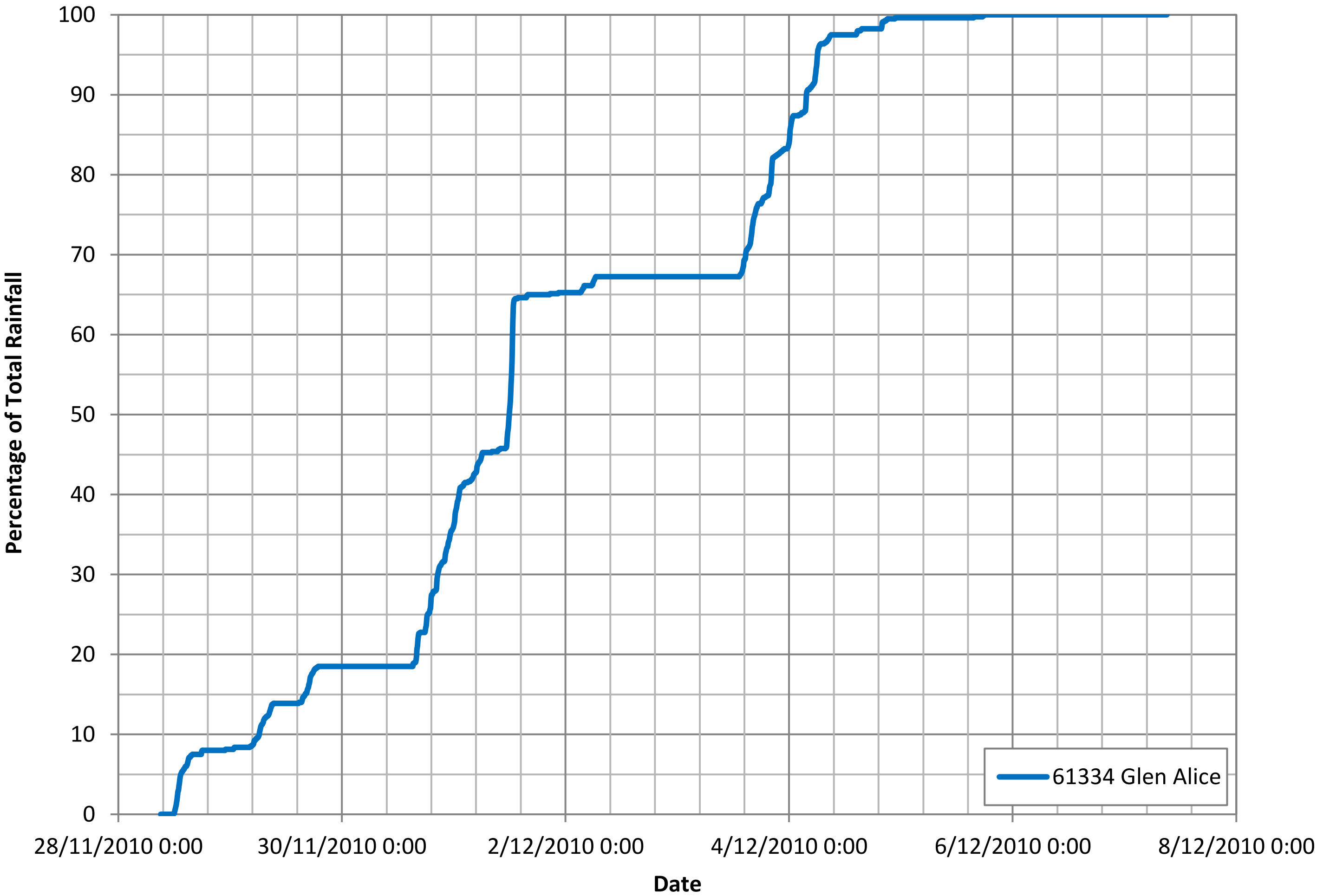
FIGURE 14
RAINFALL DATA
FEBRUARY 2003 EVENT



J:\Jobs\118033\Excel\PluviGauges_Mudgee.xlsx

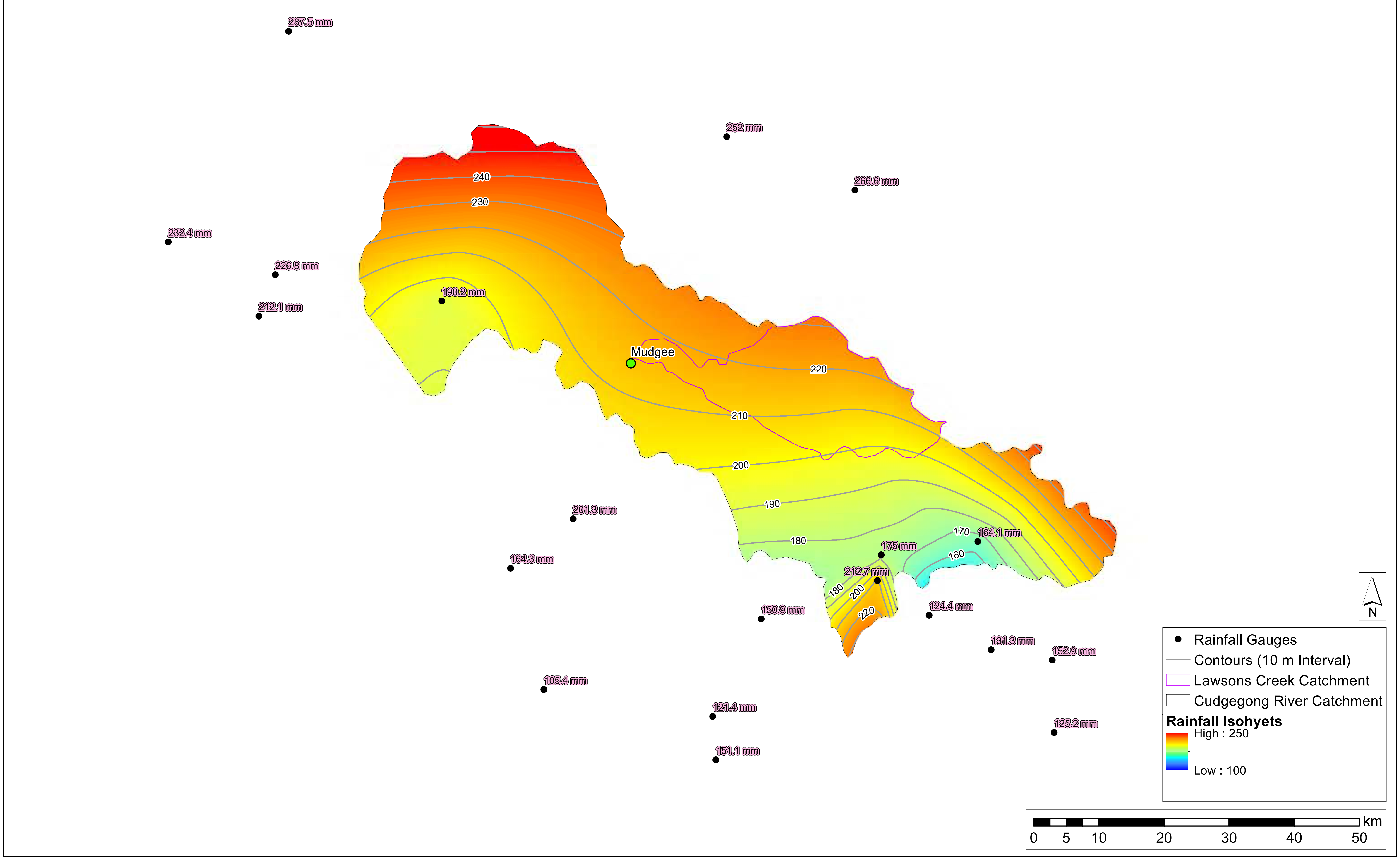
FIGURE 15
RAINFALL DATA
DECEMBER 2010 EVENT



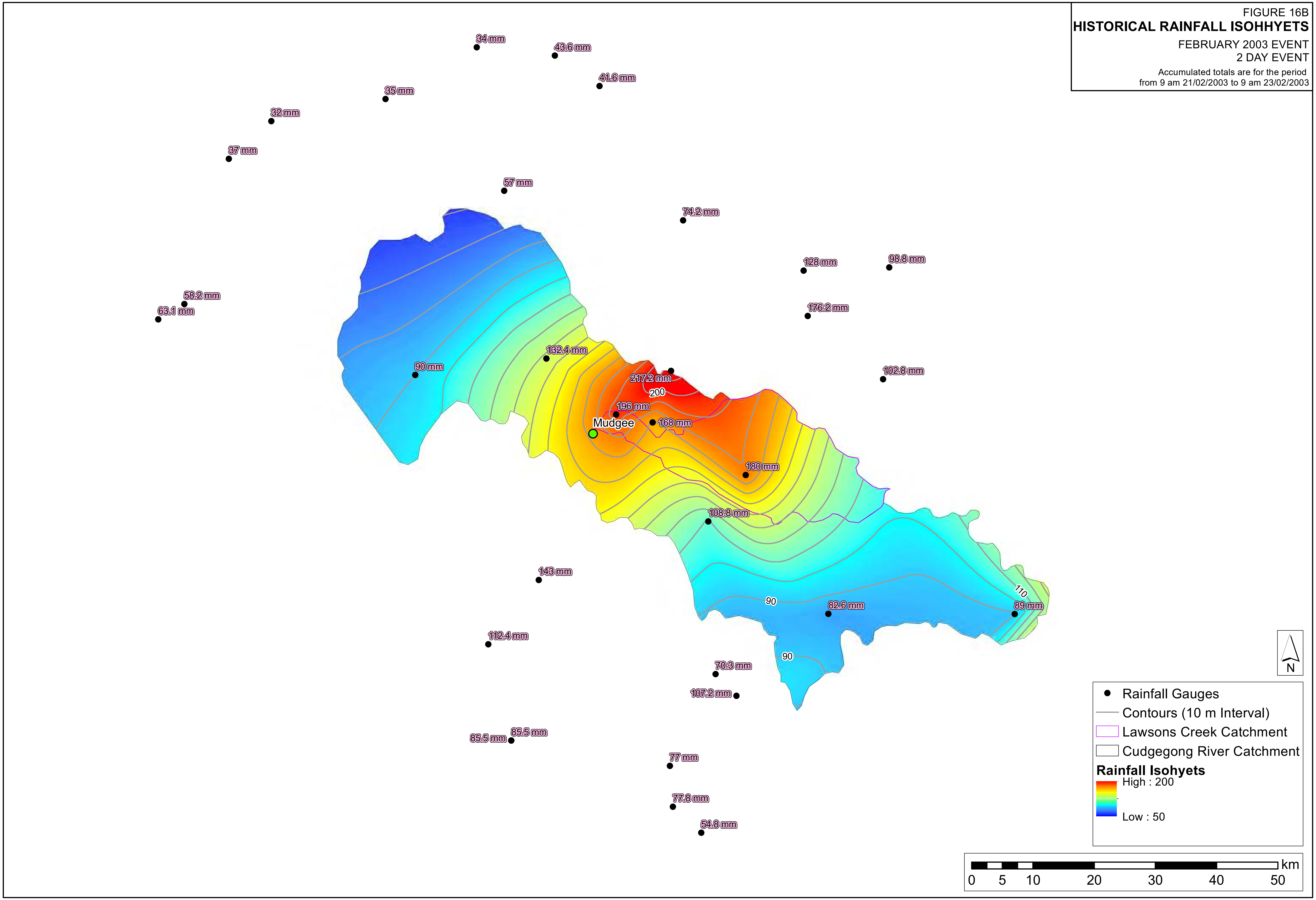


J:\Jobs\118033\Excel\PluviGauges_Mudgee.xlsx

FIGURE 16A
HISTORICAL RAINFALL ISOHHYETS
FEBRUARY 1955 EVENT
2 DAY EVENT
Accumulated totals are for the period from 9 am 24/02/1955 to 9 am 26/02/1955



J:\Jobs\118033\Arcview\ArcMaps\Figures\Figure16A_Historical_Rainfall_Isohyets_Feb_1955.mxd



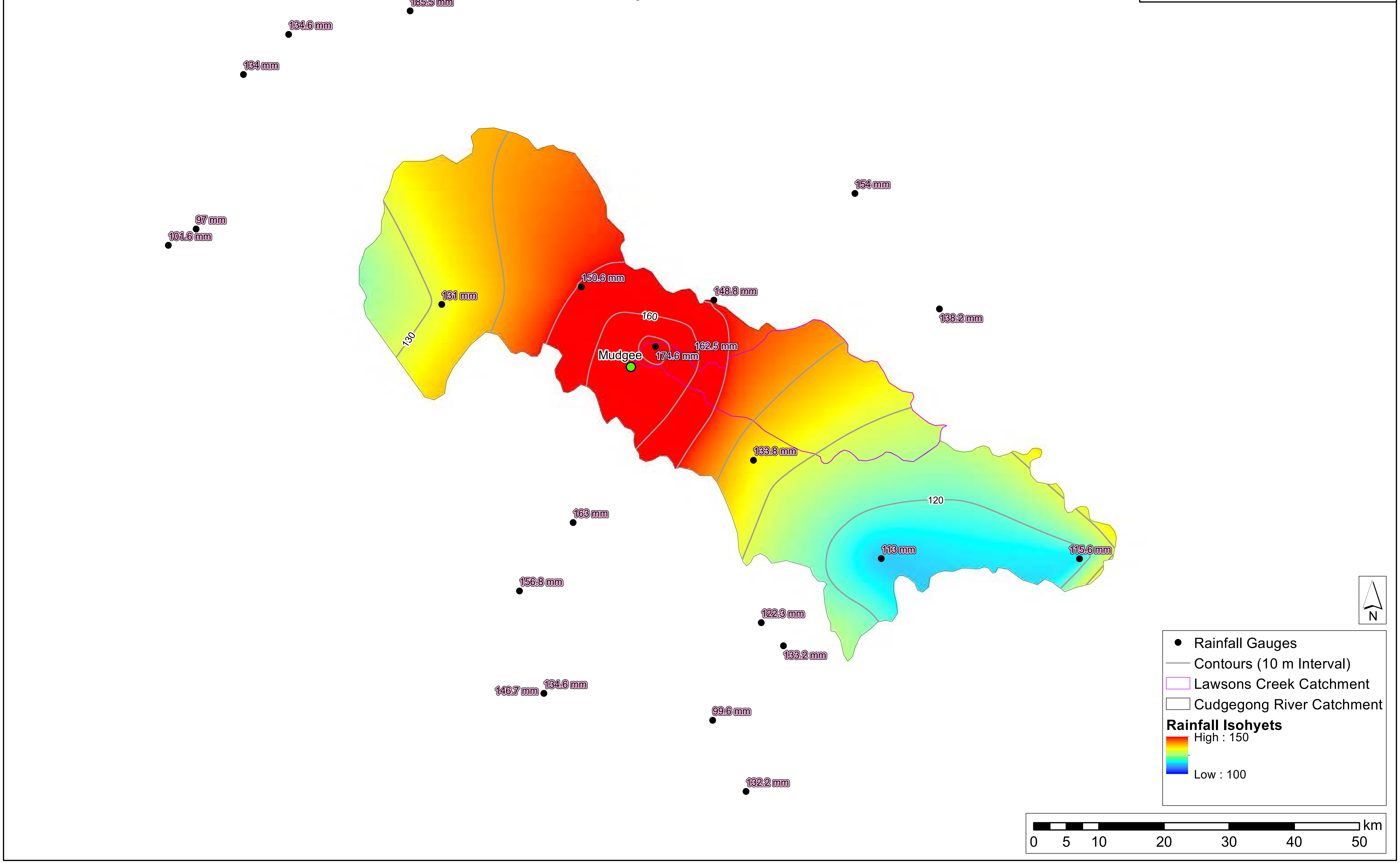
J:\Jobs\118033\Arcview\ArcMaps\Figures\Figure16B_Historical_Rainfall_Isohyets_Feb_2003.mxd

FIGURE 16C

HISTORICAL RAINFALL ISOHHYETS

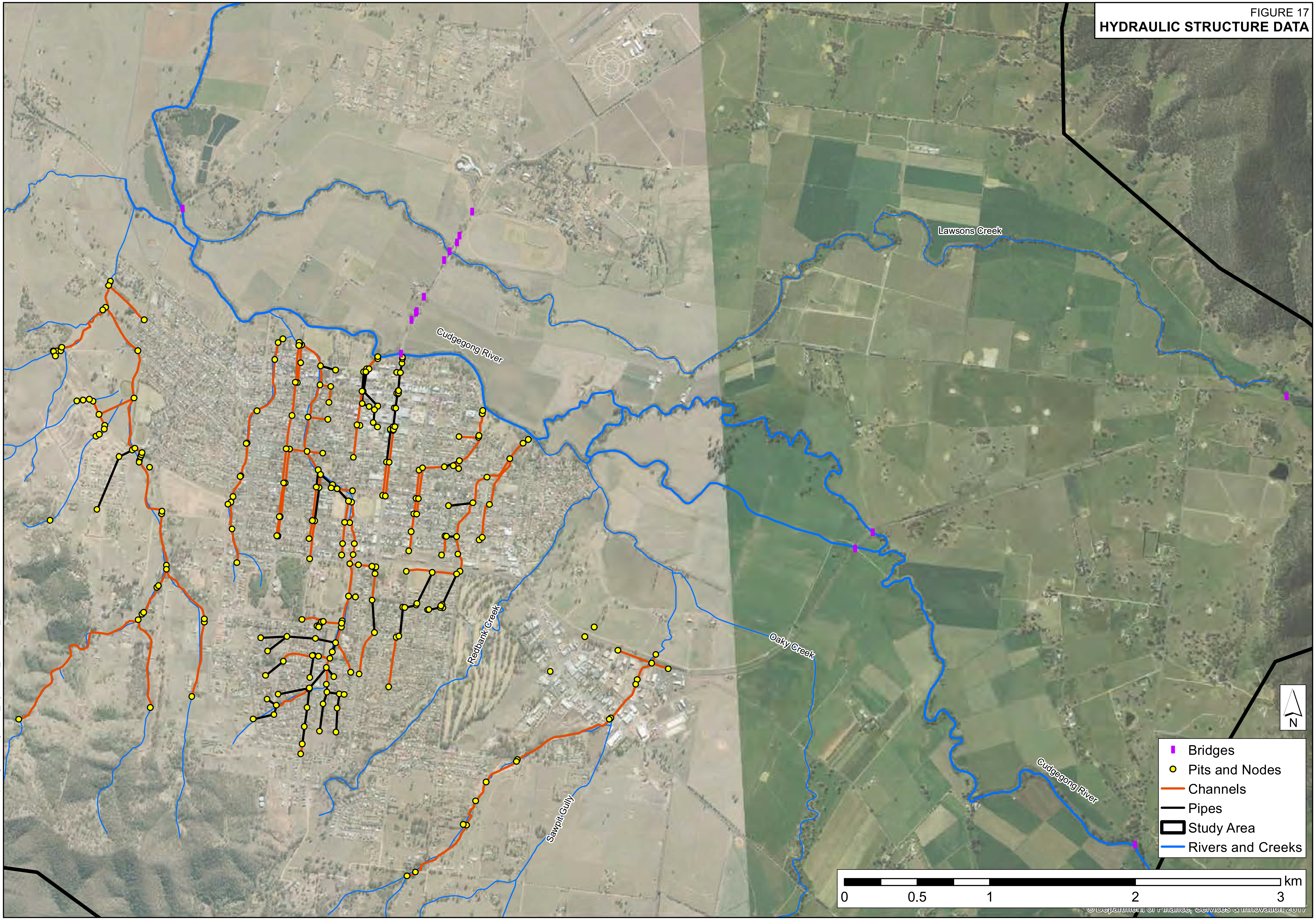
DECEMBER 2011 EVENT
3 DAY EVENT

Accumulated totals are for the period from 9 am 29/11/2011 to 9 am 02/12/2011



J:\Jobs\118033\Arcview\ArcMaps\Figures\Figure16C_Historical_Rainfall_Isohyets_Dec_2010.mxd

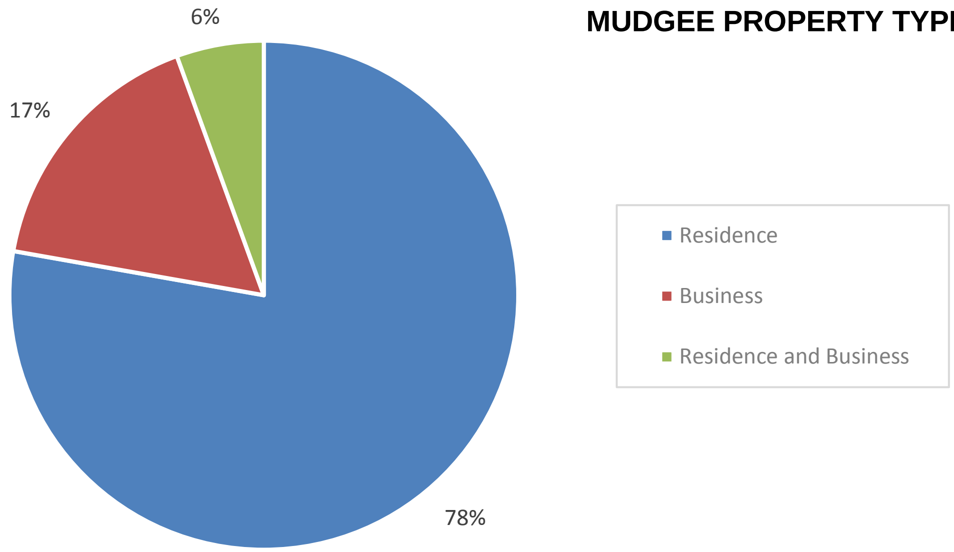
FIGURE 17
HYDRAULIC STRUCTURE DATA



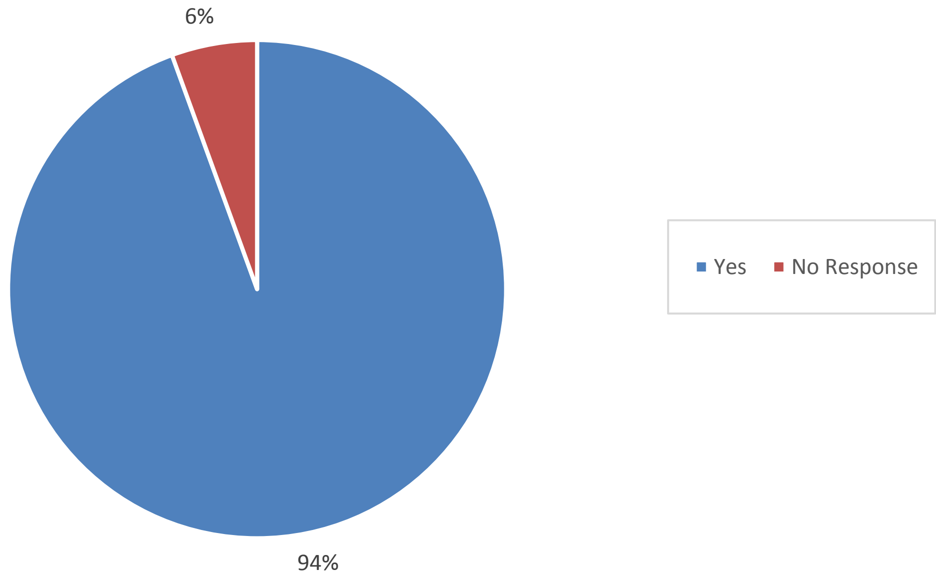
J:\Jobs\118033\Arcview\ArcMaps\Figures\Figure17_Hydraulic_Structure_Data.mxd

FIGURE 18A

MUDGEE PROPERTY TYPE



COMMUNITY AWARENESS OF FLOOD PRONE AREA



PERIOD OF TIME COMMUNITY HAS LIVED IN MUDGEE

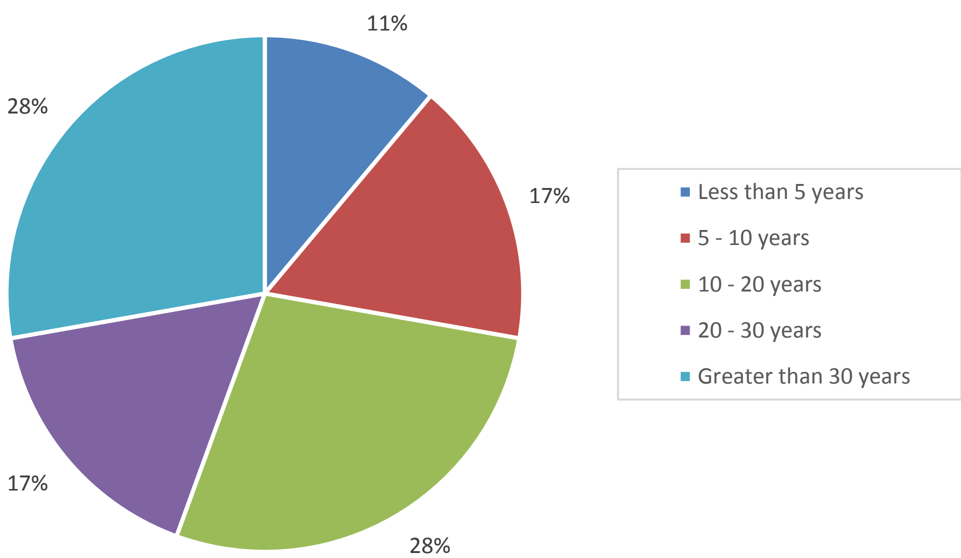
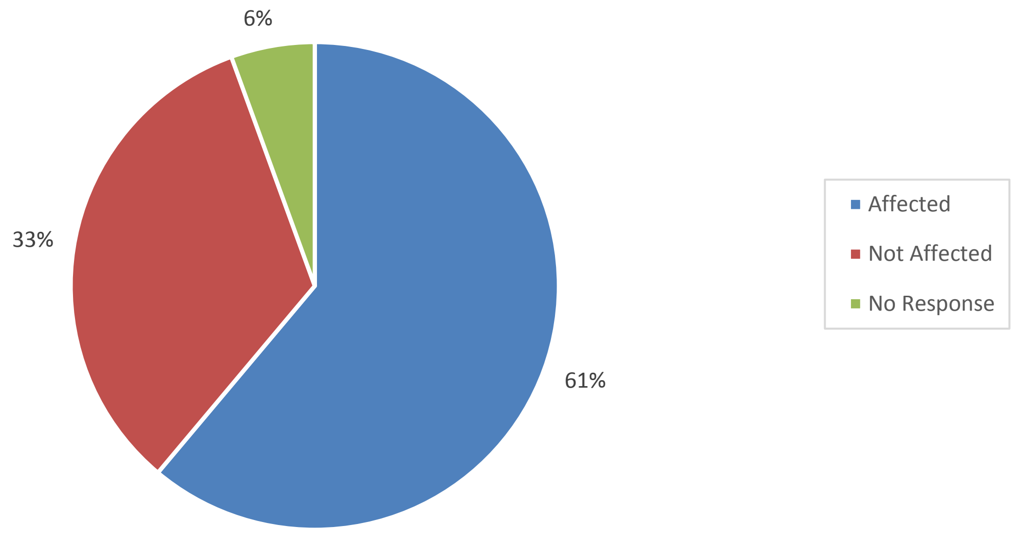
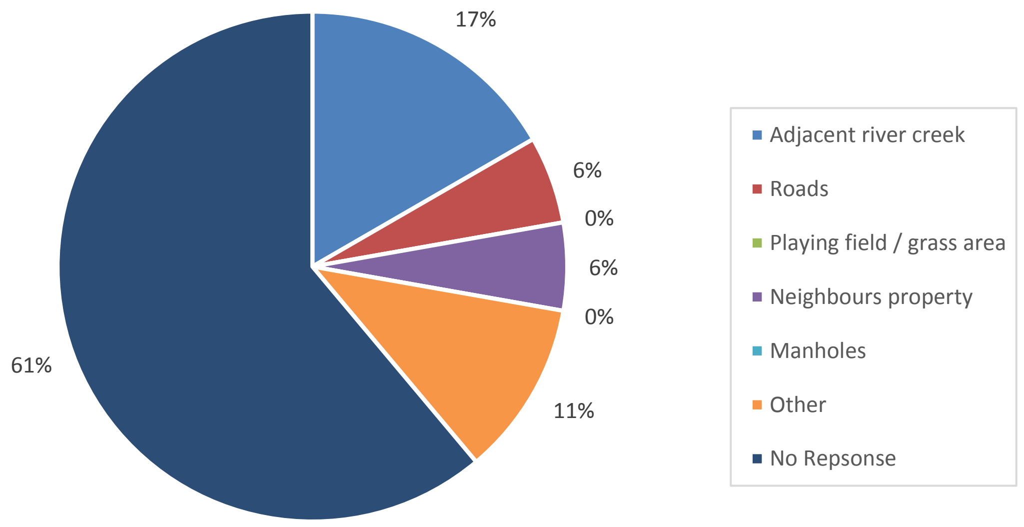


FIGURE 18B

PROPERTIES AFFECTED BY FLOODING FROM LOCAL RIVERS AND CREEKS



PERCIEVED SOURCE OF FLOODING



CONSEQUENCES OF FLOODING

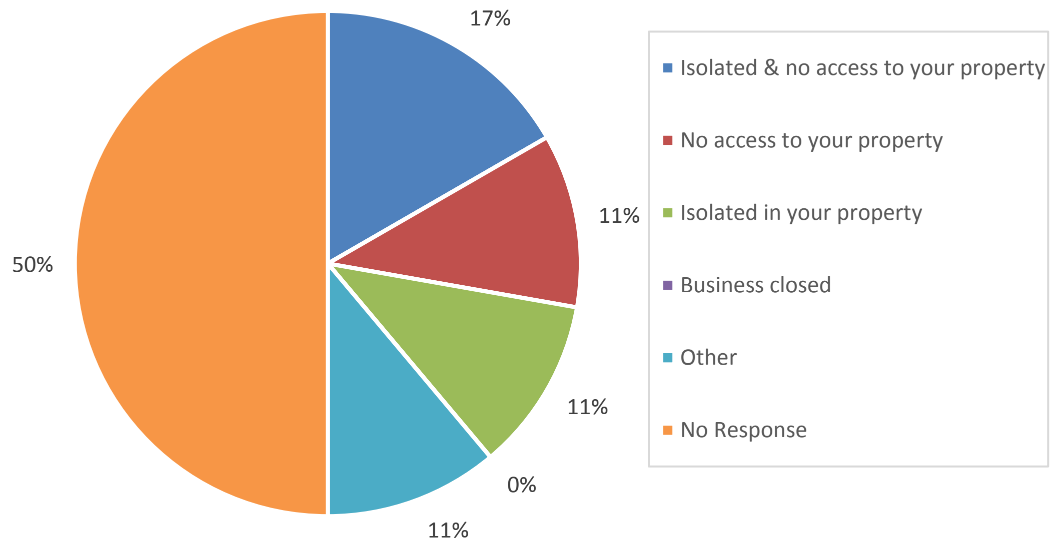
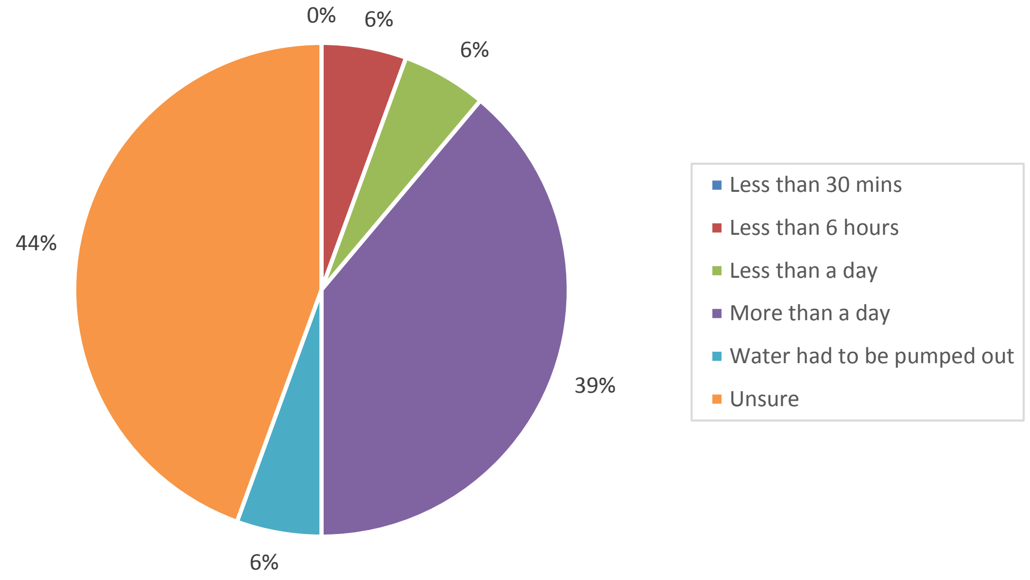
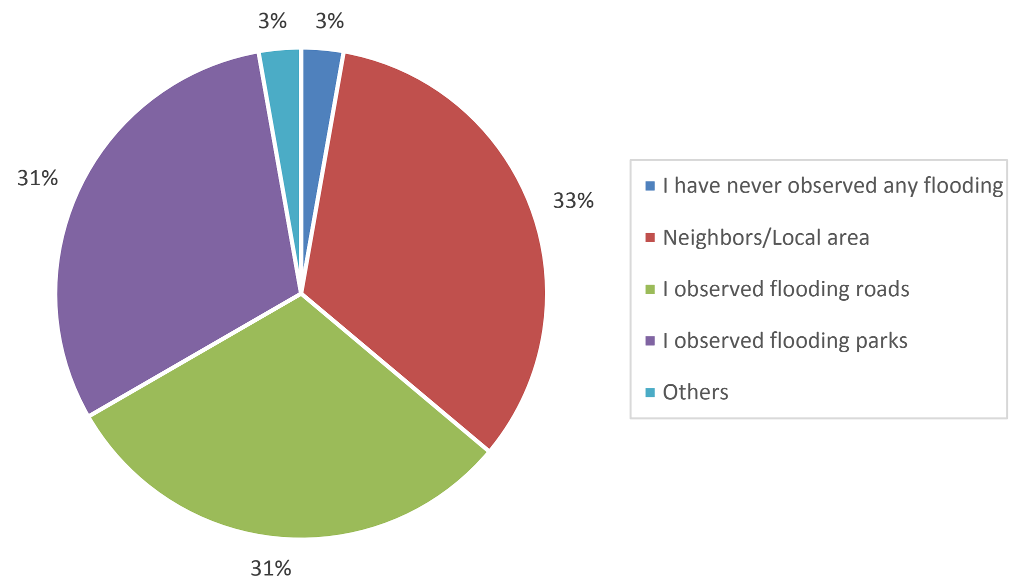


FIGURE 18C

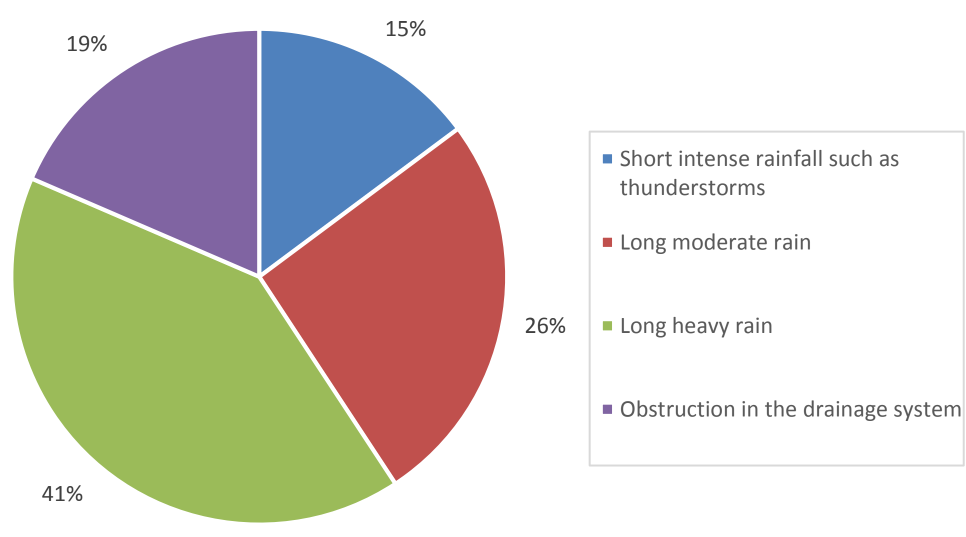
TIME FOR FLOOD WATER TO DRAIN AWAY AFTER FLOODING



NEIGHBORING PROPERTIES FLOODING EXTENT



CAUSES OF FLOODING



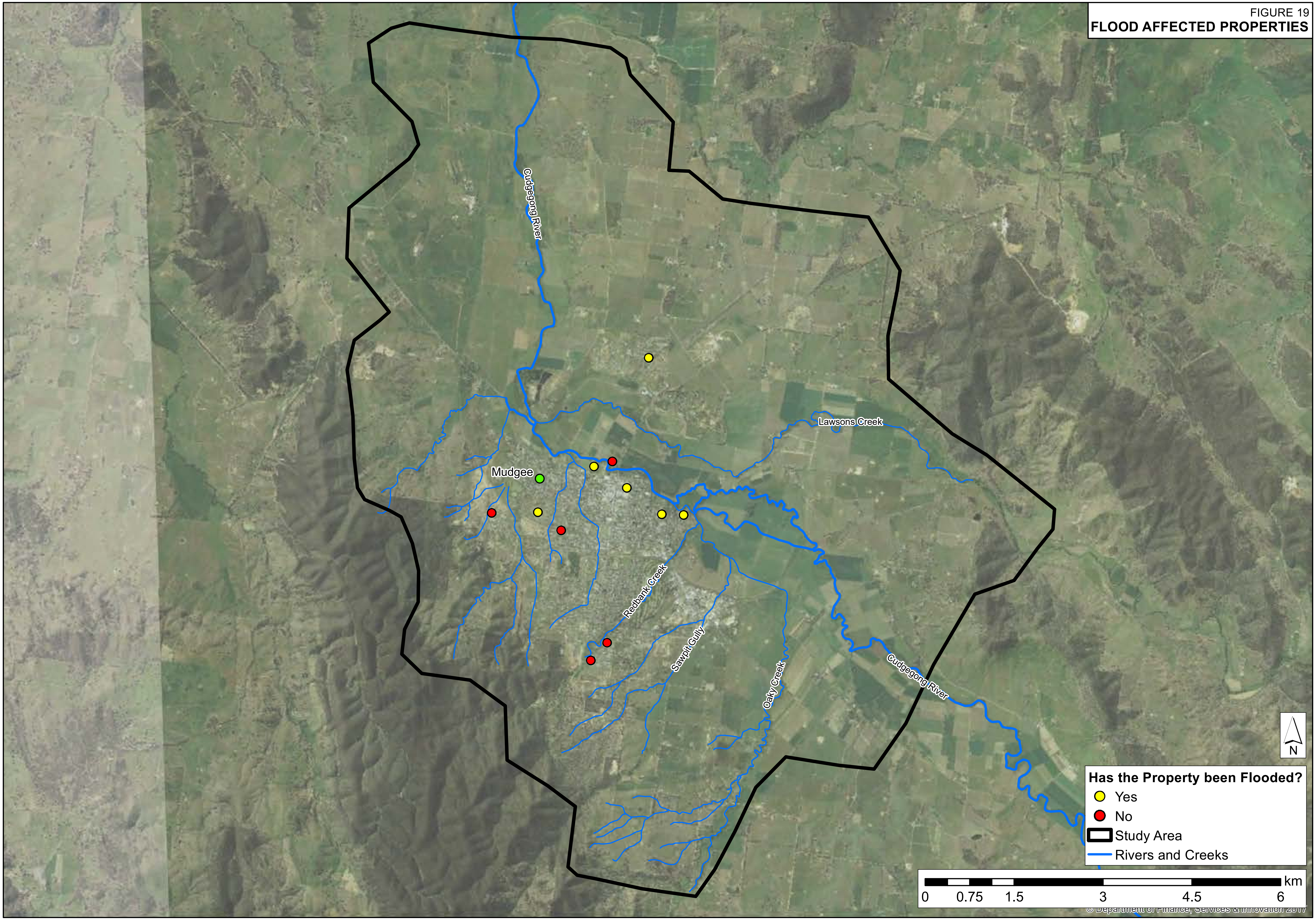


FIGURE 19
FLOOD AFFECTED PROPERTIES

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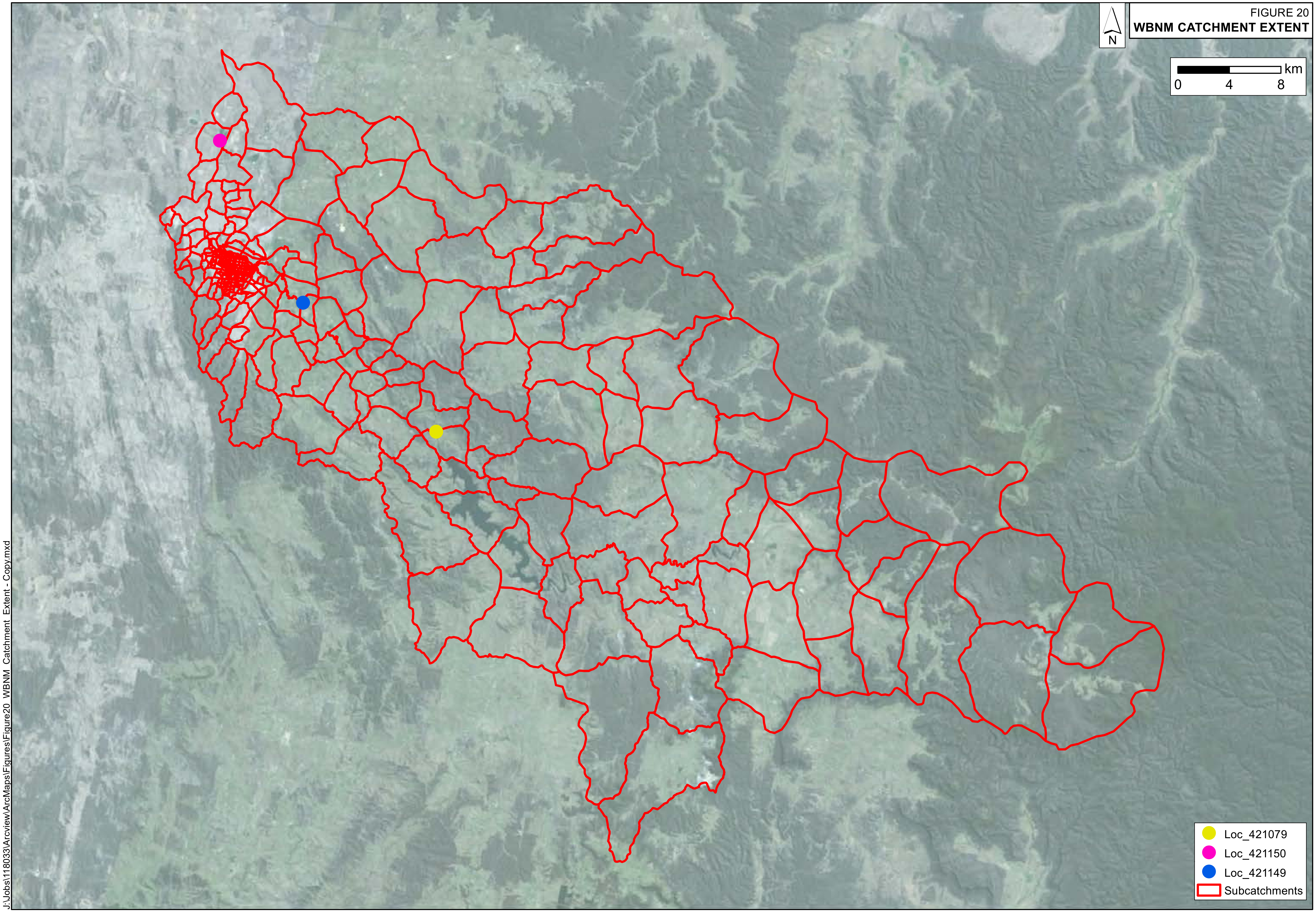
FIGURE 20
WBNM CATCHMENT EXTENT
N
km
0
4
8
Loc_421079
Loc_421150
Loc_421149
Subcatchments
J:\Jobs\118033\Arcview\ArcMaps\Figures\Figure20 WBNM Catchment Extent - Copy.mxd

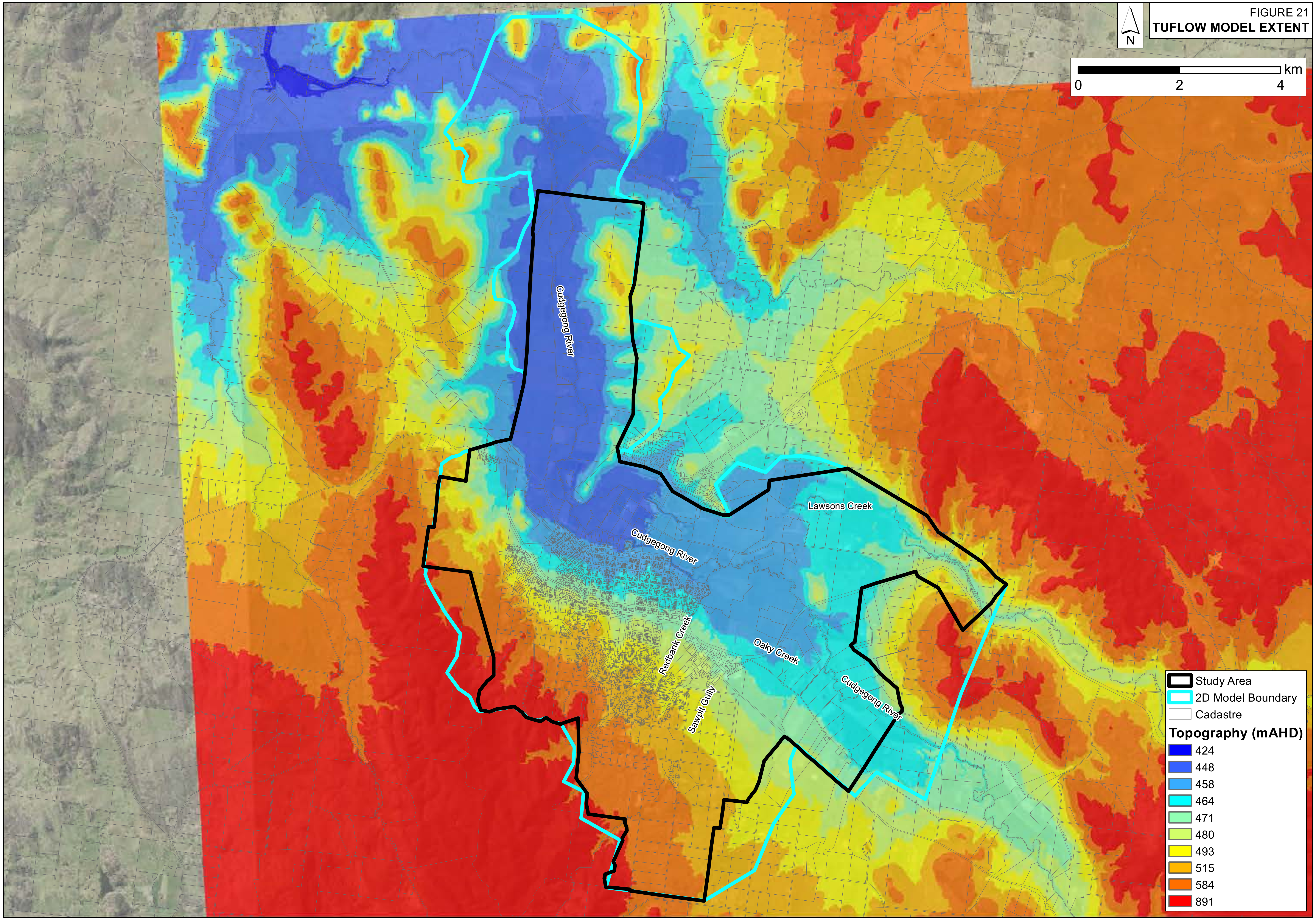

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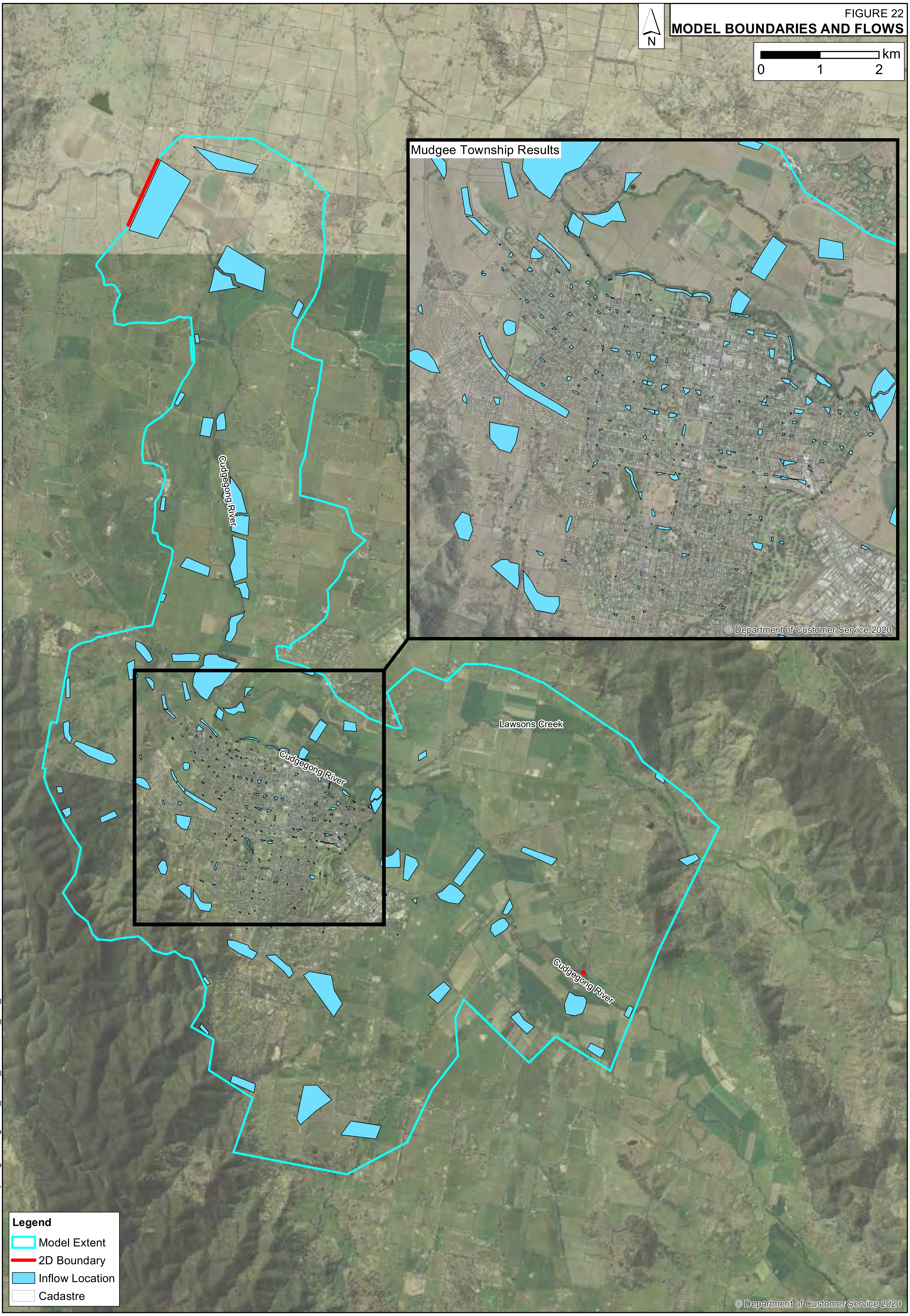
FIGURE 22
MODEL BOUNDARIES AND FLOWS



J:\Jobs\118033\Arcview\ArcMaps\Figures\Figure22_Model_Boundaries_and_Flows.mxd

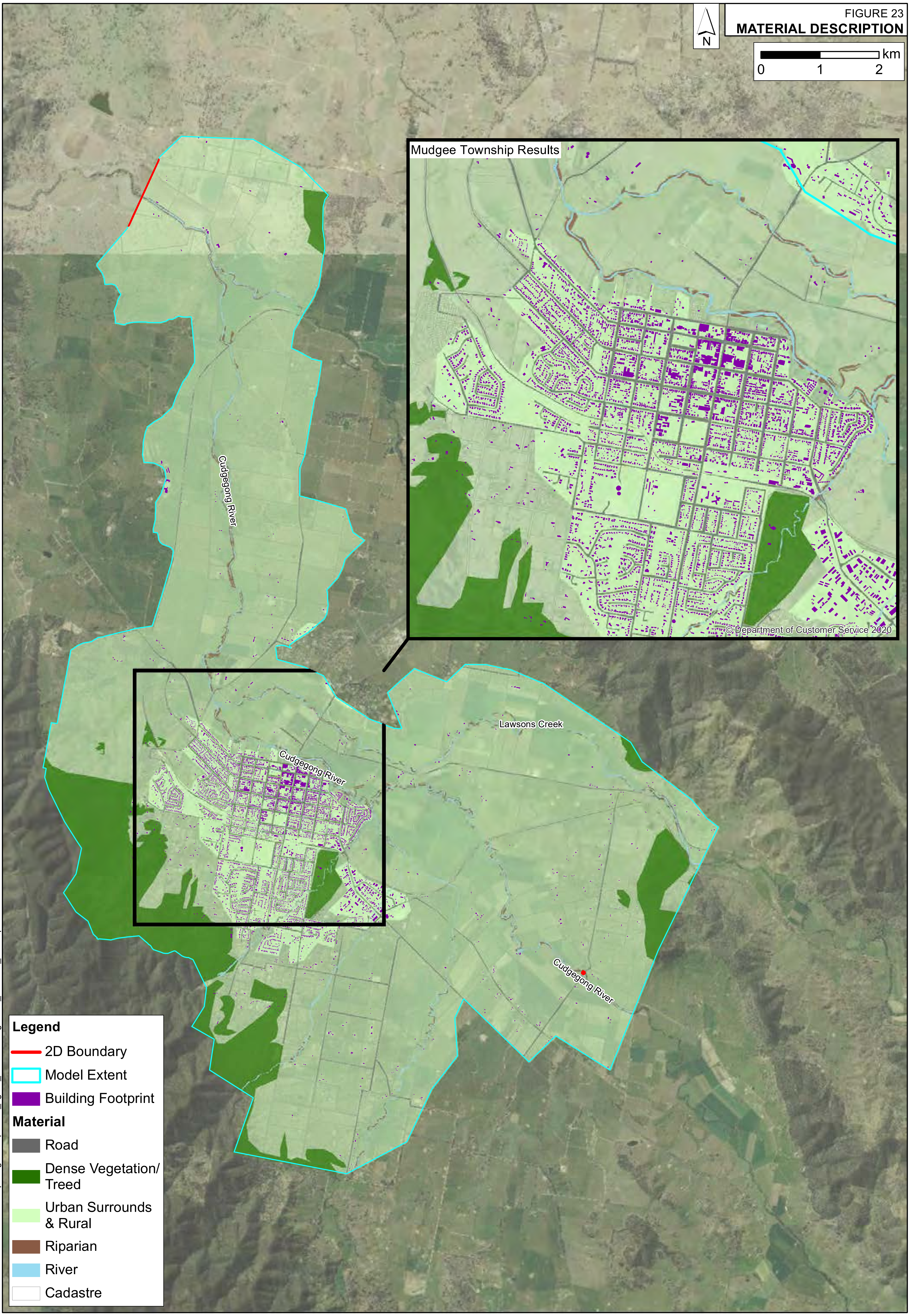


FIGURE 23
MATERIAL DESCRIPTION
N
km
0
1
2
Mudgee Township Results
© Department of Customer Service 2020
Cudgegong River
Lawsons Creek
Cudgegong River
Cudgegong River
Legend
2D Boundary
Model Extent
Building Footprint
Material
Road
Dense Vegetation/ Treed
Urban Surrounds & Rural
Riparian
River
Cadastre
J:\Jobs\118033\Arcview\ArcMaps\Figures\updated_figure_numbers\Figure23_Material_Description.mxd

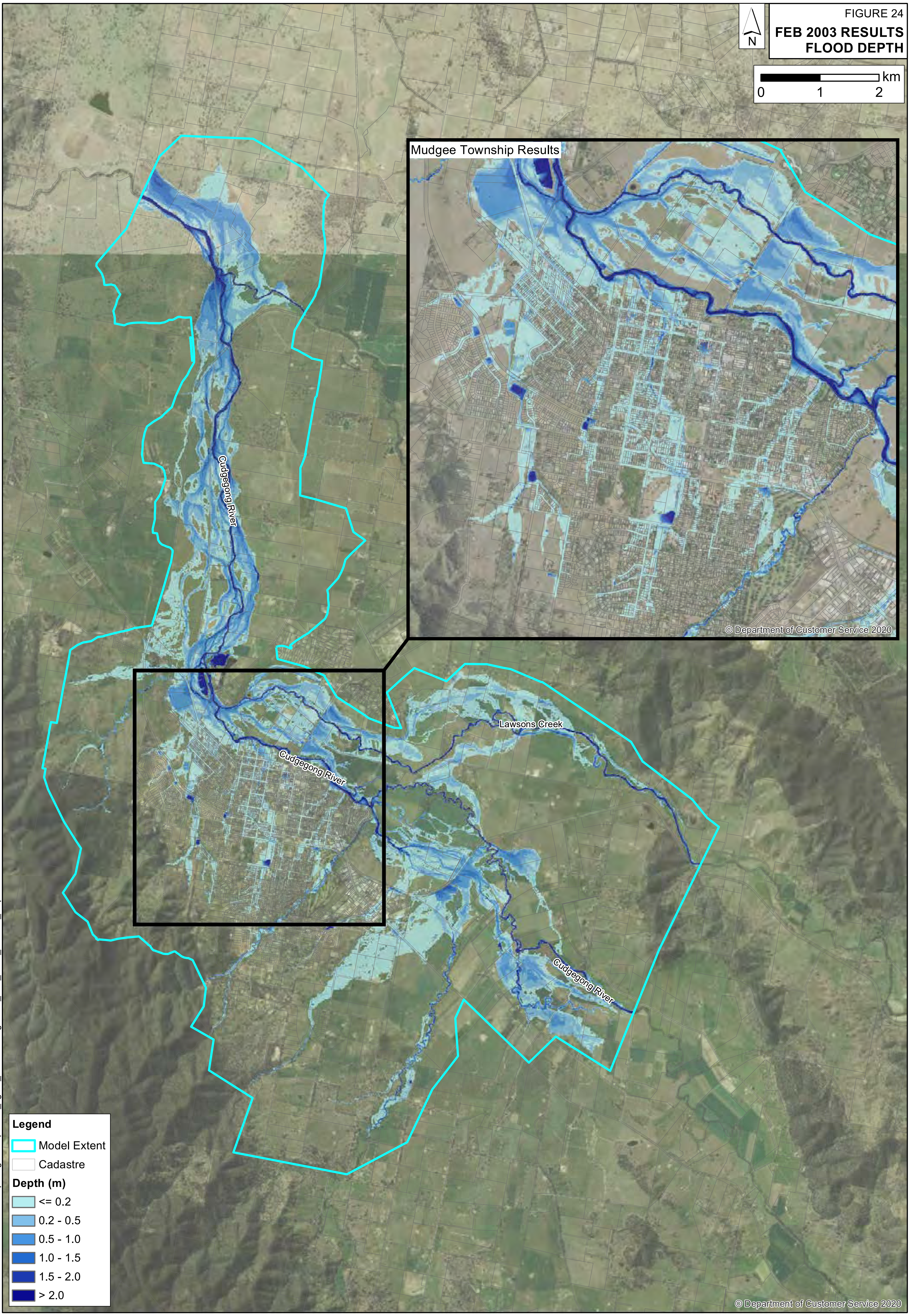


FIGURE 24
FEB 2003 RESULTS
FLOOD DEPTH
N
km
0
1
2
Mudgee Township Results
© Department of Customer Service 2020
Cudgegong River
Lawsons Creek
Cudgegong River
Cudgegong River
Legend
Model Extent
Cadastre
Depth (m)
<= 0.2
0.2 - 0.5
0.5 - 1.0
1.0 - 1.5
1.5 - 2.0
> 2.0
© Department of Customer Service 2020
J:\Jobs\118033\Arcview\ArcMaps\Figures\updated_figure_numbers\Figure24_Feb_2003_Results_Depth.mxd

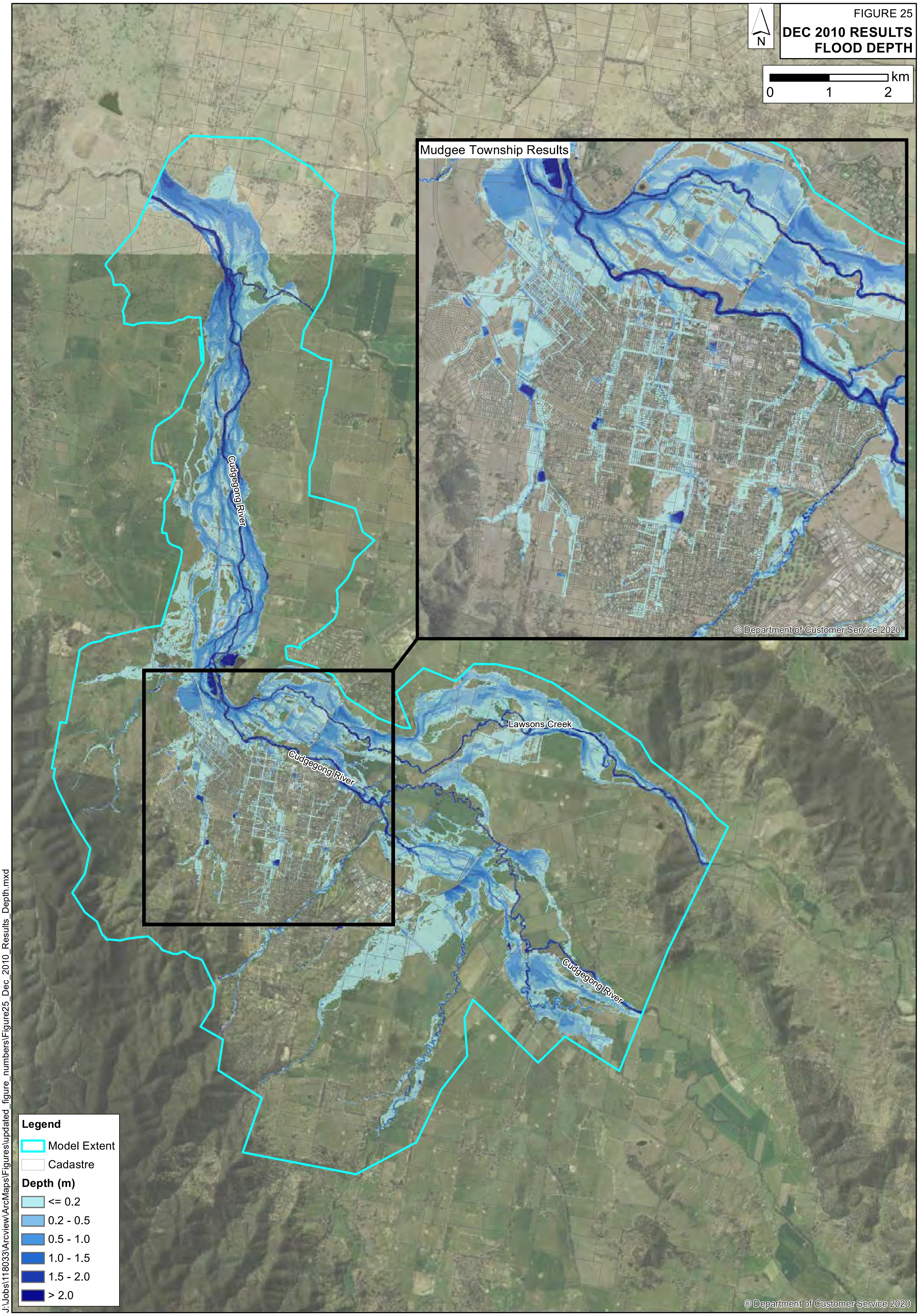


FIGURE 25
DEC 2010 RESULTS
FLOOD DEPTH
N
km
0
1
2
Mudgee Township Results
© Department of Customer Service 2020
Cudgegong River
Lawsons Creek
Cudgegong River
Cudgegong River
Legend
Model Extent
Cadastre
Depth (m)
<= 0.2
0.2 - 0.5
0.5 - 1.0
1.0 - 1.5
1.5 - 2.0
> 2.0
© Department of Customer Service 2020
J:\Jobs\118033\Arcview\ArcMaps\Figures\updated_figure_numbers\Figure25_Dec_2010_Results_Depth.mxd

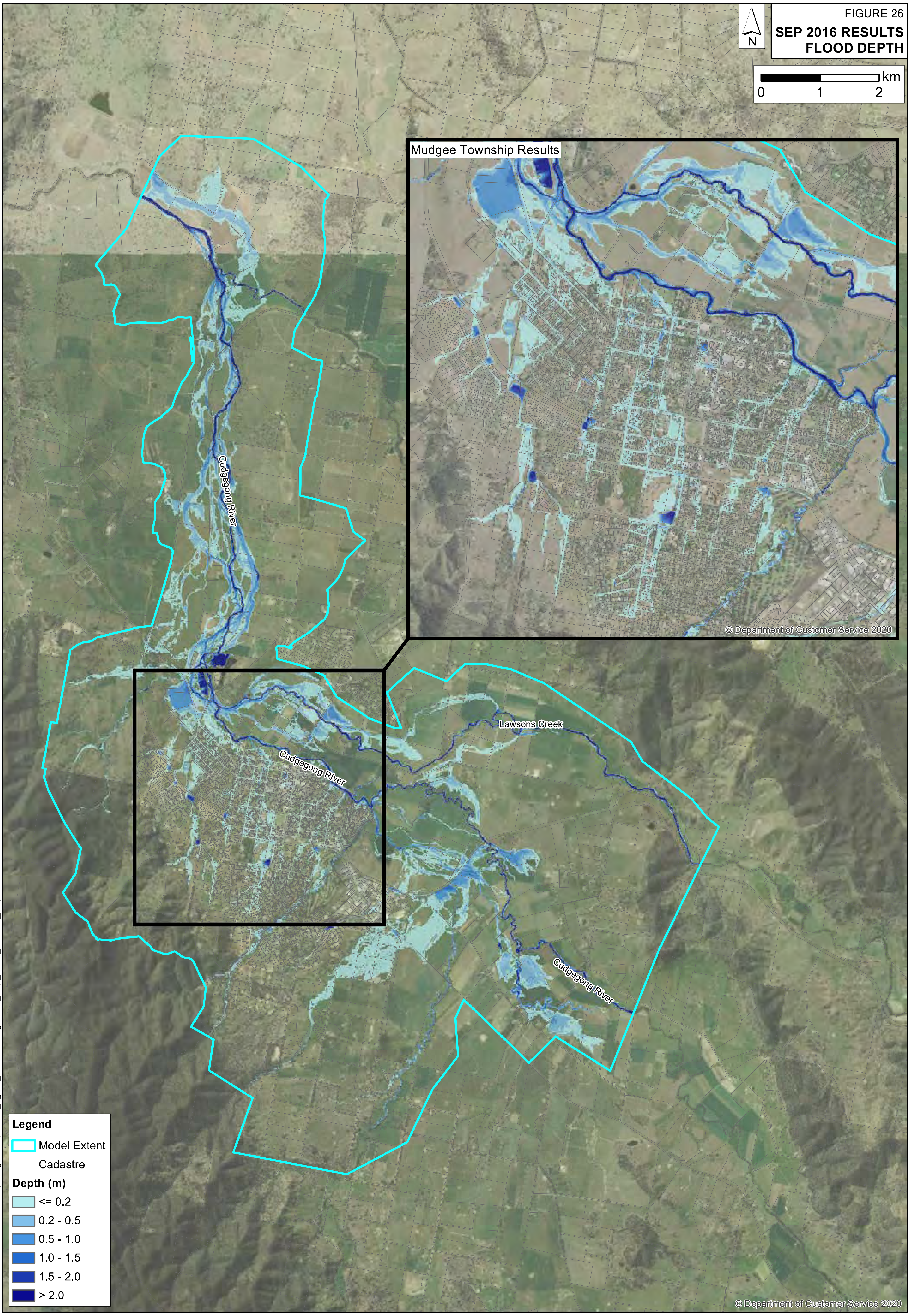


FIGURE 26
SEP 2016 RESULTS
FLOOD DEPTH
N
km
0
1
2
Mudgee Township Results
© Department of Customer Service 2020
Cudgegong River
Lawsons Creek
Cudgegong River
Cudgegong River
Legend
Model Extent
Cadastre
Depth (m)
<= 0.2
0.2 - 0.5
0.5 - 1.0
1.0 - 1.5
1.5 - 2.0
> 2.0
© Department of Customer Service 2020
J:\Jobs\118033\Arcview\ArcMaps\Figures\updated_figure_numbers\Figure26_Sep_2016_Results_Depth.mxd

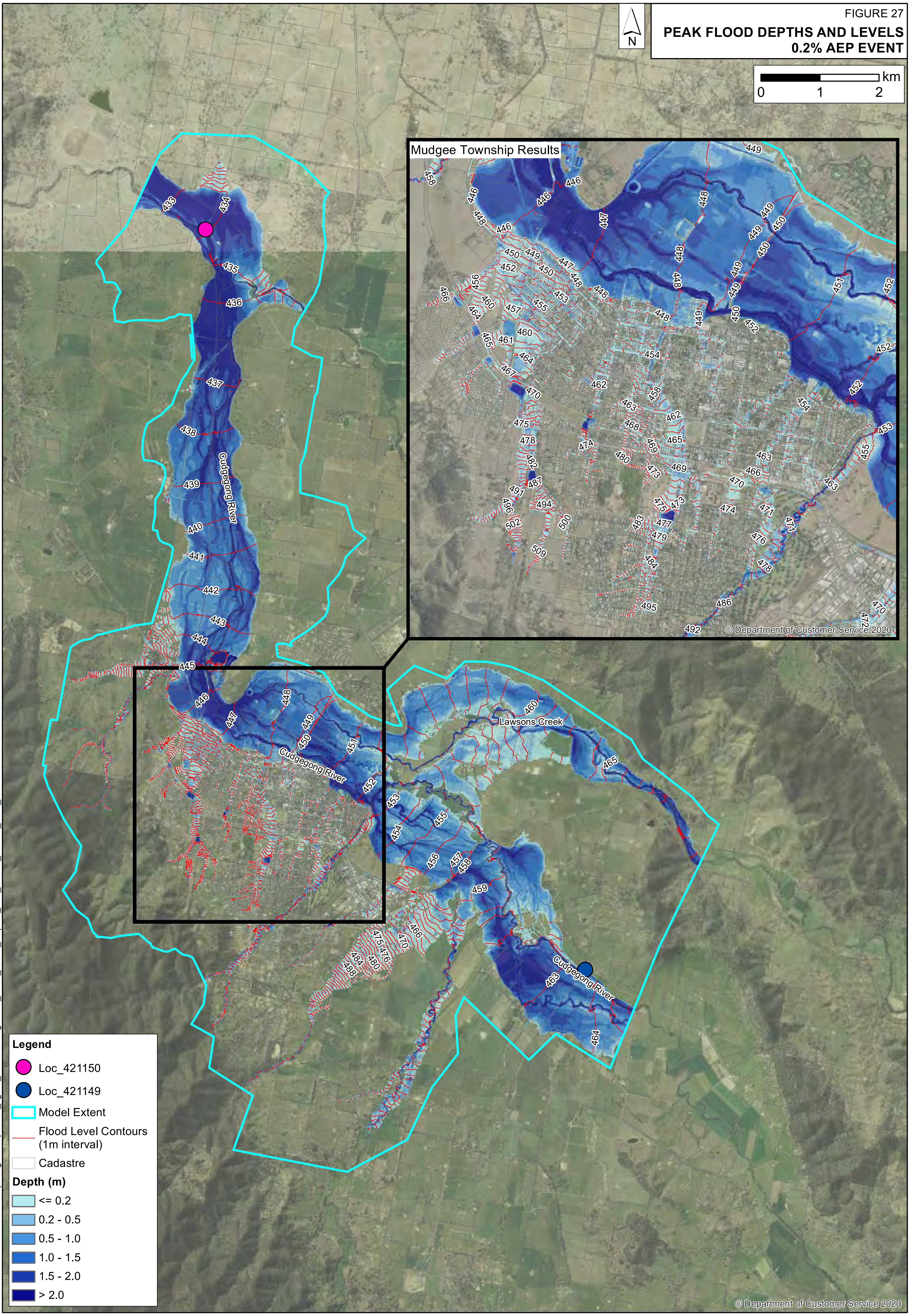


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FIGURE 28
PEAK FLOOD DEPTHS AND LEVELS
0.5% AEP EVENT

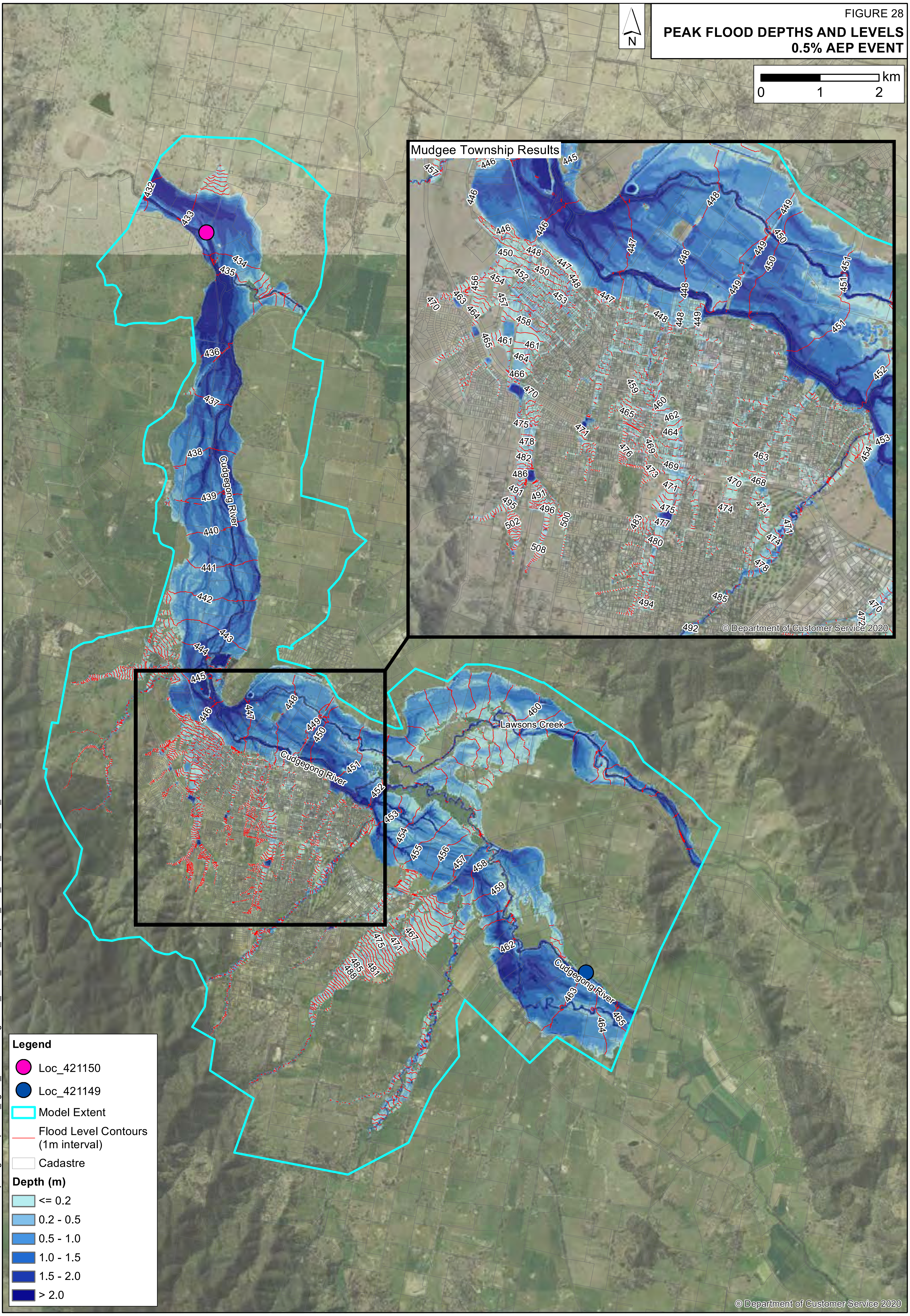

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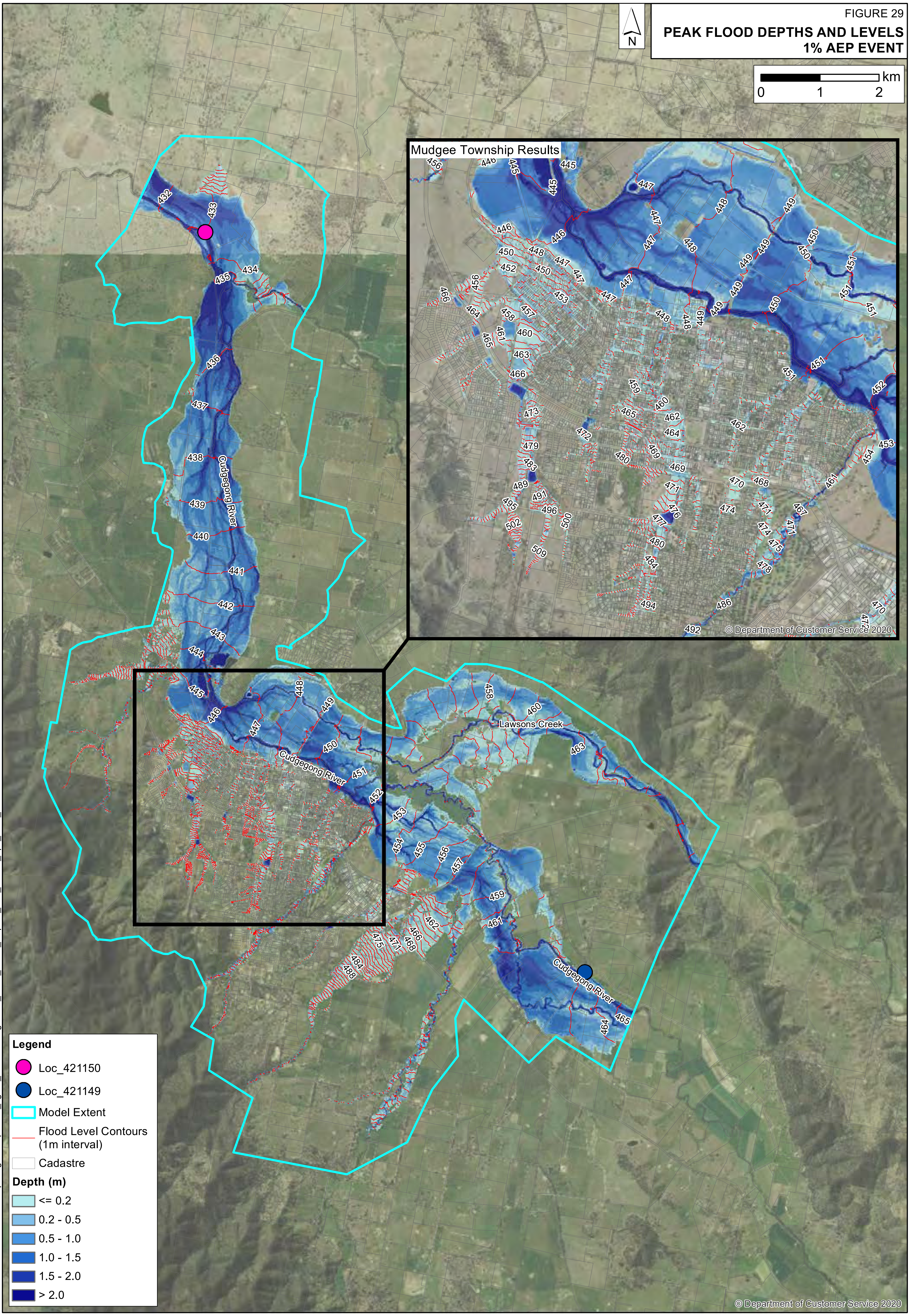
FIGURE 29

PEAK FLOOD DEPTHS AND LEVELS
1% AEP EVENT



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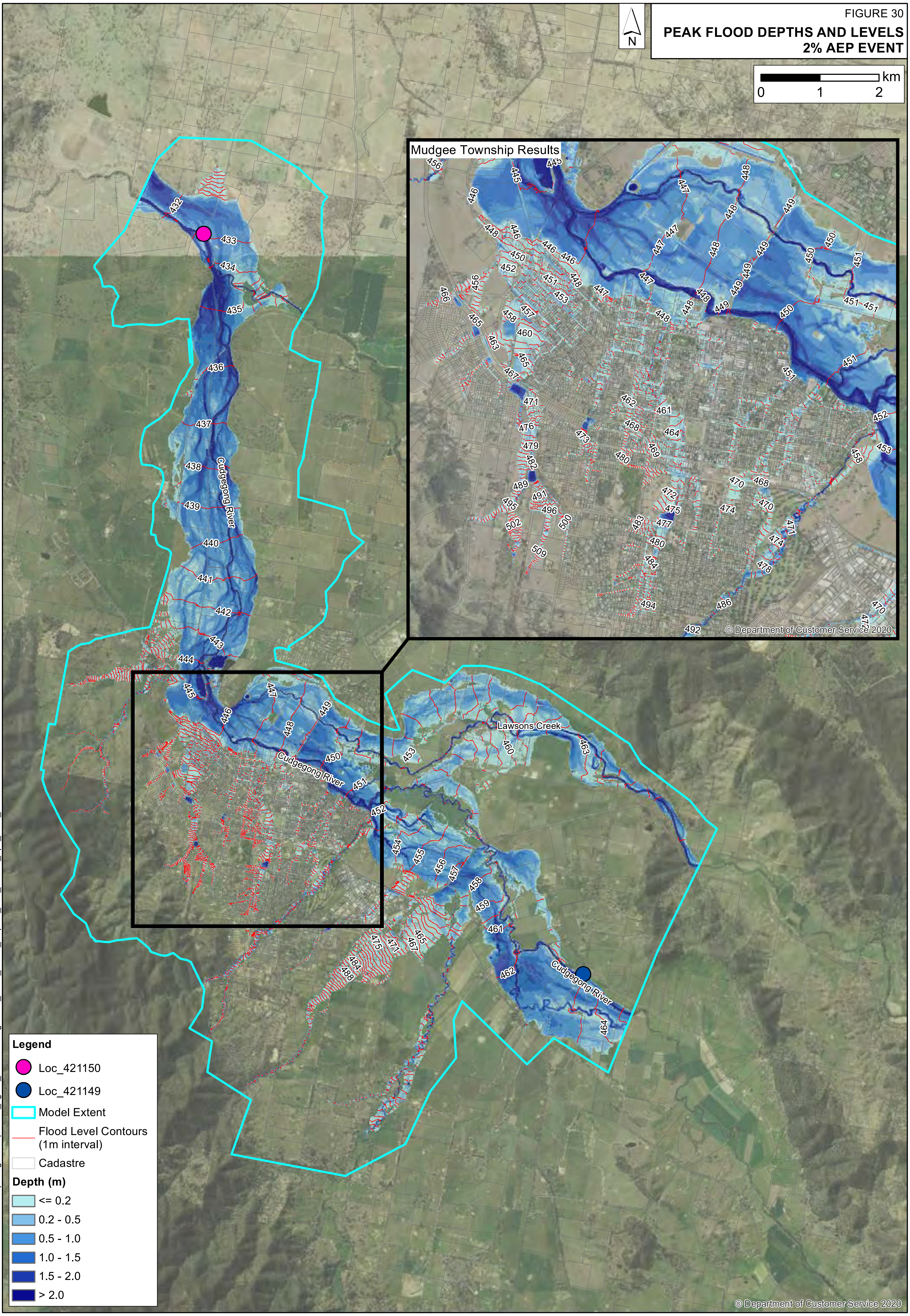

FIGURE 30
PEAK FLOOD DEPTHS AND LEVELS
2% AEP EVENT
N
km
0
1
2
Mudgee Township Results
Cudgegong River
Lawsons Creek
Legend
Loc_421150
Loc_421149
Model Extent
Flood Level Contours (1m interval)
Cadastre
Depth (m)
<= 0.2
0.2 - 0.5
0.5 - 1.0
1.0 - 1.5
1.5 - 2.0
> 2.0
© Department of Customer Service 2020
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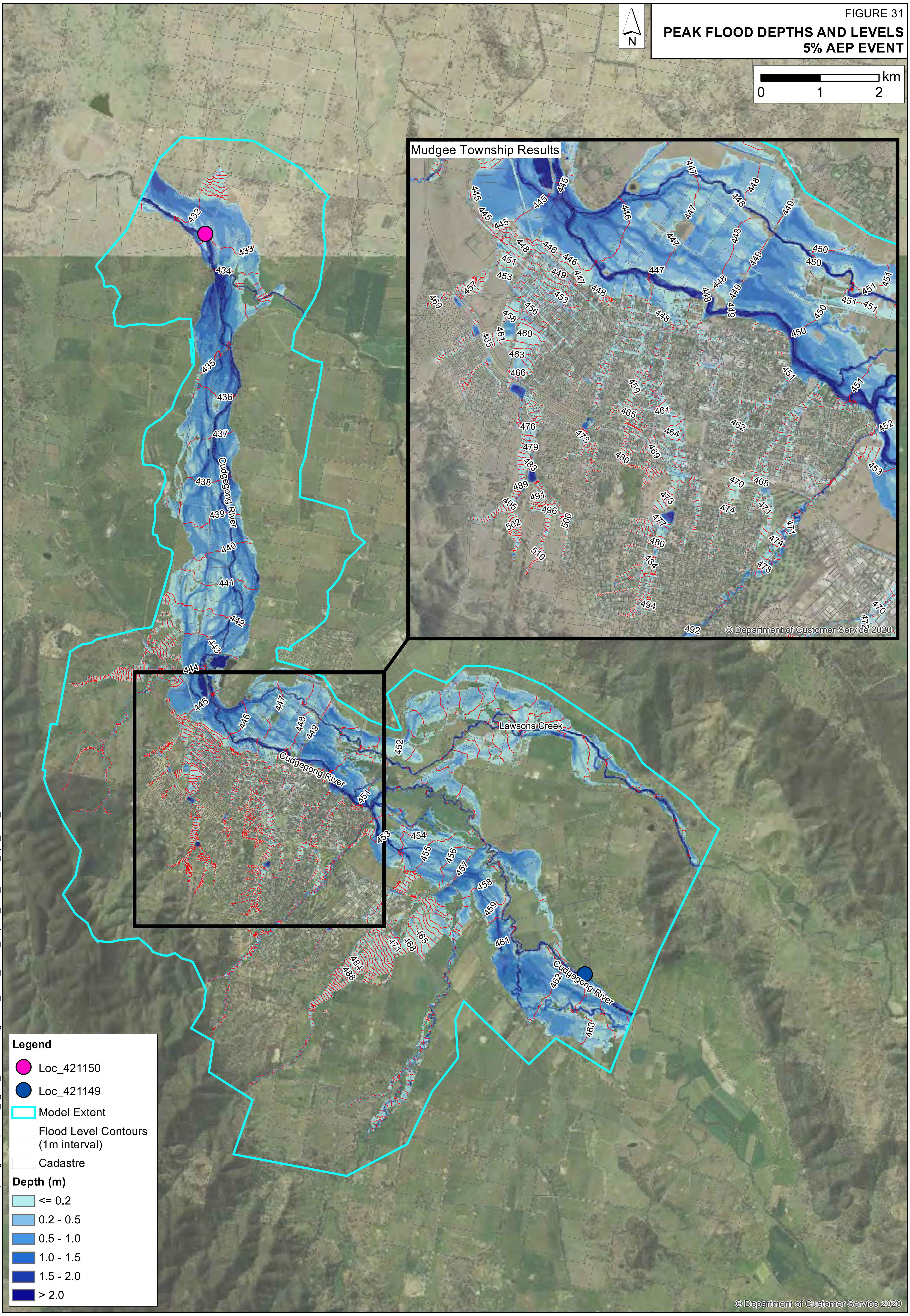
FIGURE 31
PEAK FLOOD DEPTHS AND LEVELS
5% AEP EVENT



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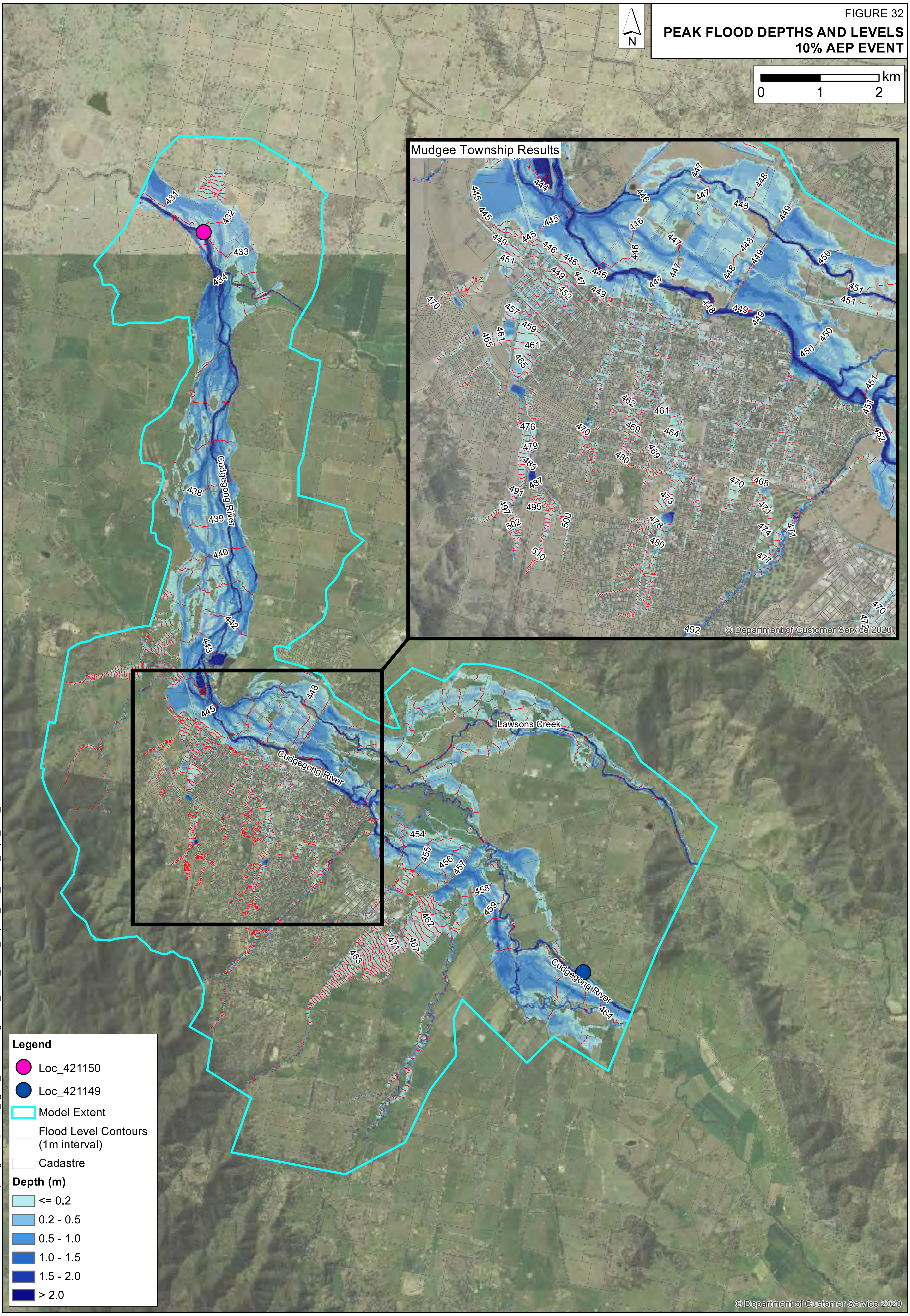
FIGURE 32
PEAK FLOOD DEPTHS AND LEVELS
10% AEP EVENT
N
km
0
1
2
Mudgee Township Results
Cudgegong River
Lawsons Creek
Legend
Loc_421150
Loc_421149
Model Extent
Flood Level Contours
(1m interval)
Cadastre
Depth (m)
<= 0.2
0.2 - 0.5
0.5 - 1.0
1.0 - 1.5
1.5 - 2.0
> 2.0
© Department of Customer Service 2020
J:\Jobs\118033\Arcview\ArcMaps\Figures\updated_figure_numbers\Figure32_Peak_Flood_Depths_and_Levels_10pc_AEP_Event.mxd

FIGURE 33
PEAK FLOOD DEPTHS AND LEVELS
20% AEP EVENT

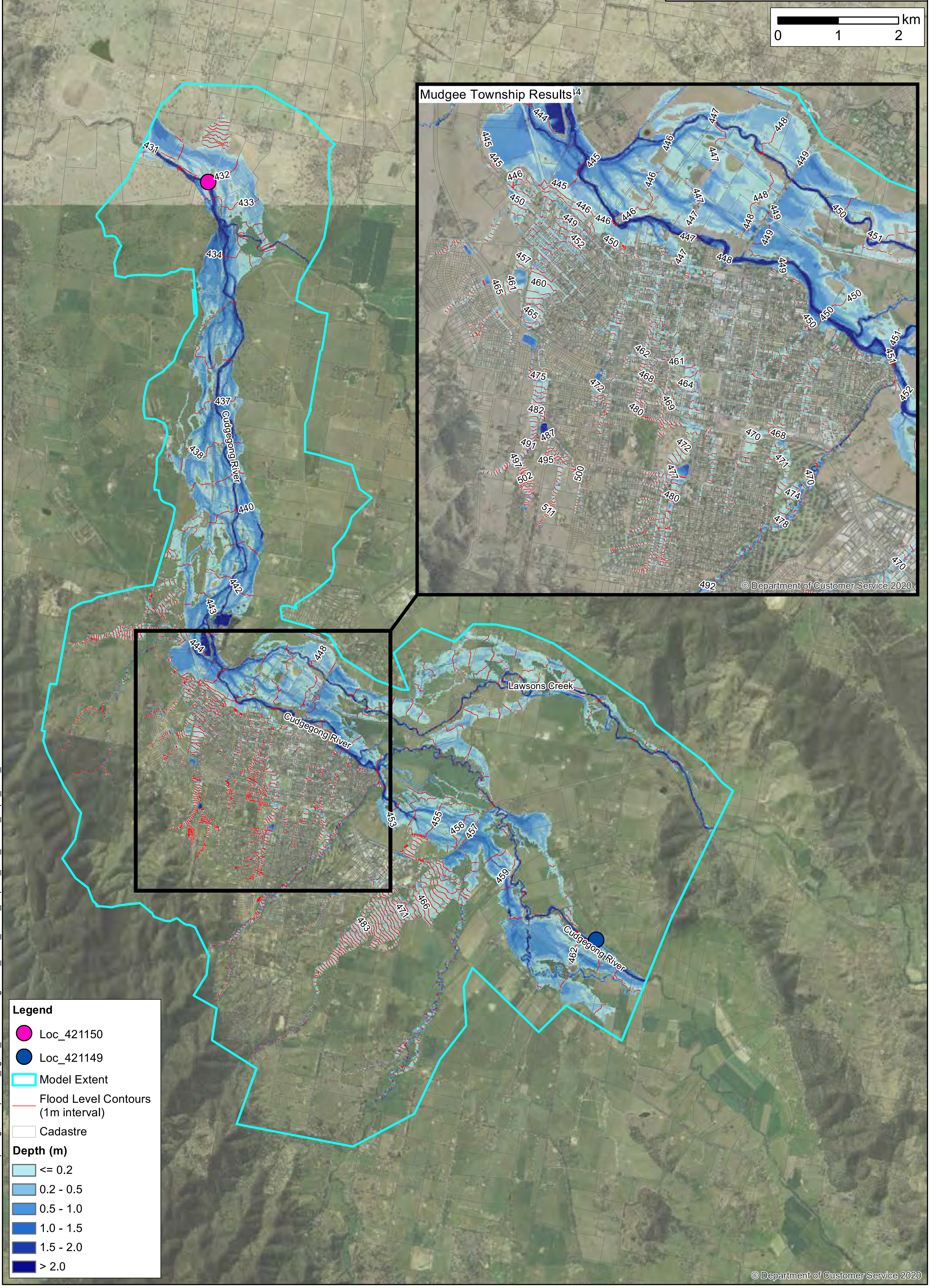

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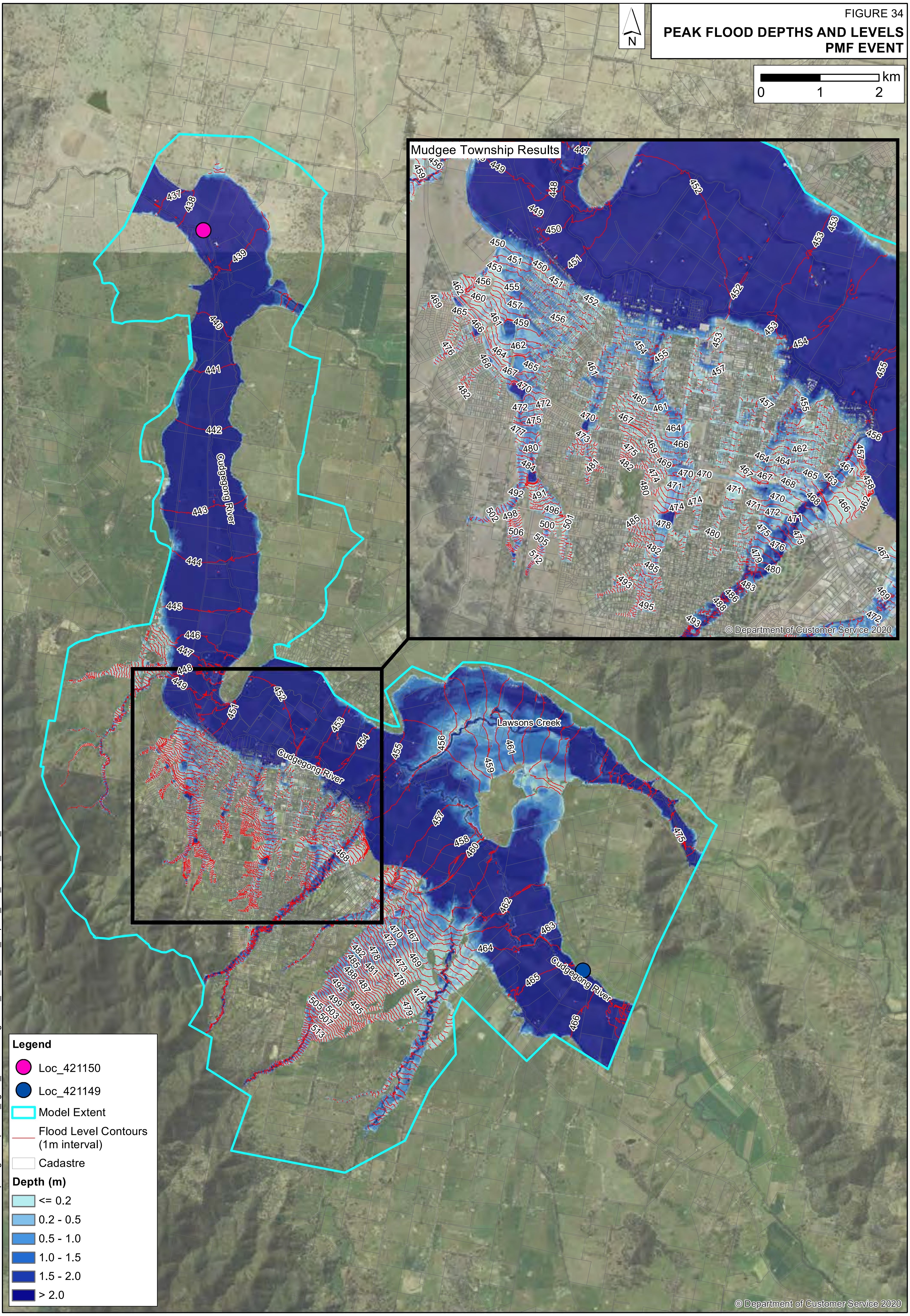
FIGURE 34
PEAK FLOOD DEPTHS AND LEVELS PMF EVENT



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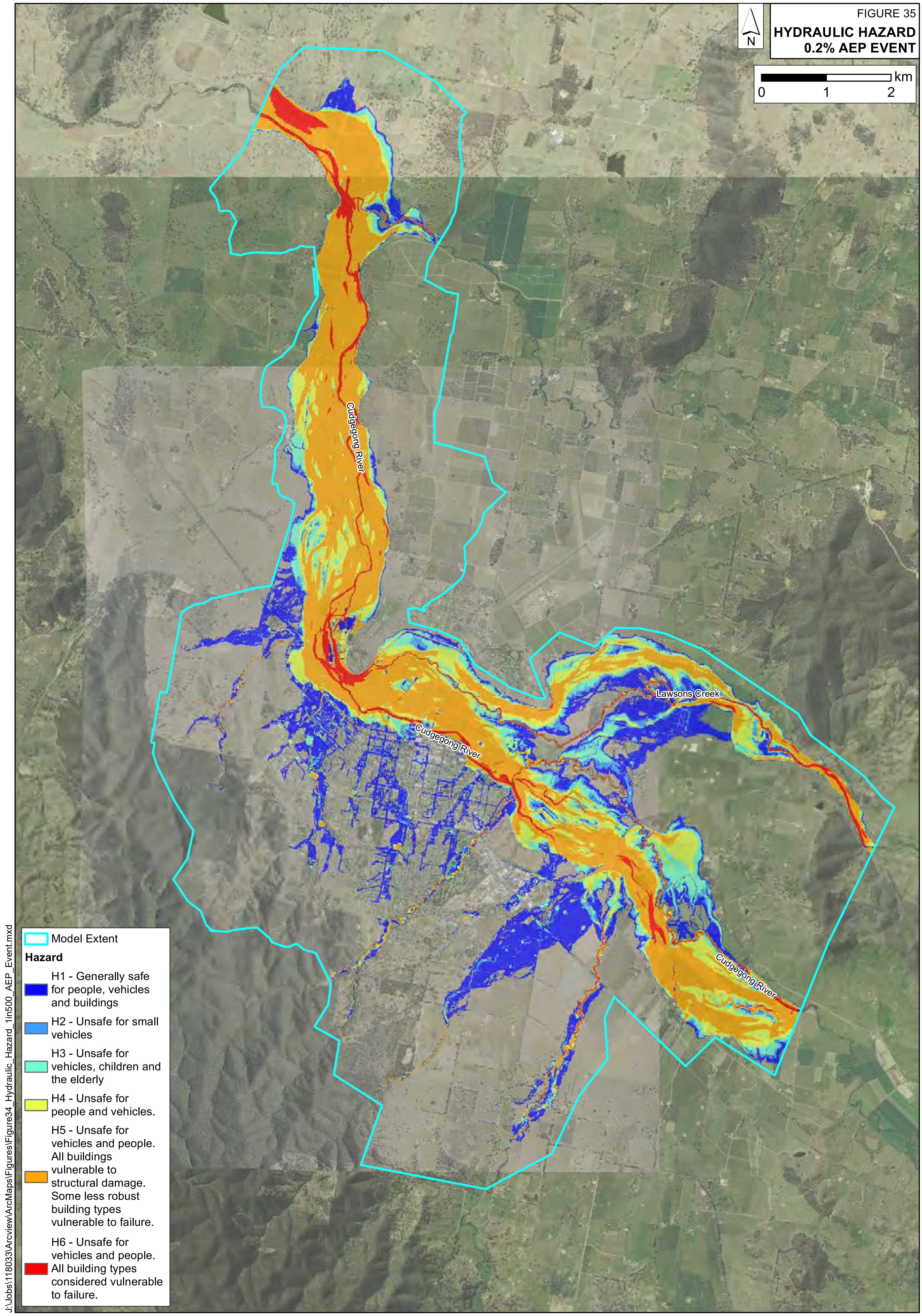

FIGURE 35
HYDRAULIC HAZARD
0.2% AEP EVENT
N
km
0
1
2
Cudgegong River
Lawsons Creek
Cudgegong River
Cudgegong River
Model Extent
Hazard
H1 - Generally safe for people, vehicles and buildings
H2 - Unsafe for small vehicles
H3 - Unsafe for vehicles, children and the elderly
H4 - Unsafe for people and vehicles.
H5 - Unsafe for vehicles and people. All buildings vulnerable to structural damage. Some less robust building types vulnerable to failure.
H6 - Unsafe for vehicles and people. All building types considered vulnerable to failure.
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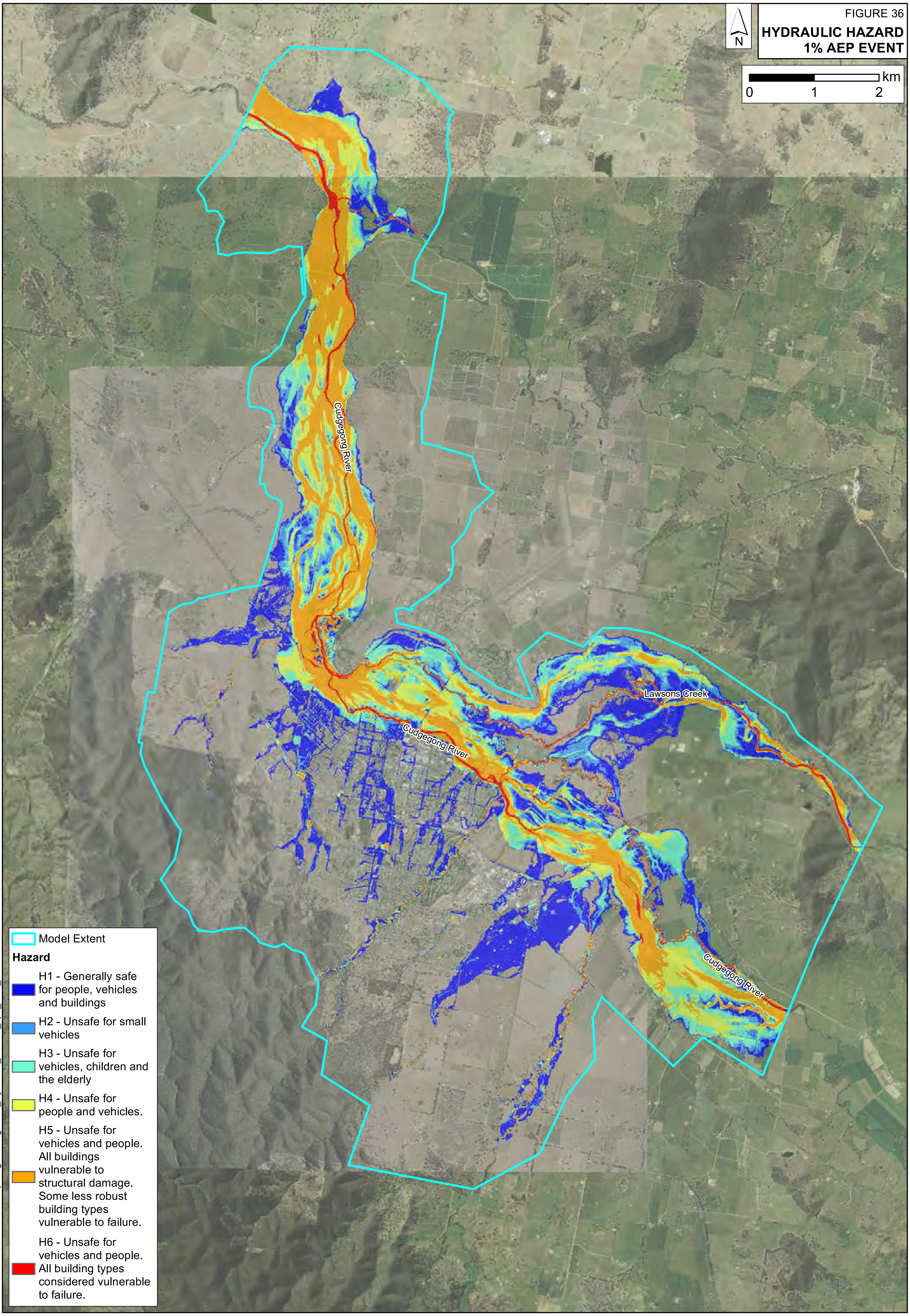
FIGURE 36
HYDRAULIC HAZARD 1% AEP EVENT



J:\Jobs\118033\Arcview\ArcMaps\Figures\Figure35_Hydraulic_Hazard_1pc_AEP_Event.mxd

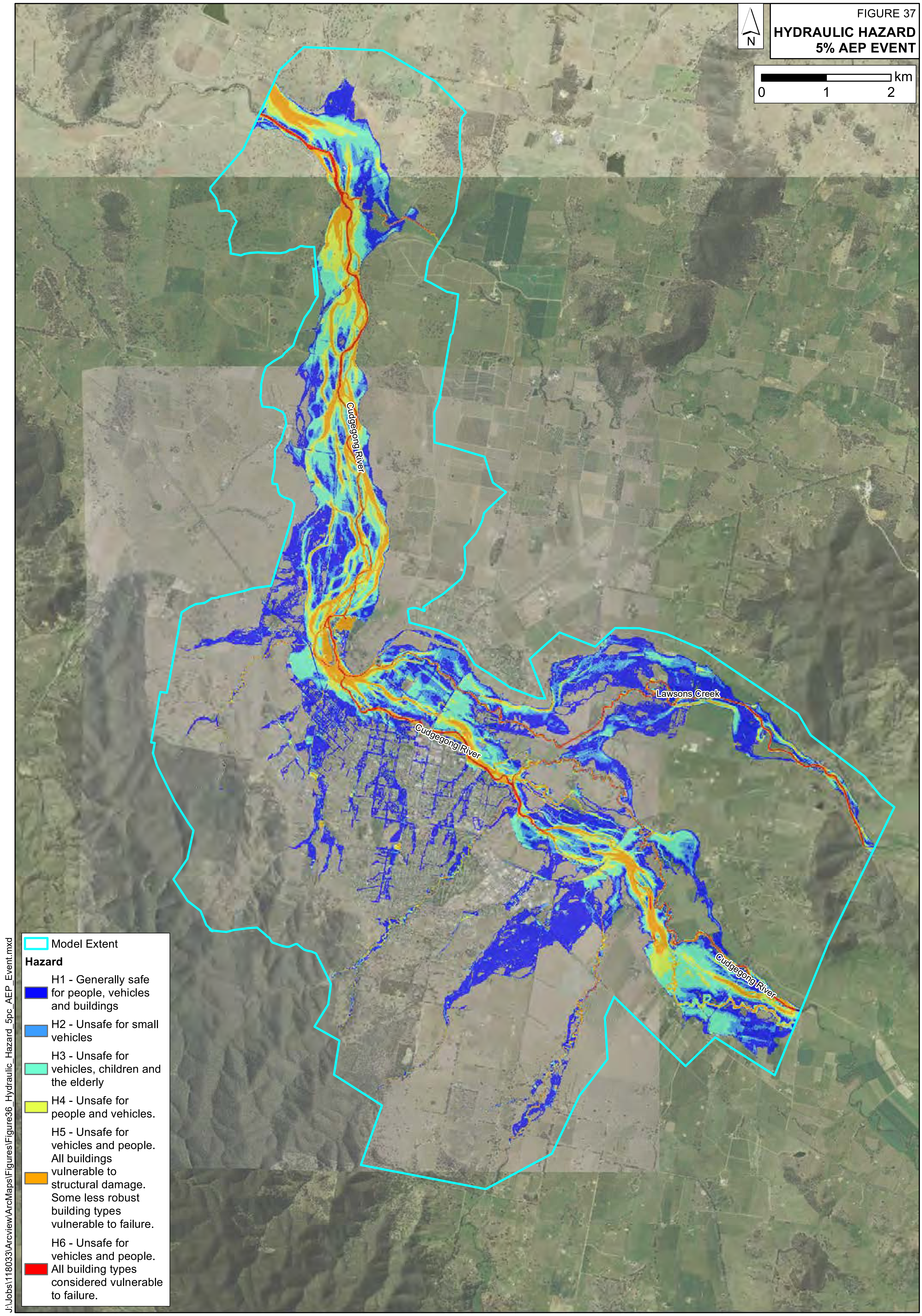


FIGURE 37
HYDRAULIC HAZARD
5% AEP EVENT
N
km
0
1
2
Cudgegong River
Cudgegong River
Lawsons Creek
Cudgegong River
Model Extent
Hazard
H1 - Generally safe for people, vehicles and buildings
H2 - Unsafe for small vehicles
H3 - Unsafe for vehicles, children and the elderly
H4 - Unsafe for people and vehicles.
H5 - Unsafe for vehicles and people. All buildings vulnerable to structural damage. Some less robust building types vulnerable to failure.
H6 - Unsafe for vehicles and people. All building types considered vulnerable to failure.
J:\Jobs\118033\Arcview\ArcMaps\Figures\Figure36_Hydraulic_Hazard_5pc_AEP_Event.mxd

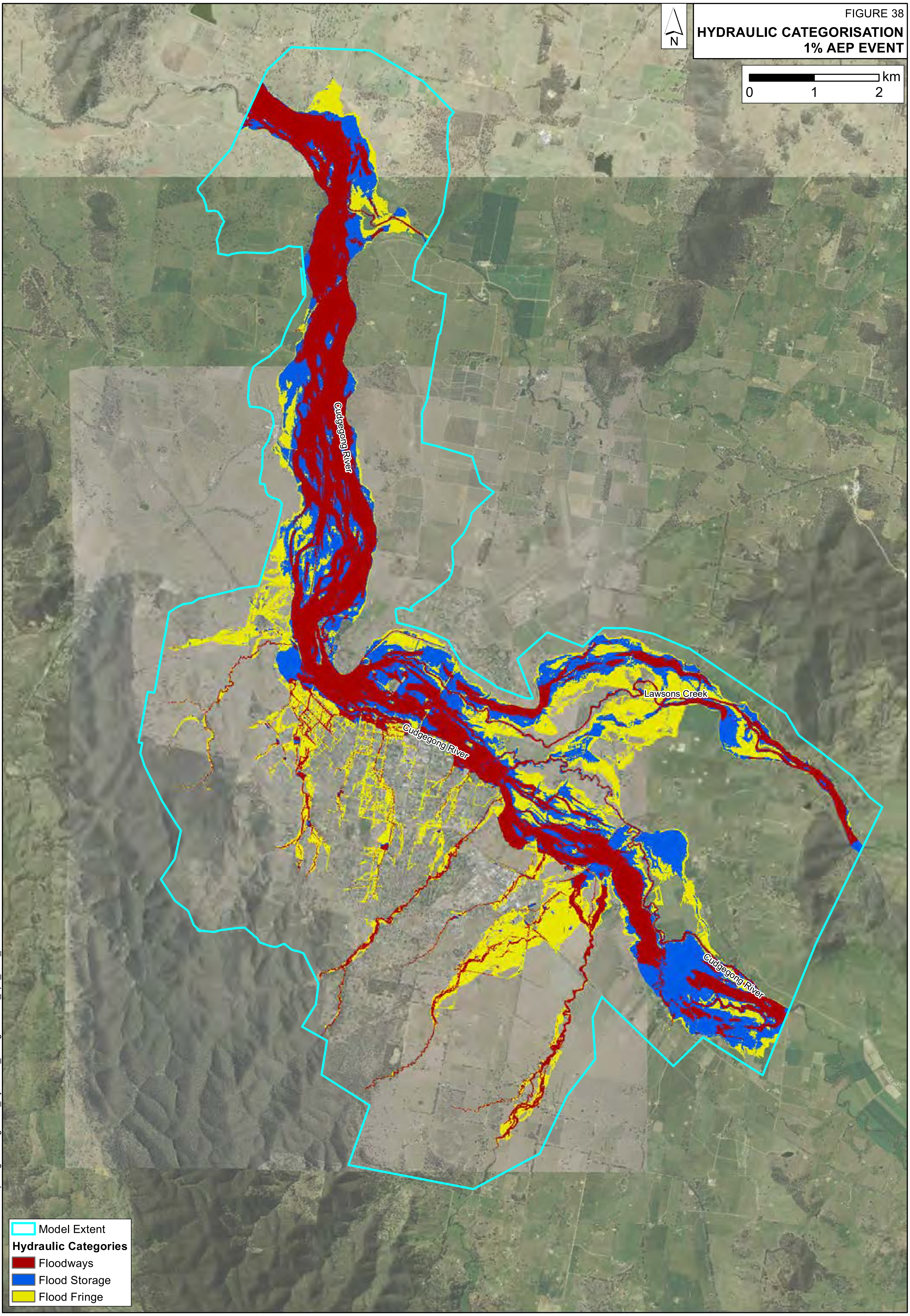


FIGURE 38
HYDRAULIC CATEGORISATION
1% AEP EVENT
N
km
0
1
2
Cudgegong River
Cudgegong River
Lawsons Creek
Cudgegong River
Model Extent
Hydraulic Categories
Floodways
Flood Storage
Flood Fringe
J:\Jobs\118033\Arcview\ArcMaps\Figures\Figure37_Hydraulic_Categorisation_1pc_AEP_Event.mxd

FIGURE 39

FLOOD EMERGENCY RESPONSE CLASSIFICATION (FERC)
PMF EVENT

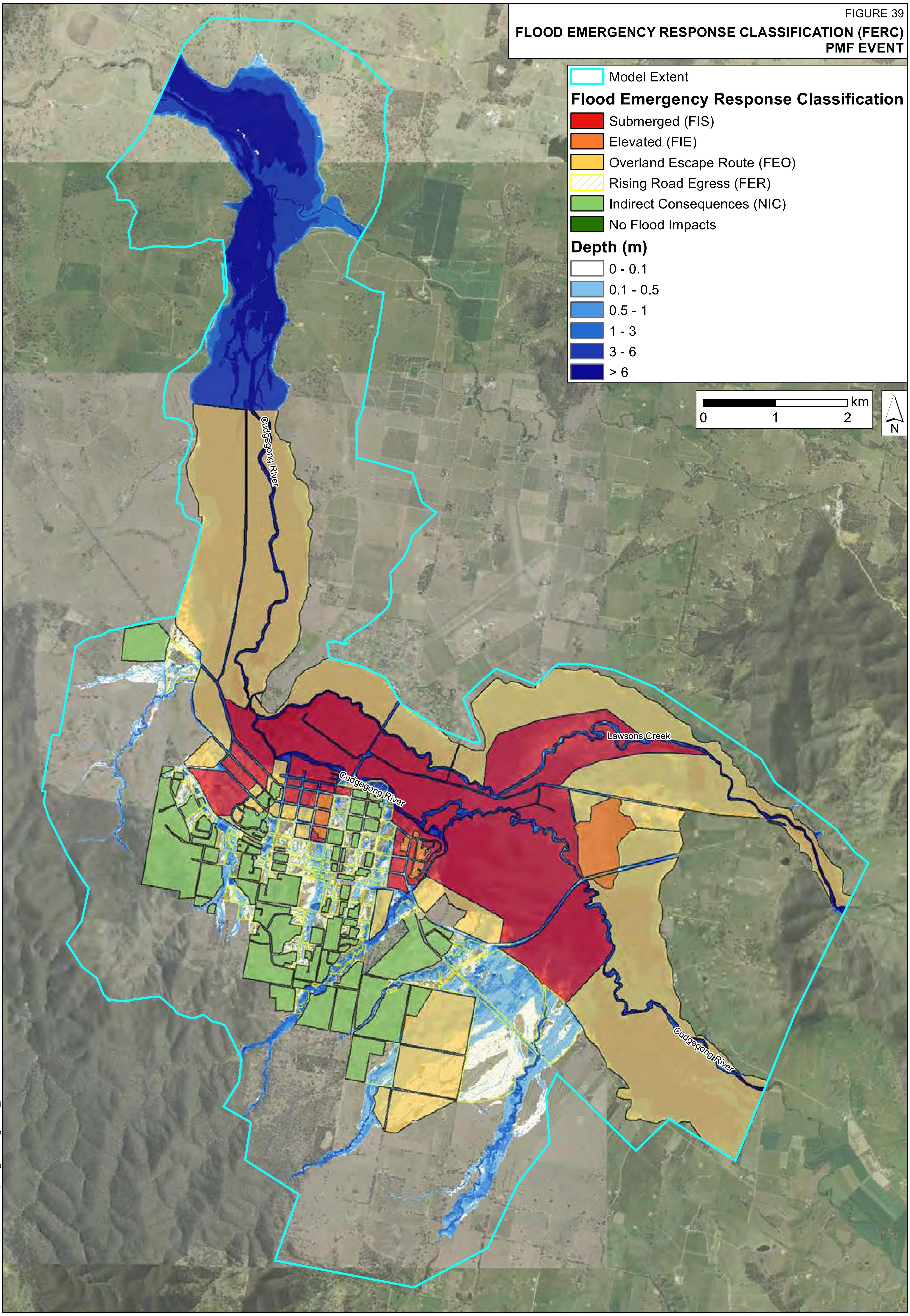


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FIGURE 40

CONSEQUENCES OF FLOODING TO THE COMMUNITY PROPERTY INUNDATED > 50MM

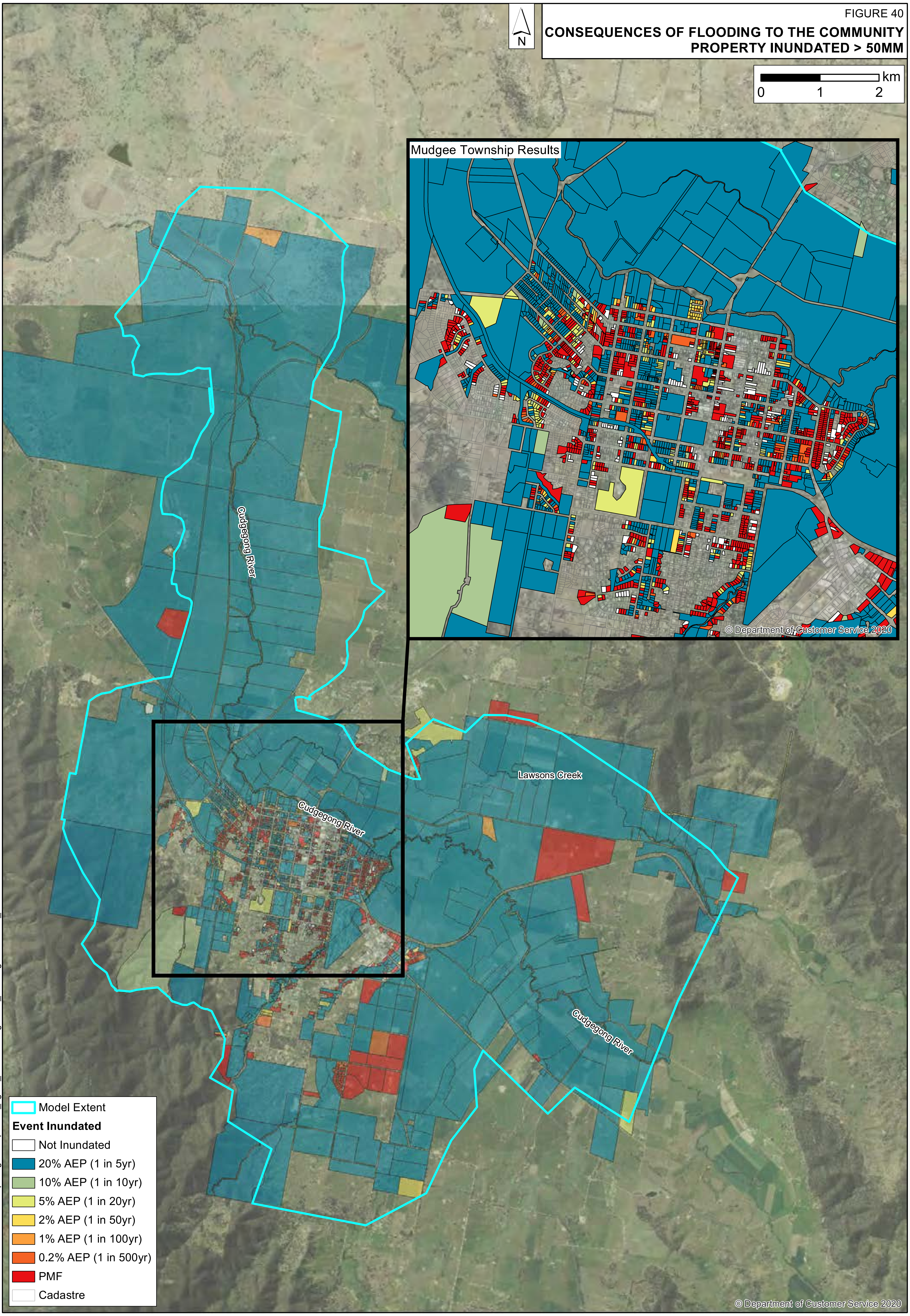

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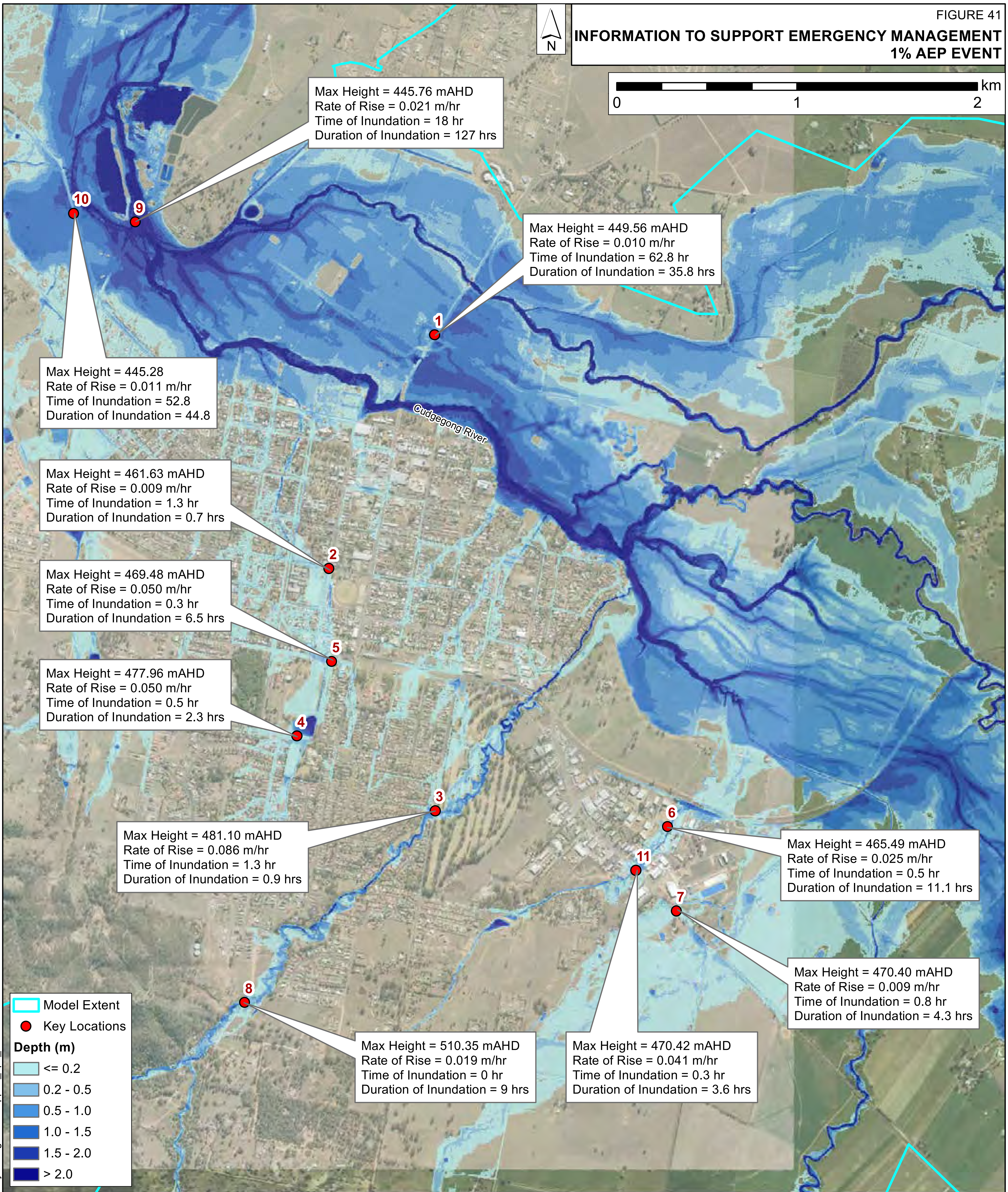
FIGURE 41

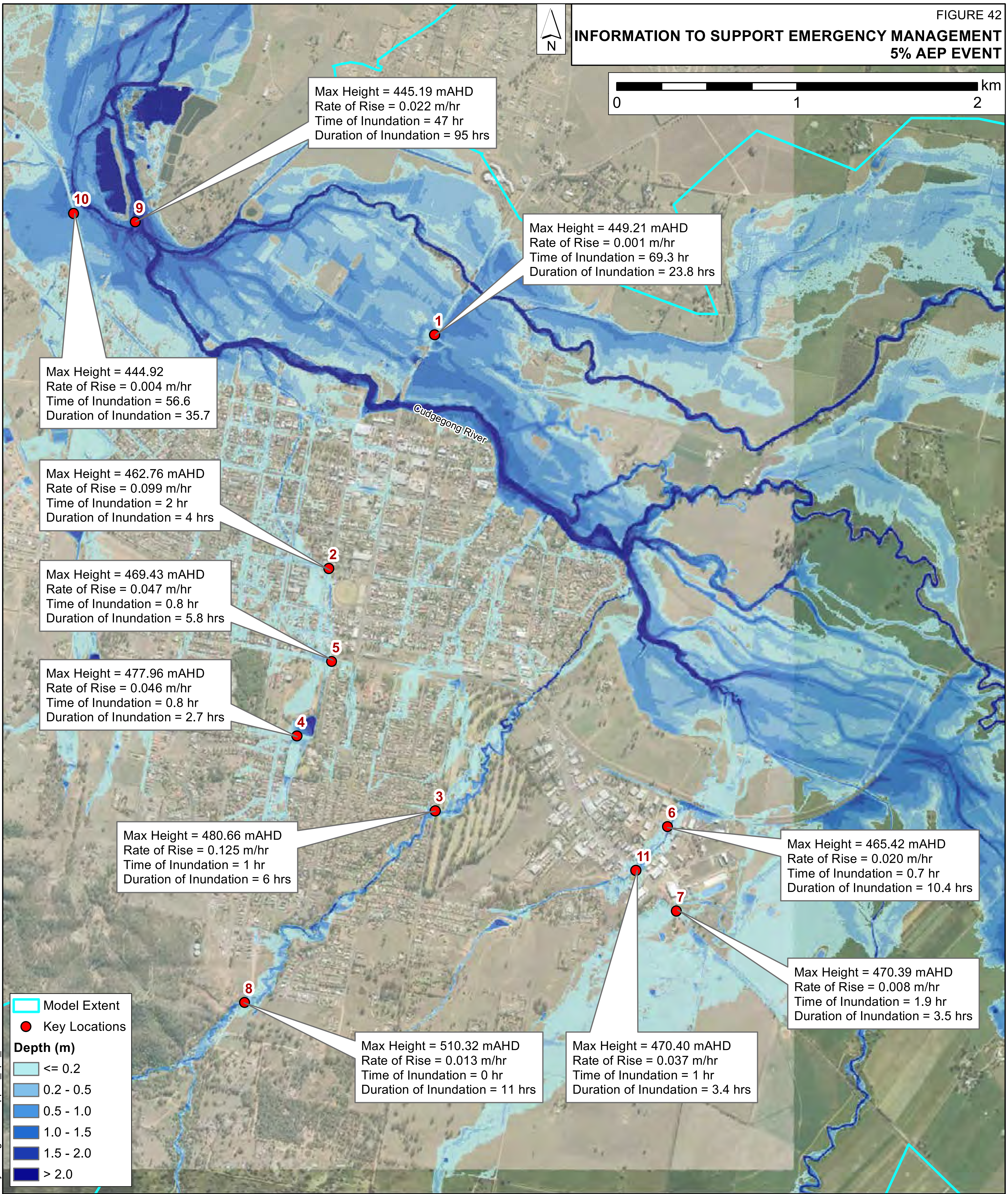
INFORMATION TO SUPPORT EMERGENCY MANAGEMENT 1% AEP EVENT



INFORMATION TO SUPPORT EMERGENCY MANAGEMENT AT KEY LOCATIONS

1. Ulan Rd at Lue Rd
2. Denison Street at Perry Street
3. Robertson Street
4. Madeira Road at Mudgee Showground
5. Nicholson Street at Atkinson Street
6. Inudstrial Avenue
7. Castlereagh Highway at Bunnings Mudgee
8. Waterworks Road at Redbank Creek
9. Putta Bucca Road at Cudgegon River
10. Castlereagh Highway South of Wilbetree Road
11. Castlereagh Highway South at Sawpit Gully

FIGURE 42
INFORMATION TO SUPPORT EMERGENCY MANAGEMENT
5% AEP EVENT



INFORMATION TO SUPPORT EMERGENCY MANAGEMENT AT KEY LOCATIONS

1. Ulan Rd at Lue Rd
2. Denison Street at Perry Street
3. Robertson Street
4. Madeira Road at Mudgee Showground
5. Nicholson Street at Atkinson Street
6. Inudstrial Avenue
7. Castlereagh Highway at Bunnings Mudgee
8. Waterworks Road at Redbank Creek
9. Putta Bucca Road at Cudgegon River
10. Castlereagh Highway South of Wilbetree Road
11. Castlereagh Highway South at Sawpit Gully

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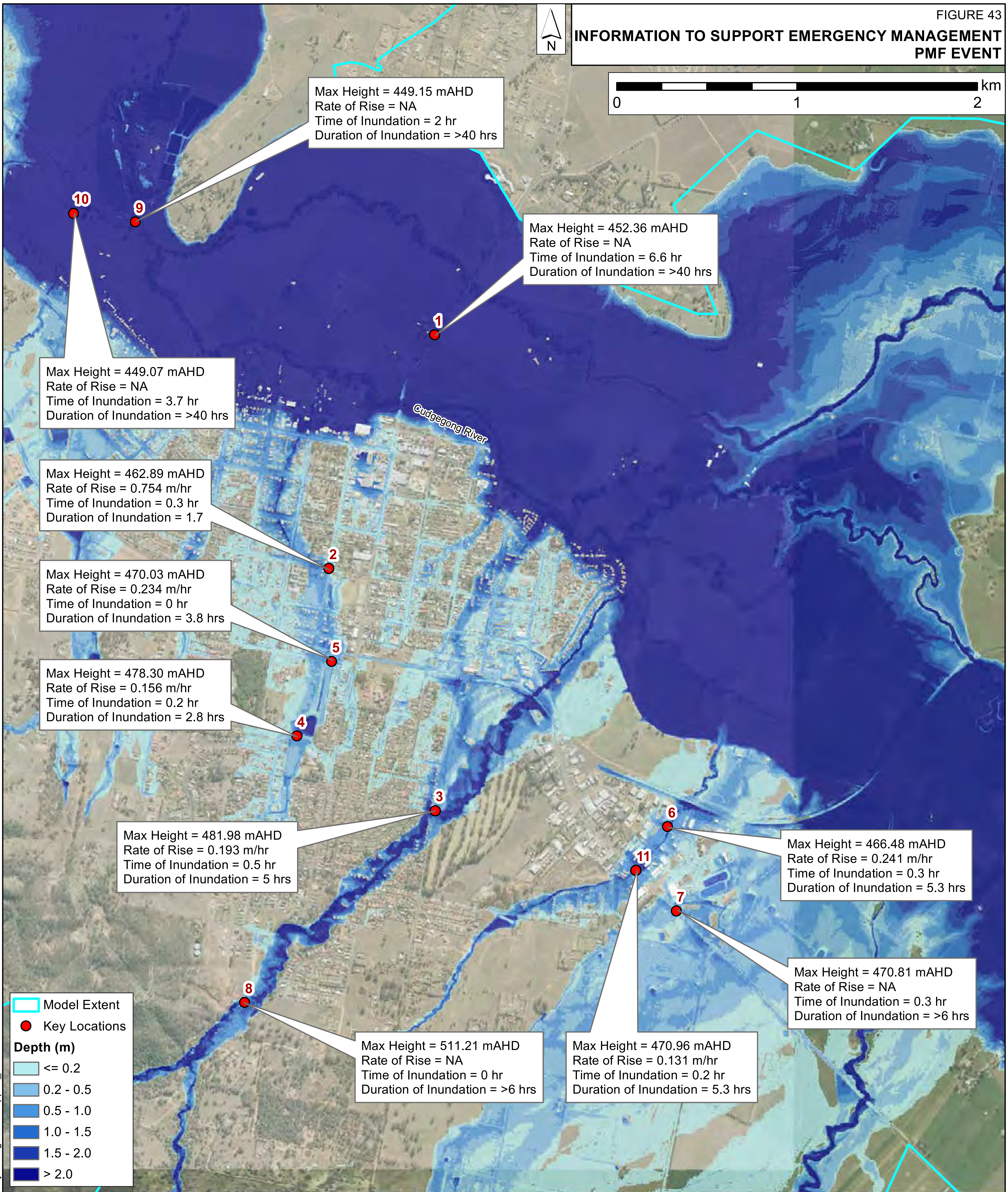

INFORMATION TO SUPPORT EMERGENCY MANAGEMENT AT KEY LOCATIONS

1. Ulan Rd at Lue Rd
2. Denison Street at Perry Street
3. Robertson Street
4. Madeira Road at Mudgee Showground
5. Nicholson Street at Atkinson Street
6. Inudstrial Avenue
7. Castlereagh Highway at Bunnings Mudgee
8. Waterworks Road at Redbank Creek
9. Putta Bucca Road at Cudgegon River
10. Castlereagh Highway South of Wilbetree Road
11. Castlereagh Highway South at Sawpit Gully

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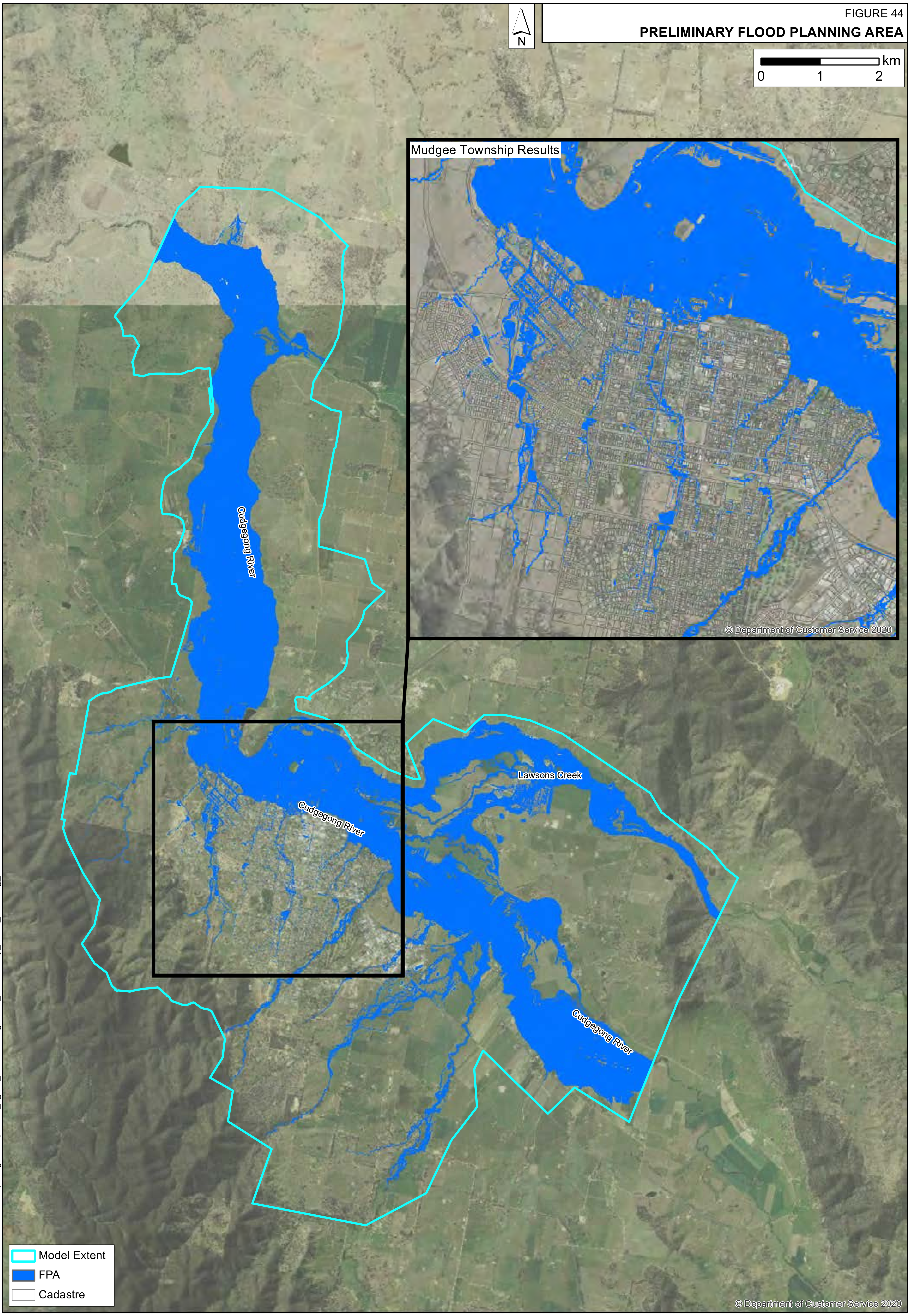
FIGURE 44

PRELIMINARY FLOOD PLANNING AREA



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